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D3.4

Final report on forward-looking DRM pathways and recommendations for upscaling and transferability

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D3.4/ Final report on forward-looking DRM pathways and recommendations for upscaling and transferability

Lead by CMCC

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Abstract

The MYRIAD-EU project developed a systemic framework and a toolkit for multi-risk, multi-sector, and multi-scale Disaster Risk Management (DRM), tested across five diverse European Pilot Studies: North Sea, Canary Islands, Scandinavia, Danube, and Veneto. Between March 2022 and August 2025, each Pilot followed a co-designed, stepwise process to map hazards and vulnerabilities, select and apply tailored tools, and develop sets of forward-looking DRM pathways tailored to their multi-risk and multi-sector profile. The report illustrates both the final results and the methodological foundations and knowledge co-production process that led to those results. The report also discusses the various choices and assumptions made in each Pilot Study, the obstacles encountered, and the lessons learnt along the way. For instance, key findings highlight the importance of contextualizing tools, combining qualitative and quantitative approaches, and engaging stakeholders throughout, whereas governance fragmentation, data gaps, and limited systemic risk awareness emerged as common challenges. The MYRIAD-EU Pilot Studies serve as lighthouses for other European regions facing similar challenges and aiming to transition towards integrated, systemic multi-risk management.

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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Executive Summary

The MYRIAD-EU project aimed to advance multi-risk, multi-sector, and multi-scale Disaster Risk Management (DRM) through the development of a systemic framework and a portfolio of methods and tools covering the whole risk assessment and management process. These products were tested, co-developed, and applied in five diverse Pilot Studies, including North Sea, Canary Islands, Scandinavia, Danube, and Veneto, which formed the heart of the MYRIAD-EU laboratory. In particular, these Pilots served as testbeds for developing forward-looking (multi-risk) DRM pathways and identifying scalable, transferable practices across Europe. Deliverable D3.4 outlines the conceptual and methodological foundations as well as the results of this effort.

Each Pilot Study was selected to reflect distinct biogeographical, socio-economic, and governance contexts while addressing multi-risk challenges due to different combinations of hazards. Together, they address 19 of the 22 most urgent climate risks identified by the European Climate Risk Assessment (EUCRA), including fluvial and coastal flooding, heat stress, biodiversity loss, crop production and infrastructure disruption.

The Pilot Studies followed a stepwise, co-designed process to develop DRM pathways. Initially, desk reviews and stakeholder consultations mapped hazards, vulnerabilities and governance landscapes to define the systemic multi-risk profile of each region. Pilots then chose from a wide suite of qualitative and quantitative tools and tailored applications to their contexts, testing 6-9 tools per region. For all the Pilot Studies, the pathways were co-developed with local, regional, and national stakeholders as part of the project's continuous knowledge co-production process. Stakeholders were engaged via workshops, interviews, and focus groups, shaping challenges, co-developing tools, validating results, and refining the pathways.

DAPP-MR (Dynamic Adaptive Policy Pathways for Multi-Risk) was applied in four Pilots to design DRM strategies across hazards and sectors. UCPM PRAF (Union Civil Protection Mechanism Peer Review Assessment Framework) guided the development of governance-focused pathways in Veneto. The Pilots tailored their DRM pathways not only to individual risks but to the multi-risk context of their regions and addressed trade-offs and synergies between sectors (e.g., tourism vs. agriculture in water use).

The North Sea Pilot focused on managing spatial competition in a dynamic land-sea interface facing increasing and interrelated risk resulting from extreme winds, storms, heat, lightning, precipitation and fog as well as coastal flooding. It applied the DAPP-MR to explore DRM pathways for energy, transport (shipping) and nature conservation. Trade-offs between offshore wind expansion and ecological protection were central. The Pilot highlighted governance fragmentation and the need for integrated marine spatial planning.

The Canary Islands Pilot addressed multi-hazard risks in a tourism-dependent island context, combining future climate risks driven by drought and heatwaves with volcanic eruption recovery needs. It applied the DAPP-MR method to design DRM pathways for tourism and food and agriculture using energy as a boundary condition. Stakeholders co-developed scenarios under optimistic and pessimistic climate futures, highlighting trade-offs in water allocation and land use. The Pilot emphasized the need for cross-sector coordination and long-term planning. Results revealed governance gaps and limited awareness of systemic risks.

The Scandinavia Pilot explored multi-hazard risks (heatwave, drought, wildfire) in climate-sensitive sectors such as energy, food and agriculture, and ecosystems and forestry. It applied DAPP-MR to design energy-specific pathways that accounts for cross-sectoral interactions as well as social dimensions. The Pilot emphasized the need for integrated

planning across sectors and scales. Results highlighted limited cross-sector coordination and data gaps. The pathways offer insights for enhancing resilience in Nordic landscapes under accelerating climate change.

The Veneto Pilot focused on compound climate risks across diverse landscapes, including coastal zones, agricultural plains, and mountain areas. It applied the UCPM PRAF to assess governance structures and co-develop general pathways, proposing a broad, baseline system-level strategy, and tailored cross-sectoral pathways, developed in response to specific risks and addressing finance, infrastructure and transport, tourism, ecosystem and forestry. The Pilot emphasized institutional fragmentation and the need for integrated, cross-sector planning.

Several lessons can be drawn from the experience gained through the MYRIAD-EU laboratory and guide the development of multi-risk pathways in other regions sharing similar challenges. For instance, effective DRM requires tailoring methods to regional or local contexts, combining qualitative with quantitative approaches to capture complexity, and engaging stakeholders early and continuously to ensure relevance and usability. Public authorities should clarify governance roles, align policies across scales and promote cross-sector collaboration to strengthen coordination and long-term impact.

The Pilots' approaches are already informing regional strategies (e.g., Veneto's Strategy on Adaptation to Climate Change (SRACC)), EU-funded projects (e.g., AQUAMAN, ECOAMARE), and transnational initiatives (e.g., Internal Commission for the Protection of the Danube River (ICPDR)). Their legacy lies in demonstrating how systemic, multi-risk DRM can be operationalized, scaled, and embedded into real-world decision-making and offering guidance for future replication and EU-wide uptake.

1 Background and methodological aspects

The five multi-hazard, multi-sector, and multi-scale MYRIAD-EU Pilot Studies, including North Sea, Canary Islands, Scandinavia, Danube, and Veneto (Section 1.1), formed the heart of the **MYRIAD-EU laboratory**. The laboratory aimed to develop forward-looking Disaster Risk Management (DRM) pathways (Section 1.2) and build legacy by drawing lessons and good practices that can be scalable and transferable to other regions throughout the EU and beyond (Section 1.3). During the project, the Pilots have successfully tested and refined a diverse set of innovative methods and tools that address complex multi-hazard and multi-sector challenges in DRM in varied geographic and socio-economic contexts. Thanks to their achievements (illustrated in Sections 2-6), they now serve as lighthouses for other European regions facing similar challenges and aiming to transition towards integrated, systemic multi-risk management.

1.1 Pilots and riskscapes

In MYRIAD-EU, five Pilot Studies were selected to cover different spatial scales, biogeographical regions, and institutional settings across the EU. Figure 1 shows the location and extent of the Pilot regions.

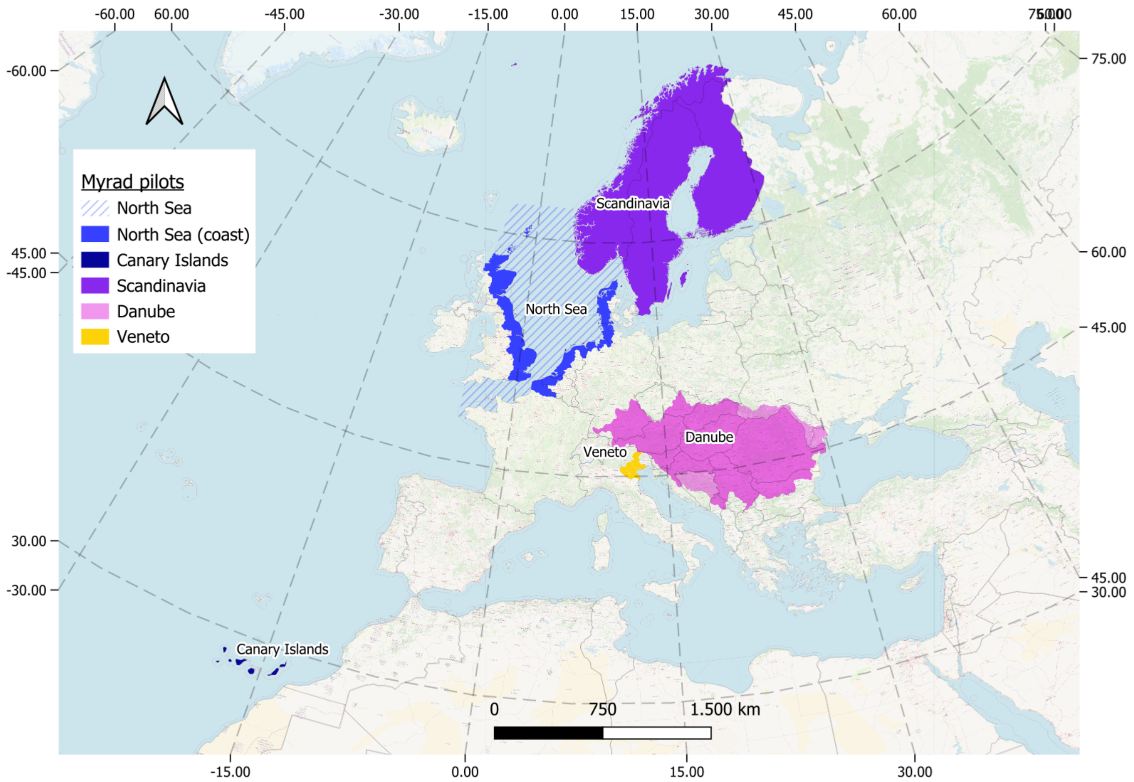


Figure 1: Location and extent of the MYRIAD-EU Pilot regions.

The **North Sea** Pilot is a multi-country region at the land-sea interface with intense pressure on space due to a need to upscale renewable energy and further develop infrastructure and transport links towards Europe, while protecting marine areas, biodiversity and ecosystems. More frequent and extreme storms are expected along with coastal and river flooding due to increased sea level. The **Canary Islands** Pilot is an island region with a strong economic dependence on tourism, whose pressure on energy and food supply, water availability and agriculture is significant. The islands are prone to interrelated hazards, such as volcanoes, earthquakes, coastal and pluvial/fluvial floods, Atlantic hurricanes and heat waves. The **Scandinavia** Pilot focuses on climate-sensitive sectors and the competition for land between energy (hydropower), forestry (wood production) and food production. Climate change is expected to influence extreme rainfall, drought, heat waves, wildfires, and biological hazards such as pine beetles. The **Danube** Pilot represents a transnational perspective with nine Member States and their macroeconomic relations. It focuses on spill-over effects due to multi-hazard and multi-risk events at regional level, mostly involving floods and drought, but also earthquakes, landslides and heatwaves. The **Veneto** Pilot is a sub-national region (North-East of Italy) of highly diverse landscapes, from mountains to plains and coastal strips, facing a myriad of interrelated hazards including wind storms, floods, droughts, forest fires, and water pollution, which affect sectors such as tourism, ecosystems and forestry, food and agriculture as well as water resources.

Each Pilot examined multi-risk challenges in their region, covering six hazards (and interrelations) and three economic sectors (and interdependencies), as summarised in Table 1.

Table 1: Challenges, hazards and sectors addressed in the MYRIAD-EU Pilots.

Pilot Studies	Challenges	Hazards	Sectors
North Sea	How can spatial planning at the interface of the land and sea environments be optimised in the face of increasing and interrelated risk?	Flood, extreme wind, storms, biological hazard, heat, thunder/hail	Energy, infrastructure and transport, ecosystems
Canary Islands	How can island regions with strong economic dependence on tourism become more resilient to multi-hazard risk?	Volcano, tsunami, flood, landslide, storm, earthquake	Tourism, water, energy, and food and agriculture
Scandinavia	How can we maintain healthy ecosystems while meeting increasing demand for energy, food, and ecosystem services, and what is the role of Nature-based Solutions?	Flood, heat, snow, drought, biological hazard, fire	Food and agriculture, forestry, and energy
Danube	How can we increase resilience to multiple disasters that impact several interconnected countries with strong macro-economic relations?	Flood, landslide, thunder/hail, drought, heat, earthquake	Agriculture, transport (navigation), and finance
Veneto	How can diverse natural landscapes from the mountains to the sea achieve a forward-looking perspective conducive to multi-risk planning?	Flood, biological hazard, fire, drought, landslide, tornado	Ecosystems and forestry, tourism, and regional finance

The European Climate Risk Assessment (EUCRA) identified 36 major climate risks for Europe and different hotspots (EEA, 2024). From those risks, there are 22 that were classified as ‘urgent to act’ or ‘more action indeed’ with medium to high confidence in current, mid-century or late-century scenarios. Table 2 shows that most of the EUCRA key risks have been investigated within the MYRIAD-EU Pilots (19 out of 22), with the exception of wellbeing due to non-adapted buildings (health), European solidarity mechanisms and public finances (economy and finance).

EUCRA also identified main hotspots particularly at risk, which include countries from Southern Europe; low-lying coastal and densely populated areas; regional and local economies that are dependent on tourism, agriculture, and fisheries; regions characterised by high levels of unemployment, poverty, emigration and ageing populations; and EU outermost regions (EEA, 2024). Figure 2 shows the extent to which the MYRIAD-EU Pilot regions overlap with the EUCRA hotspot areas. The criteria and sources used to define the borders of the EUCRA hotspots in Figure 2 are reported in Appendix 1. The North Sea coastline, especially in the UK and The Netherlands, is largely characterised by low-lying and densely populated areas. Scandinavia shows similar areas but on a much smaller scale. The Danube region displays several areas with local economies dependent on agriculture, forest, fishery and characterised by high levels of unemployment, poverty, emigration and ageing population. Veneto stands out as a hotspot encompassing all five categories, except for high levels of unemployment, poverty, emigration and ageing population. Finally, Canary Islands encompass all categories as well, with medium-high levels of unemployment, poverty, emigration and ageing populations.

Table 2: Pilots' contribution to the analysis of the EUCRA key risks.

Main Clusters	Key Risks	Canary Is.	Danube	North Sea	Scandinavia	Veneto
Ecosystems	Coastal ecosystems			X	X	X
	Marine ecosystems			X		
	Biodiversity and carbon sinks due to wildfires, droughts and pests	X			X	
	Species distribution shifts	X				
	Ecosystems/society due to invasive species			X		
	Aquatic and wetland ecosystems			X	X	X
	Soil health				X	
Food	Crop production	X			X	X
	Food security due to climate impacts outside Europe			X		
	Food security due to higher food prices				X	
Health	Heat stress – general population	X			X	X
	Population/built environment due to wildfires				X	X
	Heat stress – outdoor workers	X			X	X
	Wellbeing due to non-adapted buildings					
Infrastructure	Pluvial and fluvial flooding	X	X		X	X
	Coastal flooding	X		X		X
	Damage to infrastructure and buildings	X	X	X		X
	Energy disruption due to heat and drought	X			X	
Economy and finance	European solidarity mechanisms					
	Public finances					
	Property and insurance markets	X				
	Population/economy due to water scarcity	X			X	

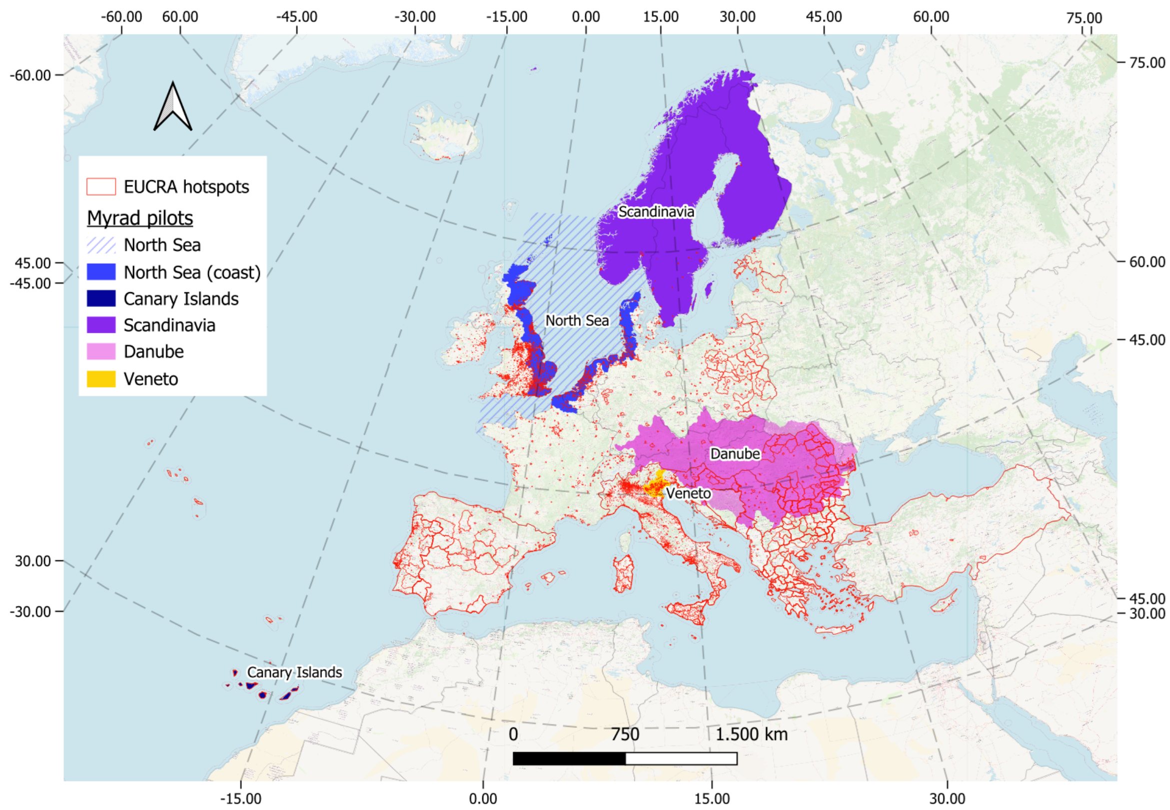


Figure 2: EUCRA hotspot areas covered by MYRIAD-EU Pilot regions.

1.2 Forward-looking DRM pathways

1.2.1 Definitions and concepts

The term **pathway** is used to indicate 'the temporal evolution of natural and/or human systems towards a future state. It ranges from sets of quantitative and qualitative scenarios or narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals' (IPCC, 2022a)[1]. This approach is well developed in climate adaptation science where the **adaptation pathways** are defined as 'a series of adaptation choices involving trade-offs between short-term and long-term goals and values. These are processes of deliberation to identify solutions that are meaningful to people in the context of their daily lives and to avoid potential maladaptation' (IPCC, 2022a).

In the context of the MYRIAD-EU project, several existing collaborative social science methods (e.g., Dynamic Adaptation Policy Pathways (DAPP) approach, DPSIR, CIrcle, Bow-Tie) were proposed to be tailored for developing **Disaster Risk Management (DRM)** pathways that assess trade-offs and synergies of various risk management strategies across hazards, sectors and scales and are specifically designed to incorporate a multi-risk, multi-sector, and systemic perspective, including both climatic and non-climatic hazards, as well as their interrelations.

DRM involves 'the application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses' (UNDRR, 2017). Importantly, the Pilots have attempted to tailor their DRM pathways not only to individual risks but to the multi-risk context of their regions, defined as the 'risk generated from

[1] MYRIAD-EU Disaster Risk Gateway: https://disasterriskgateway.net/index.php/Pathway.

multiple hazards and the interrelationships between these hazards (and considering interrelationships on the vulnerability level)' (Zschau, 2017). Interrelationships at the vulnerability level can reflect both temporal dynamics (e.g., restaurant personnel gradually recovering from the effects of a pandemic) and interactions between elements-at-risk (e.g., disruptions to supply chains caused by a pandemic increasing a company's vulnerability to the economic impacts of a subsequent flood). Such types of interrelationships between multiple sectors have been considered in MYRIAD-EU (Hochrainer-Stigler et al., 2023). For a more detailed description of hazard interrelationships and associated concepts and definitions, please see deliverable D1.2 Handbook (Gill et al., 2022).

1.2.2 Methods, tools and knowledge co-production

Within the MYRIAD-EU laboratory, a **stepwise process** guided the five Pilot Studies in shaping sets of forward-looking (multi-risk) DRM pathways. The Pilots:

- Conducted comprehensive desk reviews to take stock of existing data and information, build their regional systemic multi-risk profiles, and understand the governance and regulatory landscape at local, regional, and national levels.
- Gathered stakeholder perspectives, experiences, and needs in the field of DRM, and formulated multi-risk challenges for their region (Šakić Trogrlić et al., 2024).
- Selected appropriate combinations of methods and tools for multi-risk assessment and management to address identified challenges, drawing on the MYRIAD-EU systemic, multi-risk framework (Hochrainer-Stigler et al., 2023; Hochrainer-Stigler et al., 2025).
- Tested, co-developed and applied the selected methods and tools in collaboration with scientific project partners and local stakeholders.
- Co-developed sets of forward-looking DRM pathways, tailored to each region's specific multi-risk context.

Although the Pilots shared common objectives and work plans, the project opted for a **one size does not fit all** approach. Pilot Leads could choose the most appropriate methods and tools from a wide offer including those developed by project partners[2] (Crummy et al., 2025; Daniell et al., 2024; Daniell et al., 2025; Stolte et al., 2025; Warren & Schlumberger, 2024), available in the literature or in-house. Pilot Leads had the autonomy to determine the appropriate level of detail based on their research goals, internal expertise, and available resources. Their decisions also considered regional size, geographical complexity, and specific stakeholder requirements. This resulted in a variety of methods and tools tested for a total of 6-9 applications per Pilot. Table 3 illustrates the methods used in each Pilot Study.

[2] For more information, explore the MYRIAD-EU Dashboard: https://dashboard.myriadproject.eu/.

Table 3: Methods and tools applied in the Pilots.

Pilot Studies	Methods and tools tested and applied during the project lifetime		
	Analysis of dynamic feedback between risk drivers	*Generation of multi-risk scenarios, both direct and indirect risks*	*Risk-informed decision-making and pathways development*
North Sea	• Interview methodology[3]	• Software for multi-hazard risk scenarios[4]	• DAPP-MR[5] • Storylines for past and plausible future events[6] • CSAA using Causal Chain approach[7] • Cross-sectoral Matrix of Measures
Canary Islands	• Interview methodology	• Software for multi-hazard risk scenarios • Resilience Performance Scorecard[8] • Macroeconomic Agent Based Model (ABM)[9]	• DAPP-MR • Storylines for past events • CSAA for system definition
Scandinavia	• Interview methodology	• GRACE for both direct and indirect risks[10] • Software for multi-hazard risk scenarios	• DAPP-MR • Storylines (past events) • CSAA for system definition
Danube	• Interview methodology	• Software to create multi-hazard risk scenarios for floods, earthquakes and droughts • Macroeconomic Agent Based Model (ABM) for studying interconnectedness • Analysis of FIGARO data for studying sectoral interconnectedness in the Danube Region	• DAPP-MR for adaptation pathways for navigation and agriculture • CatSim methodology for understanding fiscal resilience of countries in the Danube Region[11] • Storylines for plausible future events • CSAA for system definition
Veneto	• Multi-risk conceptual models • Interview methodology • Deep Learning for multi-hazard susceptibility mapping • Supervised ML for multi-hazard risk assessment[12]	• Climate risk indicators • DBSCAN for multi-hazard footprints in present and future scenarios (MYRIAD-HESA[13] adaptation to local scale)	• Storylines (past and plausible future events) • UCPM Peer Review Assessment Framework (for DRM capabilities assessment)[14] • CSAA for system definition

[3] Mysiak, 2022; van Maanen et al., 2025
[4] Daniell et al., 2025
[5] Schlumberger et al., 2022; submitted
[6] Crummy et al., 2025
[7] Warren et al., 2022; Warren & Schlumberger, 2025
[8] Daniell et al., 2024
[9] Daniell et al., 2024
[10] Daniell et al., 2024
[11] Hochrainer-Stigler et al., 2015
[12] Dal Barco et al., 2024, 2025
[13] Claassen et al., 2023
[14] Mysiak et al., 2021

In four Pilot Studies, namely North Sea, Canary Islands, Scandinavia, and Danube, the multi-risk pathways were developed using the **Dynamic Adaptive Policy Pathways for Multi-Risk (DAPP-MR)** approach (Schlumberger et al., 2022; Schlumberger et al., submitted). The main goal of the DAPP approach (Haasnoot et al., 2013) is to collaboratively design long-term strategies to adapt to changing conditions such as (new) disaster or climate risk scenarios, which can be broken into manageable steps to be implemented and adapted over time. The DAPP approach produces alternative sequences of these steps as policy actions (or "pathways") under a range of different scenarios. The Veneto Pilot chose to be guided by the **Peer Review Assessment Framework (PRAF)** used under the Union Civil Protection Mechanism Peer Review Programme (Mysiak et al., 2021; Casartelli et al., 2025b). Both methods were informed by the results generated from other qualitative (e.g., Interviews, CSAA, Storylines) and quantitative (e.g., AI-based) tools.

As summarised in Table 4, the DAPP-MR applications in the Pilot Studies considered interactions across two or more hazards and led to the development of sets of sectoral pathways, including both single-sector pathways and cross-sectoral pathways, which look at interactions and trade-offs between sectors (Sections 2-6). The application of the PRAF to the Veneto Pilot also took the regional multi-risk profile into account and resulted in an initial set of general pathways and a subsequent set of tailored cross-sectoral pathways focused on key risks (Section 6). In several cases, adjustments to the original work plan (Table 3) were deemed necessary due, for instance, to stakeholders' priorities and methodological or data constraints (details in Sections 2-6).

Table 4: Summary of pathways developed in the Pilot Studies.

Pilot Studies	Short description of multi-risk pathways developed in the project
North Sea	DAPP-MR was used to balance competing objectives in spatial planning in the face of increasing and interrelated risk resulting from extreme winds, storms, heat, lightning, precipitation and fog as well as coastal flooding. The North Sea Pilot developed multi-risk sectoral pathways for energy, shipping, and nature. All possible combinations of sectoral pathways were evaluated in terms of interaction effects and number of uncertainties in an effort to identify the most likely to be chosen sets of pathways.
Canary Islands	DAPP-MR was used in La Palma as a blueprint case for other outermost and island territories. Sectoral pathways were developed for tourism and food and agriculture using energy as a boundary condition and combining volcanic eruption recovery needs with climate risks due to droughts and heatwaves. A semi-quantitative approach was applied to evaluate timing, sequencing, and feasibility of DRM measures, while explicitly addressing cross-sectoral trade-offs and dependencies.
Scandinavia	The Scandinavia Pilot adopted a national-level perspective tailored to the Norwegian context. DAPP-MR was used to develop energy-specific pathways that also account for cross-sectoral interactions with food and agriculture as well as nature and forestry. A Storyline around a past multi-hazard event (heatwave, drought, and wildfires in 2018) supported the definition of plausible future scenarios.
Danube	The Pilot focused on understanding the impacts of floods, earthquakes, and droughts on agriculture, navigation and finance. DAPP-MR was used to develop sectoral pathways for agriculture and navigation, while a risk-layering framework helped investigate the fiscal risks due to multi-hazard events. Cross-sectoral interactions were investigated to identify different tipping points indicating when transitioning to another measure, implementing a measure or cooperation between sectors become necessary.
Veneto	The Pilot focused on compound climate risks across diverse landscapes (from mountain areas to coastal zones). UCPM PRAF was applied to co-develop general pathways, proposing a baseline system-level strategy, and tailored cross-sectoral pathways for specific risks and addressing finance, infrastructure and transport, tourism, ecosystem and forestry. A Storyline around a past multi-hazard event (strong wind, heavy precipitation, storm surge in 2018) supported the definition of plausible future scenarios.

