D6.3

Interim report on collaborative systems and DAPP approaches to develop forward looking DRM pathways

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D6.3/Interim report on collaborative systems and DAPP approaches to develop forward looking DRM pathways

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Abstract

This report presents findings on two key aspects of developing forward-looking DRM pathways: (1) feedback from pilot leads on their experience with implementing the proposed collaborative systems analysis approach outlined previously in D6.2 during the first round of pilot workshops (PW1), and; (2) 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.

Collaborative systems analysis approach

In Task 6.1, we developed an approach for collaborative systems analysis to allow 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 proposed approach therefore serves as a means by which to undertake the first step of the DAPP-MR approach (Figure 4 in this report) and the equivalent context setting-related elements of the proposed MYRIAD-EU framework for systemic multi-hazard and multi-risk assessment and management. Some of the pilots applied several of the collaborative tools that were presented in D6.2 according to which pilot teams felt most comfortable and were relevant to their workshop activities and practical needs (e.g., virtual versus in-person settings). Although the collaborative systems analysis approach was not applied either systematically or in full by any pilot, this was not the intention within the context of PW1, which also had other priorities. In general, pilots conducted relatively shallow analyses of their systems together with stakeholders, focussing primarily on those aspects relating most to step 1 of the MYRIAD-EU framework. Nevertheless, the pilots were generally positive about the proposed approach and its ability to achieve its objectives. The authors look forward to the pilots deepening their analyses though (adapted) applications of the remainder of the proposed approach as they move towards assessing risks and options and developing DRM pathways during subsequent pilot meetings.

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 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 which remained valid under increasing complexity.

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)

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Table of Contents

Table of Tables

Table of Figures

1 Introduction

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 manage risks presents as one of the key challenges for policy analysts and decision makers. This report presents findings on two key aspects of developing forward-looking DRM pathways: (1) feedback from pilots leads on their experience with implementing elements of the proposed collaborative systems analysis approach outlined previously in D6.2 during the first round of pilot workshops (PW1), and (2) 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. The report is divided into two main sections dealing with each of these aspects in turn.

2 Interim report on Collaborative Systems Analysis approach (D6.2)

Collaborative systems analysis approaches are needed for forward-looking adaptive multi-risk decision making for a variety of reasons, including: (1) to avoid negative consequences when approaching problems through a sector-specific lens; (2) to aid in the formulation of system-wide objectives that both recognise and balance the inherent trade-offs within our systems; (3) to ensure a more equitable distribution of system-wide resources, costs and benefits; and (4) to help reduce the potential for stakeholder conflict. In this light, the principal purpose of collaborative systems analysis approaches is to help describe complex and 'messy' decision-making contexts and to devise appropriate framings for effective policy analysis and planning.

2.1 MYRIAD-EU Collaborative Systems Analysis approach

The objective of Task 6.1 is to develop an approach for collaborative systems analysis to allow 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 and should include all relevant system characteristics, objectives and constraints in both the current and potential future situations. The proposed approach therefore serves as a means by which to undertake the first step of the DAPP-MR approach (see Figure 4 later in this report) and the equivalent context setting-related elements of the proposed framework for systemic multi-hazard and multi-risk assessment and management (Hochrainer-Stigler et al., 2023, see Section 2.2). It should be seen as complementary to the MYRIAD-EU framework and as a set of activities to help users step through the framework. 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 deliverable *D6.2 Guidance document for Pilots on collaborative systems analysis approaches* (Warren et al., 2022), presents findings of a literature review on promising tools and approaches for collaborative systems analysis. It reflects on these and proposes a flexible, generic approach to collaborative systems analysis to serve as a general roadmap for potential users to adapt to their specific needs, capabilities and resources. Within MYRIAD-EU, pilot leads began to adapt and test elements of the approach during PW1.

The proposed approach was intended to satisfy the following five (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 comfortable.

The proposed approach consists of the following three principal iterative steps (Figure 1):

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

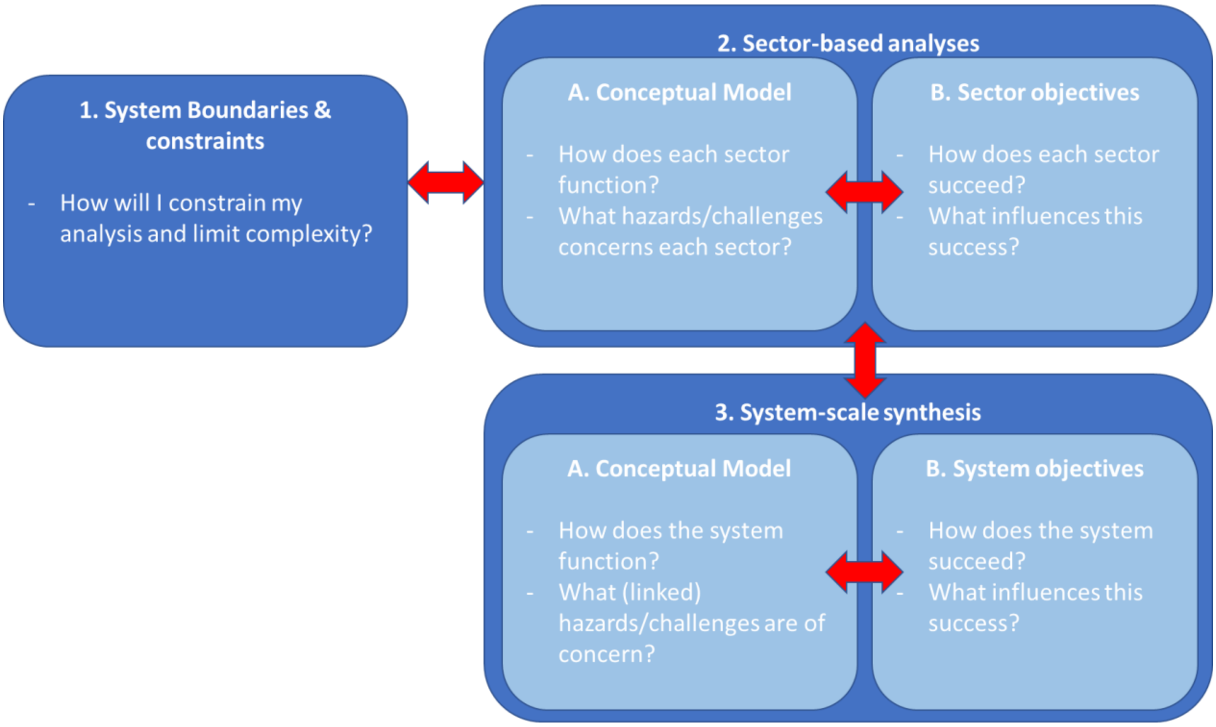

Figure 1 Proposed collaborative systems analysis approach to be applied in MYRIAD-EU

Relevant methods and tools are suggested for each of the steps, along with question prompts, which are to be treated as suggestions only. During PW1, pilot leads were invited to begin to adapt and implement self-selected aspects of the approach. They were free to adapt or use the suggested (or alternative, if preferred) methods, tools, and guidance questions to yield the necessary information to start defining the integrated decision contexts for their multi-risk, multi-sector systems.

2.2 Relationship of the proposed collaborative systems analysis approach to the MYRIAD-EU framework for systemic multi-hazard and multi-risk assessment and management

MYRIAD-EU has developed a proposed framework for systemic multi-hazard and multi-risk assessment and management (Hochrainer-Stigler et al., 2023, hereafter MYRIAD-EU framework). This framework draws upon current thinking in multi-hazard and systemic risk literature as well as insights gathered from expert feedback. The framework consists of an iterative, stepwise process comprising six major steps as presented in Figure 2. The active engagement of stakeholders is envisaged throughout the process to help build ownership and improve the legitimacy of any proposed risk management options.

