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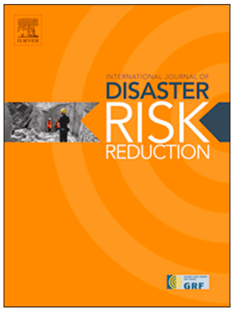

The Risk-Tandem Framework: an iterative framework for combining risk governance and knowledge co-production toward integrated disaster risk management and climate change adaptation.

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Title:

The Risk-Tandem Framework: an iterative framework for combining risk governance and knowledge co-production toward integrated disaster risk management and climate change adaptation.

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Abstract:

The challenges of the Anthropocene are growing ever more complex and uncertain, underpinned by the emergence of systemic risks. At the same time, the landscape of risk governance has become compartmentalised and siloed, characterized by non-overlapping activities, competing scientific discourses, and distinct responsibilities distributed across diverse public and private bodies. Operating across scales and disciplines, actors tend to work in silos which constitute critical gaps within the interface of science, policy, and practice. Yet, increasingly complex and 'wicked' problems require holistic solutions, multi-scalar communication, coordination, collaboration, data interoperability, funding, and stakeholder engagement. To address these problems in a real-world context, we present the Risk-Tandem framework for bridging theory and practice; to guide and structure the integration of disaster risk management (DRM), climate change adaptation (CCA) and systemic risk management through a process of transdisciplinary knowledge co-production. Advancing the frontiers of knowledge in this regard, The Risk-Tandem framework combines risk management approaches and tools with iterative co-production processes as a cornerstone of its implementation, in efforts to promote the co-design of fit-for-purpose solutions, methods and

approaches contributing toward strengthened risk governance alongside stakeholders. The paper outlines how the framework is developed, applied, and further refined within selected case study regions, including Denmark, Germany, Italy and the Danube Region.

Keywords:
Disaster risk management, climate change adaptation, knowledge co-production, systemic risk, transdisciplinary stakeholder engagement

1. Introduction

The Anthropocene continues to present new and evolving systemic risks and interconnected threats which are characterized by complexity, multiple uncertainties, and ambiguities, as well as cascading effects across scales (Renn, et al., 2020; Sillmann, et al., 2022). Departing from approaches favouring quantification (Grossi and Windeler. 2005; Woo 2012; Tilloy, et al., 2019), or single risk-centred assessments (issue discussed by Scolobig, et al., 2017) complex and often non-quantifiable risk constellations have emerged from the shared dependencies of technological and social systems and infrastructures (Sachs, 2023). These are often manifested by the failures of supply chains that remain vulnerable to disturbances and cascading ripple effects traversing the world system (Boin, 2018; Hochrainer-Stigler, et al., 2023). Whether assessed at a macro-level (such as in the case of climate change) or in terms of localised interactions, "functionality losses" with cascading potential continue to endanger global stability and its internal constituents across scales (Renn, et al., 2020). Examples of such dynamics include the COVID-19 pandemic, the ripple effects of which traversed throughout socio-economic and environmental fabrics with lasting global consequences, revealing critical interdependencies in sectors such as finance, health, and employment (Lenzen, et al., 2020).

As a case in point, flooding in the Emilia-Romagna region in Italy better contextualises such dynamics for our purposes and demonstrates the importance of situating single-hazard scenarios in the continuum of systemic risks (issue discussed by Hochrainer-Stigler, et al, 2023). As a combination of preceding droughts decreasing the permeability of the ground and storms in the Adriatic Sea preventing rivers from draining, heavy rain led to the overflowing of 23 rivers across 100 municipalities in Emilia-Romagna, triggering more than 400 landslides. Cascading impacts caused severe damage to infrastructure, contributed to the displacement of some 36,000 people, and had long-lasting effects on industry, tourism, and the environment (Arrighi and Domeneghetti, 2023; Agenzia per la Sicurezza territoriale e la protezione civile, 2023). More generally, as the connections between hazards, climate change, and socio-ecological systems evolve and grow in reach, socio-ecological systems have become prone to unpredictable and non-linear shifts manifested in catastrophic events, often with transboundary, and sometimes global impacts (Grove and Chandler, 2017; Sillmann et al. 2022; Mitra and Shaw, 2023). Consequently, risk issues today must be approached from a transdisciplinary[1] perspective, with an effort to understand risk beyond its relationship to single hazards alone – not least when considering the effects of climate change (see, for example Simpson, et al., 2021).