For all the Pilot Studies, the multi-risk pathways were co-developed with local, regional, and national stakeholders as part of the project's continuous **knowledge co-production process**[15]. This consisted of a number of key components which set it apart from traditional research approaches (Bolger et al., 2021):

- Establishing a collaborative research team per Pilot comprising both academic and non-academic actors: including Pilot Lead, researchers, and Sectoral Representatives, as well as stakeholders from the Pilot Core User Group (PCUG) and Pilot Stakeholder Groups (PSG). The latter two have a central role in the stakeholder engagement process and different levels of involvement. PSG provides broader, strategic input and feedback through participation in Pilot Workshops, while PCUG is more deeply involved in the project, contributing to product testing, framework development, and thematic work packages through interviews, focus groups, and close collaboration with Pilot Teams. The collaboration was initially supported by **Terms of Reference** and a detailed, structured work plan that aligned research activities with the needs and contexts of those expected to benefit from the research. Pilot Leads played a key role in articulating DRM challenges from the outset and in co-developing knowledge and solutions with stakeholders throughout the research process.
- A collaborative framing of the DRM challenges, and research questions: the co-production of multi-risk pathways was problem-focused and benefited from clearly identified and meaningful goals shared amongst stakeholders. Building on a stocktaking exercise and adopting a more grounded view of social, political, economic, and cultural factors, stakeholders helped refine and focus the challenges that MYRIAD-EU tools, approaches, and methods aimed to address.
- Joint knowledge co-production was achieved through collaborative scientific research and sustained **stakeholder engagement**. Pilot stakeholders were actively involved throughout the research process via two **Pilot Workshops** (2022, 2025), two **Focus Groups** (2023, 2024), **webinars** (2024), and **interviews** (2024) (Table 5; Ciurean et al., in preparation). Research findings informing the development of multi-risk pathways were shared iteratively, with feedback continuously sought to ensure relevance and usability for end users. Where needed, additional engagement activities, such as those conducted in Veneto in 2025, were organised to further refine the pathways. Built-in monitoring and evaluation surveys supported continuous learning and improvement of stakeholder interactions.
- Building on earlier knowledge co-production efforts, the integration of multi-risk pathways into practice can be achieved through several means. This began with **enhanced awareness** of place-based multi-hazard risk challenges and the complex contexts in which they arise across scales and sectors. It was further supported by the co-production of more **actionable and usable knowledge**. The next phases until the end of the project will consider mechanisms for sustained stakeholder engagement, institutional uptake, and policy alignment to ensure long-term impact and integration into real-world decision-making processes.

The involved stakeholders included: government and public agencies at local or regional level (e.g. civil protection departments, DRM authorities, environmental protection

[15] In this context, the term 'co-production' is used broadly to include related concepts such as 'co-creation', 'co-development', and 'co-design'.

authorities), research and academia (e.g. universities, research institutes), private or public sectors and industries, national and international agencies.

Table 5: Number of stakeholders participating during MYRIAD-EU engagement events (PW1 and PW2 - Initial and Final Pilot Workshop; FG1 and FG2 - Focus Group 1 and 2).

Pilot Studies	PW1	FG1	FG2	PW2	Interviews	Webinar
North Sea	3	5	5	13*	3	9
Canary Islands	22	20	11	13	25	
Scandinavia	3	14	18	13*	5	
Danube	12	3	10	6	5	
Veneto	21	6	11	12	6	
Total	**61**	**48**	**55**	**57**	**44**	

*Scandinavia and North Sea Pilots have organised PW2 jointly.

1.3 Upscaling and transferability

1.3.1 Definitions and concepts

There are many disciplines and contexts where the concepts of transfer and upscaling have been applied (Kuhlicke et al., 2021). The term **transferability** can refer to the process of moving beyond a pilot or case study to routine, repeatable services that are accessible and useful (Met Office, 2024). Transfer knowledge in subjects like Disaster Risk Reduction (DRR) targets better decision-making processes (Koria, 2009; Seneviratne et al., 2010), especially on knowledge management (Kusumastuti et al., 2021).

On the other hand, there are many definitions that can be found when talking about **upscaling** and it is sometimes used interchangeably with transferability (Dewi et al., 2018). The term has frequently been referred to as scaling up or scaling (Guentchev et al., 2023). By considering climate services, Guentchev et al. (2023) identify three dimensions for the term: **horizontal, vertical or functional**. Horizontal scaling refers to the geographical expansion or reaching many users; vertical scaling is associated with the creation of an enabling environment, for instance, organisational or political; finally, functional scaling is associated with the addition of new functions and expanding the product or service's features. The horizontal dimension is the most common approach implemented, usually related to transferring information from a smaller scale to a larger scale (Bierkens et al., 2000; Wigmosta & Prasad, 2006) or referring to work on a site-specific that goes from fine to broader spatial scales (Kunin et al., 2018). Results obtained from a given scale are invariably influenced by interactions of ecological, socio-economic, and political factors from other scales and relying on a single scale is likely to lead to missing interactions (MEA, 2003; Asare-Kyei, 2017).

In this line, some authors try to differentiate scaling up (increasing, for instance, in numbers, speed, size) from scaling out (expanding or spreading geographically) (Brander et al., 2012; Wigboldus et al., 2016; Norton et al., 2018; Kuhlicke et al., 2021). Drivers for such upscaling processes vary greatly, for instance, upscaling to a regional level (Thaler et al., 2019). This dimension is also included in some analyses done by increasing model extent and/or decreasing model resolution (Dressler et al., 2022). This exact definition is used by Asare-Kyei (2017), in this case to deal with disaster risk upscaling.

1.3.2 Recommendations for individual methods and tools

A structured tool (matrix) was built in order to collect from project partners information that describes the scalability and transferability of the methods and tools developed or applied in MYRIAD-EU. Three main groups of criteria were defined:

- Group 1 (**Methods characteristics**): refers to methodological and technical aspects of the methods, their applicability domain, and other features (e.g., data input, type of output).
- Group 2 (**Testing and application in MYRIAD-EU**): refers to how the methods were tested and applied in the project, for example the Pilot Studies, the hazards and sectors addressed, the scale or spatial resolution considered.
- Group 3 (**Qualitative evaluation for transferability and upscaling**): refers to a qualitative evaluation of the horizontal, vertical, and functional scalability of the methods, including barriers and enabling factors, based on the expert judgment of the partners responsible for the development or application of the methods.

The matrix was filled in by MYRIAD-EU partners who were responsible for the development or application of the methods and tools during the project lifetime. In total, the matrix contains 23 entries.

Regarding **Group 1 criteria**, the methods support a variety of aims (e.g., intensity-damage functions for individual hazards; AI algorithms for multi-hazard and multi-risk; models to assess direct and indirect impacts on economic sectors; Storylines to explore plausible future scenarios) and produce assessments of qualitative (4), quantitative (14) or both (5) nature depending of the available data. Several methods are flexible enough to address any hazards (both climate- and non-climate driven), or a defined hazard type (the most covered being floods, earthquakes, and heatwaves). Most of the tools can consider or analyse hazards interactions. Many tools directly or indirectly evaluate exposure and vulnerability as well as multiple risks. Several economic sectors can be addressed and some tools allow for qualitative or quantitative analysis of sectoral interdependencies. The majority of the methods account for past, current, and future scenarios. The national spatial resolution is the most frequent, followed by subnational, and local. Specific expertise (e.g., on coding, textual analysis tools, GIS, Machine Learning, or DRM policies) is often necessary to use a tool. For more than 90% of the tools, the involvement of stakeholders is considered necessary or recommended. Most of the methods are or will become open source in the future. Most of the Technology Readiness Levels (TRLs) have been attributed to categories 5 and 6, with one approach at TRL9 (PRAF).

Regarding **Group 2 criteria**, around 18 (out of 23) methods were tested within the Pilot Studies whereas the others were applied at European/global scale.

Under **Group 3 criteria**, partners have identified some **limiting factors** for the upscaling and transferability of methods and tools; for instance limited data availability and resolution, extensive modelling calibration, high computational costs, oversimplification, different timescales across sectors, need to adapt to local context specificities, limited stakeholder engagement, or uncertainty in long-term decision-making.

Regarding **horizontal scalability**, partners believe that the applications carried out in MYRIAD-EU demonstrate strong potential for transferability and scalability across diverse geographic levels, from local case studies to national, European, and even global scale, for most of the methods and tools. While highly adaptable to different governance structures and DRM priorities, their successful implementation largely hinges on the availability of specific, high-quality input data. Crucial data include: historical multi-hazard datasets; current and future climate scenarios; exposure data for selected sectors; vulnerability factors; biophysical impact data; and underlying economic and water quality data. Furthermore, early and continuous stakeholder engagement is consistently highlighted as vital for ensuring that the applications embed local knowledge and lead to the co-development of relevant and effective DRM pathways.

For **functional scalability**, partners have suggested several ways to further enhance project tools and applications in future initiatives, for example: by adding the dynamic analysis of exposure and vulnerability factors; integrating uncertainty estimation using climate model ensembles; and incorporating Earth Observation data for multi-risk impact characterisation. Other potential innovations include: further combining qualitative and quantitative data; improving processing speed; adding multi-language text analysis; and extending applicability to a wider range of hazards and sectors. Future upgrades also aim to: improve hazard data accuracy; enable dynamic and downscaled impact assessments; and develop improved visualisation tools for multi-risk pathways.

In terms of **vertical scalability**, partners believe that several methods and tools can already be mainstreamed and included in national risk management guidelines, with some already integrated in national climate adaptation guidelines (i.e., DAPP in The Netherlands and New Zealand) or at multiple territorial level (i.e., PRAF). In general, MYRIAD-EU results have the potential to inform policies with multi-hazard and multi-risk insights, and promote the inclusion of detailed vulnerability indicators. However, this would again require broader stakeholder engagement to address nationwide heterogeneity, translating local insights into policy recommendations and river basin management plans (e.g., the Danube Climate Adaptation Strategy, see Section 5).

1.3.3 Recommendations at Pilot level

Barriers and lessons learned during the project lifetime were identified in each Pilot Study, and upon them a list of recommendations for researchers and experts willing to replicate or upscale their approach. Additionally, recommendations were drawn for government and public agencies at local, national or EU/international level for actions that could remove barriers and thus enable the transferability and scalability of the approach applied in a certain Pilot Study. Pilot-specific recommendations are illustrated in detail in Sections 2-6. Here, we report a brief overview of the main commonalities.

To varying degrees, all five Pilots have encountered the following **barriers**, which were identified based on the findings presented in this report. These barriers align with the experiences described by Pilot Leads in three of the five challenge themes in the cross-Pilot study by Šakić Trogrlić et al. (2024):

- *Limited cooperation between institutions (government authorities, public agencies, private entities) within and across countries and sectors.* Institutional silos and fragmented mandates often hinder coordinated action and information sharing, reducing the effectiveness of risk governance. This lack of alignment leads to duplicated efforts, inefficient use of resources, and missed opportunities for joint action on systemic multi-risks.
- *Limited stakeholder awareness and engagement, mainly due to capacity constraints.* Many stakeholders, especially at the local level, lack access to information, tools, or training needed to understand and respond to systemic multi-risks. This results in low participation in planning processes and reduced ownership of risk reduction measures.
- *Limited data availability and quality, limited knowledge regarding climate and non-climate risk components and their interactions.* Data gaps, inconsistencies, and the absence of harmonised methodologies constrain comprehensive risk assessments and modelling. In particular, insufficient understanding of the feedback loops and dynamic effects between hazard, exposure, and vulnerability limits the ability to anticipate cascading impacts and design effective interventions.
- *Complexity of the system (multi-risk, dynamic risk, multi-sector, multi-scale).* Multi-risks are interconnected and evolve over time, cutting across different sectors

(e.g., energy, finance, agriculture, infrastructure) and spatial scales. This complexity makes it challenging to identify leverage points for action and requires integrated approaches that account for feedback loops and compound effects at the appropriate scale for decision-making.

Despite these challenges, Pilots have achieved their research goals, built a solid stakeholder network, and successfully co-developed multi-risk DRM pathways relevant for local, regional, and national actors. Based on this experience, we drew a set of **general recommendations**, valid across the five Pilots, ***for researchers and experts*** willing to replicate their approach:

- Stakeholders need to be involved in the co-development process from the early stages of any research projects. A relevant group of stakeholders do not only include government and public agencies, but also research and academia as well as representatives of the private sector and the civil society (specific business operators, municipalities and citizens). Stakeholders should also be selected across hazards, sectors, scales and countries. Diversifying the engagement also fosters participation and exchange (through, for example, workshops, webinars, interviews).
- Stakeholder expectations need to be effectively managed from the early stages of any research project. It is important that researchers and experts raise awareness about the current and future risks in the region and honestly communicate what can be done and what cannot be done with the available methods and tools. Results need to be understandable, usable, and tailored to the specific needs of the involved stakeholders.
- A 'one-size-fits-all' approach is not suitable and should not be applied at any level (transnational, national, local, sectoral). Every region in Europe faces different challenges, which depend on factors such as scale, relevant hazards, relevant sectors, governance landscape , financial capacity, therefore a tailored range of solutions in terms of methods and tools should be offered. In MYRIAD-EU, using combined quantitative and qualitative methods has proven to be crucial in disentangling complexities, filling in any existing gaps in knowledge, and communicating the results to the involved stakeholders.
- Multiple data sources (e.g., from in-situ to Earth Observation-based) should be considered and integrated in applications to increase data availability and quality.

Based on individual Pilots findings, a set of recommendations ***for government and public agencies*** aligned with identified barriers are being proposed. These aim to support the creation of enabling conditions needed for scaling up and transferring research outcomes related to DRM and climate adaptation:

- *Apply multi-criteria decision-making in policy design and DRM or adaptation planning*. Governments and public agencies should move beyond relying on single indicators, such as effectiveness or cost-efficiency, and incorporate additional decision-making criteria, such as long-term resilience, sustainability, spatial equity, and risk tolerance, when evaluating policy options and DRM or adaptation pathways. This ensures more robust, transparent, and context-sensitive choices that reflect diverse stakeholder priorities and system trade-offs.
- *Support the mapping of institutional roles and governance responsibilities at the onset of any collaborative initiative*. Governments and public agencies should support partnerships in mapping existing institutional frameworks, decision-making levels, and governance arrangements at the relevant supra-national, national, regional, or local level. This helps to clarify mandates, prevent overlaps or

gaps, and align new actions with existing structures, particularly in complex or multi-jurisdictional contexts.

- *Create or strengthen existing cross-sector, multi-level coordination mechanisms.* Permanent coordination bodies initiated by public authorities to facilitate alignment across sectors (e.g., water, agriculture, tourism, energy) and governance levels (municipal, regional, national) can support a more integrated approach on future DRM and climate change adaptation. These may include interdepartmental working groups, joint planning platforms, or shared data systems to enhance coherence in climate adaptation and risk governance strategies.
- *Recognise and engage informal and non-state stakeholders in governance processes.* Formally, recognise roles of non-state actors, such as private water associations, as key contributors to an increasingly complex risk governance landscape. Develop inclusive engagement strategies that bring these stakeholders into planning and decision-making processes from the outset, thereby increasing policy legitimacy, ownership, and effectiveness.
- *Align policy objectives across sectors to enhance coherence and avoid contradictions.* Develop, review, and revise sectoral policies considering interdependencies between sectors (or policy areas) and to ensure consistency between climate adaptation, disaster risk reduction, and sustainable development goals. Use scenario-based planning approaches to identify potential policy trade-offs and facilitate inter-ministerial coordination to promote coherent, system-wide resilience strategies (e.g., via a designated network of senior level servants attached to each sector or policy area).

Pilot-specific recommendations are reported in Sections 2-6.

1.4 Key impacts and exploitation

Despite the limitations summarised in Section 1.3.3, the Pilot Leads agree that their overall approaches can be transferred to other regions sharing similar DRM challenges, provided that the specific recommendations outlined in Sections 2-6 are implemented and individual methods and tools are adapted and tailored to the new local contexts. Table 6 summarises regions in the EU and beyond that exhibit similar challenges to those addressed by the MYRIAD-EU Pilots and have been identified as possible candidates for the transferability of Pilot approaches and results in future research initiatives.

Table 6: Regions sharing similarities with the MYRIAD-EU Pilots.

Pilot Studies	**Similar regions in the EU and beyond**
North Sea	EU regions like the Baltic Sea (high density of activities, including fisheries, shipping and offshore wind) and the Mediterranean Sea (featuring intense shipping and fisheries, whilst also serving as a key area for regional tourism) as well as other global regions facing complex and competing uses of maritime space.
Canary Islands	Any EU outermost and Mediterranean island regions.
Scandinavia	Other high-latitude regions in the EU (but also in Canada or Northern Russia) that are covered by large forests and facing combinations of heatwaves, droughts, wildfires, and ecosystem diseases.
Danube	River basins such as the Rhine, Po, or Tisa could benefit from this approach as they are exposed to similar multi-hazard risks like floods and droughts, share complex interdependencies between sectors, and display cross-border governance structures.
Veneto	Other Italian regions that are exposed to similar climate-driven multi-hazard risks.

The Pilot Leads also see opportunities to technically upgrade (e.g., through the integration of new data), downscale (e.g., by collaborating with municipalities) and upscale (e.g., by extending their applications to the national scale or informing policy initiatives at sub-national, national or transnational level) their approaches.

Efforts in this direction have already been made through academic publications and stakeholder meetings, the MYRIAD-EU project has gained increasing visibility and attracted attention, leading to several follow-up research projects. An example is the national research project ECOAMARE (ECosystem-based Adaptive MAnagement for Renewable Energy in a sustainable North Sea) where the DRM pathways developed in MYRIAD-EU using DAPP-MR will be further developed for the North Sea. Another interesting initiative is the AQUAMAN Interreg Euro-MED project, where the long-term, risk-informed and scenario-based planning developed for tourism and agriculture in the Canary Islands Pilot will be integrated with more operational, solution-driven approaches for water governance in a dedicated Living Lab. Moreover, the AI-based method used to map multi-hazard footprints in the Veneto Pilot is currently being applied to a trans-regional case study, the Adige River Basin (North-Eastern Italy), using Earth Observation data in the ESA-funded EO4MULTIHA project, demonstrating its adaptability to other scales and territorial contexts as well as its capacity to integrate new types of data. The Veneto Pilot team is also trying to establish new collaborations with other Italian regions (e.g., Calabria) to develop Storylines using the same approach as in MYRIAD-EU (Crummy et al., 2025; MYRIAD-EU Storylines Repository[16]). Finally, the work carried out in the Scandinavia Pilot has informed a research project funded by the municipality of Bergen (located on the west coast of Norway) aimed to better understand climate risks due to changes in consecutive rain events, consecutive droughts and high precipitations, as well as compound hot and dry events at the local level.

Despite the challenges inherent in ensuring stakeholder participation in the long-term, Pilots built a solid stakeholder network and co-developed multi-risk pathways relevant for local and regional actors. During the Final Pilot Workshops, Pilot Leads discussed possibilities for future uptake of their approaches and results and identified opportunities to continue the collaboration with the participating stakeholders beyond the project. For instance, multi-risk indicators used in the Veneto Pilot to identify current and future risk hotspots supported the development of the first edition of the Regional Climate Change Adaptation Strategy (SRACC) in 2024 (Regione del Veneto, 2024), whereas more recent results obtained from the AI-based modelling (Dal Barco et al., 2025; Ferrario et al., 2024; Ferrario et al., 2025b; Nguyen et al., submitted) may inform its future updates. Another example is the ongoing contribution provided to the Internal Commission for the Protection of the Danube River (ICPDR) Strategy on Adaptation to Climate Change.

[16] MYRIAD-EU Storylines Repository: https://dashboard.myriadproject.eu/storylines-repository/.

2 North Sea Pilot

2.1 Forward-looking DRM pathways

The North Sea Pilot was set up to focus on balancing competing objectives in spatial planning at the interface of land and sea in the face of increasing and interrelated risk resulting from climate change, the most significant being driven by **extreme winds, storms, heat, lightning, precipitation and fog as well as coastal flooding**. The sectors that are most sensitive to climate change and currently undergoing significant transitional change in the region have been included in this Pilot Study. Initially, these sectors were identified as i) energy, ii) infrastructure and transport, iii) ecosystem and forestry. However, based on the specific socio-economic context of the Pilot region and stakeholder discussions, the focus of these sectors was further specified into:

- **Energy**: offshore renewable energy and supporting infrastructure.
- **Shipping**: maritime transport and related industries.
- **Nature**: marine conservation and biodiversity enhancement.

The North Sea Pilot applied the DAPP-MR approach to develop forward-looking DRM pathways (Schlumberger et al., 2022; submitted). In this process, the Collaborative Systems Analysis Approach (CSAA) (Warren et al., 2022) was utilised to map the North Sea multi-risk system and Storylines (Crummy et al., 2025) were employed as a support method to enhance awareness and build capacity among the involved stakeholders (Section 1.2.2).

Applying DAPP-MR in the North Sea Pilot

During the stakeholder engagement process (Section 1.2.2 and below), the Pilot team introduced the DAPP-MR approach. It was realised that there was a need to tailor the overall approach to the interests of the participating Pilot stakeholders and keep it qualitative due to the lack of available data for the North Sea region on historical incidents and hazards. This scarcity of data was largely attributed to the fact that only a few, mostly small incidents have occurred in the past.

The first four steps of the DAPP-MR approach - including 1. Describe context, 2. Assess vulnerability & opportunities, 3. Identify policy options, and 4. Develop & evaluate pathways (Schlumberger et al., 2022) - were utilised as a guideline for capturing trade-offs and synergies across the hazards and sectors to create forward-looking DRM pathways integrating the knowledge towards multi-risk management strategies. The later steps of the DAPP-MR approach, including 5. Design adaptive plan, 6. Implement plan, and 7. Monitoring, fall outside the scope of the Pilot Study. In applying the DAPP-MR approach, particular emphasis was placed on describing the context, with a specific focus on identifying the relevant hazards and risks affecting the North Sea region.

Assessing future changes in extreme events at North Sea level

This section covers the implementation of DAPP-MR Steps 1. and 2. One of the key drivers that will impact all sectors that operate in the North Sea is climate change. Additionally, the North Sea is undergoing significant changes in terms of spatial use, due to the ambitious targets of all eight North Sea Member States to reach offshore renewable energy production, and food/fishing and nature restoration/conservation targets. Climate change and related hazards will increase risks to infrastructure and operations. While sectors can take steps to reduce these risks, limited space from developments (e.g., wind farms, cables) and marine regulations (e.g., fishing zones, marine protected areas) may worsen impacts by raising exposure. Space constraints are thus an added stressor for future sectoral risks.

To understand how future climate change hazards may impact sectors operating in the North Sea, the KNMI'23 climate scenarios (KNMI, 2023) were analysed and evaluated to identify potential impacts of climate change on the chosen sectors in the Pilot Study. This was further supported by results of interviews conducted with the involved regional stakeholders (van Maanen et al., 2025) (Figure 3).

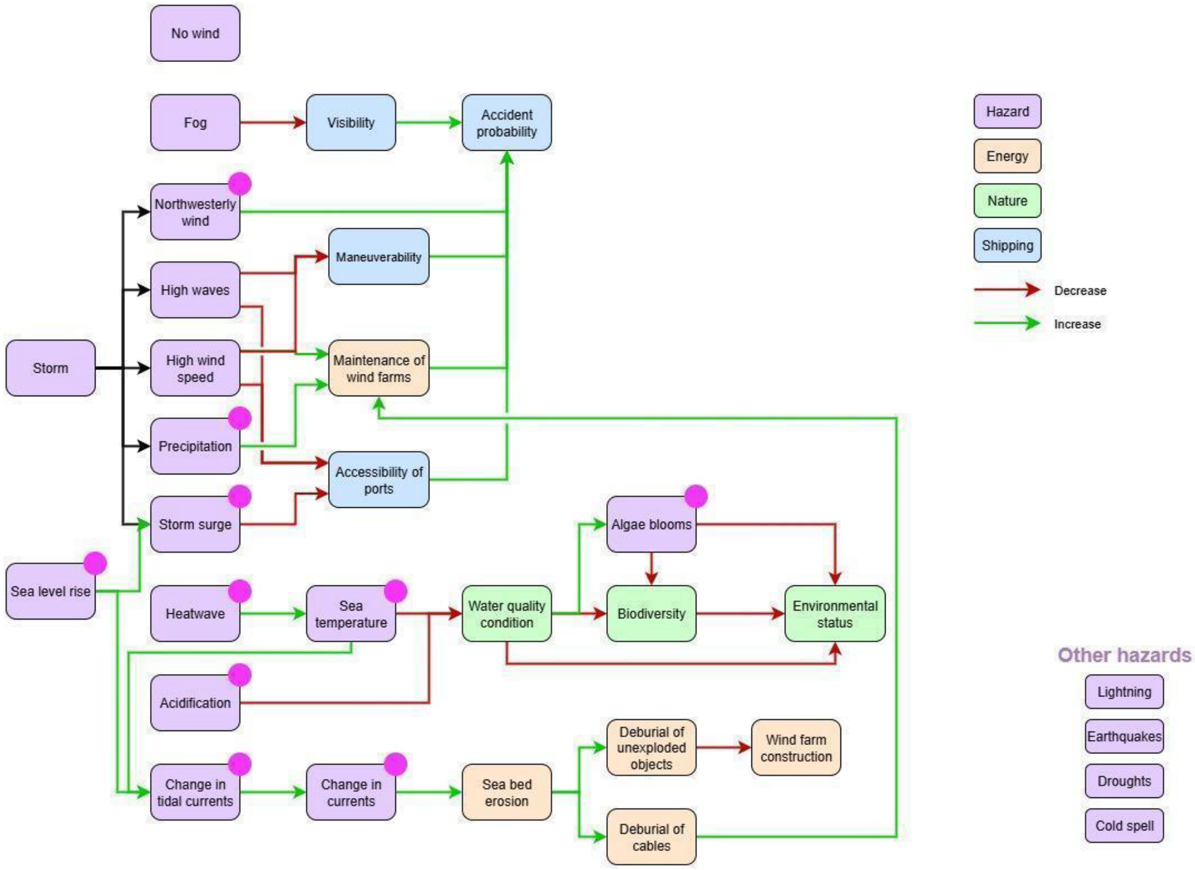


Figure 3: System analysis of the North Sea Pilot (climate change related hazards identified and depicted by a pink circle).

Defining risk management measures

This section covers the implementation of DAPP-MR Step 3. Defining risk management measures is an important activity within the DAPP-MR methodology. These measures are utilised for shaping the pathways and potential strategies. Risk management measures help stakeholders meet the objectives of their sectors in the light of a changing hazard context. The measures were identified based on input from stakeholders, collected during Interviews (van Maanen et al., 2025), an Initial Pilot Workshop and a Focus Group (Section 1.2.2 and below), in combination with a desk study. In total, 32 measures were identified during this process. Each measure was scored based on various criteria, such as sensitivity to space, and effectiveness. These criteria were identified in a joint effort with stakeholders and can ultimately support them in the creation of pathways and prioritisation of measures. The measures identified for each sector are displayed in the following Figure 4Figure 5Figure 6 (10 measures for nature, 10 for energy and 12 for shipping).

Identifying cross-sectoral interactions

This and following sections cover the implementation of DAPP-MR Step 4. Risk management in various sectors necessitates the evaluation and comparison of specific measures to understand their impacts comprehensively. To facilitate this, the Pilot team introduced a **Cross-Sectoral Risk Management Matrix**, which includes each of the individual sector-specific measures. The primary objective of the Matrix is to provide an approach to assess and compare measures across different sectors. It indicates how measures from one sector influence those in another sector. For example, the decision to open wind farms for shipping could negatively impact the energy sector, as it may increase the risk of collisions between vessels and wind turbines. The Matrix was developed by using expert judgement and a literature study. The implications and effects of the cross-sectoral risk management analysis are incorporated into the drafting and final evaluation of the pathways.

Developing sectoral pathways

The risk management measures were used to develop specific pathways for each sector. These pathways are depicted in Figure 4Figure 5Figure 6. For each sector, the objective is defined, and three distinct pathways have been developed, each based on a different underlying narrative. The pathways show which sequence of measures can be taken to ultimately achieve the sectoral objective. The measures displayed at the top are categorized and colour-coded based on their type and nature. The scenarios in the table refer to 1) low climate change scenario in which measures can be implemented over a longer time frame to meet sectoral objectives and 2) high climate change scenario in which measures must be implemented more quickly to reach sectoral objectives due to more rapid climate change.