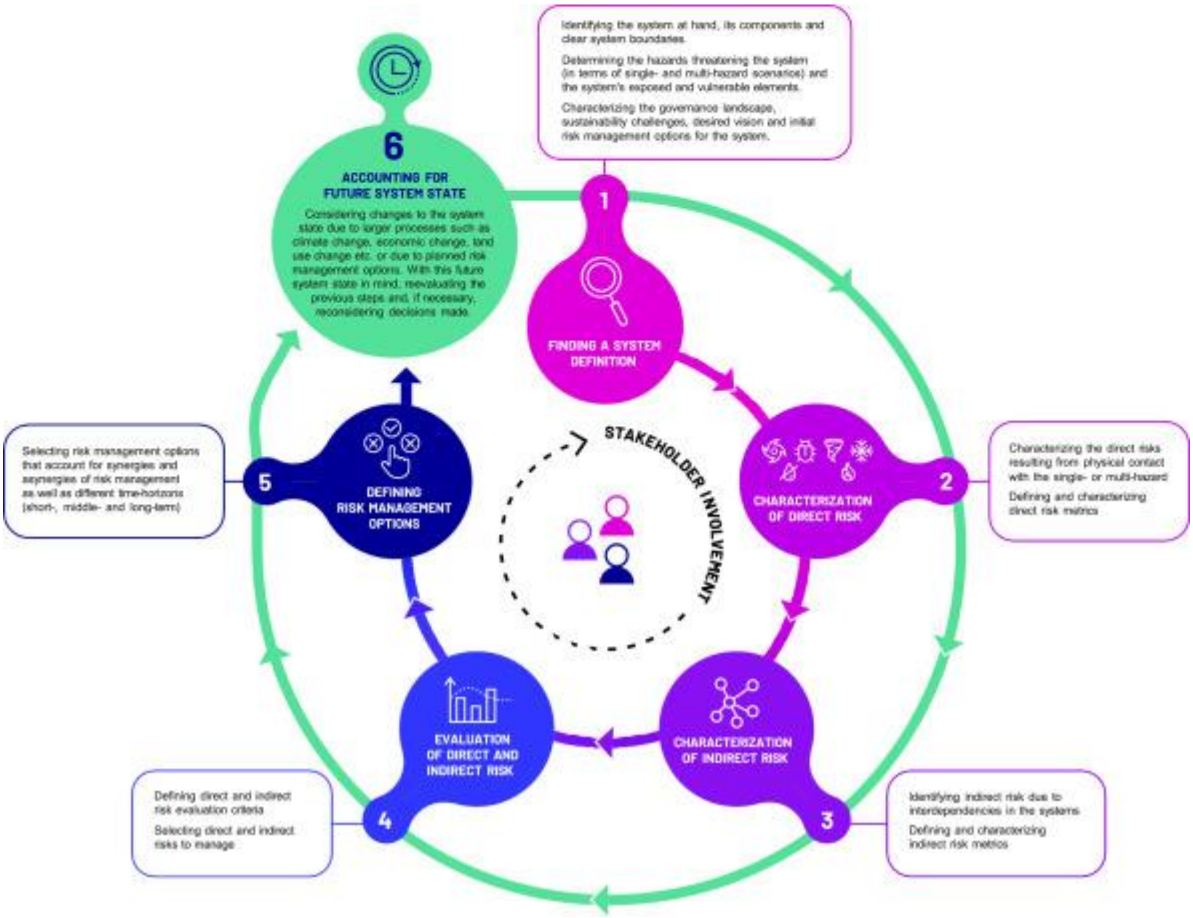

Figure 2 Six-step framework for individual, multi-, and systemic risk analysis and management (Hochrainer-Stigler et al., 2023)

The proposed collaborative systems analysis approach complements the MYRIAD-EU framework insofar 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. Table 1 presents an overview of key activities in the MYRIAD-EU framework covered by the proposed collaborative systems analysis approach.

Table 1 Activities in the MYRIAD-EU framework covered by the proposed collaborative systems analysis approach

MYRIAD-EU framework steps	Included in collaborative systems analysis approach	Not included in collaborative systems analysis approach
1. Finding a system definition	• 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	
2. Characterisation of direct risk	• Identifying direct risks resulting from physical contact with the single- or multi-hazard • Defining direct risk metrics	• Characterising direct risk metrics (i.e., assessing the risks)

3. Characterisation of indirect risk	• Identifying indirect risks due to interdependencies in the systems • Defining indirect risk metrics	• Characterising indirect risk metrics (i.e., assessing the risks)
4. Evaluation of direct and indirect risk	• Defining direct and indirect risk evaluation criteria	• Conducting the evaluation • Selecting direct and indirect risks to manage
5. Defining risk management options		• Identifying initial risk management options for the system • Assessing and evaluating risk management options • Selecting risk management options for inclusion in the adaptive DRM strategy
6. Accounting for 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.)	• Defining/specifying the future system state according to the identified factors

2.3 Application of the approach in the pilots

(Adapted) applications of the proposed approach commenced in each of the pilots during the first Pilot Workshops (PW1), conducted in November 2022. The stated purpose of these workshops was to: (1) identify the needs of each pilot's Pilot Core User and Pilot Stakeholder Groups, (2) prioritise the research questions, challenges, and opportunities, and (3) discuss the initial MYRIAD-EU framework for multi-hazard, multi-sector, systemic risk management. The proposed collaborative systems analysis approach was intended to guide the design of workshop activities to fulfil the first two purposes. It was not expected that the pilots would be able to cover all aspects of the proposed approach within PW1, but rather that they could commence activities with stakeholders to collaboratively define their decision-making contexts. That is, to focus systems analysis activities on exploring primarily the first step of the MYRIAD-EU framework. Opportunities to (adapt and) implement the remaining aspects of the approach will present themselves during later stakeholder meetings in the project.

Key outcomes of PW1 are provided in the milestone report *MS11 Milestone: Pilot Workshop 1 completed and feedback to WP2, 4-6* (Ciurean et al., 2022). A brief outline of the work conducted in each of the pilots relevant to this deliverable is included in the paragraphs below.

2.3.1 Scandinavia

The Scandinavian pilot conducted a 2.5-hour in-person workshop with stakeholders from three attending institutions. Given the limited numbers of attendees, application of collaborative methods suited to larger group settings were not feasible, but rather the pilot conducted its activities as a single, unstructured, focus-group discussion. Its conversations focussed most on the first two steps of the proposed approach (Step 1 and Step 2A), in which participants:

- Selected the (compound) hazards upon which to focus in the pilot.
- Identified the affected sectors relevant to these hazards.
- Qualitatively identified the (relative) direct and indirect impacts of these hazards on the sectors.
- Were introduced to the assessment tool to be applied in the pilot (GRACE model).

2.3.2 Veneto

The Veneto pilot conducted a 4.5-hour workshop with 23 stakeholders from 15 different institutions. Most participated in-person, with six participants joining online. Given the large numbers of participants, a high degree of inter-institutional collaboration was possible. Participants were divided into small groups and conducted discussions making notes on flipcharts with post-its. Questions posed included:

- What are the main hazards, vulnerabilities and risks you are confronted with?
- Do you face particular multi-hazard and multi-risk situations?
- How do you assess and manage these situations? Do you look at single hazards independently or also interdependencies?
- What are the existing risk management options for the hazards of interest? Which management options are missing, and are there gaps?

Participants also participated in hands-on qualitative example applications of the first 3 steps of the MYRIAD-EU framework (i.e., system definition, direct risks characterisation, and indirect risks characterisation), again applying flipcharts and post-its in moderated breakout group discussions. Other tools applied included the DPSIR framework, linear causal chains, and causal loop diagrams. The examples focussed on: (1) the impacts of extreme climate events on three sectors (tourism, ecosystems and finance), and (2) the multi-risk impacts on environmental quality, focussing on linkages between water quantity and water quality. This helped to identify the main risk management challenges and opportunities in the two pilot examples.

2.3.3 Danube

The Danube pilot conducted a 4-hour online workshop with 19 stakeholders from 13 different institutions. Approximately 1-hour of this time was spent in analysing the system and gathering stakeholder perspectives on multi-risks in the Danube Region. This was achieved through exercises conducted via the collaborative digital whiteboard software Miro. Specifically, the exercise was used to:

- Co-produce multi-hazard scenarios relevant for the Danube region and based on stakeholders' priorities.
- Understand some of the direct and indirect impacts across sectors of transport and infrastructure, food and agriculture, and finance.
- Establish the main considerations for risk management.