However, a perspective acknowledging the complex interrelationship of socio-ecological pressures, trigger events and associated uncertainties represents a monumental challenge for risk management practice. After all, it necessitates innovation that can go beyond the hierarchical or reductionist technological solutions that often fail to address cascading dynamics, transboundary tendencies, and emergent properties (Renn, et al., 2022; Schweizer,

[1] Transdisciplinary knowledge integration processes, or the co-exploration and -production of knowledge that bring together different knowledge types and actors on multiple levels across the science-society interface (Daniels, et al., 2020).

2021; Sillmann, et al., 2022). More centrally, it requires the accommodation of considerations for systemic interactions and complex risk scenarios, and understanding of their relationship with local dynamics, especially if one's interest is to address discrepancies and redundancies in their joint management across stakeholders operating on multiple levels. While there has been growing interest in systems-driven analysis of risk and uncertainty management (Steffen et al. 2011; EEA 2024; Pescaroli, et al., 2022), adequate analysis and approaches to governing risks from a systems perspective are lacking (Renn, et al., 2020; Schweizer, 2021).

Multiple governance gaps and challenges underpin this issue. For instance, risk governance is increasingly polycentric: following the shift in governance from state-centric toward market-oriented arrangements, increasingly autonomous actors are often reduced to coping with rapidly changing dynamics in an ad hoc manner (Braun, 2014: 51; Jessop, 1998; Rhodes, 2007). Lacking a shared understanding of the priority challenges and solutions, and centrally coordinated organising principles, actors at a national, regional, and global level tend to struggle in effectively coordinating, financing, and communicating actions. Adaptive governance and anticipatory action remain rare: in Europe, investing in response is still heavily preferred to long-term risk reduction (Migliorini, et al., 2019), and the integration of climate considerations into risk reduction remains a challenge (Dias, et al., 2021) Furthermore, the number of discourses and disciplines (as well as values and beliefs) involved in these deliberations complicates the ability of actors to generate a shared consensus. The governance of risks tends to be an expert-led process, which may exclude knowledges and actors required for understanding and managing risks from a holistic perspective. The issue of data interoperability and usability are also a concern: as pointed out in the context of climate services (Lemos, et al., 2012) and systemic risk management (Sillmann, et al., 2022), the ability of actors to translate available information into usable knowledge for decision-making is often constricted by highly technical or contextually unconnected data. Although numerous approaches and tools have been introduced to address these issues (section 2.2), no overarching solutions have been proposed.

Here, we introduce the Risk-Tandem framework, designed to address aforementioned issues through real-world testing, refining, and co-production of new and existing risk governance tools, processes, and solutions with stakeholders, in efforts to patch gaps between theory, data, and practical challenges. By placing knowledge co-production and stakeholder engagement at its centre, the framework creates a context-led and integrated approach to tackling risks in polycentric governance settings, characterised by abundance of technical information (that may not meet the needs of its users), disciplinary silos, and limited coordination between actors across levels. As a transdisciplinary tool, the core philosophy of the Risk-Tandem Framework is not to merely add to knowledge. Rather, it seeks to promote the use and accessibility of existing knowledge and risk information, uncover hidden-yet-relevant risk governance dynamics, and promote transdisciplinary collaboration toward improved communication, knowledge- and data interoperability, and strengthened risk governance that integrates considerations for systemic risks and climate change.

To achieve this, we combine approaches and frameworks from (previously disjointed) strands of risk research, as well as established and successfully applied approaches. These include the International Risk Governance Council's (IRGC) Risk Governance Framework (IRGC, 2019), the Tandem Framework for knowledge co-production (Daniels et al., 2020, Bharwani et al, 2024), the risk-layering approach (Mechler, et al., 2014), and the SHIELD model, developed under the ESPREssO Project[2] (Lauta, et al., 2018). Integrating lessons learned from these (further discussed under section 3), the Risk-Tandem framework supports and guides the co-production of knowledge regarding risks, risk governance systems and processes, as well as capturing opportunities for further integration of knowledge and risk

[2] Enhancing Synergies for Disaster Prevention in the European Union.

information across actors involved in disaster risk management (DRM) and climate change adaptation (CCA) for improved collaboration, policy, and practice. It is currently being applied in four case study sites ("Real World Labs", RWLs) within the DIRECTED Horizon Europe project, through which it will be further refined beyond the first iteration as introduced here. In contrast to existing frameworks and processes that are usually expert-led and developed in isolation from practical needs, Risk-Tandem is tested and redeveloped based on its application context in continuous conversation with its users, thus promoting replicability for the purposes of co-designing fit-for-purpose risk governance solutions and usable risk information elsewhere.