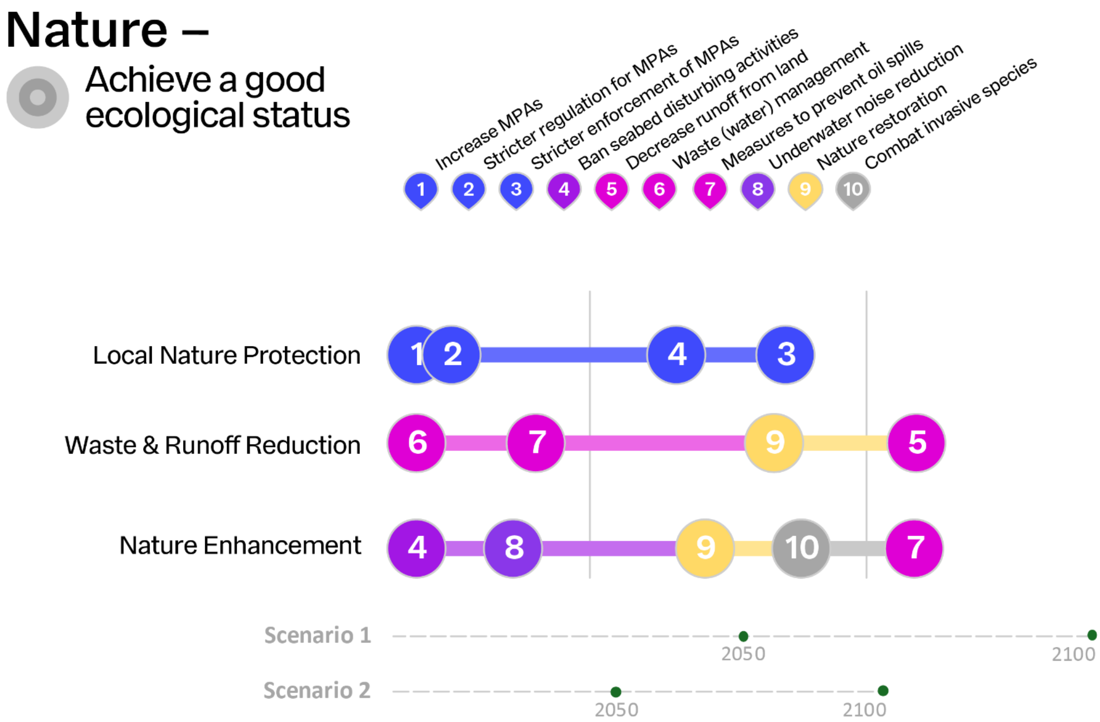


Figure 4: Sectoral pathways for nature (numbers indicate the identified DRM measures). The colours represent different types of measures that share a similar nature or focus (e.g., blue indicates measures related to Marine Protected Areas (MPAs)).

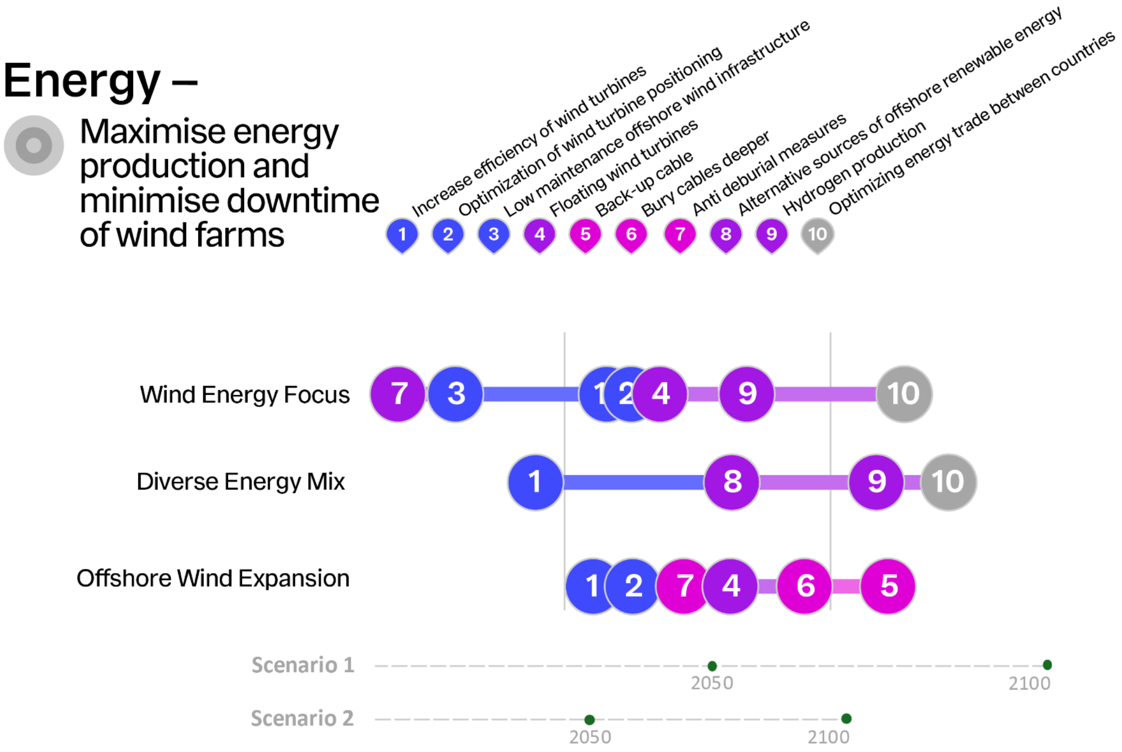


Figure 5: Sectoral pathways for energy (numbers indicate the identified DRM measures). The colours represent different types of measures that share a similar nature or focus (e.g., blue indicates measures related to wind turbine design).

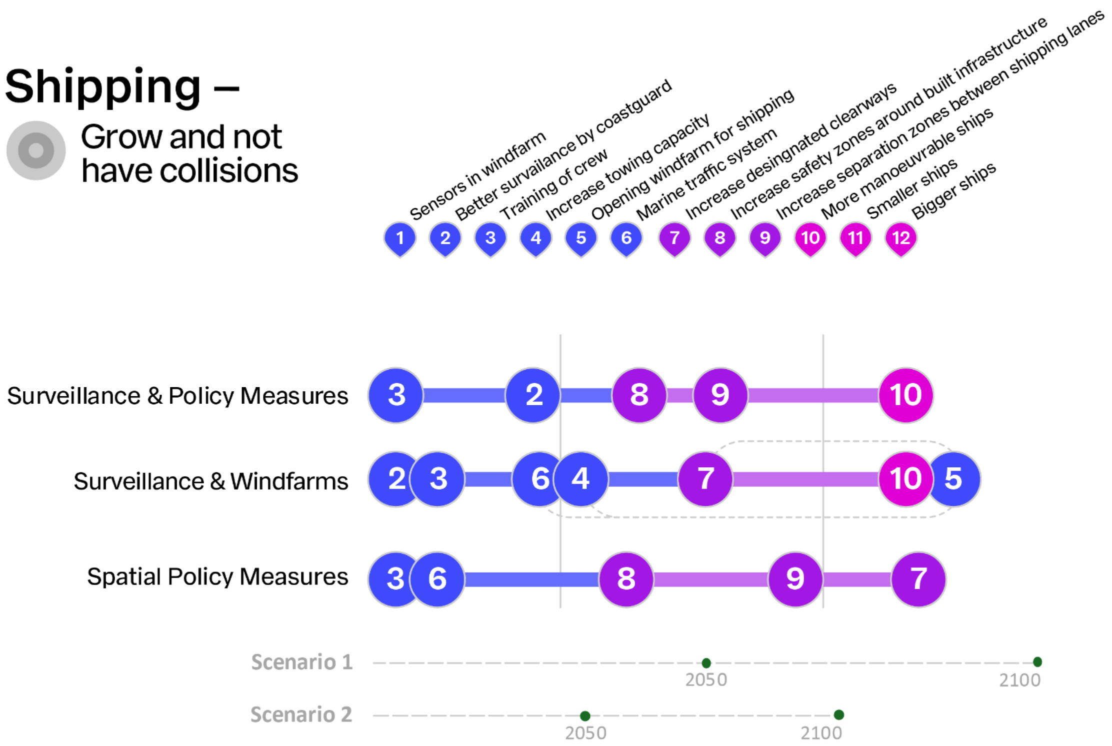


Figure 6: Sectoral pathways for shipping (numbers indicate the identified DRM measures). The colours represent different types of measures that share a similar nature or focus (e.g., blue indicates measures related to surveillance and emergency response).

Scoring and evaluating pathways

Each sectoral pathway was evaluated across four key criteria selected by the Pilot team and validated with stakeholders. First, **effectiveness**, where a higher score indicates greater success in achieving sectoral objectives. Second, **total cost**, with lower scores representing higher implementation costs. Third, **impact on maritime space**, where negative values reflect a negative impact on maritime space, while positive values indicate a beneficial impact. In this context a higher score reflects a higher negative or positive impact. Finally, each pathway is assessed for its **level of regret**, where lower scores correspond to higher regret. Figure 7 provides an overview of the results from the scoring for each pathway. It is important to note that the scores are based on expert judgment and stakeholder consultation and may therefore differ from real-world outcomes.

		Effectiveness for reaching objectives	Cost	Impact on maritime space	Regret
Nature	Waste & Runoff Reduction	6	-2	-1	-4
	Nature Enhancement	7	-3	-1	-5
	Local Nature Protection	7	-3	-2	-6
Energy	Wind Energy Focus	8	-9	3	-7
	Diverse Energy Mix	5	-9	2	-6
	Offshore Wind Expansion	8	-11	1	-6
Shipping	Surveillance & Policy Measures	6	-7	-1	-7
	Spatial Policy Measures	7	-6	-3	-10
	Surveillance & Windfarms	9	-11	0	-11

Figure 7: Results of the multi-criteria evaluation for each sectoral pathway.

The multi-criteria scoring overview offers a solid foundation for comparing and selecting the most appropriate pathway for each sector. Scores shown in red represent negative values, whereas scores in green represent positive values.

Evaluating interaction effects

As previously described, there are interaction effects between different risk management measures and sectors, which can be either positive or negative. In some cases, these effects are not yet fully understood and contribute to overall uncertainty. Figure 8 presents an overview of all possible combinations of sectoral pathways, highlighting: i) the associated interaction effects as the net result of positive and negative effects; and ii) the number of uncertainties for each sector.

The analysis of interactions between sectors reveals that most effects are positive (green cells in Figure 8), indicating potential **synergies** between sectors when implementing different pathways. Only in a few instances do pathway combinations result in negative effects, and these are limited to the energy and shipping sectors (red cells in Figure 8). The nature sector, by contrast, generally experiences only positive interactions. In addition to the identified interaction effects, there are also **uncertainties** associated with the potential interactions for each combination of pathways. These uncertainties vary significantly, with scores ranging from 1 (lowest) number of uncertainties to 9 (highest). Uncertainties arise from the different measures that make up each pathway. They reflect the unknown or unpredictable effects that one measure may have on another sector or sector specific measure. For example, it is unclear whether a measure from the nature sector, like expanding marine protected areas, might negatively impact measures in the shipping sector that require additional maritime space, such as widening of safety zones or designated clearways.

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

Figure 8: Overview of sectoral pathway interactions and uncertainties.

Since the effects of uncertainties are unclear it is challenging to incorporate them into the assessment. However, sectoral stakeholders can use these uncertainties as indicators and remain aware that additional insights may be needed before implementing the corresponding pathways.

At this stage, it remains unclear which specific sectoral pathway is preferred by stakeholders within each sector. As a result, the number of potentially preferred combinations is relatively large, making it more challenging to draw definitive conclusions. However, when focusing exclusively on the criterion of effectiveness in achieving each sector's objectives, the highest-scoring pathways are:

- **Nature**:
  - Nature Enhancement
  - Local Nature Protection
- **Energy**:
  - Wind Energy Focus
  - Offshore Wind Expansion
- **Shipping**:
  - Surveillance & Wind Farms

Based on these preferences, the following combinations of pathways are most likely to be chosen:

- Nature Enhancement || Offshore Wind Expansion || Surveillance & Windfarms
- Local Nature Protection || Offshore Wind Expansion || Surveillance & Windfarms
- Nature Enhancement || Wind Energy Focus || Surveillance & Windfarms
- Local Nature Protection || Wind Energy Focus || Surveillance & Windfarms

It should be noted that the above selection of preferred pathways focuses exclusively on the effectiveness of the pathways, without yet considering cost, impact on maritime space, or the potential for regret. As such, while the Pilot Study is completed, the broader stakeholder dialogue and decision-making process are far from concluded. For pathways to be practically implemented and cross-sector collaboration to succeed, further insights are needed into the specific measures involved, like their costs, effects, potential regrets, and spatial implications. Additionally, sectoral stakeholders must determine what they are willing to invest in terms of cost, and which criteria, such as spatial impact, risk tolerance, or long-term flexibility, are most important to them. In this context, the North Sea Pilot has demonstrated that maximising positive synergies from interaction effects and achieving the highest overall effectiveness in meeting sectoral objectives requires cooperation among stakeholders within and across sectors.

Stakeholder engagement and co-creation

Throughout the Pilot Study, stakeholders were actively engaged with the aim of ensuring a high level of co-creation. Engagement activities were structured to enable collaborative development and to incorporate diverse perspectives from various sectors. Stakeholders were involved at several key stages:

- **Initial Pilot Workshop (November 2022)**: Participants helped identify the system boundaries, relevant hazards, and risks for the different sectors. In addition, stakeholders participated in a collaborative Storyline mapping exercise, which provided a preliminary overview of potential risk management measures.
- **First Focus Group (December 2023)**: This session focused on deepening the understanding of the system. Participants contributed to discussions on relevant measures and developed potential pathways as part of another Storyline exercise.
- **Interviews (February 2024)**: Individual (1:1) interviews were conducted with representatives from the energy and shipping sectors to get more insights into their sectors. Additionally, specific sectoral measures were explored in greater detail. Interviews were also used to discuss the effectiveness of measures and their uncertainties.
- **Second Focus Group (May 2024)**: Stakeholders validated the proposed measures and examined possible interaction effects. Discussions also focused on potential combinations of measures to form sectoral pathways.
- **Final Pilot Workshop (February 2025)**: This event was jointly organised with the Scandinavia Pilot and served to present the outcomes of both Pilot Studies to a broader stakeholder audience. These final results, including the developed pathways, were shared and feedback was provided by the participants.

2.2 Recommendations for upscaling and transferability

Throughout the process, several barriers, key lessons, and recommendations emerged from applying the DAPP-MR approach in the Pilot Study and dealing with future initiatives related to risks and hazards in the North Sea context.

The North Sea Pilot represents the first application of the DAPP-MR approach in an offshore context, an environment defined by distinct hazards, climate change impacts, stakeholders, and governance frameworks. Specifically for the North Sea, the process is further challenged by a lack of disaster risk-related data and limited stakeholder awareness of these risks.

Understanding the regional and governance context

The North Sea region presents a particularly challenging setting for integrated climate risk planning, given its complex, multi-level governance structure and international context.

Moreover, it became apparent that the stakeholder readiness is relatively low and risk awareness among stakeholders is limited. These characteristics might vary significantly across regions, making it essential to tailor approaches accordingly. Mapping the governance landscape and identifying key actors, decision-making levels, and institutional frameworks is a critical first step to ensure that a case study or future project will align with existing structures and responsibilities. The following is recommended:

- At the start of a project, conduct a comprehensive situational analysis of the regional context, including institutional complexity and stakeholder dynamics. Utilise this to adapt your methodology, if required, to better match the needs of stakeholders and local conditions.
- Clearly identify the relevant governance scales (for instance, national, regional, or transboundary) and consider this in determining system boundaries and scope.
- Involve governance actors, specifically decision makers, from the start in order to get clarity on responsibilities and mandates.

Engaging stakeholders through co-creation

Effective stakeholder engagement is essential for building trust and long-term commitment from stakeholders. This is especially important in regions with a high turnover of stakeholders or when dealing with emerging industries. A key insight from the Pilot Study was that stakeholder awareness and readiness were often lower than anticipated. As a result, it was harder to convince stakeholders to participate and commit to Pilot activities. The following is recommended:

- As part of your stakeholder analysis, ensure to include an assessment on stakeholder **readiness and awareness**. Use these outcomes as a starting point for your engagement strategy.
- Co-creation leads to better results. Engage stakeholders in formulating the problem definition and scoping of the project to promote **ownership** and ensure that the outcomes match their needs and expectations.
- Consider hosting **full day/multi-day workshops**, since this will allow for more time to have insightful (informal) discussions and promote trust among stakeholders.
- Clearly communicate the **benefits** of participating in activities to stakeholders. In this way, they will know why they should invest their time in engagement.

Addressing data gaps and communicating risk

In regions like the North Sea, where historical data on extreme events may be limited and there are only limited examples of recent events with a high impact, it is more challenging to discuss and communicate about risks and hazards. This lack of risk awareness can hinder stakeholder engagement, since the urgency and relevance of addressing climate risks may not be apparent to stakeholders. To overcome this barrier, it is key to translate future climate impacts to the daily reality of stakeholders and make them understandable also for those without a technical background. The following is recommended:

- Translate technical data or high-level data (such as IPCC scenarios) to the relevant local context to make these insights **more tangible** for stakeholders.
- Use **storylines and real-world examples** to make a topic (such as risks and hazards) more understandable for stakeholders. Especially focus on how this might impact their sector and operations.

Applying DAPP-MR for multi-risk and multi-hazard planning

The DAPP-MR approach has proven to be a valuable tool for structuring stakeholder engagement and guiding adaptive planning in the face of multiple and interacting risks. By providing a flexible framework, it helps stakeholders explore which risks and hazards they are facing and how different measures can support them to formulate robust adaptation strategies. When tailored to the specific local context and the needs of stakeholders, it can facilitate a shift in the management of multi risks and increase resilience in the longer term. The following is recommended:

- Utilise the DAPP-MR as a starting point and guiding approach but also make sure to tailor it to the **local context and stakeholder needs**.
- The system analysis forms the basis of the methodology. Getting agreement on this and the **system boundaries** may take more time than anticipated, but it is a key investment for later stages of the framework.

Additional considerations for scaling up and future North Sea activities

This Pilot Study served as a valuable starting point, offering a clear example of how sectors and policymakers can implement the methodology in similar settings. Future applications could enhance the reliability and practical value of the outcomes by incorporating quantitative data and more detailed insights into specific risk management measures. Doing so may help address several key uncertainties that currently affect the robustness of results. These include uncertainties related to actual costs, effectiveness, and other parameters of the assessed measures. Moreover, the interactions between sectors and measures introduce additional complexity and unpredictability. Finally, the subjective weighting of individual criteria further complicates the interpretation and aggregation of scores.

The approaches developed and tested in the North Sea Pilot are being leveraged in follow-up projects. One such initiative is the national research project ECOAMARE (Ecosystem-based Adaptive Management for Renewable Energy in a Sustainable North Sea), which will further refine adaptation pathways for the North Sea.

The North Sea is unique in the sense that it is among the busiest and most intensively used maritime regions in the world. It combines a high density of maritime activities, such as fishing, renewable energy generation, and shipping, within a relatively small space. However, in terms of replication of the Pilot Study and its transferability to other offshore areas, the activities and outcomes might be of specific interest for the following regions:

- Baltic Sea: Also characterised by a high density of activities, including fisheries, shipping and offshore wind. It has more advanced regional cooperation at the basin level, comparable to the North Sea.
- Mediterranean Sea: Features intense shipping and fisheries, whilst also serving as a key area for regional tourism. It is increasingly facing environmental pressures.
- Other global regions: Areas facing complex and competing uses of maritime space may benefit from sectoral cooperation and integrated planning, especially for addressing their relevant local multi-risks and multi-hazards scenarios.

3 Canary Islands Pilot

3.1 Forward-looking DRM pathways

The Canary Islands Pilot sought to advance Disaster Risk Management (DRM) and Climate Adaptation by applying the Dynamic Adaptive Policy Pathways for Multi-Risk (DAPP-MR) methodology to La Palma as a blueprint case for other outermost and island territories. The analysis initially aimed to develop DRM pathways for three sectors, i.e., food and agriculture, tourism, and energy, but was then slightly refocused to develop DRM pathways for **food and agriculture** as well as **tourism**, while considering **energy as a boundary condition**, meaning that energy demand must always be met. This immutable condition reflects the centralised, regulated nature of Canary Islands' energy supply, contrasting with water, where allocations are flexible and adaptive under different climate scenarios. A notable innovation is the adoption of a semi-quantitative approach to evaluate the timing, sequencing, and feasibility of DRM/adaptation measures, while explicitly addressing cross-sectoral trade-offs such as competition over water use and the expansion of tourism accommodation capacity. The semi-quantitative approach thus not only compares sectoral measures in isolation but also makes visible the systemic trade-offs and dependencies, especially where water savings in agriculture or tourism may trigger shifts in energy demand through desalination and treatment.

In this report, we illustrate the obtained results as well as the societal feedback on the process, which involved intensive stakeholder engagement throughout, including co-development workshops, bilateral consultations, and validation exercises. We also discuss barriers and opportunities for upscaling the analysis to similar regions.

The resulting analysis generated layered, multi-scenario DRM pathways that could be stress-tested across a range of climate futures and resource constraints. This provided both a practical tool for local planning and valuable methodological insights for future multi-risk assessments in similarly complex settings, to illustrate how DAPP-MR can support more coherent, adaptive, and future-proof planning.

Main challenges

The Canary Islands face long-standing vulnerabilities typical of remote island regions: dependence on international tourism, reliance on external markets, scarce natural resources, and persistent inequality (EEA, 2024). These pressures are compounded by exposure to multiple and interacting hazards such as droughts, heatwaves, wildfires, floods, sea-level rise, and volcanic eruptions (Carrillo et al., 2025; Carrillo et al., 2022; Correa et al., 2025; IPCC, 2022b; Carracedo, 1998).

La Palma, with limited adaptive capacity, is particularly vulnerable, making it a strategic blueprint for piloting DAPP-MR (Martín-Raya et al., 2024). The 2021 Cumbre Vieja eruption exposed how risks cascade across sectors. Lava destroyed ~370 hectares of cropland, mainly banana plantations, while ash and water disruptions damaged more farmland and water infrastructure. Thousands were displaced, networks disrupted, and governance gaps revealed. Tourism suffered severe losses: 1,000 beds destroyed, 3,000 rendered unusable (25-30% of capacity), and over 500 flights cancelled, with many routes still lost (Comisión Mixta para la Reconstrucción, Recuperación y Apoyo a la Isla de La Palma, 2022). Recovery challenges - restoring around 300 hectares of banana plantations and rebuilding 25-30% of lost accommodation capacity - were taken as the starting point for DAPP-MR pathways analysis in the agriculture and tourism sectors, ensuring that post-eruption realities directly informed long-term adaptation planning.

The pathway analysis therefore combines past recovery needs with forward-looking climate risks. **Volcanic eruptions**, which caused severe losses in La Palma, are addressed through sectoral recovery entry points: restoring banana plantations and rebuilding lost accommodation capacity. In contrast, **droughts and heatwaves** were prioritised as the main hazards shaping future scenarios, reflecting both the strongest climate projections for the Canary Islands and stakeholder concerns about water scarcity and systemic stress. Together, this framing ensures that the DAPP-MR pathways connect immediate recovery challenges with the long-term adaptation demands of a multi-hazard future.

Applying DAPP-MR to the Canary Islands Pilot

The DAPP-MR approach enables decision-making under uncertainty by combining scenario planning, adaptive tipping points, and stakeholder co-design. The methodology builds on previous DAPP applications (Haasnoot et al., 2013) and extends it by integrating multi-risk and multi-sectoral dynamics and by applying a semi-quantitative, stakeholder-informed modelling framework (Schlumberger et al., 2024).

The process involved several key steps:

- **System-of-systems framing**: Using the Collaborative System Analysis Approach (CSAA) (Warren et al., 2022), stakeholders identified drivers of change, sectoral goals, and system interdependencies.
- **Scenario development**: Climate-informed scenarios were developed to reflect both optimistic and pessimistic futures, including projections of declining groundwater availability, increasing heatwaves, and sectoral resource constraints.
- **Sectoral pathway design**: Pathways for each sector were based on identifying and evaluating specific measures against climate-induced droughts, developed through several rounds of stakeholder engagement.
- **Semi-quantitative modelling**: Measures were assigned estimates of effectiveness, feasibility, and duration of impact; pathways were simulated across climate scenarios, enabling visualisation of adaptive tipping points and possible interactions.
- **Stakeholder testing and validation**: Results were presented at the Final Pilot Workshop (March 2025), where stakeholders not only validated the pathways but also actively explored different trajectories through an interactive simulation tool, assessing tipping points, trade-offs, and implementation challenges in real time.
- **Cross-sectoral pathways**: The potential for cross-sectoral tensions under extreme heatwave conditions was explored, particularly with respect to competing water needs across different agricultural and tourism water management strategies.

Main results (without sectoral interactions)

The Canary Islands Pilot is focused on food and agriculture, energy and tourism sectors due to their regional economic significance and exposure to climate-related risks. Due to the increasing water demand and energy-intensive sources such as desalination and water treatment, the water-energy nexus has been incorporated, highlighting strong dependencies between water and energy systems.

Sectoral objectives and risk measures

The pathway development process was framed by two cross-cutting assumptions. First, energy demand would always be met, reflecting centralised and regulated energy systems. Second, the water sector would not be assigned fixed resource allocations but would operate under flexible water budgets, based on future projections of groundwater availability across different climate scenarios. Each sector was assigned specific objectives aligned with the island’s development and recovery goals. Food and agriculture, focused on enhancing water-use efficiency and reducing vulnerability to droughts and market disruptions. While tourism aimed to rebuild and expand accommodation capacity while increasing resource efficiency, particularly in water consumption.

Food and agriculture pathways

The DAPP-MR approach for the food and agriculture sector focused on improving water-use efficiency in banana production. Recovery from the eruption was a central driver: the objective was to restore around 300 hectares of lost banana plantations while improving irrigation efficiency to reduce future vulnerability. A wide range of DRM/adaptation measures, including both DRM and climate-related adaptation strategies (Table 7), was identified and tested through expert interviews and literature review.

Table 7: Key drivers of change, relations relevant for the food and agriculture sector, evaluation criteria and selected DRM/adaptation measures for the food and agriculture sector pathways.

Resilient food and agriculture: increase water efficiency in light of climate change		
Drivers of future change	Likely more frequent droughts, heatwaves, and wildfires because of climate change	
	Changes in subsidy schemes	
Causal relations	Increasing uncertainty in productivity and seasonality	
	Increasing uncertainty in regulation and subsidies	
	Water availability determines crop prices, revenues and rural employment	
Long-term objective & Evaluation criteria	**Long-term objective**: foster a climate-resilient local food system reducing reliance on food imports **Evaluation criteria**: minimise water demand and ecosystem degradation	
DRM/adaptation measures	A1. Transitioning from sprinkler to drip irrigation systems	A8. Seeking organic certification as a value-added strategy
	A2. Installing soil moisture sensors to optimise irrigation	A9. Introducing pest-resistant crop varieties
	A3. Expanding the use of greenhouses, despite current limitations related to landscape protection	A10. Implementing "pica" management to prevent price collapse
	A4. Capping productivity at 65,000 kg/ha, aligning with the threshold for EU subsidy eligibility to ensure economic viability	A11. Investing in soil fertility enrichment
	A5. Covering water storage infrastructure	A12. Recovering abandoned land for cultivation of local crops
	A6. Building rainwater storage systems, such as ponds or small dams	A13. Promoting agroforestry systems
	A7. Applying mulching techniques to retain soil moisture	A14. Reducing the total area dedicated to banana cultivation as a water-saving strategy

To simplify the analysis, the semi-quantitative model narrowed its scope to decisions made by banana farmers. This choice reflects the sector's dominance in water use and the EU subsidy structures that reinforce reliance on banana monoculture, limiting diversification into alternative crops. These institutional and economic lock-ins, combined with fragmented governance and private water control, constrain adaptation options and explain why banana farming remains central to La Palma's water–risk nexus. Three strategic pathways were therefore developed:

1. **Business-as-Usual (BAU)**

2. **Sustainable Practices (SP)**
3. **Transformational Sustainable Change (TSC)**

Each pathway includes different combinations and sequences of measures, tested across six climate and governance scenarios (Table 8). These scenarios simulate optimistic and pessimistic projections of groundwater availability and assume a shift in agricultural water allocation from 75% to 85% by 2030.

Table 8: Combination of DRM/adaptation measures to increase water irrigation efficiency for the food and agriculture sector.

Water efficiency for food and agriculture: pathways' narratives and DRM/adaptation measures		
Business-as-Usual (BAU)	This pathway maintains current practices with minimal adaptation. While it delays major changes, it leaves farms vulnerable to rising irrigation costs and water scarcity. Without structural change, long-term viability declines, risking land abandonment.	A5. Covering water storage to reduce evaporation
		A1. Improving irrigation efficiency
		A2. Use soil moisture sensors
		A4. Cap productivity at 65.000kg/Ha
		A14. Reduce banana cultivation area
		A7. Mulching
Sustainable Practices (SP)	This approach introduces moderate ecological and water-saving improvements while retaining the existing cropping model. It is more resilient in the medium term but remains exposed under severe or prolonged droughts.	A10. "Pica" management (market supply control)
		A3. Expanding greenhouses
		A1. Improving irrigation efficiency
		A14. Reduce banana cultivation area
		A6. Build rainwater storage
Transformational Sustainable Change (TSC)	A more ambitious strategy, this pathway promotes structural change shifting toward diversified and climate-resilient agriculture. It supports long-term food sovereignty but requires significant institutional and financial support.	A5. Cover water storage
		A4. CAP productivity at 65.000kg/Ha
		A7. Mulching
		A13. Promote agroforestry systems
		A6. Build rainwater storage
		A2. Use soil moisture sensors to improve irrigation

As shown in Figure 9, food and agriculture pathways were tested under both best- and worst-case climate scenarios to assess their resilience, with water availability emerging as a key constraint. In addition, three water budget scenarios externally decided were considered: 75%, 80%, and 85% of current underground water extraction (the image shows a 75% water budget scenario). The semi-quantitative DAPP-MR analysis compared the three pathways (BAU, SP, TSC) with projected trends in groundwater availability. The grey-shaded scenario envelope illustrates systemic uncertainty and is used to track how long each strategy remains viable under variable conditions. Key findings are summarised as follows:

- **Interplay between water budgets and climate uncertainty**: Water budget constraints influence timing of adaptation, but climate assumptions have greater impact. Scenario testing showed timing differences of up to 50 years based on climate variation, while water budget scenarios shifted tipping points by less than 10 years. Robust strategies must therefore perform well across diverse climate futures.