Via this exercise, (uncertain) scenarios of interest could be prioritised and key causal relationships qualitatively identified.

2.3.4 North Sea

The North Sea pilot conducted an 8-hour in-person workshop over two days (2x 4-hours) with 6 stakeholders from 3 institutions. The increased workshop time meant that more time could be allocated to interactive collaborative exercises than in other pilots. The pilot applied linear causal chains and causal loop diagrams on flipcharts with post-its and markers and explored questions relating to all three steps of the proposed approach. Topics of discussion included:

- System boundaries of the North Sea (sectoral, geographical, temporal, etc).
- Sectors affected by any identified (multi-)hazards, and their interactions.
- Potential scenarios for the future.

Following the workshop, the North Sea pilot team used the workshop outputs to propose a multi-risk conceptual model of the system to guide its remaining policy analysis activities. This model included drivers of future change in the North Sea, the relevant hazards and interrelationships, potential measures available to mitigate risks, as well as sets of long-term sector objectives and related metrics.

2.3.5 Canary Islands

The Canary Islands pilot conducted a 4-hour in-person workshop with 23 stakeholders from 20 institutions. The key collaborative activity during the workshop was a 90-minute simulation exercise, in which participants were divided into 4 groups. Each group was confronted with a specific (and uncertain) multi-hazard scenario. Specifically, each table was tasked to:

- Identify and describe at least three of the most important (risk- or non-risk-related) challenges faced by their sector/company or institution for the coming decade.
- Prioritise their main challenge.
- Identify possible impacts of a first hazard on their sector in terms of both direct and indirect risks.
- Propose alternative solutions to mitigate the vulnerabilities highlighted by the first hazard.
- Identify possible impacts of a second hazard, in light of the proposed solutions to the first.

The pilot essentially undertook the first two steps of the proposed approach, focussing most on using the simulation exercise to define each sector-based system, its boundary conditions and key elements.

2.4 Feedback from the pilots

Overall, pilots were neutral about the usefulness of the collaborative systems analysis approach during preparations for PW1 as the presented approach went well beyond the stated objectives of the workshop. Some found it more useful than others, with the aspects relating to building a conceptual model of their multi-hazard, multi-sector systems the most valued. This is unsurprising given the focus of the first workshops on generating an initial understanding of the characteristics of their systems. Pilots found the guidance questions the most useful elements of the deliverable that informed their workshop preparations.

With respect to the three steps of the proposed approach, two pilots (Scandinavia, Canary Islands) included preliminary activities relating to steps 1 and 2A (i.e. establishing system boundaries, constraints and initial conceptual models of individual sector relationships), while three pilots (Veneto, Danube and North Sea) also managed to include preliminary analyses of inter-sector interactions (step 3A). None of the pilots systematically applied (parts of) the approach using the suggested tools, but rather adapted the activities and guidance questions to design their own series of interactive discussions (as was the intention).

Despite the constraints presented by PW1, the pilots were generally positive about the proposed approach and its ability to achieve all five of its objectives set out in Section 2.1. They were especially positive about the flexibility of the approach, as well as its ability to generate a common, shared understanding of integrated systems. The authors look forward to the pilots continuing to use the suggested approach and tools to guide future context-setting discussions with stakeholders during subsequent MYRIAD-EU pilot meetings.

The pilots also made several general observations in relation to the proposed approach. One of the pilots observed that the approach demands strong and effective facilitation to lead discussions and help to synthesise system complexities for stakeholders. Another pilot expressed having experienced difficulty in adapting the approach within the context of PW1 given the time allocated to analyse its multi-risk system. Interest was expressed in a shortened version, highlighting the most important aspects to cover. On the other hand, other pilots 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.

Two additional tools were also identified with which to augment those listed in the deliverable. The first was the use of storyline narratives to unpack system relationships and interactions, and the second was the use of two-dimensional impact matrices to establish and qualify the interdependencies between sectors. Annex 1 provides a brief introduction to these, and we propose to include these in the final catalogue of tools to be presented as part of D6.4.

2.5 Observations following application of the approach in the pilots

In general, the proposed collaborative systems analysis approach was used to inform preparations of PW1 to some extent. For example, some pilots applied several of the associated tools presented in the deliverable, particularly DPSIR and those relating to establishing causal relationships. Others adapted elements of the approach through their analyses of system boundaries, constraints, challenges and opportunities. Only one pilot (North Sea) designed workshop activities to deal explicitly with each of the three steps of the proposed approach, looking at system boundaries, sector-based considerations, and system-wide considerations. Several other pilots adapted the steps of the proposed approach, insofar as they considered sector and system-wide considerations concurrently. In all workshops, the depths of analysis made possible were relatively shallow, due predominantly to the limited time allocated to the task. This meant that pilots could not undertake detailed discussions on sector and system interactions, nor on objectives and indicators/metrics (i.e., steps 2B and 3B of the approach) together with their stakeholders.

However, we recognise that conducting such detailed discussions went beyond the stated objectives of the workshops. It was never the intention that the pilots needed to complete activities relating to all elements of the approach and the MYRIAD-EU framework during PW1. Rather, the focus of systems analysis activities in these workshops was on the first step of the MYRIAD-EU framework. The authors look forward to the pilots deepening their analyses through (adapted) applications of the remainder of the proposed approach as they move towards assessing risks and options and developing DRM pathways during subsequent pilot meetings.

Finally, although the approach is presented as being flexible and open to adaptation, the activities contained therein nevertheless stem from the need to set up an adequate problem framing to both assess and evaluate risks via the MYRIAD-EU framework and for the systematic development of multi-risk pathways via the DAPP-MR methodology (see Section 3). The latter method follows a similar approach to the collaborative systems analysis approach of first analysing sector challenges and identifying potential pathways independently, before attempting to synthesise these into a single set of multi-risk pathways for the system as a whole. It is for this reason such emphasis is placed in the collaborative systems analysis approach on establishing an agreed set of (measurable) sector and system objectives (i.e., definitions of ‘success’; steps 2B and 3B of the approach). The authors look forward to the pilots building on the preliminary PW1 system analyses with their stakeholders to establish agreed sets of relevant metrics to guide the formulation of their DRM pathways.

2.6 Concluding remarks

Based on the shallow, (adapted) applications of the collaborative systems analysis approach implemented in the pilots and the feedback received on the proposed approach, we conclude that revision to the approach is not yet required at this time. Although the complete approach could not yet be applied during PW1, this was never the intention of the approach. PW1 was the initial engagement of pilot stakeholders with MYRIAD-EU and as such it could only cover initial, preliminary analyses of the multi-risk systems within the pilots. The authors look forward to receiving further feedback on the proposed approach, methods and tools as the pilots elaborate these analyses together with their stakeholders during later meetings.

3 Proposed approach to developing forward-looking DRM pathways: DAPP-MR (Task 6.2)

Task 6.2 aims to extend the existing Dynamic Adaptation Policy Pathways (DAPP) approach (Haasnoot et al. 2013) to be fit for use in a multi-hazard, multi-sector setting. The task has been led by DRES, with close support of VUA, UKRI BGS, Risklayer, and ULL. Representatives of the pilots have provided useful feedback during the WP6 meetings and are further expected to increase their contribution as activities evolve. The first months of the MYRIAD-EU project were used to tailor the DAPP approach to DAPP-MR (DAPP for multi-risk). A conceptual scientific paper on DAPP-MR was published, and the approach applied in a synthetic case to be published in a forthcoming paper. The following text summarises some of the key findings from Schlumberger et al. (2022) and Schlumberger et al. (in prep).