The paper is organized as follows. We first discuss the context in which the framework is developed in section 2. In section 3 we introduce a selection of relevant frameworks that inform the Risk-Tandem Framework. Then, we present the Risk-Tandem Framework for guiding DRM/CCA stakeholders on integrated risk governance and knowledge co-production in section 4. Advantages, limitations and experiences from real world applications are discussed in section 5. Finally, section 6 provides conclusions and an outlook to the future for the Risk-Tandem Framework.

2. Governing complexity and approaches to holistic risk management

Understanding the complex and systemic nature of multiscalar climate and disaster risks is crucial to achieve ambitions for vulnerability and risk reduction as outlined in the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015), the Paris Agreement (UNFCCC, 2015), and the Sustainable Development Goals (SDGs) (UN, 2015). Given the complexity of networked societies and their coupling with ecological systems, the domain of risk management must extend toward analysing natural and human factors that underpin risks (Pescaroli and Alexander, 2018), including the dimensions of conjoint natural and technological hazards (Cruz, et al., 2014). Therefore, the assessment, measurement, modelling and governance of risks necessitates transdisciplinarity, stakeholder engagement, and knowledge co-production, combining information across sectors, disciplines, and scales toward improved understanding of their interrelatedness and the dynamics between, for instance, socio-economic and environmental processes, and the uncertainties associated with these (Pescaroli and Alexander, 2018; Norström, et al., 2020; Cosens, et al., 2021; Lawrence, et al., 2022). Next, we discuss these issues in more detail vis-à-vis complexity and challenges of governance, laying out the reasoning for the selected frameworks and the need for knowledge co-production as presented in the Risk-Tandem framework.

2.1 Risk governance and complexity

As discussed previously, the issue of complexity represents numerous challenges for actors involved in "risk governance" (Schweizer, 2018), a term which seeks to capture the totality of actors, institutional structures and processes that guide and restrain the collective ability of actors to deal with risks (Klinke and Renn, 2019). Conventional approaches to managing cascading or non-linear developments are often unable to capture uncertainties and ambiguities involved in rapidly evolving risk scenarios (nor the effects of climate change), and thus necessitate interdisciplinary and cross-sectoral approaches – including the engagement of scientists, practitioners and policymakers (Renn, et al., 2020). However, it is worth situating the concept of "governance" within global socio-economic developments since the strengthening (or transforming) of approaches to risk governance partly hinges upon the ability of actors to address their context.

If one strives to bridge the decision-making of DRM and CCA actors toward coordinated management of complex risks, acknowledging the socio-economic realities that underpin their ability to do so is essential (Boholm, et al., 2010). Although it could be argued that the need to research and understand risk governance emerges from the increasing complexity of risks today, governance literature highlights a wider trend moving from state-centric toward market-oriented arrangements (Jessop, 1998; Comaroff and Comaroff, 2009; Rhodes, 2007; Braun, 2014). As centralised and hierarchical mechanisms evolved via the deployment of various free market-oriented legalities, institutions, policies, and ideologies (Comaroff and Comaroff, 2009), the acts of governance are thus continuously negotiated within these constraints, via the self-organisation of relatively autonomous actors (Jessop, 1998). This is not to say that the landscape of governance actors is characterised by disorder. These structures and processes remain characterised by rules and hierarchies of power, and influence over policies is unequally distributed across governance actors – a reality that must be accounted for.

This juxtaposition between structure and autonomy has implications for risk governance and management. Diversification of state functions, for instance, contributes to the increasing number of actors, approaches, and discourses involved in climate and disaster risk management (including the dissolution of finances), creating a need for cross-sector interdisciplinarity and increased collaboration. Marketisation of higher education and expert knowledge (Collyer, 2014) also contributes to the expansion of disciplinary niches, creating exclusive languages that hinder collaboration between actors. Renn (2008) describes this situation with the term “ambiguity” referring to the plurality of legitimate viewpoints. Polycentricity also influences accountability, or the institutional relationship or arrangement in which an agent can be held to account by another agent or institution (Bovens, 2010). In a space where coordinated regulation, monitoring and accountability are necessary to manage risks and to mitigate risk creation, greenhouse gas emissions, or environmental degradation, a clash between the underpinning context and actors working within it becomes evident. As discussed by Cosens, et al. (2021) in the context of governing complexity, it is necessary to account for (and critically reflect) these underlying dynamics, and meet them with science and adaptive governance approaches if one hopes to drive change within the socio-ecological system through collaboration and learning (in this case, towards the holistic management and reduction of risks).