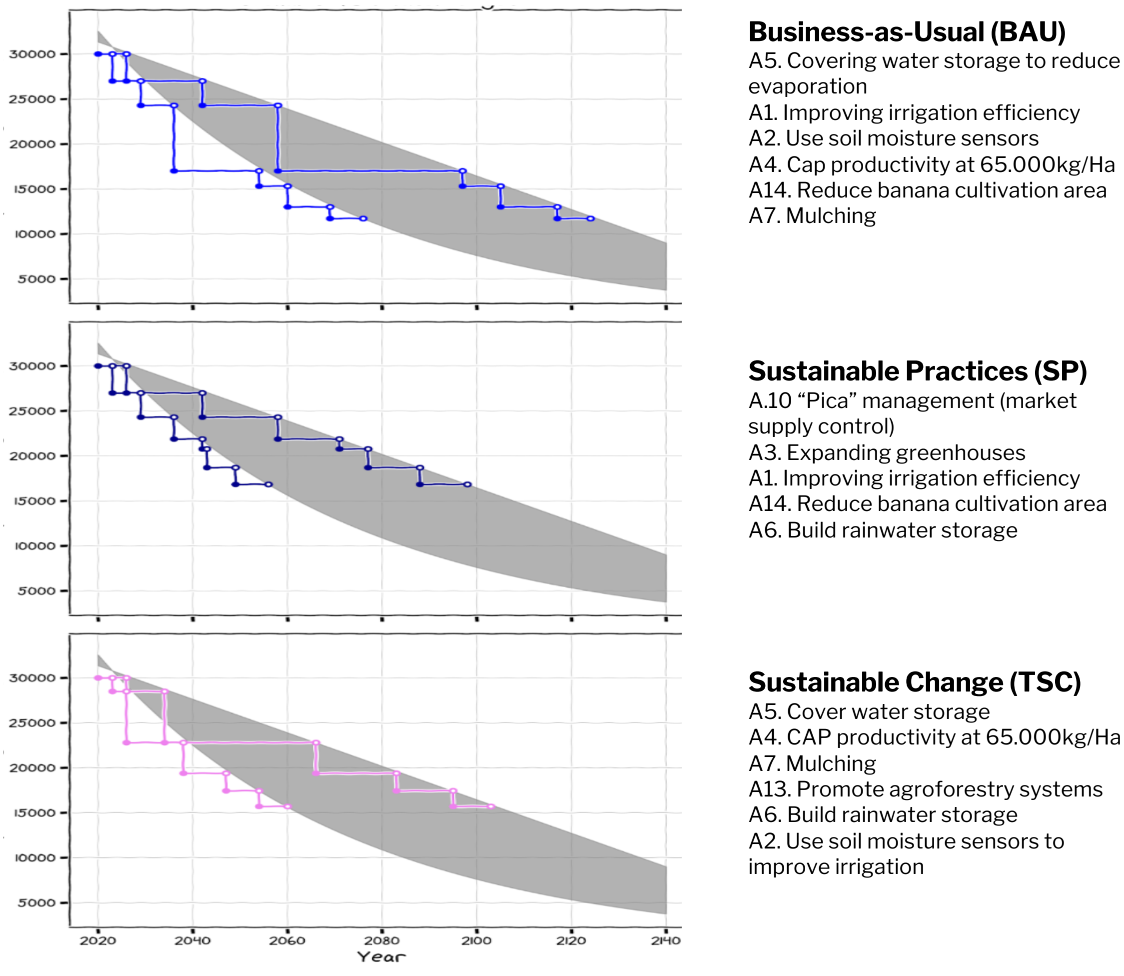


Figure 9: Semi-quantitative pathways for the food and agriculture sector under optimistic/pessimistic climate scenarios with a water budget of 75%. Vertical axis represents the available/required water budget (1000m3/year).

- **Strategic differences across pathways**: The BAU strategy surprisingly shows high mid-term performance due to early adoption of drip irrigation. SP distributes moderate-effort measures more evenly but are less transformative. TSC prioritises structural transformation through ambitious early measures but introduces challenges in long-term feasibility and implementation complexity.
- **Timing, sequencing, and adaptive flexibility**: Effective adaptation depends not only on the choice of measures but their sequencing. BAU introduces a mid-term high-impact measure that eases later pressure. In contrast, TSC may lead to accelerated exhaustion of options and institutional strain due to front-loaded complex actions.
- **Pathway robustness under systemic uncertainty**: Some strategies intersect the lower bound of the scenario envelope early, signalling potential failure under worst-case climate scenarios. TSC provides greater resilience but at higher cost and effort. This highlights the importance of combining technical feasibility with adaptive robustness.
- **Governance considerations and institutional feasibility**: Stakeholder insights reinforced that implementation feasibility matters. BAU benefits from prioritizing less contentious measures (e.g., drip irrigation), while TSC includes actions

requiring broader consensus (e.g., crop area reduction). Governance fragmentation and private water control limit response capacity.

- **Toward integrated and adaptive planning**: The DAPP-MR approach enables blending of tactical and transformational actions based on scenario developments. No single strategy is best across all futures, but robust planning should combine scalable solutions, timely shifts, and ongoing monitoring.

Figure 10 summarises the comparative participatory evaluation (Focus Group 2) of the three agricultural adaptation pathways using six criteria: implementation costs, maintenance and feasibility, regret/payback period, regulatory restrictions, and uncertainty. The BAU pathway performs best in terms of feasibility (score: 7) and low implementation costs (-6). It faces no significant regulatory barriers and achieves a neutral score in terms of regret and uncertainty, reflecting its high acceptability among stakeholders and alignment with existing practices. However, it may lack long-term transformational capacity. In contrast, the SP pathway, although grounded in ecological improvements, scores lower on feasibility (6) and faces moderate regulatory challenges (-2) due to land-use and water infrastructure interventions (e.g., agroforestry and rainwater harvesting). Its implementation cost is slightly higher (-8), though its low-regret profile makes it a viable medium-term strategy. The TSC pathway aims for structural change and long-term resilience, but scores lowest on feasibility (5) and faces the highest regulatory constraints (-5), especially due to greenhouse expansion and land reallocation. While its cost (-7) is lower than the SP pathway, the governance burden is higher, making it more demanding in terms of institutional capacity and stakeholder alignment.

Multi-criteria scores	Measures sequence	Implementation costs	Maintenance & feasibility	Regret/Payback period	Regulatory restrictions	Uncertainty
◇ Business as usual (BAU)	Cover water storage Soil moisture monitoring Implement drip irrigation Limit productivity to 65,000 kg/ha Reduce the area of banana cultivation Apply mulching	-6	7	0	0	0
◇ Sustainable farming practices	Cover water storage Limit productivity to 65,000 kg/ha Apply mulching Promote agroforestry systems Build new rainwater storage systems Soil moisture monitoring	-8	6	0	-2	0
◇ Sustainable transformation (structural changes)	"Pica" market supply management Install greenhouses Reduce the area of banana cultivation Build new rainwater storage systems Soil moisture monitoring	-7	5	0	-5	0

Figure 10: Scorecard of multi-criteria evaluation of water efficiency pathways for agriculture sector.

The results highlight the trade-offs between short-term feasibility and long-term robustness, showing that while BAU is the most immediately viable, achieving systemic transformation will require significant institutional support and regulatory adaptation.

Tourism pathways

The analysis then expanded to include La Palma's tourism sector, where recovery from the eruption's destruction of 25-30% of bed capacity was taken as a starting point. The challenge is not only to rebuild lost infrastructure but also to rethink how future growth aligns with resource constraints. For instance, recovery and adaptation in La Palma require reducing reliance on water-intensive banana monocultures through diversification and efficient irrigation. At the same time, tourism development must shift from coastal resort expansion toward rural-ecological models that promote more sustainable land use (Table 9).

Table 9: Drivers of future change, key relations relevant for the tourism sector along with elements that might be affected by measures or by other sectors, evaluation criteria and DRM/adaptation measures.

Resilient tourism: strengthen competitiveness and resilience by combining capacity expansion with greater water efficiency		
Drivers of future change	Likely more frequent droughts, heat waves, and wildfires because of climate change	
	Global tourism trends: potentially changing tourist preferences towards more sustainable and authentic experiences	
Causal relations	Droughts affect water availability for accommodation, landscapes and crop cultivation (and thus food and water costs)	
	Destination image is determined by the quality and quantity of local resources and ecosystem	
	Water, energy and food costs determine destination competitiveness	
	Trend-aligned offers and changes in tourism determine the attractiveness of the destination	
Long-term objectives & Evaluation criteria	**Long-term objective:** Create less resource intensive tourism **Evaluation criteria 1:** Expanding tourism bed capacity to restore and strengthen market competitiveness **Evaluation criteria 2:** Improving water efficiency in tourism establishments to reduce vulnerability to water scarcity and climate stress	
DRM/adaptation measures to (1) increase bed capacity	TB1. Vacation homes, under current standards or redesigned with sustainable practices	
	TB2. Expansion of existing hotels, using either current or more sustainable approaches	
	TB3. Construction of new hotels, incl. sensitive zones or with water-intensive amenities	
	TB4. Development of eco-lodges, using existing standards	
	TB5. Promotion of community-led, regenerative accommodation models	
DRM/adaptation measures to (2) increase water efficiency	TW1. Installation of water-saving fixtures	TW5. Water-efficient laundry systems/pools
	TW2. Implementation of grey water recycling	TW6. Real-time water monitoring
	TW3. Use of water-efficient landscaping	TW7. Repurposing of swimming pools
	TW4. Water conservation awareness campaigns	TW8. Water imports (as a last alternative)

Two evaluation criteria were defined to achieve the long run objective and guide adaptive planning: expanding tourism bed capacity to restore competitiveness and increasing water efficiency in establishments to improve climate resilience.

For evaluation criteria 1 (Expanding tourism bed capacity to restore and strengthen market competitiveness), three tourism growth pathways were developed:

1. **Business-as-Usual (BAU)**: Prioritises rapid recovery through conventional expansion of vacation homes and hotels.
2. **Extensive, Reactive Tourism (ERT)**: Favors gradual growth through sustainable options like eco-lodges and community-led models.
3. **Intensive, Proactive Tourism (IPT)**: Accelerates bed growth using new hotels in sensitive zones with high water demands.

Figure 11 compares the three tourism expansion pathways. The IPT option shows lowest costs and fastest payback but weaker regulatory feasibility and guest experience; the ERT pathway delivers the best guest experience and lowest uncertainty but faces the highest costs, longest payback, and strong regulatory barriers; while the BAU approach mirrors

IPT on costs and payback, avoids major hurdles, but offers only moderate guest satisfaction and limited long-term resilience.

Multi-criteria scores	Measure Sequence	Implementation costs	Maintenance complexity, Feasibility across accomodation types	Regret/Payback period	Regulatory constraints	Guest experience	Uncertainty
Intensive, proactive tourism	New Hotels (sensitive zone), Vacation Homes (current standard), Hotel Expansion (Current standard)	-5	0	1	-3	-1	1
Extensive, reactive tourism	Hotel Expansion (Sustainable Practice), Community-led accommodations, Eco Lodges (current standard), Vacation Homes (Sustainable Practices), Vacation Homes (Sustainable Practices)	-8	0	8	-6	13	0
Business as usual	Vacation Homes (current standard), Hotel Expansion (Current standard), New Hotels (water intensive Amenities)	-5	0	1	-3	-1	1

Figure 11: Multi-criteria scores for combinations of tourism measures to increase accommodation capacity.

These results underscore the trade-offs between short-term feasibility, long-term sustainability, and systemic ambition. While the BAU and IPT pathways appear more feasible in the short run, they risk locking the island into resource-intensive trajectories that accelerate water scarcity and increase vulnerability to climate extremes. The ERT pathway, though more ambitious and challenging to implement, holds promise for positioning La Palma as a model for regenerative, climate-resilient tourism, aligning recovery with long-term resource security.

The three pathways are illustrated in Figure 12, providing trade-offs between early recovery and long-term resource sustainability. The BAU and IPT pathways breach resource constraints earlier, while ERT pathways provide greater resilience but slower capacity expansion.

For evaluation criteria 2 (Improving water efficiency in tourism establishments to reduce vulnerability to water scarcity and climate stress), tourism water efficiency was assessed using two pathways:

1. **Small Measures Only (SMO)**: Focuses on low-cost, non-disruptive options, including the following measures: water-saving fixtures; water-efficient landscaping; water-efficient pools; water-efficient laundry systems; and grey water recycling.
2. **Fundamental Changes (FC)**: Includes structural retrofits like water-saving fixtures; greywater recycling; pool repurposing; and water-efficient laundry systems.

Figure 13 provides a sample of semi-quantitative pathways to increase water efficiency in La Palma's tourism sector, modelled across a 4% groundwater allocation scenario, as a showcase for alternative water budgets (5-6%). This scenario tests how different combinations of adaptation measures perform under optimistic and pessimistic drought conditions, capturing timing, feasibility, and systemic stress.

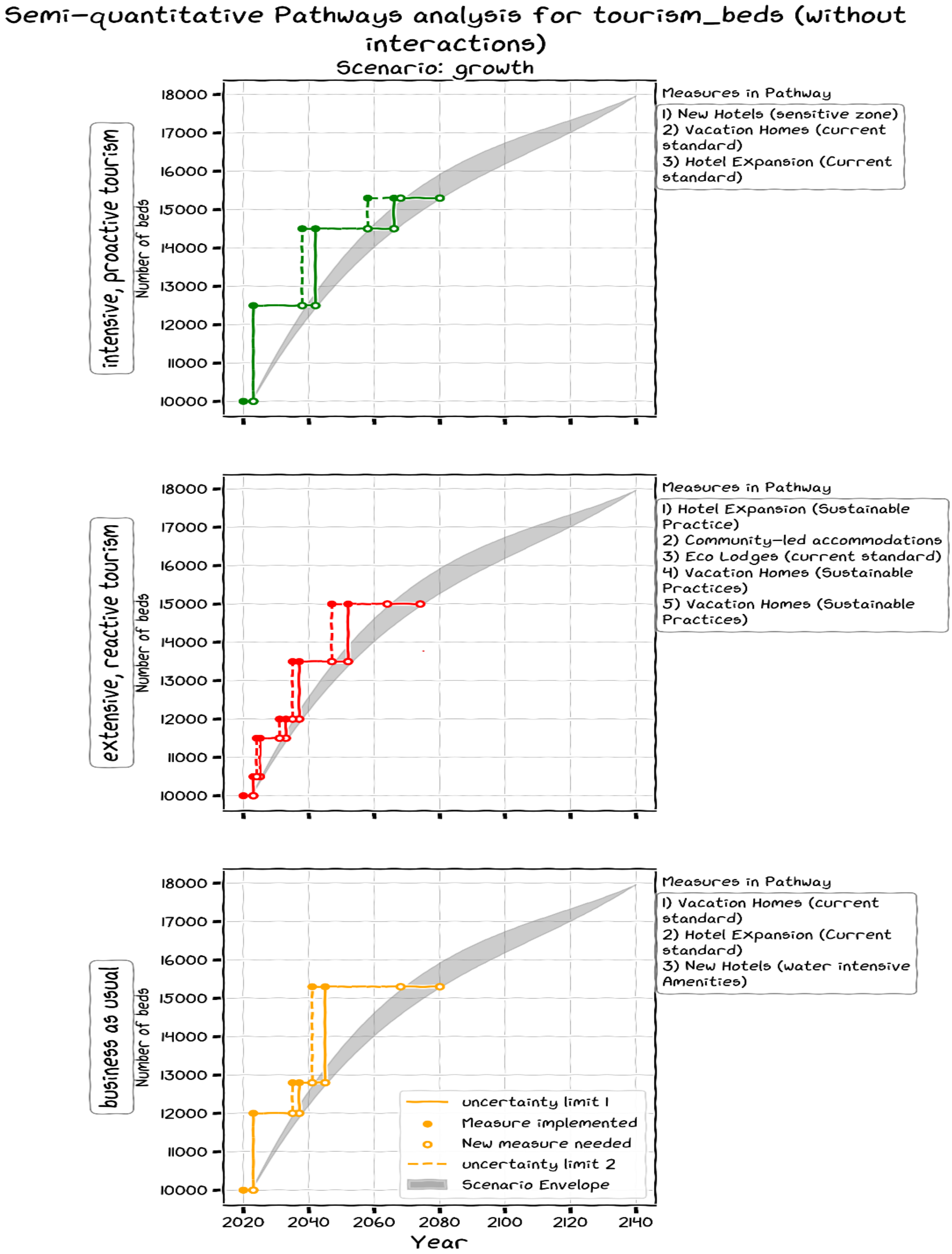
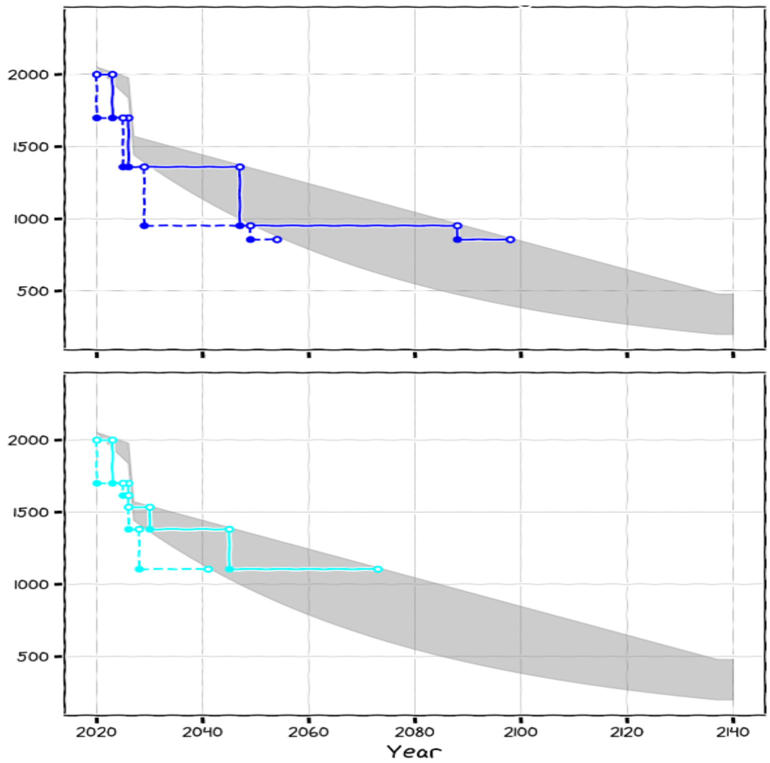


Figure 12: Semi-quantitative pathways for tourism capacity expansion in La Palma.



Fundamental Changes (FC)

1. Water-saving fixtures
2. Greywater recycling
3. Pool repurposing
4. Water-efficient laundry systems

Small Measures Only (SMO)

1. Water-saving fixtures
2. Water-efficient landscaping
3. Water-efficient pools
4. Water-efficient laundry systems
5. Grey water recycling

Figure 13: Semi-quantitative pathways for tourism water efficiency, using a scenario of 4% of water budget. Vertical axis represents the available/required water budget (1000m3/year).

Figure 14 shows multi-criteria scores from local stakeholders during Focus Group 2. The outputs indicate that incremental-only approaches offer short-term acceptability but may quickly exhaust their potential under extreme scenarios. In contrast, structural water-efficiency investments offer more robust long-term benefits, though they may require greater regulatory coordination and upfront investment. The outputs reinforce that structural transformation is not only about reducing water use - it is also about building adaptive capacity, minimising regret, and maintaining sectoral viability as a risk compound.

Multi-criteria scores	Measure Sequence	Implementation costs	Maintenance complexity, Feasibility across accomodation types	Regret/Payback period	Regulatory constraints	Guest experience	Uncertainty
Fundamental Changes	Water-saving devices Greywater recycling systems Swimming pool conversion Efficient laundry systems	-8	0	5	-2	0	1
Small measures only	Water-saving devices Low-water-use landscaping Water-efficient swimming pools Efficient laundry systems Greywater recycling systems	-10	0	7	-1	5	1

Figure 14: Multi-criteria scores for combinations of tourism measures to increase water efficiency.

Tourism's sensitivity to water allocation is critical. Even slight reductions in allocated water - such as a 4% share of groundwater - can trigger early tipping points in pathways relying solely on small-scale efficiency measures. This underscores the sector's limited buffer capacity under conditions of stress. FC pathways, by contrast, maintain operational viability longer in severe drought scenarios. Their inclusion of structural and technical upgrades (e.g., greywater recycling and repurposing of pools) results in greater robustness and fewer disruptions. Timing and sequencing also emerge as decisive. Pathways that delay structural interventions - such as SMO strategies - quickly exhaust adaptation options, especially as climate conditions worsen. Early action with scalable, transformative measures provides smoother transitions and avoids system shocks.

Tourism inter-sectoral adaptation policy interactions

To further explore the tensions between tourism capacity growth and resource allocation efficiency, *Figure 15* shows the implications of this tension by simulating drought-adaptation pathways under three different water budget scenarios (4% of total allocation) and under a growth scenario for tourism beds (S1) - an extensive, reactive tourism model.

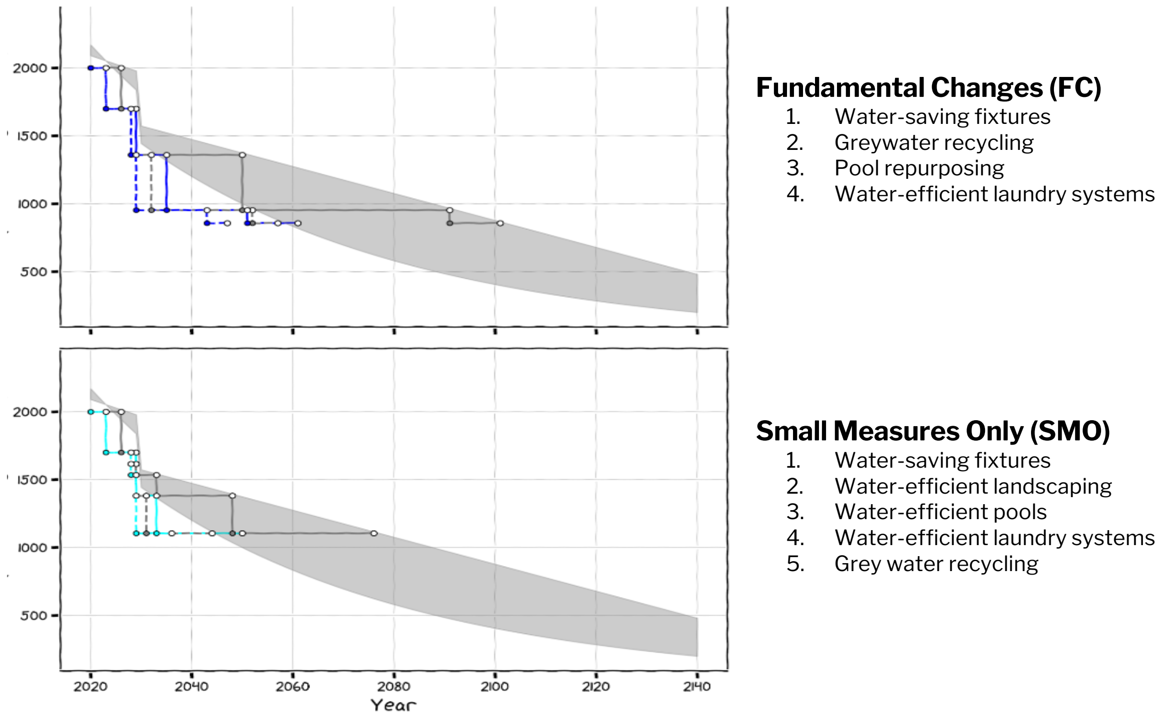


Figure 15: Re-evaluation of semi-quantitative drought-adaptation tourism pathways as it responds to capacity growth with extensive-reactive tourism (4% of water budget). Vertical axis represents the available/required water budget (1000m3/year).

Figure 15 overlays inter-sectoral interactions, specifically, how increasing bed capacity affects water demand, bringing forward tipping points that require the implementation of additional measures. Optimistic and pessimistic scenario-pathways with interactions (light and dark blue) and without interactions (grey), under both FC (top) and SMO (bottom) strategies, illustrate how future feasibility is reshaped when internal sectoral dynamics (e.g., growth in tourism accommodation) are combined with resource constraints.

A clear pattern emerges: when sectoral growth is considered, the buffering capacity of adaptation pathways significantly decreases. This is visible in the shorter horizontal distances between adaptation steps, indicating that each implemented measure provides less temporal relief before the next intervention is required. As a result, pathways become more reactive, with adaptation measures triggered earlier and more frequently, particularly under the SMO strategy, where limited effectiveness leads to rapid exhaustion of feasible responses. In scenarios without interaction, water demand is assumed to remain constant or only climate-driven, enabling longer feasibility periods for each pathway. However, once growth in tourism beds is factored in, the available water budget is quickly outpaced - especially under SMO strategies - causing tipping points to occur significantly earlier in both optimistic and pessimistic climate futures.

Figure 15 demonstrates how neglecting key internal drivers of change can mask critical vulnerabilities and delay the recognition of necessary adaptation steps.

Advancing cross-sectoral and multi-hazard DRM pathways

Building on the sectoral pathways developed for tourism and for food and agriculture, the Pilot integrated cross-sectoral and multi-hazard aspects. Figure 16 presents the evolving supply buffer for tourism and banana production under different sectoral strategies over the planning horizon. The evolving supply buffer is defined as the difference between projected available water (based on water budgets) and sectoral demand using previous pathways. This metric allows us to assess the ability of each pathway to absorb sudden increases in demand, such as those triggered by extreme heatwave events.

The first image in Figure 16 illustrates *the water supply buffer* for banana and tourism strategies. Structural pathways in both sectors maintain more resilient buffers than incremental ones. BAU in tourism leads to volatility after 2050, and SMO in food and agriculture depletes its buffers by 2060. The second image identifies *periods of overlap* when both sectors simultaneously experience critically low water buffers. These co-occurrence years highlight how sectoral dynamics, if misaligned, can exacerbate systemic risk. The third image quantifies the number of years between 2020 and 2140 when both sectors face simultaneous high-risk periods under various combinations of sectoral pathways. Combinations with incremental measures - especially in tourism - lead to the most frequent overlaps, while combinations involving transformational strategies offer greater systemic resilience.

This analysis represents a first iteration of dynamic policy exploration for multi-risk DRM, focusing on water demand in tourism and food and agriculture under both drought and heatwave conditions. The results show that, especially in the tourism sector, current water demand reduction measures are insufficient under compounding risks. Further refinement could involve testing sensitivity to climate projections, revising assumptions around measure feasibility, and integrating supply-side water solutions (e.g., desalination and wastewater reuse, already considered in the island water planning). Importantly, these measures carry energy costs - especially in La Palma's isolated, fossil-reliant system - underscoring the importance of integrating energy into cross-sectoral DRM planning. In practice, this dependence on fossil-based electricity makes water adaptation measures highly vulnerable to fuel price volatility and carbon lock-in, reinforcing the need to align DRM pathways with the island's renewable energy transition (Mirkova and Padrón-Fumero, 2025).