3.1 The DAPP-MR framework

In recent literature, three themes are detectable that are relevant to characterise multi-hazard and multisector interactions to design pathways: (1) effects of multiple, interacting hazards; (2)

dynamics and interdependencies of sectors; and (3) trade-offs and synergies of DRM policy options across different sectors and different spatial and temporal scales:

Multi-hazard interactions: 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). This information is necessary to understand what hazard processes influence the extent and severity of certain hazards. Additionally, the level of correlation between hazards is important: uncorrelated hazards will lead to random interactions, while bidirectionally correlated hazards (e.g., owing to the same or correlated drivers) or uni-directionally correlated hazards (e.g., one hazard might trigger another one) influence the probability of the combined occurrence.

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. In the literature, four different intersectoral interrelations are discussed: (1) One system is connected to another system and relies on it to operate; (2) Spatial proximity can lead to bi-directionally correlated responses in multiple systems; (3) Shared markets, implications of post-disaster consumption, and business interruptions can have consequences across scales; and (4) Governance structures including, local communities play a role in vulnerability characteristics and the effectiveness of response and recovery efforts.

Trade-offs and synergies of DRM policy options: 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 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. Consequently, policy options should be characterised in terms of their potential effectiveness, readiness, lead time until full effectiveness, duration of benefits, societal acceptability, governability, potential co-benefits, and potential negative collateral effects.

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.

Many of the identified aspects of multi-risk systems touch upon the spatial and temporal dynamics of vulnerabilities and opportunities. They further determine the adaptation tipping points (ATPs) and Opportunity tipping points (OTPs). ATPs are defined as “*the moment when the magnitude of change is such that a current management strategy can no longer meet its objectives. As a result, adaptive management is needed to prevent or postpone these ATPs.*” (Nanda et al., (2018), p. 3, based on Kwadijk et al., (2010)), while OTPs are “*points at which a particular action becomes feasible or attractive, for example because of lower costs of actions or technical developments.*’’ (Haasnoot et al., 2019, p. 86). Therefore, we investigated whether ATPs and OTPs are capable of dealing with the increased level of interdependence. In Figure 3, four different pathways are grouped together in varying combinations illustrating the implications of hazard interactions, cross-sectoral interdependencies, and policy option interactions on the shape of different pathways.

Colours represent different policy options. New policy options are implemented after an ATP (circle) or OTP (triangle) is reached. Dotted lines indicate the potential effects of interactions (red dashed lines) on pathways, ATPs, and OTPs. Generally, four effects can be identified:

- The timing of ATPs can be delayed (circle moves to the right) because of synergies between policy options (Figure 2a). Example: Room for the river is primarily a flood risk protection measure, but due to its design it also increases groundwater recharge from the river due to its extended flood plains. As such it could be beneficial for measures that rely on available groundwater resources (e.g. for irrigation).
- New OTPs can emerge for various reasons (Figure 2b), e.g., multi-sector synergies could lead to additional available resources or willingness to cooperate in other ways to implement policy options that would not be feasible otherwise. Also, multi-hazard synergies (e.g., increased risk awareness) could reduce resistance regarding certain protection measures. Example: investments in a very high dike system might not be financially attractive when only considering the impacts on one sector, however, when accounting for all damages that can be prevented by the large dike system, it might become a viable option.
- Conversely, the timing of ATPs can occur earlier (circle moves to the left) when trade-offs between different policy options lead to asynergies or effects of multi-hazard interactions that exacerbate impacts (Figure 2c). Example: Cultivating drought resilient crops might reduced drought damages but increase flood damages due to increased flood vulnerability of the crops.
- Finally, certain policy options can be inhibited (red cross cuts off pathway) because of trade-offs, meaning that only one of the two measures can be implemented because of political, financial, or spatial reasons (Figure 2d). Policy options can also be inhibited by multi-sector trade-offs resulting from contradicting objectives or perspectives. Example, a spatially demanding measure like room for the river might be feasible as long as urban areas are still small as only a small fraction of residents has re-settle. If the number of potentially re-settled residents becomes too large, it becomes unattractive. Similarly, while a municipality might consider room for the river as a flood protection measure, it contradicts the needs of the agricultural sector by reducing land that can be used for crop cultivation.

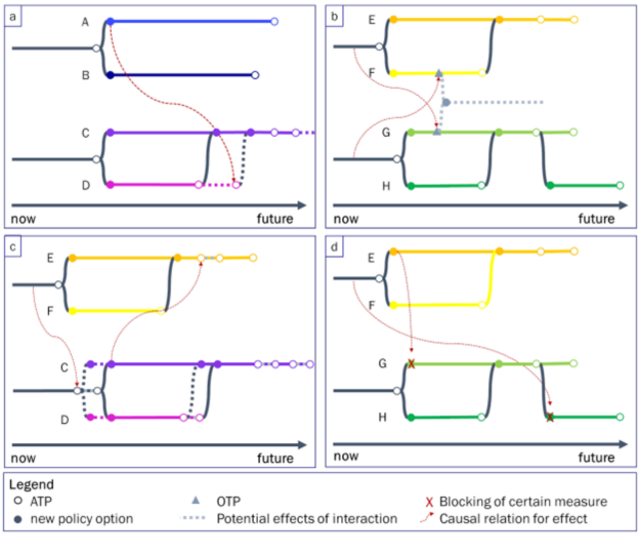

Figure 3: Set of illustrative combinations of two pathways. The coloured lines represent alternative portfolios of policy options (options A, B, C, D, E, F, G, and H). The panels visualise the potential interaction effects on the timing of Adaptation Tipping Points (ATPs) and Opportunity Tipping Points (OTPs) caused by hazard interactions, cross-sectoral interdependencies, and policy option interactions: (a) delaying ATPs, (b) new OTPs, (c) rushing ATPs, (d) and blocking of ATPs. cf. Schlumberger et al. (2022).

As part of the analysis, we showed how to enrich DAPP with contextual multi-risk elements without changing its stepwise approach. 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, as shown in Figure 4. 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.

DAPP-MR helps to capture interactions, trade-offs, and synergies across hazards and sectors. We show that DAPP-MR may guide multi-sector processes to integrate knowledge toward multi-risk management in a stepwise manner. DAPP-MR can be seen as an analytical basis and first step toward an operational, integrative, and interactive framework for short-to long-term multi-risk DRM.

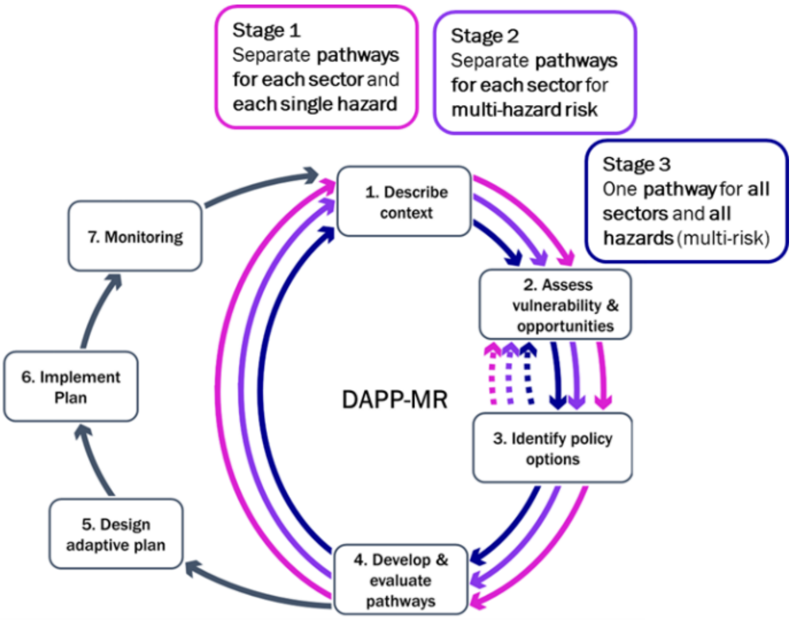

Figure 4 Analytical framework of DAPP-MR to develop and evaluate adaptation pathways to manage complex multi-risk systems. cf. Schlumberger et al. (2022)

3.2 Application of DAPP-MR as a quantitative approach

We explored the utility of DAPP-MR using a synthetic multi-risk case study. The case study, named Waas-MR, is based on a river stretch in the Netherlands and incorporates current state-of-the-art knowledge regarding the interacting effects of floods and droughts and their impacts on different sectors. The Waas-MR case study builds upon previous work on the 'Waas' case study, which was used to test water management strategies under long-term climate change scenarios. Applying a model-based approach, our analysis aimed to investigate how DAPP-MR can be applied for the quantitative development and evaluation of pathways and how multi-hazard and multi-sectoral interactions affect the flexibility and robustness of DRM strategies. Additionally, we examined the implications of using DAPP-MR for decision-support and the decision-making process itself.