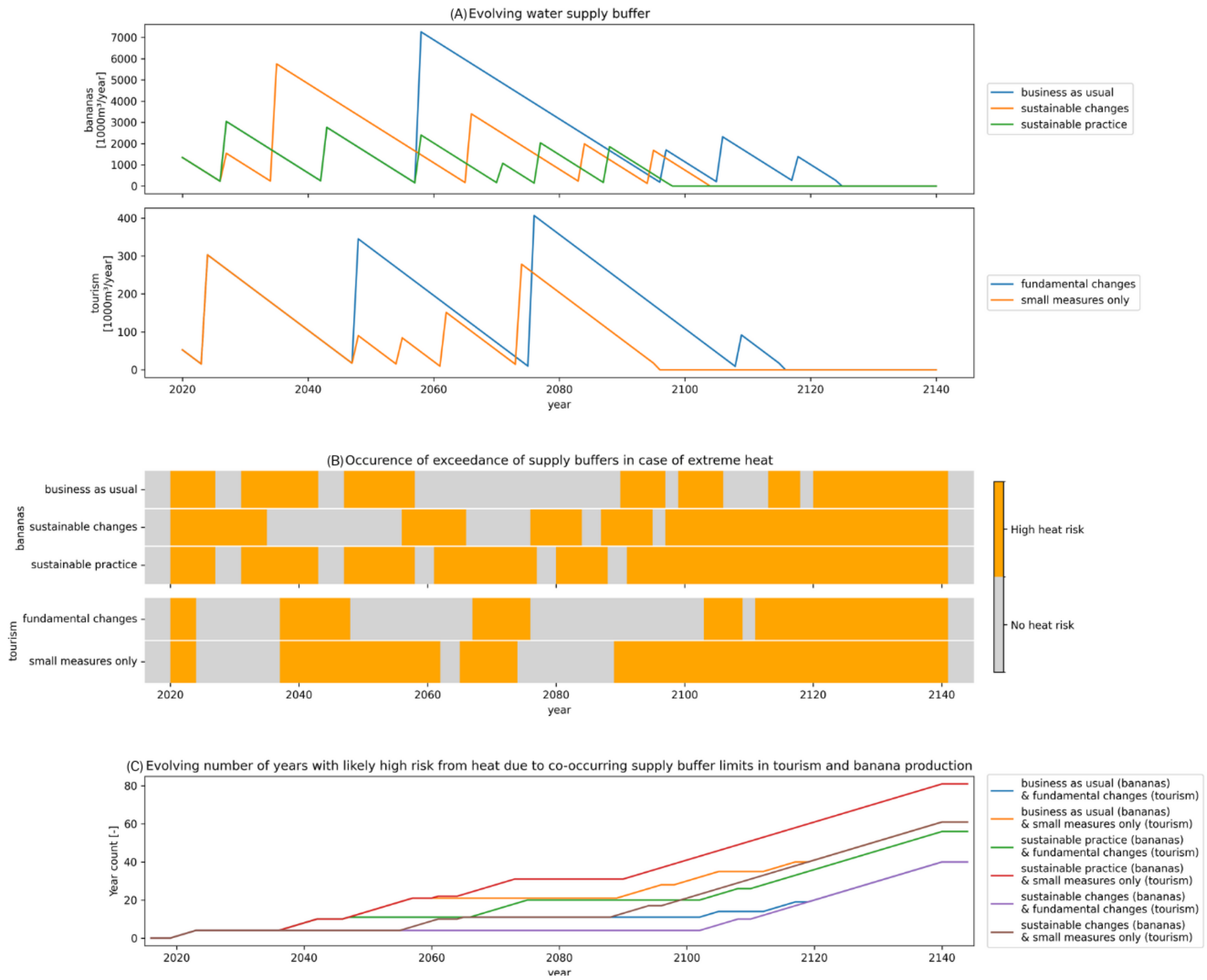


Figure 16: Agriculture and tourism sectoral interactions as heatwaves are integrated into the scenario analysis. (A) Evolving water supply buffer; (B) Occurrence of exceedance of supply buffers in case of extreme heat; (C) Evolving number of years with likely high risk from heat due to co-occurring supply buffer limits in tourism and banana production.

3.2 Recommendations for upscaling and transferability

The Canary Islands Pilot shows the value of applying DAPP-MR in a participatory, semi-quantitative way to design long-term pathways for tourism and for food and agriculture under multi-hazard, resource-constrained scenarios. It highlights that growth-driven strategies (e.g., bed expansion, banana intensification) often conflict with water security, whereas early transformative measures, though politically difficult, offer greater long-term resilience. Limitations such as simplified assumptions, exclusion of market dynamics, and lack of full cross-sector modelling reflect the early stage of the DAPP-MR application rather than flaws in the framework.

Barriers

- **Fragmented governance**: Water is split between public and private actors, while agriculture, tourism, and water remain siloed, hampering integrated risk management. This fragmentation is not only a technical issue but a systemic governance barrier, as no single authority currently has the mandate to align water, agriculture, and tourism planning under multi-risk conditions. At the same time, this gap highlights the need and opportunity for multi-level governance frameworks that can institutionalise cross-sectoral alignment.

- **Economic dependency**: Reliance on tourism and water-intensive banana monoculture creates institutional lock-ins, increasing exposure to multi-hazard risks and slowing transformation. These dependencies tie livelihoods and revenues to volatile global markets while increasing exposure to multi-hazard risks, making systemic transformation politically and socially difficult. Yet these very lock-ins illustrate where EU and regional policy could most effectively support diversification and resilience.
- **Scenario constraints**: Pathway design relied on simplified assumptions, excluding feedback from markets and policies (such as EU subsidy reforms, shifts in global tourism demand, or energy price shocks) that could decisively reshape sectoral viability. At the same time, the exercise demonstrated how powerful the pathway-building approach can be as a platform to explore such feedback in future iterations, turning these limitations into opportunities for deeper systemic learning.
- **Stakeholder gaps**: Small tourism operators, local communities, and informal actors were underrepresented in the co-production process. This not only reduced legitimacy but also missed critical insights from those most directly exposed to crisis recovery and long-term adaptation challenges. Going forward, targeted methods (e.g., participatory games, storytelling tools) can help ensure their knowledge and priorities are systematically embedded.
- **Data gaps**: The absence of long-term, high-resolution data on water, tourism, and agriculture restricted the ability to fully test assumptions, detect compound tipping points, and evaluate cross-sectoral interactions. This reduced the robustness of results and limited their transferability to other contexts. At the same time, these shortcomings clearly demonstrate the strategic importance of investing in interoperable, integrated data infrastructures across sectors, an area where MYRIAD-EU can provide both a proof of concept and a roadmap for future European initiatives.

Lesson learned: the strategic value of DAPP-MR

The Pilot demonstrated that the DAPP-MR approach adds value by clarifying when and how measures should be introduced, highlighting the importance of combining early low-regret actions with long-term transformative strategies; using scenario envelopes to stress-test adaptation options and navigate uncertainty; revealing how tourism growth and agricultural water use are tightly interlinked and must be planned together; and underscoring that success ultimately depends on flexible governance, with institutions able to adjust policies as risks and conditions evolve. A central insight is that sequencing matters: delaying structural measures can rapidly exhaust feasible options under severe climate futures, while early adoption of scalable actions avoids system shocks and reduces institutional strain. The Canary Islands Pilot thus shows how DAPP-MR can move beyond single-sector planning toward systemic recovery-linked adaptation, a lesson transferable to other Pilots and outermost regions.

Recommendations

To support the effective transfer of the DAPP-MR approach beyond the Canary Islands Pilot, particularly to other outermost regions, small islands, or tourism-intensive territories in the EU, a set of strategic recommendations has been identified (

Table *10*). These build directly on the lessons learned and barriers encountered during the project lifetime. Implementing these actions can enhance the development of long-term, risk-informed strategies that better align resilience, sustainability, and economic viability in the face of compounding climate and systemic risks.

Table 10: Risk-informed strategic recommendations for upscaling and transferability.

Recommendations for upscaling and transferability	
Apply DAPP-MR in other tourism-dependent, water-stressed regions	Identify tourism-reliant regions vulnerable to water scarcity and multi-hazard risks.
	Use DAPP-MR to explore trade-offs between economic development, resource sustainability, and climate resilience.
Strengthen cross-sector coordination and risk governance	Promote institutional mechanisms to align tourism, agriculture, water, and energy planning.
	Integrate hazard interaction findings into land-use, tourism, and disaster planning policies.
	Foster multi-level governance linking municipal, insular, and regional decision-making.
Enhance data infrastructure and evidence-based decision making	Invest in interoperable climate, socio-economic, and infrastructure data systems.
	Develop tools that combine downscaled climate projections with hazard and exposure maps.
	Encourage open data sharing across agencies and stakeholder groups.
Institutionalize participatory planning	Embed co-development processes into formal governance frameworks (e.g., tourism boards, water councils).
	Ensure sustained engagement with underrepresented stakeholders through tailored tools (e.g., visual storytelling, scenario games).
Mainstream NbS for water and risk management	Align EU and national policies (e.g., WFD, FD, CAP) to incentivize NbS adoption in island settings.
	Encourage public-private partnerships for NbS in tourism hotspots and agricultural buffer zones.
	Adapt NbS strategies to the scale and governance reality of islands and outermost regions.
Support knowledge translation and regional learning	Create simplified DAPP-MR training and communication materials for local governments and SMEs.
	Facilitate structured exchange across regions through adaptation hubs, twinning initiatives, and scenario planning workshops.
	Use science-policy interfaces to translate complex model results into actionable planning guidance.

Connecting the MYRIAD-EU approach with AQUAMAN

The Canary Islands Pilot Study carried out in MYRIAD-EU and the AQUAMAN Interreg Euro-MED project (AQUAtic systems' evaluation for the Mitigation of wAter scarcity in mediterranean islaNds and coastal tourist destinations under severe pressure) share a strategic commitment to advancing sustainable water management in Mediterranean regions facing mounting climate stress. While MYRIAD-EU applies a multi-hazard, systemic, and forward-looking planning approach to design DRM pathways for key sectors (such as tourism, food and agriculture), AQUAMAN focuses on the co-creation, testing, and upscaling of practical water efficiency solutions through real-world experimentation in Living Labs. In AQUAMAN, the University of La Laguna (ULL) will lead the Canary Islands Living Lab aimed to test context-specific water-saving innovations and identify the enabling conditions and institutional barriers to their adoption in tourism- and agriculture-dependent island settings.

This convergence creates a unique opportunity to embed long-term, risk-informed planning into the operational, solution-driven focus of AQUAMAN. By bridging the strategic foresight and scenario-based planning developed through MYRIAD-EU with the implementation and innovation ecosystem of AQUAMAN, the Canary Islands Living Lab can become a hub for integrated, anticipatory water governance. This cross-project collaboration not only enhances the robustness and relevance of local adaptation efforts but also contributes to the development of scalable, transferable models for tackling water scarcity in EU outermost, Mediterranean, and island regions. Moreover, it offers a concrete pathway for strengthening the role of Living Labs as platforms for both innovation and long-term resilience planning, reinforcing the EU's capacity to respond to interconnected water, climate, and economic challenges.

Positioning AQUAMAN alongside MYRIAD-EU ensures that strategic foresight is not left as an academic exercise but is directly translated into operational experimentation, providing the EU with a model for how long-term systemic planning can be embedded within practical water and climate governance initiatives.

4 Scandinavia Pilot

4.1 Forward-looking DRM pathways

The Scandinavia Pilot applied the DAPP-MR (Schlumberger et al., 2022; submitted) and Storyline (Crummy et al., 2025) approaches to develop forward-looking DRM pathways. In particular, the Pilot used the **heat, drought, and wildfire** past event that occurred in 2018 in a simplified Storyline (Ducros et al., 2024; MYRIAD-EU Storylines Repository[17]) to investigate the socioeconomic impacts of this multi-hazard event. The assessment highlighted the complex cause-and-effect relationships under specific conditions, which supported the scenario development and improved understanding during the implementation of the DAPP-MR approach.

In this section, we focus on illustrating the results obtained from the use of DAPP-MR in the Pilot Study. The DAPP-MR approach was applied qualitatively, drawing on expert judgment and integrating knowledge drawn from the literature review. The analysis was initially aimed to address three sectors: energy, food and agriculture, ecosystems and forestry. After initial interactions with regional stakeholders, it was then re-focused to deepen understanding of the **energy system** and investigate its interactions with other sectors, including **food and agriculture** as well as **nature and forestry**. The shift from ecosystems and forestry to nature and forestry reflects both literature review results and stakeholders' preferences for a broader framing that captures not only ecological processes but also landscape, biodiversity, and cultural values relevant to the nature aspects. Moreover, the **social dimension** is introduced to account for social acceptance and public support for various climate adaptation measures, which turned out to be an important issue from the stakeholder discussions. This analysis also aims to inform forward-looking DRM pathways, explore plausible future scenarios, and establish priorities for further research in a multi-sectoral perspective. Recognising that energy-related DRM measures are typically formulated at a broad scale, the Pilot adopted a **national-level perspective** tailored to the Norwegian context, with potential to be applied to other Scandinavian countries facing similar DRM challenges by adapting to the local context.

As shown in Figure 17, the implementation of the DAPP-MR approach for the Scandinavia Pilot followed a stepwise process. We began with system framing and scoping, followed by the identification of relevant DRM measures. This process built on knowledge gathered through stakeholder engagement, including Interviews, two Pilot Workshops, and two Focus Groups (Section 1.2.2). The development of the energy-specific DAPP-MR was also informed by the discussions held during the Initial Pilot Workshop (PW1) and the two Focus Groups. Insights from these activities are documented in van Maanen et al. (2025) and Holm et al. (submitted). Based on these findings, we extended the pathways to include cross-sectoral interactions between measures, thereby broadening the scope of the analysis. These cross-sectoral interactions reflect a broad perspective that considers factors such as social acceptance, impacts on nature, energy security, economic profitability, resilience to climate shocks (including multi-hazards), and interactions across sectors, particularly between food and agriculture and forestry. This process also incorporated insights from Ducros et al. (2024), which explored the cross-sectoral impacts of energy-sector measures in multi-risk contexts.

[17] MYRIAD-EU Storylines Repository: https://dashboard.myriadproject.eu/storylines-repository/.

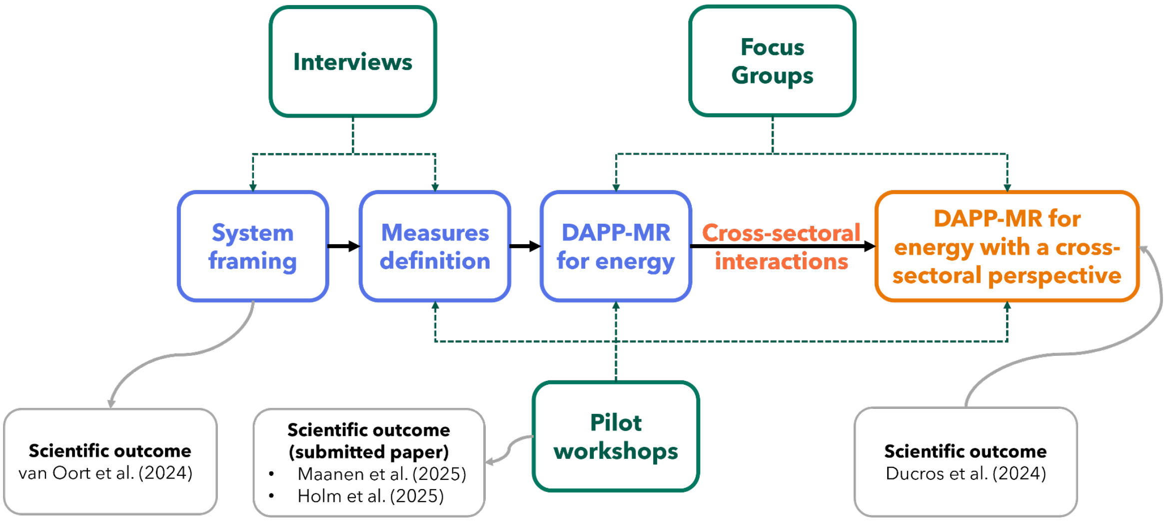


Figure 17: DAPP-MR implementation for the energy sector in the Scandinavia Pilot (steps and information sources).

System framing for the energy sector

The electricity sector is critical to Norway. Norway produces its electricity while the surplus is exported to other Nordic and Northern European countries to balance intermittent generation, which provides economic benefits in the region. By 2023, hydropower accounted for nearly 90% of electricity generation in Norway (Energy Facts, 2025). The dominant share of hydroelectricity presents a good opportunity for climate change mitigation and the electrification of other sectors. By complementing hydropower with variable renewable sources like wind and solar, the electricity sector becomes a key driver in the transition toward a sustainable energy system. However, the sector faces increasing exposure to climate-related hazards, such as floods, droughts, storms and landslides. These increasing climate risks from extreme events or multi-hazards make a forward-looking DRM approach crucial for long-term energy security and resilience.

To build the pathways, the Pilot began with system framing, concentrating on adaptation to extreme events and multi-hazards related to water availability in Norway and addressing both excess and scarcity due to hazards such as heat stress, droughts, wildfires, extreme precipitation, and flooding. As illustrated in Figure 18, the system definition is organised around three core components: drivers of future change, causal relationships, and a long-term objective that guides resilience-building and adaptation planning.

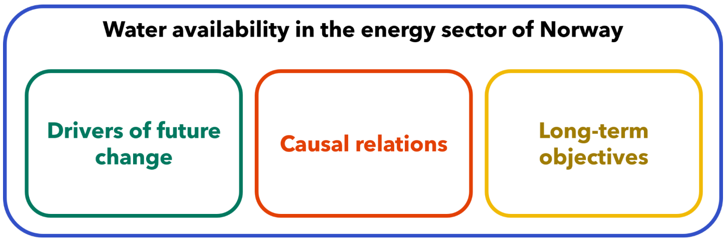


Figure 18: System framing under the DAPP-MR approach for the energy sector.

Drivers of future changes

First, the Pilot defined the drivers of future changes. Norway's energy system is facing growing challenges and transformations driven by multiple factors that impact future water availability. Climate change is expected to increase precipitation variability - both spatially and temporally - leading to climate variations such as consecutive rain events or droughts to heavy rainfall. These shifts pose risks to hydropower production, which relies on stable water inflow patterns. At the same time, rising energy demand from both domestic and EU markets, combined with societal and industrial needs, is putting additional pressure on the energy system. While efforts to improve energy efficiency in both production and consumption are underway, the integration of more intermittent renewable sources like wind and solar - on both land and at sea - requires a more flexible and adaptive energy infrastructure. Water availability is further challenged by competing land-use priorities, including agriculture, forestry, tourism, and nature conservation, with Norway aiming to protect 30% of its natural areas (up from the current 18%). Moreover, periods of excessive water inflow demand effective flood control measures, while water will also be increasingly needed for future energy production and irrigation. In parallel, technology development is gaining momentum, with neighbouring countries like Sweden and Finland investing in small modular nuclear reactors. Similar discussions are emerging in Norway, where small-scale nuclear power could diversify the energy mix and reduce dependence on hydropower, potentially easing water-related constraints in the long term.

Long-term objectives

The long-term objectives for DRM in Norway's energy sector focus on building a more resilient and sustainable system in response to growing climate variability and evolving societal needs. As the sector becomes increasingly exposed to fluctuations in water availability and more variable renewable energy sources, enhancing system flexibility is essential. This includes improved short-term balancing through technologies like batteries - particularly important for managing hourly variability (DNV, 2024) - and long-term adaptability through seasonal flexibility enabled by hydrogen storage and strengthened interconnections in Norway and across Europe. Energy saving and storage solutions, including hydrogen, batteries, and strategic water use, will play a key role in ensuring system stability. At the same time, DRM strategies must align with broader societal goals: ensuring energy security for households, industries, and critical sectors; maximising economic value; and achieving climate neutrality through low greenhouse gas emissions. These efforts must also support Norway's commitments to EU targets on nature and biodiversity, manage water resources equitably across sectors, reduce flood risks, and minimise land-use conflicts among energy, agriculture, forestry, tourism, and conservation.

Causal relations

During the project, the Pilot participated in a study, which assessed the economic impacts of multi-hazards in the Scandinavian region (Ducros et al., 2024). This work provided valuable insights into the causal relationships within the energy system. As shown in Figure 19, single and combined natural hazards, such as heat, drought, floods, and extreme precipitation, can cause fluctuations in the water supply for the hydropower system. Periods with too little water may reduce electricity production, while excessive water inflow can decrease production efficiency and lead to wasted hydropower generation. In both cases, extreme reservoir levels, whether too high or too low, can damage infrastructure or the power grid. Increased variability in water levels poses operational challenges for reservoir management, which in turn affects electricity supply stability. These effects may have wide-ranging and cross-sectoral consequences for the socio-economic system. For instance, the higher electricity prices during drought seasons increase industrial production costs and affect individual consumption behaviour. The case study by Ducros et al. (2024) shows that such impacts include changes in household income, cross-sectoral energy use, employment, industrial competitiveness, trade balance, and GDP.

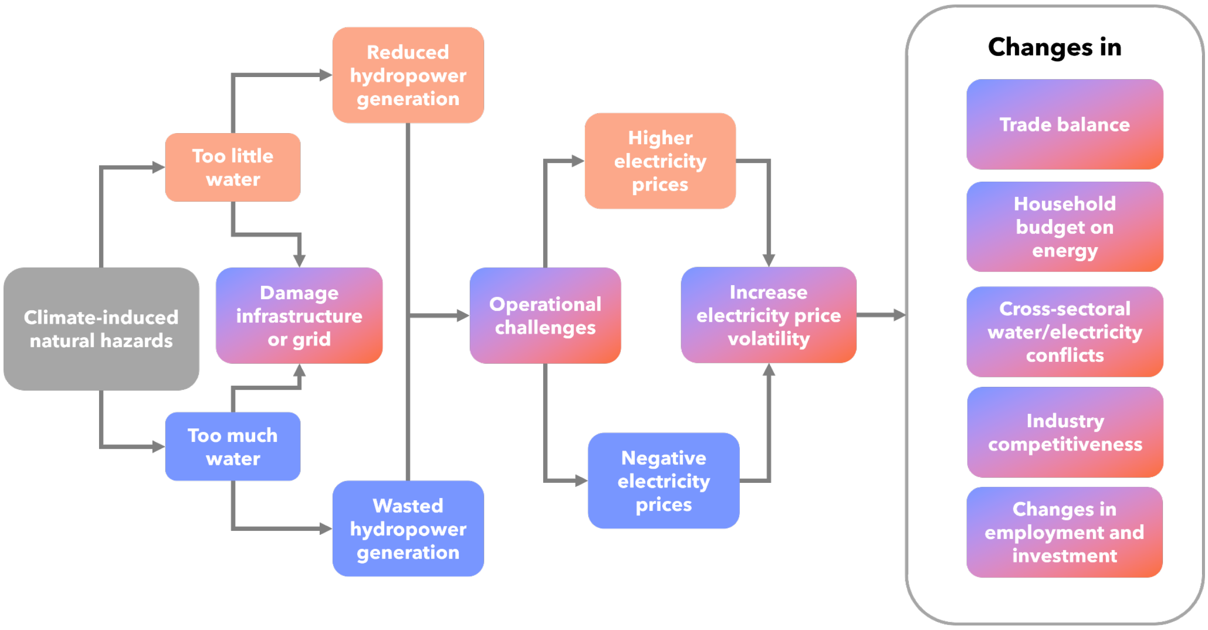


Figure 19: Flowchart of causal relations between climate-induced multiple hazards and impacts on the energy sector.

Define the measures for energy sector

By integrating the underlying drivers of future change and the identified causal relationships, the Pilot defined a set of DRM measures for the Norwegian energy sector. These measures are based on expert knowledge within CICERO and review of various reports (Norsk Industri, 2023; Statnett, 2023a; Statnett, 2023b) and are mainly designed to boost sector production and efficiency. They also support the sector's long-term objective of reaching CO_2 mitigation, transformation and sustainable production. The identified measures are listed in Table 11.

Table 11: DRM measures for the Norwegian energy sector.

DRM measures	**Description**
1. N-S grid link	Enhance the electrical grid infrastructure to strengthen the transmission of electricity between northern and southern Norway.
2. Offshore wind	Offshore wind turbine installed in the sea in Norway.
3. Onshore wind	Development of wind turbines on land.
4. Region link	Improved electricity grid connectivity within the Nordic countries (Norway, Sweden, Denmark, and Finland) enhances the ability to share energy across borders.
5. Extension of storage capacity	Increase water storage capacity in reservoirs in central and southern Norway (where most hydropower plants are located).
6. Regulations for water storage	Implement regulations to ensure the sustainable management of water storage and hydropower resources. It includes filling, maintaining, and electricity generation.
7. Solar PV	Installation of solar photovoltaic panels both on building rooftops (residential, commercial, and industrial) and as large-scale solar farms.
8. Bioenergy	Use organic materials (such as wood, agricultural waste, and other biomass) for energy production.

Pathways for the energy sector

The target of the energy pathways is to advance Norway's electricity system to increase sector production and efficiency aligned with the significant transformations in the energy and power sector by 2050.

The Pilot formulated pathways, as shown in Figure 20, based on existing reports from various sources and expert knowledge on the development of electricity transformation including Energy Transition Norway 2023 (referred to as Norsk Industri) (Norsk Industri, 2023), Nordic Grid Development Perspective 2023 (referred to as Nordic Grid) (Statnett, 2023a), System Development Plan (referred to as Statnett) (Statnett, 2023b). The timing and sequence of the measures defined in each step of the pathways are aligned with the years in which significant increases in electricity generation from the respective energy sources are projected. Particularly, Norsk Industri (2023) refers to the Energy Transition Norway 2023 outlook developed by Norsk Industri (the Federation of Norwegian Industries) in collaboration with DNV[18]. It represents an industry-driven perspective on the energy future of Norway. The Nordic Grid Development Perspective report (Stattnet, 2023a) is a joint outlook by the four Nordic TSOs (Energinet, Fingrid, Statnett and Svenska Kraftnät). This report provides the vision of the Nordic transmission operators on future power systems up to 2050. The System Development Plan report (Statnett, 2023b) reflects the roadmap for the power system development of the Norwegian TSO. The Alternative Pathway is a custom pathway based on expert knowledge from both the CICERO team and stakeholders to explore a transition strategy. The selection of measures and the design of the time sequence are informed by various literature sources. This pathway prioritises the early implementation of extended storage capacity, bioenergy, and internal grid links to ensure basic system flexibility and infrastructure readiness. Wind power development is planned for a later phase, anticipating improved social acceptance and reduced costs.

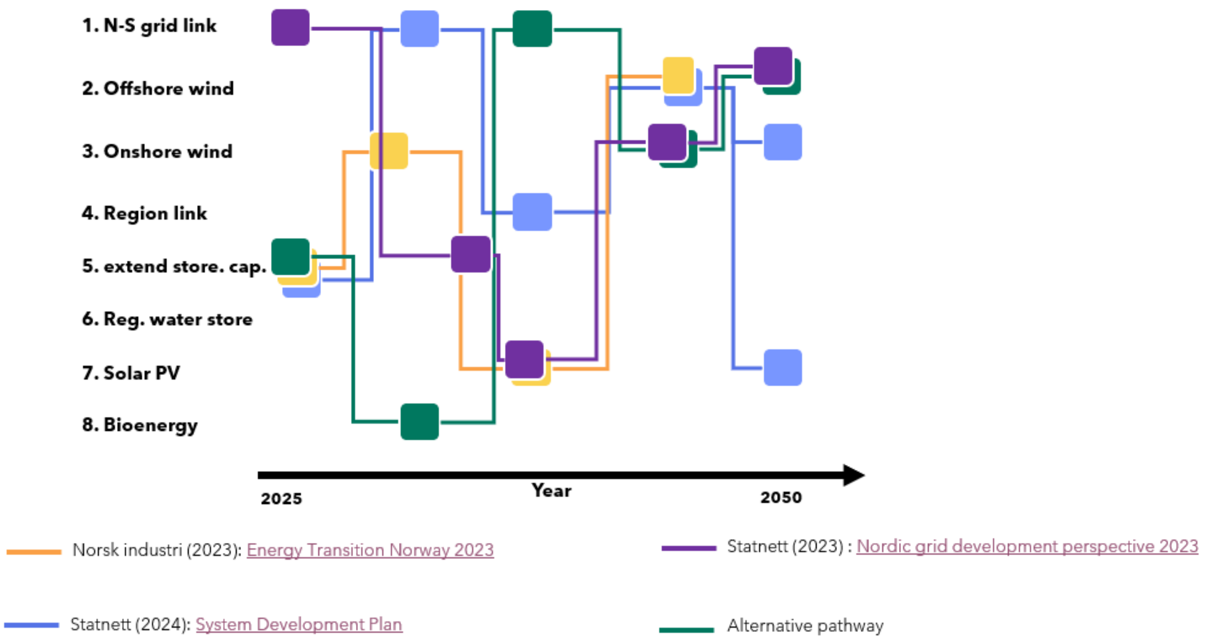


Figure 20: Pathways for the energy sector as defined in three published reports and within MYRIAD-EU (alternative pathway). The relevant measures are listed on the left.

[18] DNV is a global quality assurance and risk management company headquartered in Norway.

The distribution of capacity extension across various measures including offshore/onshore wind, reservoir extensions, solar PV and bioenergy in different pathways is illustrated in Figure 21. All pathways indicate that 30-40% of capacity extension is expected through offshore wind development. However, there is a notable variation in the development of onshore wind. The alternative pathway suggests less than 30% capacity expansion from solar, whereas the pathway in Statnett (2023a) projects a higher share of 47%.

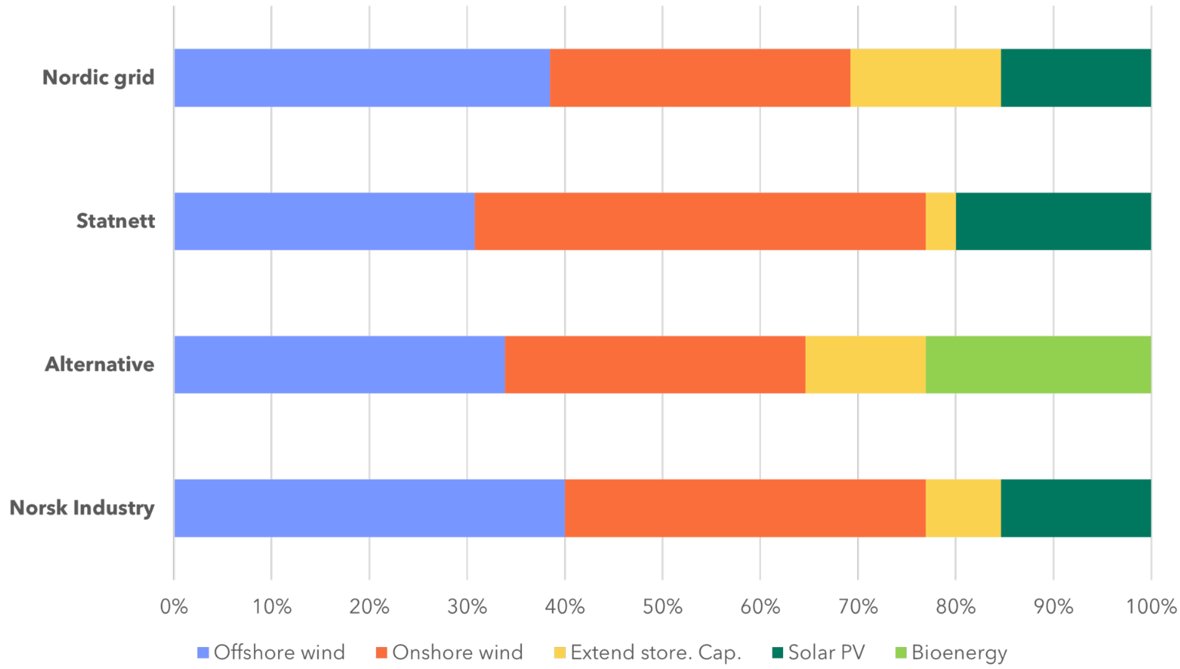


Figure 21: Capacity extension under different pathways.

Interactions between energy and other sectors

In this step, we take a cross-sectoral perspective to understand the synergies and trade-offs between energy-specific measures and their impacts on other sectors in Norway. This broader perspective includes the following aspects:

- Social acceptance
- Impacts on nature and ecosystems
- Energy security
- Economic profitability
- Resilience to climate shocks, including multi-hazards
- Cross-sectoral interactions, focusing on agriculture and forestry

To support this work, we reviewed the existing literature on cross-sectoral and multi-dimensional impacts. In the following paragraphs, we focus on the current discussions in the literature related to social acceptance, biodiversity impacts, and cross-sectoral effects.

Existing literature has examined the issue of social acceptance in relation to wind farm developments in Northern Europe. Nordic Council of Ministers (2025) provide guidelines for studying social acceptance as a prerequisite for the green transition, with wind power playing a key role. The main affected sectors include the fisheries and shipping industries. Reckhaus (2022) investigates the ongoing conflict between offshore wind farms (OWFs) and the fishing industry in the North Sea. Schupp et al. (2021) analyse the drivers, barriers, and consequences - both positive and negative - of the potential multi-use of OWFs and fisheries. Notably, a key factor contributing to the current conflict is the lack of involvement of local fishing communities. Westerlund (2020) investigates social acceptance of wind energy in urban areas in Finland. Leiren et al. (2020) highlight the factors shaping community acceptance of onshore wind energy developments across several countries, including Norway. Their study reviews key aspects such as the technical characteristics of wind energy projects, environmental and economic impacts, societal effects, contextual factors, and individual characteristics. Ellis and Ferraro (2016) conduct a comprehensive pan-European review, emphasising key determinants of local acceptance: perceived costs and benefits, degree of public participation, landscape impacts, and financial ownership. Across these studies, issues of procedural and distributional justice emerge as the main causes of low acceptance of wind power development.

Then, we reviewed the literature on the negative impacts of energy measures on the natural environment and biodiversity. Statnett (2025) acknowledges that grid development can affect bird species and cause moderate levels of deforestation. Gilad et al. (2024) find that electricity grid expansion leads to habitat loss and fragmentation. However, Statnett (2025) also notes that “deciduous undergrowth in power line corridors can serve as important grazing areas for wild deer.” Wind power projects have been associated with significant adverse effects on nature, including impacts on marine biodiversity (Nordic Energy Research, 2022; Dankel, 2024; American Clean power Association, 2022) and onshore bird diversity (May et al., 2021, Laranjeiro et al., 2018; Rydell et al., 2012). While reservoir expansion and improved water regulation can enhance flood control and potentially preserve habitats during droughts, Geist (2021), Gracey and Verones, (2016), and Gilad et al. (2024a) report significant terrestrial habitat loss and reduced water quality (Hrachowitz et al., 2021). In the context of bioenergy, several studies have investigated the impacts of forest-based bioenergy development in Sweden, Finland, Denmark, and Norway. These include Hansen et al., (2021), Wolfgang et al., (2022), de Jong et al., (2014), Amiandamhen et al., (2020), which point to forest degradation and biodiversity loss, particularly due to unsustainable residue or stump extraction. Winberg (2024) also examines the potential of agriculture-based bioenergy in Sweden, noting its potential to degrade ecosystem services and reduce biodiversity if not managed sustainably.

In terms of cross-sectoral impacts of energy-related measures, we focus our review of literature primarily on the interactions between the energy sector and other key sectors for our Pilot Study, i.e., agriculture and forestry. These interactions often involve trade-offs between positive and negative effects, which are documented in the literature. Olkkonene et al. (2023), Stattnet (2023a) and Nordic Energy Research (2019) emphasise that strong internal and cross-border electricity grid development is essential for grid stability and the electrification of industries, including agriculture, forestry, and transport. Ejemo and Soderholm (2015) show that onshore wind turbines can provide additional income for farmers through land leasing arrangements. Similarly, Lu and Merwade (2024) note that the extension of reservoirs for improved flood control supports water supply stability and flood mitigation, benefiting agriculture and forestry by enhancing irrigation and protecting against extreme weather events. For agrivoltaic systems, several studies highlight their potential to improve land-use efficiency and offer clear benefits to the agricultural sector (Elkadeem et al., 2024; Di Sabatino et al., 2025, Green Dealflow, 2023).

The literature also highlights several cross-sectoral negative impacts. For example, improved grid connections within Norway and across neighboring Northern European countries can lead to negative consequences for agriculture. Gilad et al. (2024b) and PSCW (2013) report that transmission line construction may disturb farmland through soil compaction, erosion, and disruption of field operations. Aguiar et al. (2021) point out that cross-border grid trades can lead to network congestion externalities, creating reliability risks for electricity supply in agricultural and other sectors. Land-use change is another important issue. The development of onshore wind farms presents challenges for both agriculture and forestry due to land occupation, habitat fragmentation, and operational disruption (Enevoldsen, 2016; Kiesecker et al., 2024). Although agrivoltaic systems offer dual land use, they can also lead to land-use conflicts and require specialised land management. Similar concerns arise with bioenergy production, where intensifying land competition can negatively affect land availability for traditional agricultural and forestry production (Wolfgang et al., 2022).

Evidence-based sources provide important insights into how developments in grid infrastructure, wind power, reservoir and flood control infrastructure, solar photovoltaic (PV) systems, and bioenergy in Norway and the broader Nordic region can enhance resilience to multi-risk climate shocks, including extreme weather events such as droughts and heatwaves. For instance, Noman et al. (2024) find that decentralised renewable energy systems, including wind, solar, bioenergy, and hydropower, can significantly improve energy efficiency and system stability. This, in turn, helps buffer against extreme events and reduces air pollution. Similarly, Roth and Schill (2023) show that geographically distributed wind farms help smooth out fluctuations in energy generation caused by climate variability, thereby improving resilience during periods of low renewable output. In addition, Fälth et al. (2024) highlight that hydropower reservoirs in Sweden provide both high production capacity and serve as a buffer against energy droughts, ensuring reliable electricity supply during extended dry or low-wind periods.

By integrating these findings from the literature with expert knowledge, we developed the matrix shown in Figure 22, which evaluates each energy-specific measure across multiple resilience-related dimensions. Each measure is assigned a subjective score ranging from -3 to +3, reflecting its estimated synergies or trade-offs with key aspects. 0 indicates that the literature does not show clear positive or negative effects of the measure on the specific resilience dimension in question. A score of 1 to 3 represents effects of the measure, with higher values suggesting more consistently reported synergy effects. A score of -1 to -3 reflects trade-offs or adverse consequences of the measure. Also, the larger the absolute value, the more widely reported the negative effects.

DAPP-MR for energy and evaluation (various scenarios)

Next, we evaluated the pathways by combining the corresponding cross-sectoral scores (as shown in Figure 22) for each pathway. When computing the aggregate score for each pathway, we applied the installed capacity of each energy measure (as shown in Figure 21) as the weighting factor. Figure 23 presents a qualitative assessment by translating quantitative scores into qualitative categories (as the benchmark case). For each aspect, we ranked the values across different pathways to define relative boundaries. The lowest value is assigned the lowest qualitative score (e.g., $ or +/-), and the highest value is assigned the highest score (e.g., $$$ or +++/---). The sign of the value is reflected in the symbol: + indicates the positive impact, while - indicates the negative impact. If the difference between the highest and lowest values across pathways is relatively small (less than 10% of the lowest value) the highest score is adjusted to a mid-range level (e.g., $$ or ++/--) to reflect the limited variation.

This method allows for comparative assessment across pathways and helps identify the optimal pathway based on overall performance across multiple criteria. As shown in Table 16, the alternative pathway is the optimal option when compared to the three other pathways under the benchmark scenario. This pathway offers lower cost, moderate levels of social acceptance challenges and environmental impacts, while ensuring a high level of energy security and positive cross-sectoral net benefits. Furthermore, it demonstrates the highest economic profitability within the energy sector and strong resilience to climate shocks.

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

Legend	-3	-2	-1	0	1	2	3

Figure 22: Score matrix of energy-specific measures (rows) against multiple resilience-related dimensions (columns).

Pathway	Static Cost	Social acceptance	Nature impact	Energy security	Economic Profitability	Resilience to shocks	Cross-sectoral (agriculture forestry)
Norsk industry	$$$	--	--	+	++	+	++
Alternative pathway	$$	-	-	++	+++	+++	+
Statnett	$$	--	--	++	+++	++	+
Nordic	$$$	-	-	+++	++	+++	++

Figure 23: Evaluation for all pathways: benchmark case.

Furthermore, we provide an example of how to visualise cross-sectoral interactions within sector-specific pathways, as illustrated in Figure 24. The labels +/++/+++ indicate the extent of capacity extension of DRM measures. The dashed lines highlight the notable cross-sectoral impacts of specific measures. The grey block indicates that the corresponding capacity extension (in this case, for onshore wind development) is under high uncertainty, which is mainly due to the social acceptance issues, as also reflected by the dashed line.

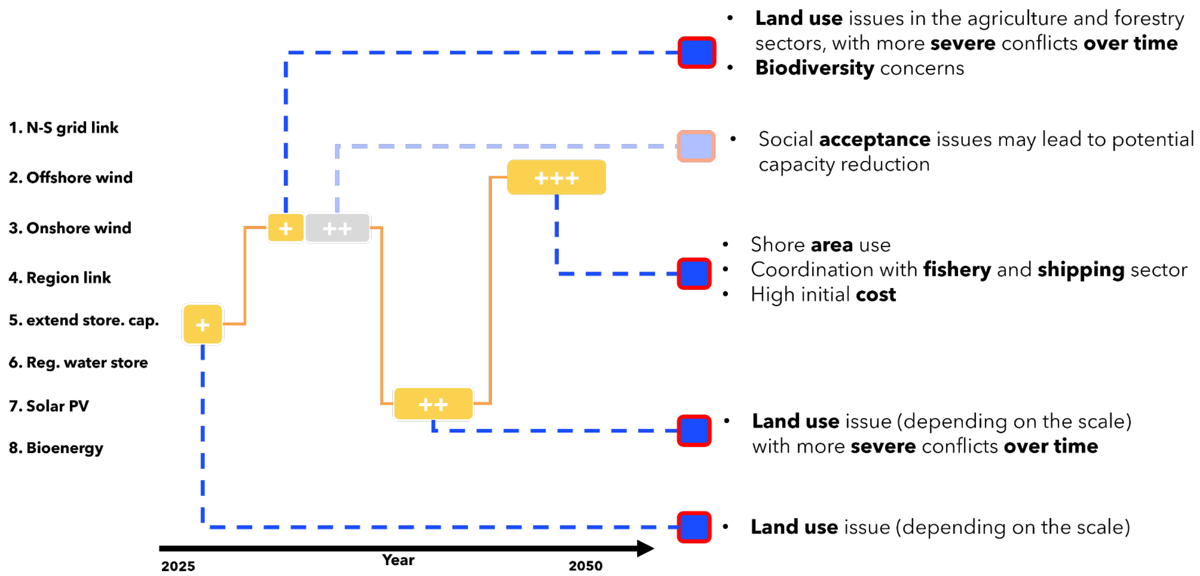


Figure 24: Example of the cross-sectoral impact of measures in the energy sectoral pathway: Norsk Industri (2023).

Moreover, we implemented the evaluation of pathways under an alternative scenario of "social acceptance barrier". This scenario is defined by the assumption of strong social resistance to large-scale onshore wind development. In addition, solar power capacity is constrained due to land use conflicts as time goes by. To meet the overall capacity expansion target under these constraints, there is a higher and more urgent demand for offshore wind power development. Particularly, this will shift the capacity extension share for the pathways as shown in Figure 25.

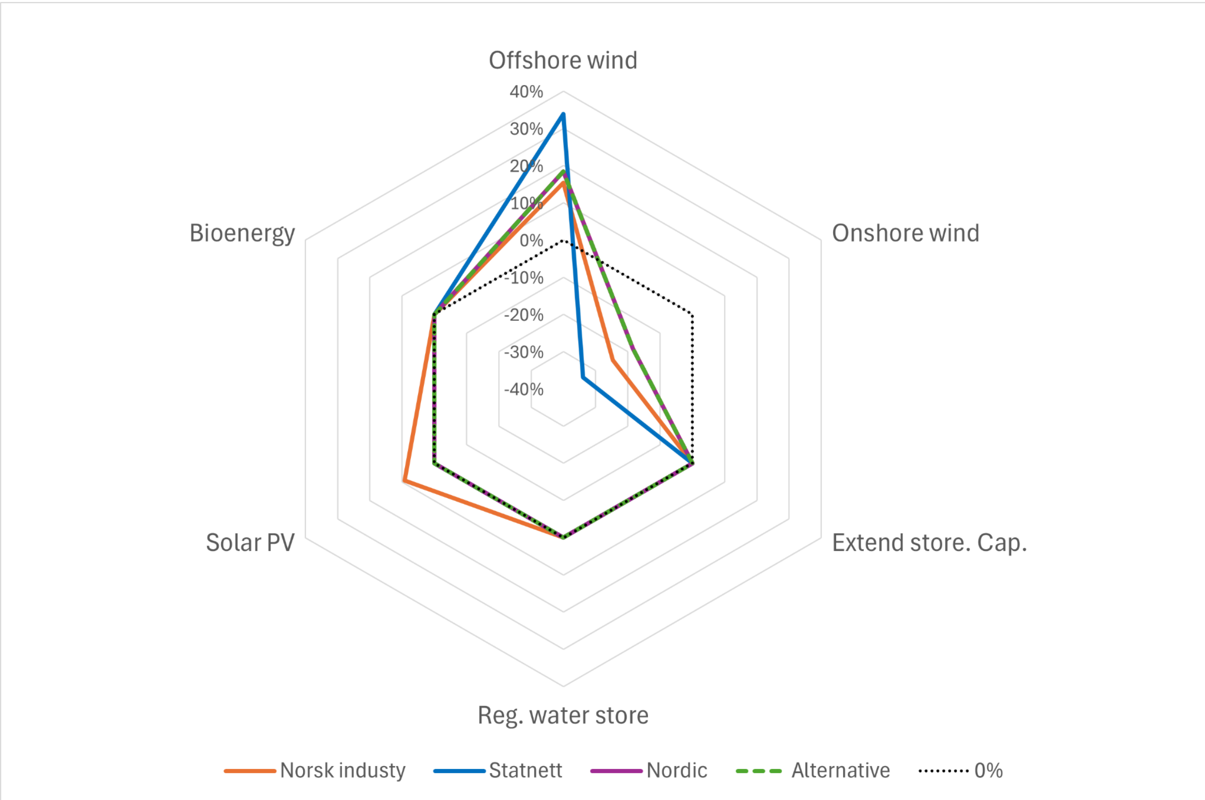


Figure 25: Changes in capacity extension under the alternative scenario of "social acceptance barrier" compared to the benchmark case in Figure 21.

Employing the same evaluating procedure as in the benchmark case, we find that the social acceptance barrier to onshore wind development matters the most in cost, economic profitability and cross-sectoral impacts. As shown in Figure 26, changes relative to the benchmark case are highlighted in red and green. Red indicates increased impacts, while green indicates decreased impacts compared to the benchmark (Figure 23). We also find that the Norsk Industri (2023) pathway provides a relatively good score despite the moderate growth in cost (Figure 26) compared to the benchmark case.

Pathway	Static Cost	Social acceptance	Nature impact	Energy security	Economic Profitability	Economic Profitability	Resilience to shocks	Cross-sectoral (agriculture, forestry)
Norsk industry	$$$$	-	--	+	++	+	+	++
Alternative pathway	$$$	0	-	++	+++	++	+++	++
Statnett	$$$$	-	--	++	+++	++	++	++
Nordic	$$$$	0	-	+++	++	+	+++	++

Figure 26: Evaluation for all pathways: social acceptance barrier scenario.

Conclusions, reflections and limitations

To conclude, we applied the DAPP-MR method by integrating energy-specific measures into a broader analysis of cross-sectoral impacts on multi-hazard risk management, with a focus on Norway. Our results highlight that although cost-efficiency, economic profitability and sustainable production are important, it is also vital to consider other dimensions, particularly the cross-sectoral interactions. The literature indicates that sector-specific measures can have considerable implications for nature, social acceptance, and interconnected sectors. These implications may potentially influence the resilience to climate shocks. In some cases, these interactions may lead to rebound effects that impact sectoral costs. Furthermore, we find that the optimal pathway varies across scenarios. This highlights the importance of flexibility and uncertainty in decision-making. Most importantly, our analysis emphasises that DRM/adaptation strategies should not be developed only from a sectoral-specific perspective, but rather through a multi-dimensional approach which could connect economic, environmental, social and cross-sectoral factors under different scenarios.

Our analysis has limitations in the following aspects. First, our study presents an initial application of the DAPP-MR approach, with a limited focus on energy-related measures in Norway and their cross-sectoral interactions. Instead, the full DAPP-MR approach is designed to account for the complexity of multi-sectoral measures in parallel. Our simplified method is due to the inherent scale challenges across sectors through the investigation. For example, the risk management measures in the agricultural sector are typically implemented at the local level, forestry measures often involve long-time horizons, while energy-sector measures are more frequently addressed at the national level. These inconsistencies in spatial and temporal scales made it challenging to fully apply the DAPP-MR method across all sectors at the same time. However, this analysis may be seen as the first step toward a comprehensive multi-sectoral implementation of the DAPP-MR, and the DAPP-MR has potential to be implemented at local level with sufficient data. Second, this analysis is based only on qualitative information due to limited availability of spatial and sector-specific data for each measure under various scenarios. Nonetheless, our analysis could be expanded in future research to combine both quantitative and qualitative assessments for context/scenario-specific planning. Finally, although this study has considered the multi-hazard risk profile of Norway, we did not disaggregate the different hazard combinations. This is mainly because the energy measures we included already cover a wide range of climate risks in general (including multi-hazards). For further research, a more detailed study could use different scenarios to analyse how well the measures work under specific combinations of climate hazards.

4.2 Recommendations for upscaling and transferability

The application of the DAPP-MR approach in the Scandinavia Pilot has provided insights into both future research opportunities, limitations and challenges of cross-sectoral multi-hazard risk management. Based on our experience in MYRIAD-EU, we identified several key points for upscaling and transferability of the methodology and lessons learned.

- **Downscaling**: Lessons from the side project with the municipality of Bergen building on the Scandinavia Pilot.
  The Pilot's work shows potential for downscaling cross-sectoral multi-hazard risk assessment to local level, although the DAPP-MR approach is applied at national level. Particularly, in 2024, CICERO got the opportunity to participate in a commissioned research project for the municipality of Bergen, focusing on climate risks from multi-hazards for the municipal area. This work was built on MYRIAD-EU to better understand climate risks from changes in consecutive rain events, consecutive droughts and high precipitations, compound hot and dry events at the local level. The MYRIAD-EU Handbook (Gill et al., 2022) was used to define key terms related to this research in Norwegian and to introduce relevant concepts. The side project with Bergen stakeholders confirmed the value of focusing on a few multi-hazards that are relevant and important at the local level.
  Some of the barriers identified in this project included the spatial resolution of the climate data, the difficulty of combining climate data with other types of data (e.g., land-use) and the uncertainty associated with the future changes in combinations of hazards.
  This work has the potential for transferability to <u>other municipalities or regions in Norway and more generally in Northern Europe</u>, especially in areas facing combined hydrological and heat-related risks.

- **Upscaling**: Using the macroeconomic model GRACE to assess wide-spread impacts of multi-hazards across sectors.
  To explore the broader socioeconomic consequences of multi-hazard events, the Pilot employed the macroeconomic GRACE model. GRACE provides a valuable tool for upscaling the sectoral-specific climate impacts to the macroeconomic level. GRACE is a multi-sectoral, multi-regional computable general equilibrium model. GRACE links local and sectoral biophysical impacts of multi-hazards to the economic outcomes, including changes in prices, output, and trade, at national level. It helps to understand systemic multi-hazards risk which usually affects multiple sectors at the same time. In Ducros et al. (2024), the model is used to assess the cascading impacts of the 2018 multi-hazard events across sectors and countries, particularly through the trade linkages between Scandinavia and the rest of Europe. Relevant work has also been conducted in MYRIAD-EU WP5, which focuses on quantifying indirect and interregional risks from multi-hazards using several macroeconomic loss models, including GRACE. Overall, these cross-region applications demonstrate how natural shocks in one region can have spillover effects on economic outcomes in other regions.
  The main limitation of this approach lies in the granularity of the GRACE model. In particular, the model is better suited for national or international policy analysis than for local or sub-national planning. Additionally, there are gaps in sectoral coverage, especially in representing non-market value sectors such as ecosystem services.

- **Transferability**: Similarities with other high-latitude regions covered by large forests and facing combinations of heatwaves, droughts, wildfires as well as ecosystem diseases.
  The economic analysis of the Scandinavia Pilot focusing on heat, drought and wildfires that occurred in Summer 2018 in Northern Europe could be relevant for other regions in the world (Ducros et al., 2024; MYRIAD-EU Storylines Repository[19]), facing similar impacts and challenges associated with climate change. Similar regions could be found in Canada or Northern Russia, which are facing increasing exposure to climate-driven wildfires due to warmer and drier conditions as a result of climate change (e.g., the 2025 Canadian wildfires (New York Times, 2025)).

However, there could be contextual differences that should be considered when transferring the approach to other countries. These include variations in forest and land management practices, political and institutional context, and economic structures. For instance, differences in governance systems or sectoral interdependencies may influence how climate risks are perceived and managed. Also, the geographical scale of regional and international interaction between sectors, including forestry, agriculture and energy, may differ in other countries, which could affect the transferability. Likewise, energy dependencies, one of the key elements of the economic structure, differ significantly across the Scandinavian regions, which also poses challenges for transferability. Thus, the transfer or adaptation of the method should be **tailored to the specific local context**.

[19] MYRIAD-EU Storylines Repository: https://dashboard.myriadproject.eu/storylines-repository/.

myriad_eu Reducing risks together

5 Danube Pilot

5.1 Forward-looking DRM pathways

The Danube Pilot was designed to explore how the effects of multi-hazards can spread across the region, with a particular focus on the strong economic ties between neighbouring countries. Guided by extensive stakeholder involvement, the Pilot concentrated on understanding the impacts of **floods, earthquakes, and droughts**, which are hazards identified as having the potential to affect the region on a larger scale.

Sector-wise, the Pilot placed particular emphasis on **finance**, food and agriculture, as well as infrastructure and transport. In the process of applying the DAPP-MR methodology, we especially focussed on **navigation** as a subsection of the infrastructure and transport sector as it represents a critical cross-border lifeline, where disruptions can cascade rapidly through trade, supply chains, and mobility in the wider Danube region. Therefore, we refer to the navigation sector in the following paragraphs. Within the food and agriculture sector, our analysis concentrates on **agriculture**, as it is the most hazard-sensitive component and a key driver of food security and rural economies in the Danube region. The following paragraphs therefore refer specifically to agriculture.

The DAPP-MR methodology was implemented specifically for the agriculture and navigation sectors, while the finance sector was addressed using a risk-layering framework focusing on fiscal risks due to multi-hazard events. Given the large scale of the Danube Region, the Storyline approach was used to navigate the complexity of not being able to provide localised solutions (Crummy et al. 2025). The work conducted in this Pilot was primarily qualitative, drawing on the insights and expertise of both stakeholders and external professionals. Rather than producing fixed DRM strategies for specific sites, the process elicited a broader understanding of multi-risk dynamics in the region from the stakeholders involved. It also emphasised the interconnected nature of risks across sectors and borders, underlining the critical need for cross-sector and transnational collaboration.

Initial phase of development of multi-risk pathways for food and agriculture as well as navigation in the Danube Region

In the Danube Pilot, the development of DRM pathways using DAPP-MR was carried out through a structured and collaborative process alongside WP6 (details in the following pages) (Schlumberger et al., 2022; submitted). This process followed key steps such as building system understanding, exploring future scenarios, and evaluating potential management options.

Understanding the system

We began with a system analysis using the DPSIR framework (for a description of the framework refer to OECD, 2003), covering the agriculture, navigation, and finance sectors. This allowed us to identify sector-specific drivers of change, assess their pressures, and link them to current system states, potential impacts, and possible responses. The outcome was a sectoral overview that defined objectives and broad categories of risk management responses (Figure 27). We also developed diagrams mapping causal interrelationships of flood and drought impacts to visualise multi-hazard dynamics (Figure 28 and Figure *29*).

Agriculture sector						
Drivers of future change	Increased policy emphasis on the reduction of environmental and climate footprint of the food system	Maintaining levels of agricultural production	Increase in frequency and severity of hydrometeorological extremes, namely floods and droughts	Increasing competition for water resources and land use with other sectors		
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

Transport sector					
Drivers of future change	Increase in frequency and severity of hydrometeorological extremes, namely floods and droughts	Increasing competition for water resources and land use with other sectors	A wider policy push for environmentally-friendly navigation options		
Causal relations	Low water levels on the Danube reduce water-based transportation routes, lead to decreased capacity of navigation, and rising costs of transport	Floods negatively influence navigation safety, damage critical infrastructure and equipment, and lead to closure of inland navigable waterways			
Objectives	Ensure navigation safety	Protect critical infrastructure	Environmentally-friendly navigation (navigation projects do not cause river system deterioration)	Ensure continuous navigation and supply chains	
Responses	Change the ship	change the river	logistics improvement	further flood and drought risk management	innovation

Finance sector			
Drivers of future change	Increase in frequency and severity of hydrometeorological extremes, namely floods and droughts	Fiscal gaps increasing	Rising probability of other related risks (e.g., compound hazards, pandemics, energy costs due to conflict)
Causal relations	Insurers increase premiums for natural hazard related risks which leaves households/firms uninsured	Uninsurable losses	Governments become insurers of last resort
Objectives	Increase fiscal resilience and close fiscal gaps	Analysing fiscal risks using pan-European instruments to address (climate) risks	Determine risk reduction and risk financing options based on the risk layering approach
Responses	Risk layering options: risk reduction, risk financing, financial assistance		

Figure 27: Overview of the definition of the sectoral systems.