DAPP-MR was used as the analytical framework for the conceptualisation of the multi-risk Waas-MR case study and development and evaluation of potential pathways. Following three stages of analysis, the number of interactions within the case study was gradually increased (first stage: siloed, no interactions across hazards or sectors, second stage: multi-hazard, interactions across hazards, third stage: multi-risk, interactions across hazards and sectors). While we used steps one to three (see Figure 4 above) in all three stages to gradually develop a multi-risk system conceptualisation, our study mainly focused on applying the three stages to step 4, namely the development and evaluation of DRM pathways.

3.2.1 Brief description of the case study

The synthetic Waas-MR case study is a lowland river stretch. It covers approximately 75 km² of riparian land of different use (e.g., for settlements, and agriculture). The agricultural sector directly experiences impacts of floods and droughts to crop yield. The urban sector suffers from flood impacts on residential buildings. Lastly, the inland shipping sector is vulnerable to low river discharges during dry periods. Every sector has a set of DRM measures to reduce future risk.

Each sector in the Waas region wants to effectively manage climate risks by implementing sequences of DRM measures (referred to as "DRM pathways") over the course of 100 years. Each sector aims to achieve two DRM objectives: (1) minimise drought/flood related damages, and (2) minimise additional costs associated with investment and maintenance of risk management measures. Most interactions between the sectors occur as interactions between different sectoral DRM measures. Three multi-hazard interactions are considered: co-occurring or preceding droughts can amplify flood damages to the agricultural sector; preceding droughts can increase the probability of floods and trigger additional flood impacts on the agricultural and residential sectors; and consecutive flood events can influence the vulnerability and exposure of the residential sector.

3.2.2 Developing and evaluating DRM pathways in a quantitative approach

DAPP-MR suggests a bottom-up approach for the development and evaluation of DRM pathways in multi-risk settings. This means that multi-risk pathways are developed starting from individual sectoral risk strategies (current siloed thinking, stage 1). For example, available options for the agricultural sector in Waas-MR to address flood risk are first assessed in a siloed approach (“What are the best pathways for flood risk management?”). In stage 2, flood-drought interactions are accounted for to develop multi-hazard conscious pathways (“What are the best flood risk management pathways given flood-drought interactions and the simultaneous presence of drought risk management measures?”). And finally, in stage 3, all multi-risk interactions are accounted for resulting in multi-risk conscious pathways for the agricultural sector to deal with floods (“What are the best flood risk management pathways given flood-drought interactions and the simultaneous presence of risk management measures of other sectors towards floods and droughts?”). This helps to reduce complexity for the development and analysis of the pathways options and offers intermediate information to sectoral actors involved in a DAPP-MR process. Thus, to develop and evaluate DRM pathways for multi-risk systems in the Waas-MR case study, we applied the approach as visualised in Figure 5.

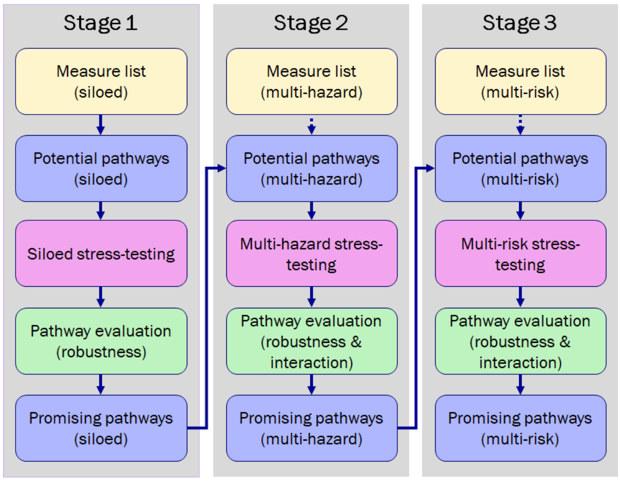

Figure 5: Operationalised staged approach for the development and evaluation of DRM pathways. Starting with a stage 1 analysis, the measure list (yellow) is used to develop potential pathways for siloed DRM (blue). These pathways are stress-tested using the Waas-MR model across a range of climate scenario ensemble members (pink). The pathway performance across these uncertainties is evaluated in terms of robustness (green) to identify pathways with promising performance (blue). For stage 2, these promising

pathways form the set of potential conscious multi-hazard DRM pathways. Additional potential pathways extend this set developed based on multi-hazard-specific DRM measures. Given that stage 2 accounts for the interactions across multiple hazards and the corresponding measures, potential DRM pathways are stress-tested across various climate scenario ensemble members and combinations with other sector-hazard pathways. The pathways performance across these uncertainties is evaluated in terms of robustness and interactiveness to identify pathways with promising performance accounting for multi-hazard interactions. Again, these promising stage 2 pathways are used to form the set of potential pathways for stage 3 in combination with additional pathways developed based on stage-3 specific measures. Similar to stage 2, the potential pathways are stress-tested and evaluated similar to stage 2. As a result, promising multi-risk pathways can be identified.

Identifying potential pathways

DRM measures for each sector and each hazard were used to create potential pathways, meaning plausible sequences of measures of a sector to deal with flood or drought risk across the planning horizon. This is done using a storyline approach (Shepherd et al., 2018). We identify different potential pathways that either: a) rely first on large, structural measures, and later additional small measures; or b) interchangeably implement large, structural measures and smaller ones; or c) start with small, cheaper options and add additional more costly measures later in the planning horizon. As a result, a set of 9 to 15 potential pathways were identified for each sector to manage one specific hazard risk.

Although DAPP-MR suggests that potential pathways tested in one stage can be reduced to a set of promising pathways as input for the next stage, we identified promising pathways for each stage without eliminating them from further analysis. This approach allowed us to consider the potential drawbacks of removing pathways during the analysis, as it may have resulted in overlooking better-performing pathways that consider a wider range of interactions.

Stress-testing potential pathways using the Waas-MR model

Building on Haasnoot et al. (2012), we implemented the Waas-MR case study as an integrated assessment meta-model (IAMM, e.g., Saecki, 1998) as shown in Figure 6. The Waas-MR model simulates the impacts from droughts and floods in the region at a spatial resolution of 100m x 100m, timesteps of 10 days, projecting impacts 100 years into the future. Impacts are simulated for three sectors: agriculture, urban, and shipping. To account for deep uncertainties, we used a set of transient scenarios of evaporation, precipitation and discharge as drivers of flood and drought events to simulate impacts over time to capture different climate scenarios and natural variability.