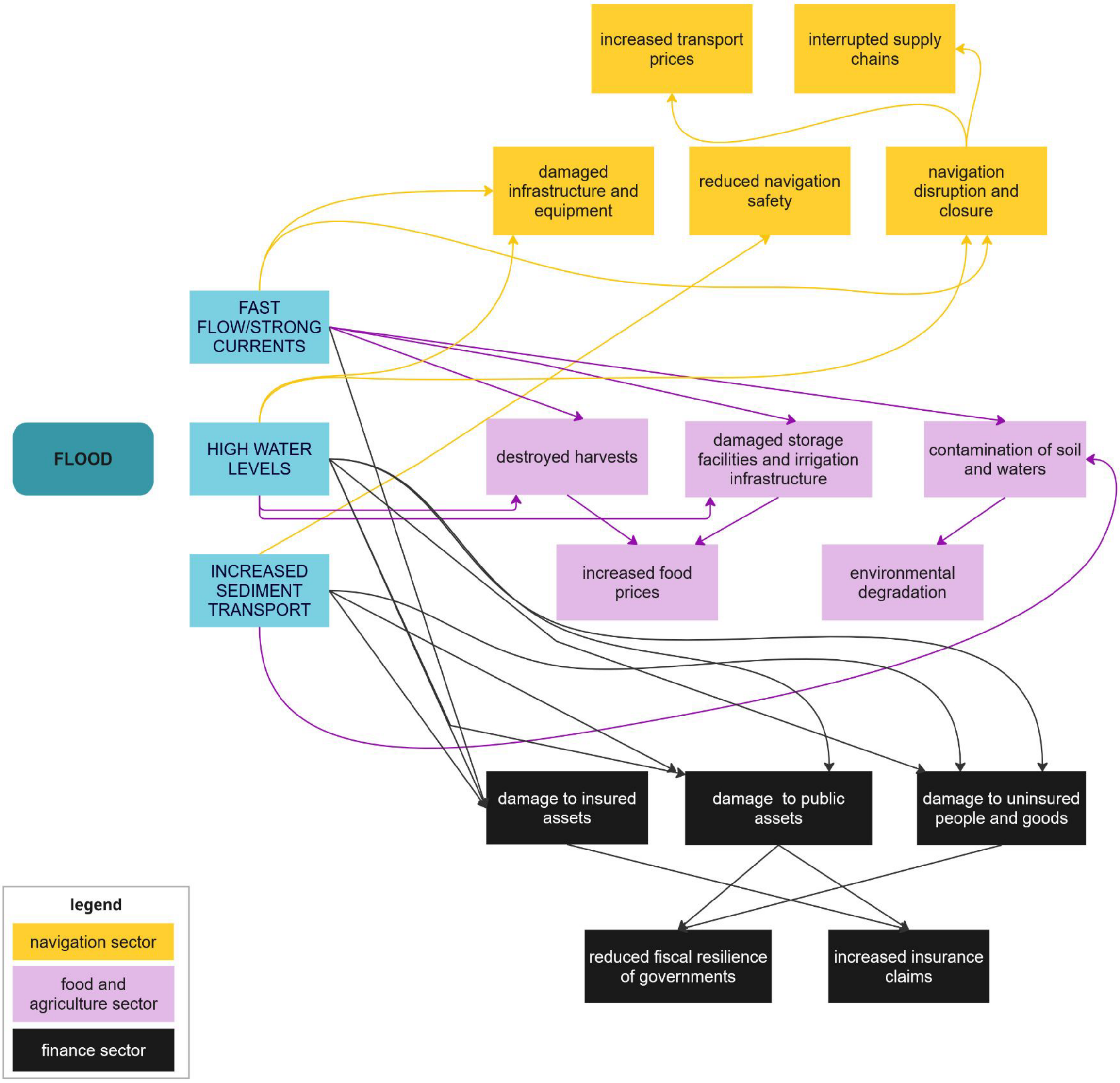


Figure 28: The causal relationships of flood impacts.

Developing future scenarios

In parallel, we defined future climate scenarios based on IPCC reports (Bednar-Friedl et al., 2022; Figure 30) and regional sources like the Danube Climate Change Adaptation Strategy (ICPDR, 2019). Scenarios were created for 2050 and 2100, with a particular focus on the projected effects of global warming on key sectors. Navigation-specific scenarios assumed a 20% and 40% increase in activity by 2050 and 2100, respectively. For agriculture, regional variability in climate projections, soil, and water conditions made it difficult to define a uniform scenario.

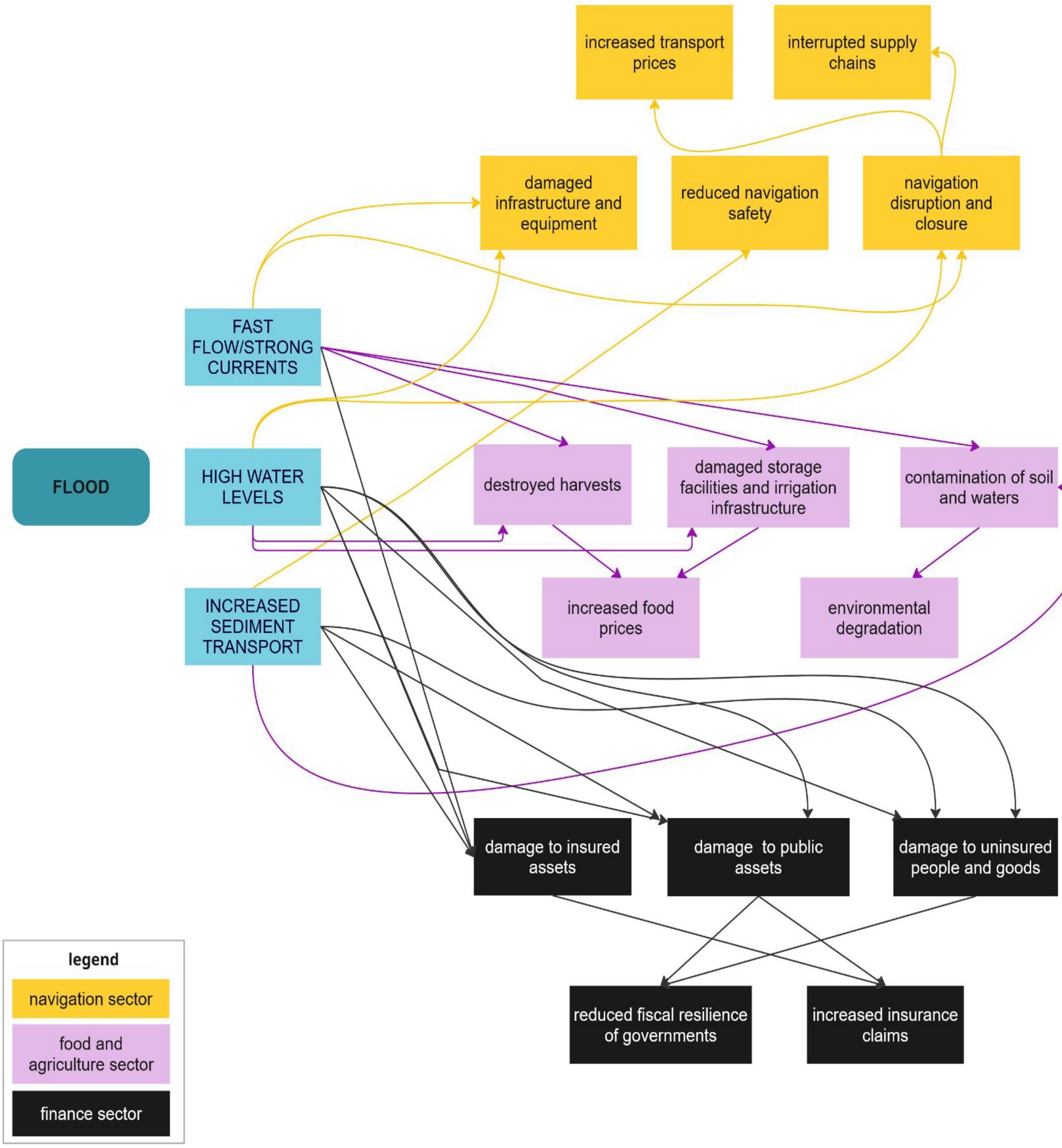


Figure 29: The causal relationships of drought impacts.

Identifying and sequencing management measures

Through a desk review, we identified 13 potential DRM measures for the navigation and agriculture sectors, and evaluated them for their effectiveness, cost, acceptance, and timeliness. The evaluation was based on our expertise and knowledge gained from our desk review. These informed the creation of draft sectoral DRM pathways through the sequencing of options best aligned with the individual sector's goals (Figure 31). The navigation pathway focused, amongst others, on measures to manage fluctuating water levels and increased traffic, while agriculture emphasised soil and water management to address extreme heat, drought, and pollution.

KEY DRIVERS	EFFECTS ON SECTOR	GLOBAL WARMING	SITUATION IN 2050	SITUATION IN 2100
Across sectors				
Climate change	Increased frequency and intensity of droughts and floods negatively impacting three sectors (as shown in system definition and causal loops)	Low CC (1.5-2.0)	Wet regions becoming wetter, dry drier. E.g., summer months up tp 15% drier Increase in floods throughout most of a region. E.g., 10-20% larger peak flows Increase in droughts and low flows in substantial parts of the region Increase in damage from extreme events throughout the region (e.g., yield losses and infrastructure)	Wet regions becoming *increasingly* wetter, dry *increasingly* drier. *Further* Increase in floods throughout most of a region *Further* increase in droughts and low flows in substantial parts of the region *Further* Increase in damage from extreme events throughout the region (e.g., yield losses and infrastructure)
		High CC (3+)	*All as above*, not a large difference between low and high CC.	All as above, just assumed *more extreme*. E.g., summer months up to 30% drier, 10-30% of increase of peak flows.
Sector specific				
(NAVIGATION) Increase in river navigation			+ 20%	+ 40%

Figure 30: Future scenarios identified for the Danube Region.

Finance sector and cross-sector integration

The finance sector's pathway was built on the concept of risk layering and fiscal risk analysis (Hochrainer-Stigler and Reiter, 2021). For the Danube Region, government financing resources available in the event of an extreme hazard were estimated using the CatSim methodology (Hochrainer-Stigler et al., 2024). These resources were then compared to the potential losses from hazard events. A key risk metric is the return period of the first event where available resources are no longer sufficient to cover all losses. This metric helps determine which "risk layer" a government belongs to. For example, if financial resources are very limited, even relatively frequent events may already create a fiscal gap. In this case, the government would fall into the first risk layer. Being in this layer implies that priority should be given to risk reduction measures. The fiscal gap and risk-layer for the Danube Region governments change if single or multi-hazards are looked at or if climate change impacts are included and can be related to the food and agriculture and transport sector.

Changes in fiscal risk over time due to climate and global changes were estimated based on available information from the CDRI (Coalition for Disaster Resilient Infrastructure) dataset which showed an increase in fiscal risks in future scenarios, and consequently the need to further strengthen and enable cross-sectoral risk management strategies. Cross-sectoral links emerged between agriculture and navigation, particularly around water availability and climate hazards. These interdependencies shaped the future development of cross-sectoral risk management strategies, which became especially apparent in the Final Pilot Workshop (PW2), when cross-sectoral DRM pathways were co-developed with stakeholders (details in the following sub-section).

category	option	helps to achieve the objective of minimizing crop losses	helps to achieve the objective of securing good soil condition	societal acceptance	costs	timeliness
Crop management practices	1.Climate-resilient crop varieties	++	++	+	--	M/L
	2. Crop rotation and diversification	+	++	+	-	S/M
Water management	3.improved irrigation techniques	++	++	-/+	--	M
	4.Retention basins	+	+	-/+	--	M
	5. Groundwater management	+	++	++	--	M/L
Soil conservation and management	6. Nutrient Management	++	++	++	+	M/L
	7.Alternative to conventional tillage	+	++	++	-	S/M
Risk management and financial instruments	8.Crop insurance	+	0/+	-/+	-	S
	9.Government Support	+	+	-/+	-	S
	10.Early Warning Systems	+	+	++	-	S
	11.Diversifica-tion of energy resource	+	0	-/+	--	M/L
Flood proof infrastructure	12.Flood proof infrastructure	+	+	++	--	M
Further flood and drought management	13.Research and development (R&D)	++	++	++	-	S

Figure 31: List and evaluation of management measures for the agriculture sector. (S= short-term goal, M = mid-term goal, L = long-term goal; ++ = highly desirable in terms of achieving sector goals, gaining social acceptance, costs; - - = highly undesirable in terms of achieving sector goals, gaining social acceptance, costs).

Co-developing phase with stakeholders: validation and initial sectoral pathways

Stakeholder input was gathered through several activities, most notably during the first Focus Group (FG1) held in December 2023. Participants helped validate our system understanding and actively contributed to the assessment and sequencing of management measures. That is to say that they helped verify or correct how we evaluated the management measures according to their effectiveness in achieving sectoral goals, their timeliness, cost and social acceptance. During FG1, we co-developed the first draft DRM pathways for the navigation sector, which was a valuable step towards sectoral DRM pathways, ensuring they were relevant and aligned with stakeholder needs. Following FG1, we also held individual Interviews with stakeholders already engaged in the Danube Pilot, as well as project Sectoral Representatives and external experts throughout 2024. The interviews provided further insights and feedback on the selection and evaluation of management measures and gave early input on how such measures might be sequenced.

Cross-sectoral risk management matrix

To explore how measures within one sector might affect others, we created a **Cross-Sectoral Risk Management Matrix** that compiled all previously identified sector-specific measures. This tool allowed for a structured comparison and evaluation of potential cross-sector impacts, making it easier to see how actions in one domain could influence outcomes in another. Since the nature of these interactions can vary greatly depending on the policy context - such as whether collaboration across sectors is prioritised or whether the focus lies more on grey infrastructure - we also applied a Storyline approach to reflect these different strategic directions. For this, we devised navigation DRM pathways that prioritise engineered, technocratic approaches, while others had a support/insurance or a management/innovation focus. For the agriculture sector, the DRM pathways either focused on infrastructure adaptation, integrated regional coordination or transformative, nature-based adaptation. The findings from this analysis were essential in guiding the development of cross-sectoral risk management DRM pathways.

Following this, two preliminary DRM pathways were developed for both the agriculture and transport sectors (Figure 32 and Figure *33*). Each pathway represented a unique sequence of measures aligned with a particular strategic direction or hypothetical scenario, ranging, for instance, from approaches emphasising hard infrastructure to those prioritising more transformative risk management solutions. As stated before, the design of these draft DRM pathways was heavily informed by input from stakeholders and experts gathered during the FG1 and the individual interviews held in 2024.

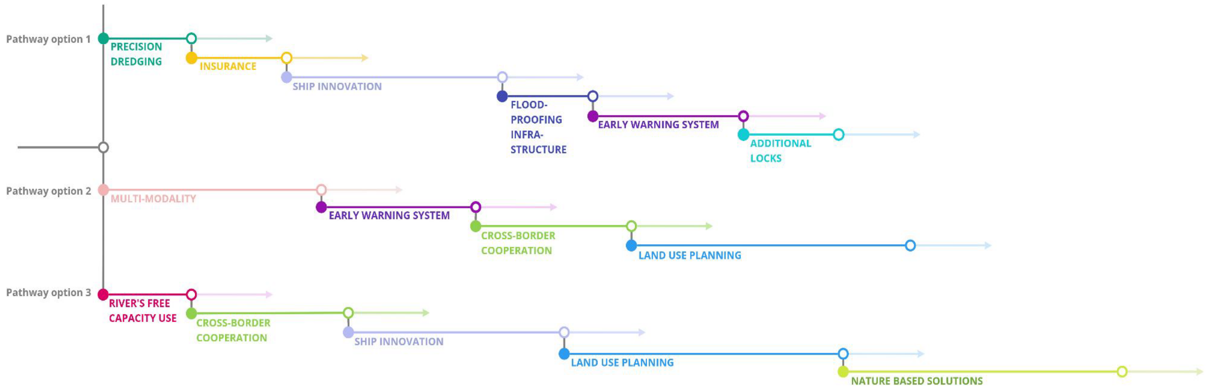


Figure 32: Draft sectoral DRM pathways for the navigation sector.

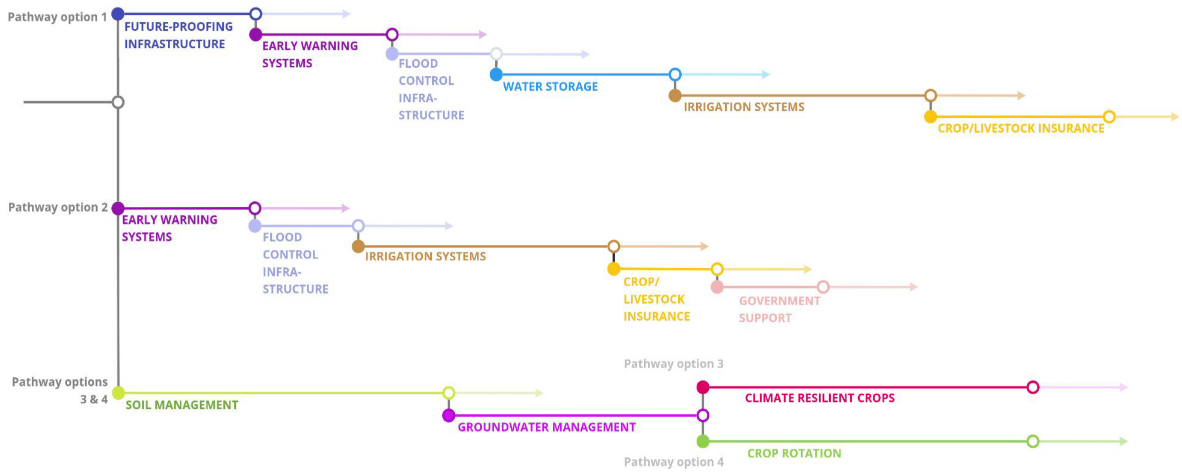


Figure 33: Draft sectoral DRM pathways for the agriculture sector.

To validate the relevance and applicability of these DRM pathways, we presented them to a set of core stakeholders for feedback. The stakeholders found the sequencing of measures difficult as the Danube Region spans 14 countries, making it clear that a single, uniform solution is not feasible for this region. Stakeholders were hesitant to validate a specific sequence or to accept the exclusion of measures in a pathway, as all measures were seen as potentially useful depending on the sub-region in question. Stakeholders emphasised that different parts of the Danube Region would require different approaches. Furthermore, the idea of serial sequencing was particularly challenging to the stakeholders, who preferred or expected several measures to be implemented concurrently rather than in strict order.

Going from single-sector to cross-sectoral pathways

The Final Pilot Workshop (PW2) in 2025 played a crucial role in refining the single-sector DRM pathways and co-creating cross-sectoral ones. A key focus of this workshop was the validation of the single-sector DRM pathways previously developed for agriculture and navigation. This validation process involved critical review sessions where stakeholders were asked to examine both the logic and feasibility of proposed measures, as well as the realism of the pathway narratives. Through facilitated discussions and guided evaluation tools (e.g., scoring matrices and group reflections), participants assessed the appropriateness of the proposed sequencing of measures under different future scenarios. The feedback provided helped refine the DRM pathways, particularly by identifying missing or misrepresented measures and re-emphasising the importance of context-specific adaptability.

Building on this validation, the workshop also included a dedicated co-creation segment for the development of cross-sectoral DRM pathways (Figure 34). In this participatory process, stakeholders collaboratively mapped out interactions across sectors and governance levels, explicitly considering how timing, funding, and institutional alignment could affect the feasibility of joint implementation. Using visual facilitation tools, like MIRO and color-coded mapping of interactions, the participants worked together to build draft intersectoral DRM pathways that integrate key no-regret measures (e.g., early warning systems) and distinguish between enabling conditions (e.g., cross-border cooperation) and sector-specific dependencies. This process not only fostered mutual understanding but also laid the groundwork for a shared roadmap across sectors.

The insights and results from the workshop were subsequently integrated into the existing DAPP-MR work to ensure consistency and coherence across all components. This integration helped align the newly co-created cross-sectoral DRM pathways with the earlier stakeholder inputs and analyses.

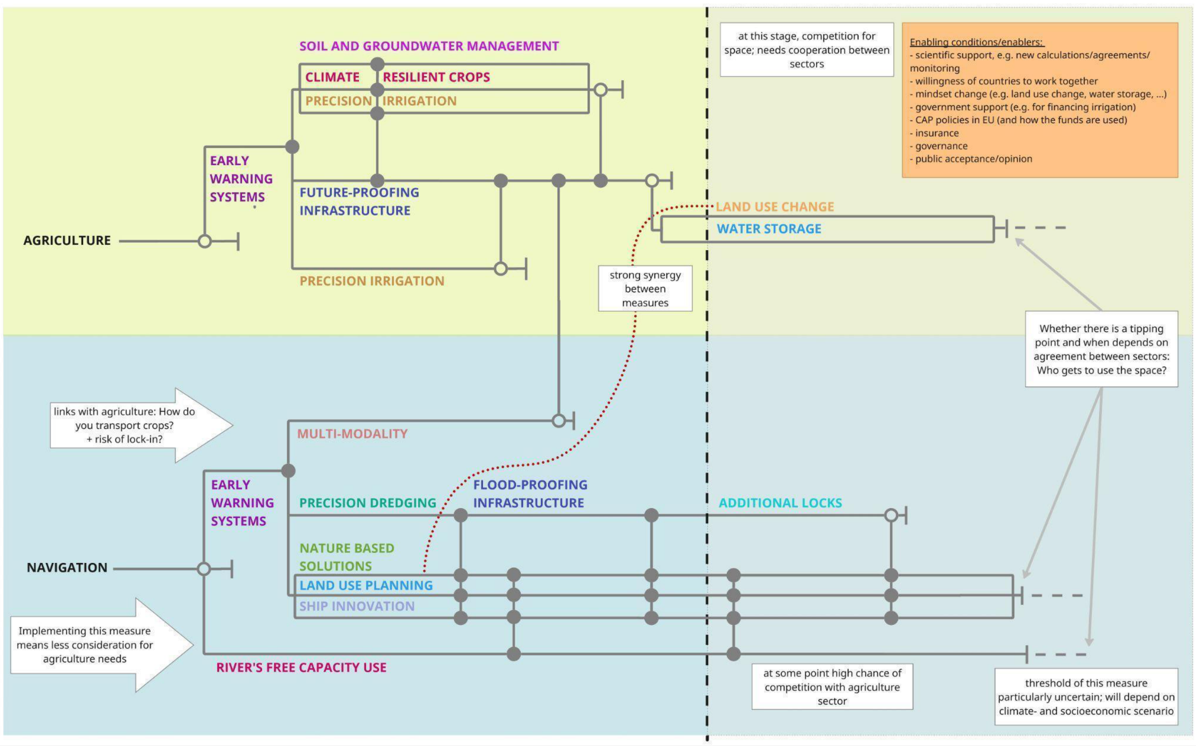


Figure 34: Cross-sectoral DRM pathways for the agriculture and transport sector. Colored-in circles indicate points at which one can transition to a different DRM measure (so-called opportunity tipping points (OTPs)), empty circles are adaptation tipping points (ATPs), at which point other measures have to be implemented. The vertical, dotted line indicated the point in time where competition between sectors reaches a level that requires cooperation.

5.2 Recommendations for upscaling and transferability

Lessons learnt and recommendations

The experience of the Danube Pilot provides several lessons on how the DAPP-MR approach can be upscaled and transferred to other contexts. The vast geographic, political, and socio-economic diversity of the Danube river basin made it clear that a one-size-fits-all methodology is neither feasible nor useful. Instead, we recommend **adopting a multi-level implementation strategy**, whereby DAPP-MR is first applied at national or sub-national levels and later synthesised to the regional scale. This would allow for results that are both locally relevant and operational while still contributing to shared regional insights. Similar transboundary river basins in Europe, such as the Rhine, Po, or Tisa, may benefit from this approach. Within the Danube itself, sub-regional applications, for instance Upper, Middle, Lower Danube, could provide more actionable strategies while maintaining alignment with regional goals.

A second recommendation is to **embed participatory processes** to address the persistent challenge of fragmented cross-border and cross-sector coordination. The Pilot showed that interviews, workshops, and co-creation of scenarios not only grounded the analysis in local realities but also helped overcome institutional fragmentation by building trust and shared understanding across countries and sectors. For successful transferability, stakeholder involvement should be **continuous** both to validate modelling assumptions and to interpret outputs in ways that reflect diverse governance settings.

Given the region's data gaps and variability, a third recommendation is to **develop context-sensitive and flexible tools**. Risk assessments and models need to be adaptable to heterogeneous data environments and governance systems, with transparent assumptions and outputs that can be interpreted at multiple scales (local, national, regional). For agent-based modelling in particular, the Danube Pilot showed that compromises in granularity are necessary: while 1:1 scale modelling captures heterogeneity more precisely, it is computationally unfeasible. A 1:100 scale proved to be a workable balance, offering useful insights while remaining computationally tractable. When transferring the method elsewhere, careful calibration of model detail to available resources and intended use is advised.

Another key lesson is that **narrative and storyline-based approaches are indispensable** for navigating uncertainty and contextualising cross-sector interdependencies. In the Danube, Storylines allowed stakeholders to explore how different governance and societal priorities (e.g., grey vs. green infrastructure) could shape DRM pathways. For transferability, we recommend combining such qualitative approaches with quantitative modelling, to capture both systemic dynamics and local realities. These narrative tools also proved effective for communicating complex multi-risk dynamics to non-expert stakeholders and could be used more widely for awareness-raising and education.

Finally, the Danube Pilot highlighted the importance of **recognising complex interdependencies between sectors**. Measures that appear beneficial in one sector may generate trade-offs in another, depending on the broader policy environment. For future applications, it is essential to explicitly integrate such interdependencies into pathway design and to test options under multiple governance and policy Storylines.

In sum, the approach developed in the Danube Pilot has potential for reuse and adaptation in other EU regions that face similar challenges. For instance, river basin regions such as the Rhine, Po, or Tisa could benefit from this approach as they are exposed to similar multi-hazard risks like floods and droughts, and because they also display cross-border governance structures. These regions also share complex interdependencies between sectors. Also, smaller-scale application within the Danube basin itself, for example in specific sub-regions like the Upper Danube (Germany/Austria), Middle Danube (Hungary/Slovakia) or Lower Danube (Romania/Bulgaria), could allow for further exploration of adaptation options tailored to local conditions, while still being aligned with regional-level goals. In particular, national or sub-national application of DAPP-MR would allow for the development of more concrete and actionable strategies and may lead to even stronger stakeholder engagement. Also, regions undergoing fast economic transformation or where sectoral trade-offs are especially visible, such as in Eastern Europe or the Balkans, may find the flexible, scenario-based approach useful in navigating complex socio-environmental transitions.

Key impacts and exploitation

Beyond the MYRIAD-EU project, the insights and methods developed in the Danube Pilot are already being taken forward in ongoing initiatives. In particular, the Pilot team is contributing to the update of the Danube River Basin Management Plan, expected in 2027, where the systemic and cross-border perspective applied in MYRIAD-EU supports efforts to strengthen regional cooperation on climate resilience. The work on cascading risks and sectoral interdependencies has been used to inform discussions with policymakers and regional authorities, ensuring that adaptation planning accounts for multi-hazard interactions and transboundary spill-over effects. The stakeholder relationships developed during the project are strong, and have already led to offers to present results at steering group meetings of key organizations, as well as opportunities to contribute to upcoming updates of regional management strategies. In addition, members of the Pilot team are working together with partners and stakeholders on joint publications to distribute the project outcomes more widely. These activities demonstrate that the Danube Pilot has created a lasting basis for collaboration, opening DRM pathways for future projects and policy initiatives that build on the systemic approach tested within MYRIAD-EU.

6 Veneto Pilot

6.1 Forward-looking DRM pathways

In the context of the Veneto Pilot, two complementary types of forward-looking DRM pathways were developed: general multi-risk DRM pathways and tailored cross-sectoral DRM pathways. They were designed to address future systemic and compound risks expected to intensify due to climate change and socio-economic transformations in the Veneto Region.

The **general multi-risk DRM pathways** propose a broad, system-level strategy to provide an integrated foundation for long-term resilience planning and therefore do not address a specific list of hazards. Hence, the measures included in the general multi-risk DRM pathways can be adapted further based on risk-specific priorities. The **tailored cross-sectoral DRM pathways**, by contrast, are developed in response to specific risks with a focus on cascading and cross-sectoral impacts. They specifically address the following sectors: **finance, infrastructure and transport, tourism, ecosystem and forestry**. In addition, the **civil protection** sector is extensively covered due to the active participation of its local representatives in the Pilot activities.

The development of both types of pathways allows for a twofold approach to DRM: the general pathways act as a policy and planning baseline, while the tailored pathways support targeted, risk-informed decision-making under complex future scenarios.

Methods and information sources

To support the development of general multi-risk DRM pathways and tailored multi-risk and cross-sectoral DRM pathways a combination of sources and methodologies was employed. Figure 35 illustrates the approach and methods used for the co-production with local stakeholders of both Pathways and Storylines (Vaia 2018 and Vaia 2074), the latter being crucial for informing the tailored cross-sectoral pathways. As shown below, it is worth noting that the processes were interlinked, with cross-sectoral pathways built on the general multi-risk ones (Figure 35).