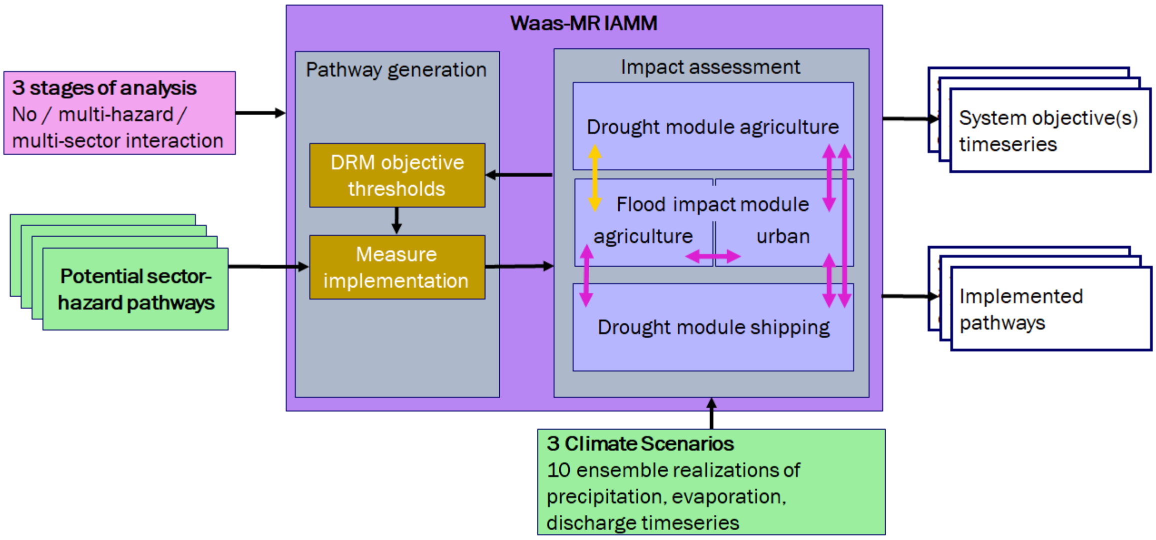

Figure 6: Schematisation of the Waas MR model to stress-test pathways. The model generates system objective(s) time series and implemented pathways (white) for a specific climate scenario ensemble realisation and (combination of) potential sector-hazard pathways (green). Waas-MR consists of three different sectoral impact modules (blue). Pathway generation is determined by DRM objective thresholds for each time-step and the given potential sector-hazard pathway. The stage of analysis (pink) specifies the type of interactions and dependencies of the physical processes modelled by the IAMM (corresponding to DAPP-MR stages). Black arrows describe the general flow of information. Additional flow of information for stage 2 (yellow) and stage 3 (pink & yellow arrows) are shown as examples for the agricultural drought risk management.

We assumed that a sector would implement new measures from a given potential sector-hazard DRM pathway, when a respective Adaptation Tipping Point was surpassed. As an example, we assumed that the agricultural sector could bear with expected annual damages up to 7MEur. However, exceeding this threshold was deemed dangerous for the livelihood of the farmers and thus would require taking on additional DRM measures. The choice of these thresholds was arbitrary but has significant effect on the timing and frequency of implementing new measures. E.g. the higher the thresholds, the scarcer the implementation of new measures. We chose for values that were deemed reasonable and allowed us to explore the interaction effects between different pathways. In stage 1, pathways were developed and stress-tested for three climate scenarios with 10 ensemble realisations each. For stage 2 and stage 3, the potential presence of (an)other sector-hazard specific pathway(s) could affect the performance of pathways. For example, the timing and choice of DRM measures of the urban sector result could affect the physical processes that drive DRM decisions of the agricultural sector in a stage 3 analysis. To account for the potential implications for shifting implementation timing, synergies and trade-offs between different sector-hazard pathways, combinations of pathways were considered as an additional source of uncertainty in stage 2 and stage 3.

Performance evaluation

Depending on the stage of analysis, we evaluated the performance of potential pathways based on one or two criteria: The robustness criterion was used to assess the performance of a pathway under the range of uncertainties across all stages of the analysis while an interdependency criterion was considered in stage 2 and 3, where multi-hazard pathway combinations or multi-risk pathway combinations might affect the DRM objectives of a given potential pathway.

3.2.3 Discussing the results

We discussed three different aspects of multi-risk DRM pathways: (a) identifying promising pathways based on the robustness values of the DRM objectives; (b) shifts in implementation timing of measures; and (c) interactions across different pathways. A full presentation of the results is beyond the scope of this report.

The analysis of robustness performances 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. In this context, making use of a staged approach to analyse and justify certain cause-effect relations was very useful. In that way, it was made explicit whether certain patterns occurred across different stages of the analysis, were unique to one stage or climate scenario, or influenced by multiple processes (on different interaction levels). This guided the analysis and pathways justification by narrowing down the number of possible pathways per stage which frequently remained valid even under increased complexity. Using the case study, some key findings regarding the analysis were discussed:

- Pathways that were promising in less complex conditions (e.g., siloed DRM) can become less attractive due to changing performance of the pathway itself or of its alternatives when accounting for interactions.
- Some pathways' effectiveness increases due to multi-hazard interactions, while others are unaffected or experience higher damage reduction which can have varying implications for the long-term performance of a pathway and the need to implement new measures.
- A short-term trade-off for multi-hazard or multi-risk systems can lead to earlier implementation of new measures which can delay further trade-offs or measure implementation needs and influence overall pathway performance.
- Interaction effects can have significant implications on the short-to-long-term strategies for one scenario/uncertainty combination.

To delve a bit deeper into the interactions between specific pathway pairs, bi-directional interaction heatmaps are used, as visualised in Figure 7, to gain insight into these pair-wise interactions. This figure demonstrates how different drought-agriculture pathways influence the flood damage of a given flood-agriculture pathway (bottom triangles) and, vice versa, the influence of different flood-agriculture pathways on the drought crop damage performance of a given drought-agriculture pathway (top triangles). Higher values indicate a positive interaction effect (synergy), meaning a reduction in damages, while lower values indicate an increase in damages (trade-off).

The measure to implement flood resilient crop systems is part of the flood-agriculture pathways (namely pathways 1, 2, 3, and 11) and has a strong synergistic effect on the drought damages of drought-agriculture pathways 1,2,3, and 9 leading to decreased drought agricultural losses across both the analyzed climate scenarios. A closer look reveals that these flood-agriculture pathways introduce flood resilient crops early on. This measure accentuates the drought susceptibility of crops, leading to amplified drought damages post-implementation. The scale of this damage increase appears to prompt the introduction of additional DRM measures in specific ensemble realisations based on set decision value thresholds.

Additionally, drought-agriculture pathways, specifically pathways 1, 2, 3, 8, and 9, showcase a synergistic interaction with flood-agriculture pathways 5, 6, 7, and 8, although this isn't uniformly observed across all climate scenarios. Interestingly, under a more intense climate scenario, every drought-agriculture pathway seems to result in diminished flood damages. This observation is counterintuitive, given that none of the drought-agriculture pathways encompass measures specifically designed to mitigate flood risks. Instead, they appear to heighten the agricultural sector's vulnerability to droughts. A possible rationale for this observation is the augmented flood exposure leading to escalated flood damages, which then surpasses the threshold to activate additional flood-agriculture measures. This theory finds support in scenario D, where only those drought-agriculture pathways with measures that directly trade-off (like the flood resilient crops measure which raises flood susceptibility) lead to diminished flood damages in agriculture. A key takeaway is that short-term disadvantages (like increased vulnerability) might pave the way for more considerable long-term benefits.

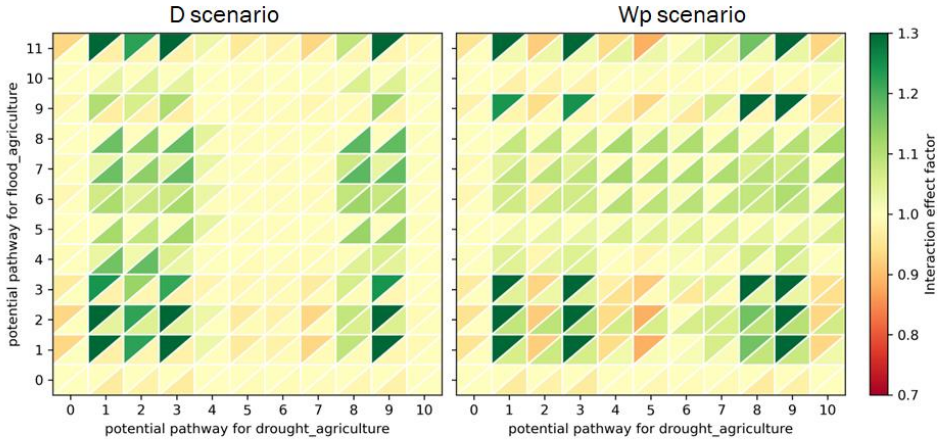

Figure 7: Bidirectional heatmap to explore the interaction effects for flood-agriculture and drought-agriculture pathways pairs on the drought losses (top triangles) and the flood damages (bottom triangles) for the D scenario (left) and Wp scenario (right) for stage 2. The Interaction effect factor is calculated for flood damages by normalising the given loss value for a specific pathway pair (e.g. flood-agriculture pathway 11, drought-agriculture pathway 4) by the flood damages value for flood-agriculture pathway 4, in case no drought-agriculture measures would be implemented (drought-agriculture pathway 0). Values larger than 1 suggest synergistic effects, values smaller than 1 suggest a negative influence of drought-agriculture on the flood-agriculture objective value.

Figure 8 represents the varying timing of implementing the first, second, third and fourth measures for different sector-hazard pathways and climate change scenarios. Per scenario the top half violin captures the distribution of timings across the ensemble realisations under stage 1, the bottom half violin captures the distribution across the ensemble realisations and multi-hazard pathways combinations under stage 2. The height of the violin at a given time is an indication of how frequent a (first, second, third, fourth) measure is implemented at this specific time. In this way, shifting implementation timings due to multi-hazard interactions or measure-measure interactions can be easily explored for a specific pathway.

The below examples demonstrate that cause-effect relations leading to shifting implementation patterns are complex and heterogeneous. For example, Figure 8 shows that the timing of measures of pathway 1 do change but still follow similar patterns. On the other hand, as the plot for pathway 2 shows, multi-hazard and measure-measure interactions can lead to significant shifts in the pathways. These shifts do not have to be homogenous, e.g., shifting the implementation of all measures towards the present. As shown in the example of pathway 2 for the Wp scenario, an increase and earlier timing of second measure (green) implementation in stage 2 compared to stage 1 coincides with a significant delay of implementing a third measure (brown) . What role the earlier second measures play with regards to the delayed third measures is not obvious from these visualisations. Lastly, as shown in the plot regarding pathway 3, multi-hazard and measure-measure interactions may have minor effect on shifts in timing but a greater effect on the implementation likelihood. For example, a second measure is more often implemented in stage 1 leading to higher violins. In stage 2, the timing of implementation seems similar, but the frequency of implementation across the ensemble realisations is reduced significantly.

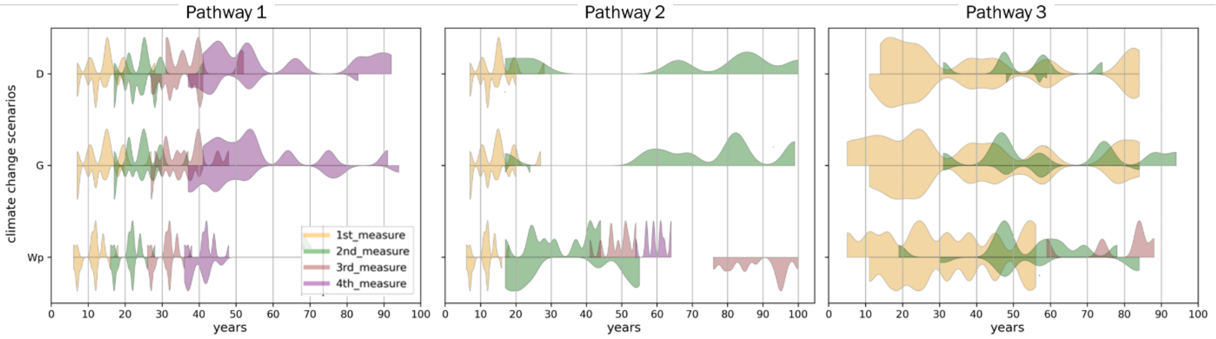

Figure 8: Comparison of timing of measure implementation for different sector-hazard pathways in siloed approach (top violins) and accounting for multi-hazard interactions (bottom violin) across various climate scenarios. Changes in timing patterns can be diverse.

3.3 DAPP-MR in the context of the MYRIAD-EU framework

In addition to the development and application of DAPP-MR outlined above, WP6 has also engaged in a series of internal discussions between WP2 (MYRIAD-EU framework development) and the DAPP-MR development team in recent months to align both frameworks and identify how they can be synthesised. In line with the iterative character of the MYRIAD-EU project, this consolidation exercise is ongoing. Here we report some preliminary insights from the perspective of this work package (WP6) on the differences, similarities and potential ways forward.

A comparison of the current version of the MYRIAD-EU framework and DAPP-MR is summarised in Table 2. In discussions with WP2, it has been identified that the current version of the MYRIAD-EU framework and the DAPP-MR framework are complementary. While the MYRIAD-EU framework emphasises and analyses the details of the multi-risk assessment, DAPP-MR emphasises the analysis of management alternatives and the temporal dependence of long-term strategies. The current version of the MYRIAD-EU framework encompasses five steps to derive multi-risk management options for a specific system state (at a given time) and then continues to repeat these steps for one (or multiple) future states of the system. In this way forward-looking DRM-pathways, meaning sequences of measures to be taken over the years can be formulated. Alternatively, DAPP-MR engages in 7 steps to develop similar strategies while iterating through these steps to integrate more and more complexity (starting from the current siloed practice to the desired multi-risk integration).

Table 2: Comparison of the current version of the MYRIAD-EU framework and DAPP-MR

	Current version of MYRIAD-EU framework	**DAPP-MR**
General	Focus on multi-risk assessment	Analysis of management alternatives & temporal dependence
Theoretical basis	Systemic risk, quantitative risk assessment	Decision-making under deep uncertainty, exploratory modelling, scenario thinking
Strength	• Thorough understanding of system-of-systems • Quantification of semi-static multi-risk (for a given system definition)	• Streamlined approach to analyse short-to-long-term developments • Focus on stress-testing DRM alternatives • Reduce multi-risk complexity of analysis by staged approach
Weakness	• Discretising future into different timings limits options to account for temporal dependence/path-dependence of development • No guidance on how to deal with future uncertainty (yet)	• Lower level of detail regarding multi-risk dynamics • Applicable only when long-term uncertainties/developments are relevant • Limited awareness of stakeholders of the underlying concepts

Both approaches have their pitfalls and strengths. For DAPP-MR, the key pitfall identified is that the staged approach (developing pathways first in a siloed approach and then integrating), potentially requires a lot of effort from stakeholders because most sectors/stakeholders are unfamiliar with the concept of pathways and do not have their own pathways ready to directly start integrating these to account for multiple hazards or the pathways of other sectors. However, DAPP-MR is rooted in the context of exploratory monitoring and thus is methodologically sound when it comes to the analysis and evaluation of future options. The concept of pathways is inherently built into the methodology.

On the other hand, the current version of the MYRIAD-EU framework benefits from a thorough user understanding of systemic risk and risk assessment, but (currently) faces limitations regarding the assessment of DRM options (and future conditions). In particular, the discretisation of the future into independent steps limits considerations of temporal dependence and path-dependence of any proposed DRM measures.

However, it is important to note that, the methodological differences between the DAPP-MR framework and the current version of the MYRIAD-EU framework not only capture the variety of theoretical approaches to the topic of multi-risk DRM that exist in literature, but also address the varying needs and interests from potential users. As such, elements of both frameworks can be used to derive the next iteration of the MYRIAD-EU framework.

In the context of these discussions, the DAPP-MR development team has commenced testing the methodology for the qualitative development of multi-risk pathways in three pilot regions, namely the North Sea, Scandinavia and the Canary Islands. Making use of the variety of contexts, and pilot specific challenges, we are exploring the strengths and weaknesses of the proposed approach which can further serve to refine both, the DAPP-MR framework and the MYRIAD-EU framework.

As a way forward, we are planning to further engage in the ongoing discussions with WP2 and the pilots to deepen the understanding of each other's approaches to find a suitable approach to synthesise the two frameworks and offer different approaches to users depending on their needs and interests.