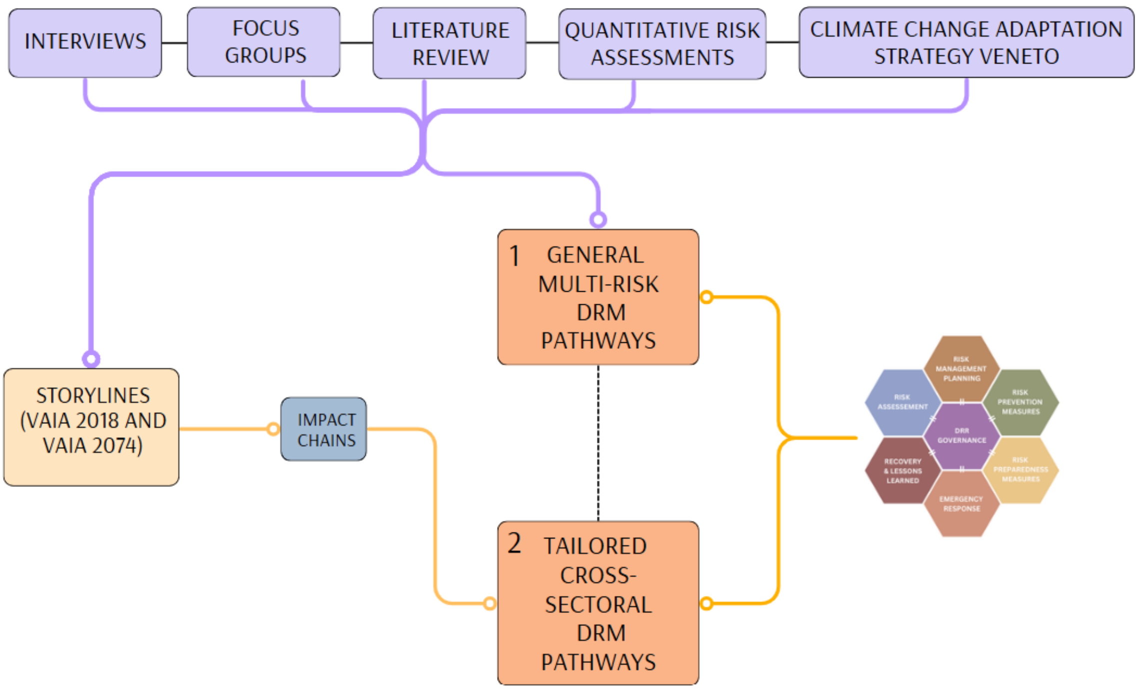


Figure 35: Overview of the process used to develop the Storylines of Vaia 2018 and Vaia 2074 and the multi-risk DRM pathways (both general and tailored).

The multi-risk dimension of both DRM pathways was informed by several elements, including Storylines, which show a complex combination/sequence of hazards; the AI-based multi-risk assessment results; and qualitative inputs from the local stakeholders. These elements are described in the following pages. Together, these sources enabled the development of DRM pathways that go beyond single-hazard logic and instead promote a systemic, cross-sectoral understanding of risk.

Development of the general multi-risk pathways

As shown in Figure 35 above, the development of the general multi-risk DRM pathways drew upon a broad range of sources. These included qualitative data from interviews and three Focus Groups with key local stakeholders involved in the project (van Maanen et al., 2025; Casartelli et al., submitted), literature review, and quantitative results derived from AI-based multi-risk assessments focused on the Veneto Pilot (Ferrario et al., submitted; Ferrario et al., 2025a). In addition, the Strategy for Climate Change Adaptation (SRACC) of the Veneto Region (Regione del Veneto, 2024), along with its associated consultation process, provided valuable input.

- **Interviews and Focus Groups**: Provided insights on the most relevant combination of hazards and key vulnerabilities affecting the region, expected changes in exposure and vulnerabilities, and key strengths and areas for improvement in the regional DRM system.
- **Literature review**: Offered relevant information on key environmental and socio-economic characteristics of the region as well as their expected future changes.
- **AI-based multi-risk assessments**: Provided useful insights about multi-hazard clusters' characteristics and distribution, as well as future trends in multi-hazard events (Ferrario et al., submitted; Ferrario et al., 2025a).
- **SRACC consultation process**: Consisted of thematic meetings where a diverse group of local stakeholders from Veneto Region contributed insights on two main fronts: (1) challenges related to future climate change impacts in the Veneto Region; and (2) proposals for Climate Adaptation (CA) and DRM measures. More than 300 contributions were collected, analysed, and reworked through a multi-phase process. Contributions concerning climate-related challenges supported the development of the Storylines, while those on CA and DRM measures along with additional measures extracted from the Annex of the SRACC preliminary draft formed the basis for the first draft of the general multi-risk DRM pathways.

Then the preliminary draft of the general multi-risk DRM pathways was reviewed, harmonised, and systematically categorised using the Peer Review Assessment Framework (PRAF), developed under the Union Civil Protection Mechanism (UCPM) Peer Review Programme to assess disaster risk governance systems (Casartelli et al., 2025b). The PRAF is structured into seven thematic areas (hexagons): 1) Governance of Disaster Risk Reduction; 2) Risk assessment; 3) Risk management planning; 4) Risk prevention measures; 5) Risk preparedness measures; 6) Emergency response; and 7) Recovery and lessons learned (Figure 36).

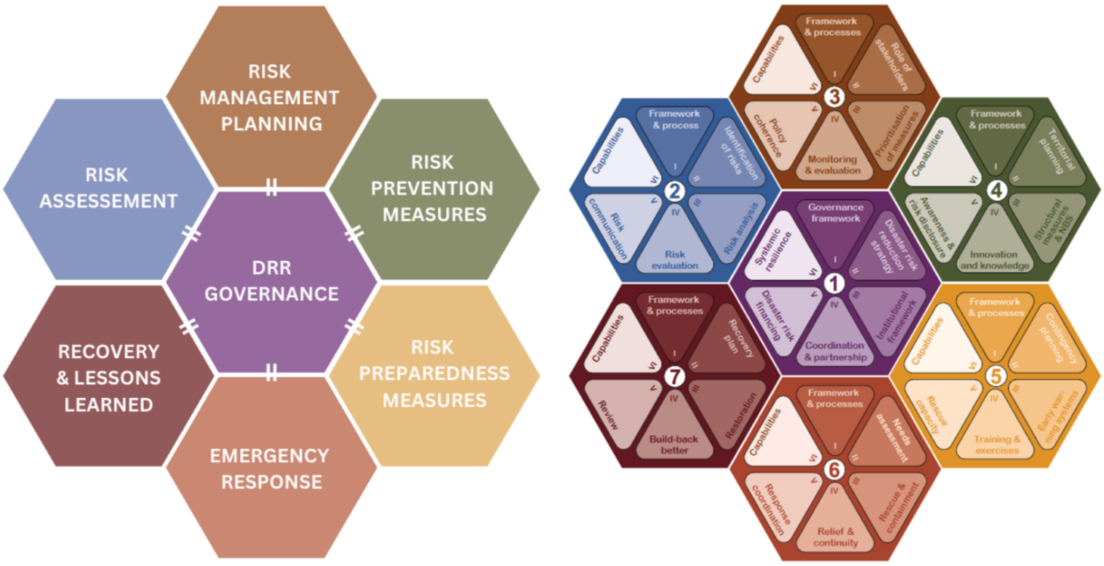


Figure 36: The seven thematic areas of the UCPM Peer Review Assessment Framework (PRAF) and related sub-topics (source: Casartelli et al., 2025b).

Figure 37 presents a set of general multi-risk DRM pathways for each PRAF thematic area. These measures were validated and prioritised (i.e., selected from a wider pool of options) based on stakeholder input collected during a Third Focus Group discussion in October 2024. The multi-hazard component is embedded in the pathways identified, with each measure addressing multiple hazards and their interactions (e.g., the improvement of the legislative framework for land consumption and de-paving was specifically identified as a key prevention measure to increase resilience against urban flooding and heatwaves).

Development of the tailored cross-sectoral pathways

In a subsequent phase, the general multi-risk DRM pathways were further unpacked to develop the tailored multi-risk and cross-sectoral DRM pathways, specifically designed to address selected cross-sectoral risks that might affect the Veneto Region in the near future.

First, the Storylines were developed for a selected benchmark event of Vaia 2018 and future plausible event Vaia 2074. The Vaia storm of 2018, which affected Italy, Austria, France and Switzerland (Giovannini et al., 2021), has been recognised as an extreme hydrometeorological event characterised by multiple hazards often compounding and with cascading effects (Pittore et al., 2023), whose frequency and intensity are likely to be influenced by climate change (Bouwer, 2019; Pinto et al., 2012). Such late autumn and winter storms are being increasingly observed in southern Europe and particularly in the Alps (Gobiet et al., 2014), where they threaten environmental and socio-economic systems (Ulbrich et al., 2013), thus showing the need to foster a holistic approach in risk assessment and management adopting forward-looking DRM pathways. In Veneto, the storm extensively impacted almost the entire region with **strong wind in the mountainous area, storm surge in the coastal area, and heavy precipitation in most of the territory**. A combination of weather-related hazards (strong wind, storm surge, river and coastal flooding, flash floods, landslides) caused severe consequences on different sectors in the near, mid, and long term.

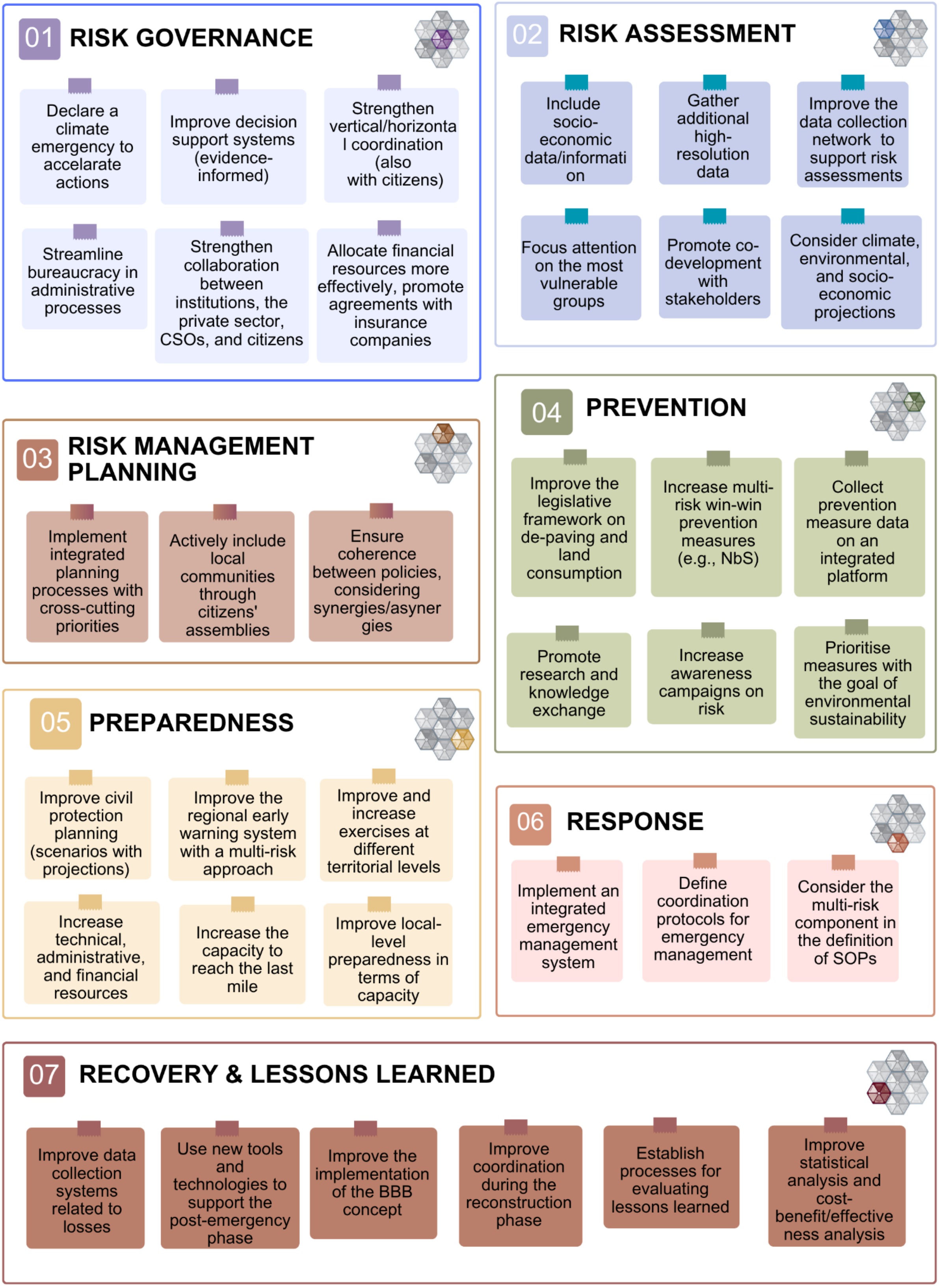


Figure 37: General multi-risk DRM pathways following the PRAF thematic areas. Each post it is representative of one general pathway.

The Storylines of Vaia 2018 and Vaia 2074 were developed based on the MYRIAD-EU Storyline Approach (Crummy et al., 2025). The Storyline of Vaia 2074 explores how such an event might unfold 50 years from now, considering evolving climatic, social, and environmental conditions (Casartelli et al., submitted). Details on the methodology will be available in an upcoming paper (Casartelli et al., submitted). The Storylines are publicly available via the ArcGIS StoryMap tool (Casartelli et al., 2025a).

Second, based on the impact chains related to Vaia 2074, three **cross-sectoral key risks** were identified:

- **Economic crisis and shortage of economic resources due to a downsizing tourism economy and declining agricultural product (Risk 1)**
- **Prolonged interruption of critical infrastructure and inefficient emergency response due to cascading impacts of consecutive disasters (Risk 2)**
- **Increased morbidity and mortality due to limited access to healthcare, greater prevalence of chronic and infectious diseases, primarily driven by frequent and prolonged heatwaves (Risk 3)**

Tailored pathways were grounded on these three key risks. As with the general pathways, the tailored pathways were structured according to the seven PRAF thematic areas. They were subsequently validated with local stakeholders during the World Café session held at the Final Pilot Workshop in February 2025.

Initially all the three key risks were scheduled for discussion during the World Café. However, due to the unexpected absence of some stakeholders at the workshop, the decision was made to focus solely on Risk 1 and 2. Therefore, tailored DRM pathways were developed for these two risks only.

Figure 38 presents a snapshot of the tailored multi-risk and cross-sectoral DRM pathways addressing the "Governance of disaster risk reduction" PRAF thematic area for the two cross-sectoral key risks mentioned above (Risks 1 and Risk 2). A complete version, presented as an infographic, will be featured in a forthcoming scientific publication (Casartelli et al., submitted).

During this process, the limited engagement of some stakeholders, especially from the finance and tourism sectors, reduced the scope of perspectives feeding into the pathways. Since effective DRM planning depends on broad and active collaboration, future initiatives should invest more in targeted stakeholder mapping and engagement strategies to ensure balanced participation across all relevant sectors and strengthen the applicability of the results.

CROSS-SECTORAL KEY RISKS

	RISK 1: Economic crisis and shortage of economic resources due to downsizing tourism economy and declining agricultural product	**RISK 2:** Prolonged interruption of critical infrastructure and inefficient emergency response due to cascading impacts of consecutive disasters
GENERAL CROSS-SECTORAL PATHWAYS	**TAILORED PATHWAYS - RISK GOVERNANCE***	
Declare a climate emergency	Strengthen climate policies to incentivise sustainable investments, technologies, green infrastructure, and de-paving	Adopt more decisive climate policies and promote the introduction of regulations/guidelines for the design of resilient infrastructure and structures
Improve decision support systems	Implement and promote the use of a geo-referenced DSS shared among the economic actors	Implement a geo-referenced DSS shared among infrastructure/essential services managers and civil protection
Streamline bureaucracy in administrative processes	Simplify access to insurance incentives; Establish effective extension services to assist small-holder farmers/SME in administrative processes	Simplify and speed up administrative processes to make infrastructure more resilient (e.g., electrical infr./buffer zones)
Strengthen collaboration between institutions, the private sector, CSOs, and citizens	Foster PPP and dialogue to develop economic diversification strategies in high-risk areas	Establish moments of dialogue to discuss opportunities for joint improvement
Strengthen vertical/horizontal coordination	Establish a permanent cross-sectoral committee for economic resilience and collaboration protocols for emergency management	Strengthen the coordination between civil protection, infrastructure/essential services managers
Allocate financial resources more effectively, promote	Enhance financial planning and anticipatory financing; expand accessible	Encourage the private sector to invest in making infrastructure more

Figure 38: A snapshot of tailored cross-sectoral multi-risk DRM pathways developed for the Veneto Region for two key risks. For simplicity, only the "Governance of disaster risk reduction" PRAF thematic area is displayed.

6.2 Recommendations for upscaling and transferability

The methodology adopted in the Veneto Pilot has two main features: (1) a **mix-method approach** integrating quantitative and qualitative tools; and (2) an emphasis on **stakeholder engagement from early stages** and throughout the project. Combining quantitative tools (e.g., AI-based modelling) with qualitative ones (e.g., Storylines, PRAF) for multi-risk assessment and pathway development proved effective in capturing both technical and contextual dimensions of risk. Stakeholders' input collected from the early stages of the project complemented literature review and data analysis, supported validation, and ensured local relevance. This strengthened ownership and enriched results and their usability. Therefore, when transferring this methodology to other regions or contexts, we recommend maintaining these two main features.

The quantitative approaches applied in the Veneto Region - such as multi-risk indicators and AI-based modelling - are flexible in nature and can be upscaled or transferred to other EU regions with similar environmental characteristics or risk profiles, provided that adequate data are available. Potential applications include areas facing compound risks and diverse landscapes from mountains, low plains, to coastal regions with shared challenges. For example, the DBSCAN-based method used to map multi-hazard footprints in the Veneto Pilot is currently being applied to a transregional case study, the Adige River Basin (North-Eastern Italy), using Earth Observation data (ESA-funded EO4MULTIHA project), demonstrating its adaptability to other scales and territorial contexts as well as its capacity to integrate new types of data.

Multi-risk indicators and AI-based tools were used in the Veneto Pilot to identify current and future risk hotspots and dynamics. Multi-risk indicators supported the development of the first edition of the Regional Climate Change Adaptation Strategy (SRACC) in 2024 (Regione del Veneto, 2024) whereas more recent results obtained from the AI-based modelling (Dal Barco et al., 2025; Ferrario et al., 2024; Ferrario et al., 2025b; Nguyen et al., submitted) may inform its future updates.

On the qualitative side, narrative-based approaches such as Storylines have been used to communicate complex future multi- and systemic risks, while forward-looking DRM pathways were developed using the PRAF. These tools are suitable for transfer or upscaling/downscaling to <u>other regions, regardless of administrative scale, if strong stakeholder collaboration is established</u>. This is already underway through new collaborations with <u>Mediterranean partners and other Italian regions (e.g., Calabria)</u>. Additionally, Storylines proved to be effective for risk communication to non-experts, as confirmed by one of our stakeholders who asked for permission to use it for dissemination and education purposes (e.g. during visits from schools).

For successful replication, several aspects of the above-mentioned approaches should be carefully considered and, where necessary, adapted. These include the context-specific nature of AI models, the availability and quality of data, and the dynamics of stakeholder participation. Below, we outline key factors that influence transferability, along with corresponding recommendations.

Context-specific nature of AI models: The models were trained on the risk and hazard scapes in the region, and their conceptual model was discussed and developed together with local stakeholders. The implementation of the models and their limitations strongly depend on the availability of data in the case study. The following is recommended for researchers and experts:

- When applying to other regions, a suitable set of locally relevant indicators should be used, and models should be trained on new input data.

Maintaining or enhancing AI models accuracy and effectiveness: The algorithms employed in this study follow key principles of robustness, transparency, and explainability. They demonstrate robustness through rigorous testing on new datasets and ensure reproducibility with hardcoded random seeds. They are developed within a purpose-built environment tailored to maintain consistency and reliability throughout the modelling process. However, their continued effectiveness requires regular updates and improvements. The following is recommended for researchers and experts:

- Regularly retrain or fine-tune with updated data.
- Continuously engage with local stakeholders to validate results and collect data for the training of the AI models.
- Explore the use of more advanced algorithms for improved modelling, such as Recurrent Neural Networks or Graph Neural Networks.
- Use multiple climate models/climate ensembles or multiple runs of the same model, but with different initial conditions, to give more robustness to AI models.

The granularity and quality of the impact data directly influence the implementation of AI models: Impact-based datasets are necessary to identify multi-hazard events via AI models and reduce false positives identified via statistical methods. The lack of an impact-based catalogue for multi-hazard events is limiting the validation of the multi-hazard and multi-risk analysis via AI models. Moreover, the lack of impact location data and their temporal homogeneity prevent the consideration of local vulnerability and exposure. Additionally, applications of advanced algorithms (e.g. Graph Neural Network, Long Short-Term Memory) for spatial-temporal modelling and improving the understanding of multi-risk dynamics are limited due to constraints in impact data's granularity. Finally, some assessment endpoints directly relevant to the sectors were not included in the AI models due to the lack of impact data. The following is recommended for researchers and experts:

- Use advanced tools in monitoring impacts like remote sensing or unstructured text mining to improve accuracy and granularity of impact data.

The following is recommended for government and public agencies at local, national and international level:

- Initiate and support a process of standardisation of impact-based data collection at regional, national and/or EU/international level.

Micro-dynamics of risks (the effects of local interventions) are not captured in the AI models due to the lack of data: The models are able to capture the multi-risk dynamics of land use and climate patterns. However, local interventions and adaptation measures were not integrated in the AI models due to the lack of geospatial and temporal data. Therefore, management measures (e.g., dredging channels for flood events), their synergies and trade-offs, are not part of the AI models. The following is recommended for researchers and experts:

- Integrate management measures (e.g., coastal adaptation strategies, river interventions) into the algorithm to enable sensitivity analyses to assess their effectiveness.

Limited participation of institutions and stakeholders in research projects, including insufficient engagement of stakeholders from certain sectors (e.g., tourism) throughout the various phases of the project. Engaging key stakeholders from the early stages is essential to support a participatory process, as it fosters co-development and strengthens stakeholders' sense of ownership and active involvement throughout. Also, the careful selection of stakeholders with extensive knowledge of risk governance systems and their gaps is of paramount importance to ensure meaningful results and an inclusive participatory process. The following is recommended for researchers and experts:

- Consider conducting stakeholder mapping to identify the right stakeholders to engage and to ensure inclusivity.
- Start engaging key actors (stakeholders) while drafting the project proposal.
- Consistently maintain interaction with stakeholders by providing regular updates and increasing the frequency of meetings to promote more collaboration and exchanges.
- Improve scientists' skill needed to establish fruitful collaboration with stakeholders.
- Make research results understandable, usable and tailored to the specific needs of local stakeholders.

The following is recommended for government and public agencies as well as private sector representatives who participate as stakeholders in research projects:

- Clarify institutional needs and views ahead and be more proactive to get the most out of your involvement in research projects.

Limited collaboration and coordination between institutions, e.g., due to complexities of the regional risk governance system and/or challenges in coordination and communication: In the Pilot, the application of PRAF highlighted areas for improvement in institutional coordination and helped to define DRM pathways to tackle these issues. The following is recommended for government and public agencies:

- The PRAF is a comprehensive tool that can effectively support the identification of pathways towards greater resilience by enabling a structured self-assessment of DRM capabilities. Consider using the PRAF to conduct a self-assessment of DRM capabilities and define DRM pathways.

Limited awareness of multi-hazard risks: Understanding and awareness among stakeholders and citizens of multi-hazard risks are often somewhat limited. Therefore, a clear and targeted explanation plays an important role. The following is recommendations for researchers as well as government and public agencies:

Consider using Storylines as a tool to improve risk awareness campaigns and raise awareness about multi-hazard and systemic risks. Also, reference scenarios in the form of narratives could be used to effectively conduct stress-tests.

7 Final remarks

The MYRIAD-EU Pilots show that Europe's risks are increasingly systemic, spanning hazards, sectors, and borders. From the coastal lowlands of the North Sea to the volcanic Canaries, the forests of Scandinavia, the cross-border Danube, and the Veneto floodplains, each region illustrates Europe's diverse but interconnected "riskscapes". Despite their differences, common patterns emerge: compounding climate extremes such as floods, droughts, wildfires, and storms; socio-economic dependencies on sectors like energy, agriculture, and tourism; and governance challenges in coordinating across jurisdictions. Europe's risk reality is therefore defined less by single hazards and more by multi-risk dynamics that amplify vulnerabilities and cascade across systems.

These findings align strongly with the European Climate Risk Assessment (EUCRA), where 19 of the 22 most urgent risks were also addressed by the Pilots. The overlaps highlight Europe's key challenges: low-lying coasts exposed to sea-level rise and storms, climate-sensitive economies under pressure from heat and drought, and regions with existing vulnerabilities such as unemployment, ageing populations, or out-migration. Together, they point to a continental challenge: Europe must simultaneously manage intensifying climate extremes and the socio-economic fragilities that heighten their impacts.

The MYRIAD-EU experience shows that Europe's resilience depends on embracing systemic, multi-risk approaches. DRM pathways co-developed with stakeholders demonstrate how methods and tools - from scenario Storylines to AI-supported risk mapping - can guide decision-making, provided they are tailored to local contexts. At the same time, the transferability of approaches across regions proves that lessons can travel, inspiring action elsewhere, if adapted to local realities. To meet its urgent risks, Europe will need to align governance, strengthen data and institutional capacities, and adopt flexible strategies that look across hazards, sectors, and time horizons.

The DRM pathways co-developed in the Pilots were tailored to the specific multi-risk profiles and adaptation challenges of each region. As such, they provide insights for policymakers: they can inform the design of strategies, support the prioritisation of investments, and enable the selection of effective DRM options that work across hazards and sectors. By bridging science, practice, and governance, the MYRIAD-EU experience illustrates how multi-risk approaches can move beyond research into actionable frameworks that strengthen resilience across Europe.

A defining feature of the Pilots was their close collaboration with local and regional stakeholders from the earliest stages. Considerable effort was invested in building awareness of the systemic risk challenges facing each region and in fostering institutional recognition of the need for multi-risk approaches to DRM and adaptation. Despite inevitable challenges and barriers, this engagement helped establish trust, created ownership of results, and ensured that pathways were relevant to real-world decision-making contexts.

This document represents part of the legacy of MYRIAD-EU. The approaches, findings, and tools developed by the project can support other EU-funded initiatives, both current and future, as well as stakeholders working on practical applications of multi-risk concepts in different pilot regions. By demonstrating how multi-risk methods can be applied in practice, MYRIAD-EU contributes to a shared European knowledge base that strengthens synergies between projects and accelerates innovation in DRM and climate adaptation.

8 Ethics Policy and Data Management Plan

The research informing this deliverable adheres to the principles set out in D8.1 Quality, Ethics, and Risk Management Plan (Ward et al., 2021) and in D8.3 Data Management Plan (Daniell et al., 2022). Specifically, this work follows the ethics policy for the creation and collection of data during interviews, workshops, focus groups, and during the recruitment of participants. All stakeholder engagement events were preceded by strict and complete documentation including information sheets, informed consent forms, and confidentiality statements. Approval was sought and provided through the BGS Research Ethics Committee (reference BGSREC-2024-001).

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Appendix 1

Indicators and thresholds considered to define the borders of the EUCRA hotspot areas.

EUCRA hotspots areas	Indicator and threshold	Sources
Countries from south Europe	The list of countries belonging to this hotspot area is indicated in the EUCRA report.	EEA 2024
Low-lying areas (coastal)	Coastal area's threshold calculated for a 1-in-100-year event combined with a 2 m Sea Level Rise.	H2020 project CoCliCo and Thiéblemont et al. (2024).
Densely populated areas	Populated areas with a density of at least 1500 inhabitant/km^2 (European Union, 2019).	Center for International Earth Science Information Network - CIESIN - Columbia University.
Regional and local economies that are dependent on tourism, agriculture, fisheries	• Tourism - List of regions (NUTS 2 and 3) with more than 12% tourism employment share, which are regions with strongly tourism-dependent economies. • Agriculture, forestry and fisheries - List of regions (NUTS 3) with employment rate on agriculture, forestry and fisheries higher than 16.4 %, considering all employment categories.	EUROSTAT Statistical Atlas and Structural business statistics
Regions characterised by high levels of unemployment, poverty, emigration and ageing populations.	A combination (mean values) of Social and Economical Vulnerability Indexes from JRC Risk Data Hub is used, which characterize the level of unemployment, poverty, emigration and ageing. High vulnerability, i.e. more than 80%, is considered.	JRC Risk Data Hub