3.4 Next steps

Identifying DRM strategies that are robust across a wide range of future conditions and flexible enough to adapt to various situations at a reasonable cost and account for multi-hazard and multi-sectoral interactions presents a significant challenge. In response to these challenges, we have developed the analytical framework of Dynamic Adaptive Policy Pathways for multi-risk systems (DAPP-MR) to develop and evaluate sequences of DRM strategies. We have developed a multi-risk case study to test the development and evaluation of DRM pathways. However, a crucial gap remains in tools that can effectively compare and communicate the performance and interaction effects of DRM pathways. As a next step, we aim to design a set of information visualisation techniques to support the assessment of DRM pathways in multi-risk environments. Following a systematic design process proposed by Munzner (2009), we make explicit choices regarding the formulation of the analysis problem, users, their analysis goals and corresponding encoding and manipulation options. A pivotal element of this approach will be to make use of validation activities to confirm or adjust made choices. In this way, threats to the utility of the designed visualisation can be addressed, notably designing for the wrong problem (i.e., users are not interested in what we show), wrong abstraction (i.e., the visualisations do not show the right thing), wrong encoding/interaction (i.e., how we show the data does not work). For validation of these choices, we will engage a targeted group of experts from the field of adaptation, DRM and long-term decision-support through workshops and interviews and other potential users of such visualisations through a widely spread questionnaire. We will explore the options for commonly used approaches (e.g. Score Cards, Pathways Maps) and additional techniques.

Furthermore, we will test the DAPP-MR conceptual framework within (at least three of) the Pilot regions. The testing will help to refine the proposed method. Additionally, tools like a Serious Game will be developed to make the concept/opportunities and challenges of DAPP-MR applications more accessible to potential users of the approach.

4 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 manage these risks 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) feedback from pilots leads on their experience with implementing elements of the proposed collaborative systems analysis approach outlined previously in D6.2 during the first round of pilot workshops (PW1); and (2) 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.

Collaborative systems analysis approach

In Task 6.1, we developed an approach for collaborative systems analysis to allow 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 proposed approach therefore serves as a means by which to undertake the first step of the DAPP-MR approach (Figure 4 in this report) and the equivalent context setting-related elements of the proposed MYRIAD-EU framework for systemic multi-hazard and multi-risk assessment and management. Some of the pilots applied several of the collaborative tools that were presented in D6.2 according to which pilot teams felt most comfortable and were relevant to their workshop activities and practical needs (e.g., virtual versus in-person settings). Although the collaborative systems analysis approach was not applied either systematically or in full by any pilot, this was not the intention within the context of PW1, which also had other priorities. In general, pilots conducted relatively shallow analyses of their systems together with stakeholders, focussing primarily on those aspects relating most to step 1 of the MYRIAD-EU framework. Nevertheless, the pilots were generally positive about the proposed approach and its ability to achieve its objectives. The authors look forward to the pilots deepening their analyses though (adapted) applications of the remainder of the proposed approach as they move towards assessing risks and options and developing DRM pathways during subsequent pilot meetings.

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 conducing 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 case study, named Waas-MR, is based on a river stretch in the Netherlands and incorporates current state-of-the-art knowledge regarding the interacting effects of floods and droughts and their impacts on different sectors (agriculture, urban, inland shipping). Each sector aims to achieve two DRM performance objectives: (1) minimise drought/flood related damages, and (2) minimise additional costs associated with investment and maintenance of risk management measures. 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 helped to illuminate pathways which remained 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. Addressing this gap will serve as the focus of our activities in the immediate future, along with wider testing of the DAPP-MR conceptual framework in the pilot regions.

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Annex 1: Additional tools identified by the pilots

1. 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 multitude of ways in which a storyline can be developed. MYRIAD-EU is developing its own approach under Task 6.3, which will be reported on later in the project. A preliminary version of the proposed approach is presented below in Figure 9.

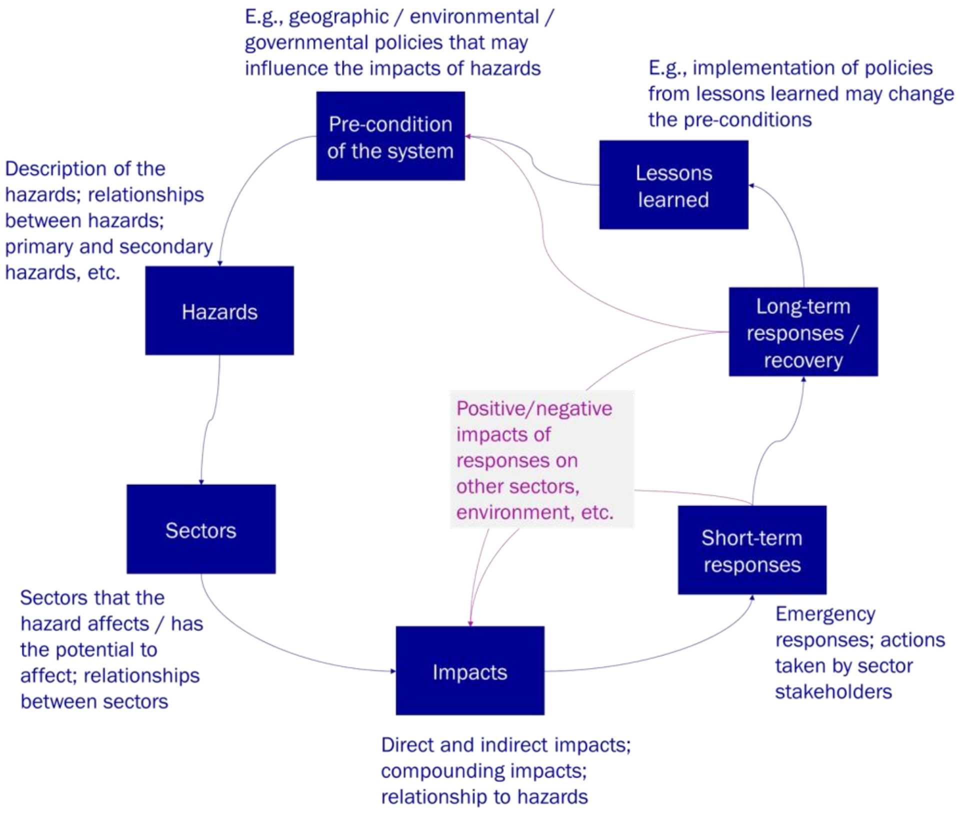
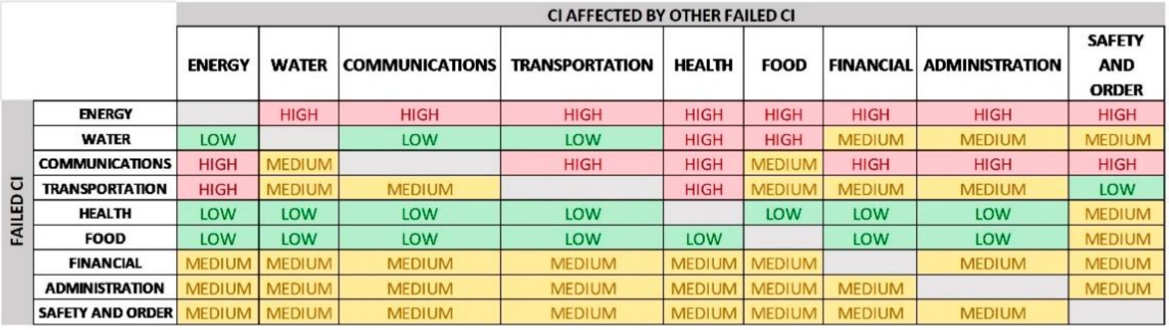


Figure 9: Preliminary MYRIAD-EU approach to the storyline development

2. Interdependency impact matrices

Interdependency impact matrices (Lomba-Fernandez et al., 2019), have been proposed for critical infrastructure systems to explore the interdependences, 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 10.



		CI AFFECTED BY OTHER FAILED CI								
		ENERGY	WATER	COMMUNICATIONS	TRANSPORTATION	HEALTH	FOOD	FINANCIAL	ADMINISTRATION	SAFETY AND ORDER
FAILED CI	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 10: Interdependency matrix for a sectoral analysis of critical infrastructure in a city (Lomba-Fernandez et al., 2019)