Finally, complexity also creates ambiguity and uncertainty that permeates throughout the decision-making process of both risk management and adaptation actions. Although DRM and CCA have emerged in different policy arenas, associated frameworks and policies do recognize the need for integration, alignment, and coherence to capture efficiencies and synergies. However, gaps in governance, capacity, communication, and data/modelling are hindering efforts to achieve integration from national to local levels (Islam et al. 2020; Leitner et al., 2020; Hochrainer-Stigler, et al., 2024). Further, ambiguity can manifest in the mismatch between the relevance of the information that is needed compared to what climate (or other) science can provide (Singh et al 2018) or the different points in the decision-making process that this data is needed (Jack et al., 2020). The inability to identify relevant information or key decision points can stem from the different value placed on various types of information or knowledge and a lack of understanding of the needs and challenges of the decision context. Uncertainty can arise due to a variety of factors, such as insufficient data or reasonably contestable interpretations of sets of data. Uncertainty can also stem from normative deliberations related to the uncertain outcomes of a given choice (Taebi et al. 2020; Hofbauer 2023). Namely, the values that drive a given adaptive measure, for example reducing the financial damage a coastal area might face, could clash with future plans, such as rewilding said coast (Taebi et al 2020).

The growth of modern communications and information networks also underpin a digital revolution, accompanied by the increasing availability of datasets (Migliorini, et al., 2019). As such, an unprecedented amount of non-standardised risk information is now available for decision-making, hosted by governments, non-governmental organisations, the scientific community, private industry, and other stakeholders. This also generates uncertainty; sometimes data is subjective, incomplete, incorrect, and can be interpreted in different ways (van Keulen, 2012). However, concerns for interoperability and usability of information have received less attention (Migliorini, et al., 2019; Lemos, et al., 2012), which complicates the ability of actors to build a reliable understanding of risk, uncertainty, and complexity amidst an excess of information.

2.2 Accounting for complexity in risk analyses and approaches

The issues of complex risk, risk governance, data interoperability and usability are often addressed in literature dedicated to risk analysis and management. In discourse on risk management and adaptation, considerable effort has been dedicated toward their integration, in efforts to address redundancies and to support synergies toward coordinated action between already overlapping disciplines (Islam, et al., 2018; Kelman, et al., 2018; Birkmann and von Teichman, 2010; Soares and Buontempo, 2019; Leitner et al., 2020). In the literature on risk governance, the need to manage complexity, uncertainty, and ambiguity are well-established themes (Renn, et al., 2011; Klinke and Renn, 2011), including the management of risks from multi-risk perspectives that consider interdisciplinarity and the inclusion of stakeholders across levels (Renn, et al., 2018; Renn and Schweizer, 2009; Schweizer and Juhola, 2024; Schweizer and Renn, 2020;). Stakeholder engagement frameworks and approaches have been introduced to mitigate the issues of expert-led governance, encouraging the inclusion of vulnerable groups and non-traditional ways of knowing into the process of deliberating risks (Schweizer and Renn, 2020; Hochrainer-Stigler, et al., 2024). In systemic risk literature, the need for translating transformational risk management into practical policy options has been similarly highlighted as a response to complexity (Hochrainer-Stigler, et al., 2023). For improved data interoperability and usability, literature is expanding to support the co-production of knowledge for systems' understanding and climate services' co-design toward risk informed decision-making (Jack et al., 2020; Daniels, et al., 2019; Soares and Buontempo, 2019; Carter et al., 2019). This extends to how different co-production *principles* should inform the design and development of climate services that can account for big picture systems thinking that is still connected to local level data (McClure et al., 2024) and how this can be applied in different decision domains and contexts (Bharwani et al., 2024). Yet, they have not been brought together in a comprehensive manner.

Current attempts to incorporate considerations for complexity and interacting risks into analysis include Gill, et al. (2022), where the authors examined the potential for multi-risk management via the integrated examination of hazards and their relational dynamics. Starting from the "classic" representation of disaster risk and impacts as a function of hazard, exposure, and vulnerability (Wisner, et al., 2004), they continued to add a temporal dimension to examine how changes in exposure and vulnerability (especially in multi-hazard contexts) constitute evolving risk dynamics. Similarly, Hochrainer-Stigler, et al., (2020) have proposed an approach where individual hazard events and risks are placed on the continuum of systemic risks, separated only by the notion of dependencies. As such, interactions and interdependencies have also become an important dimension of risk analyses, following the increasing number of network effects between, for instance, climate change and hazard impacts, relationships between socio-economic vulnerabilities, changing environments and risk (Kelman, et al., 2015), and the increased recognition of the threats of compound and cascading disasters (Pescaroli and Alexander, 2018; Cruz, et al., 2015; Pescaroli, et al., 2022). Simpson et al. (2021), Hochrainer-Stigler, et al, (2022) and Pescaroli and Alexander (2018) have provided examples of approaches that could support transitions from a single to multi-risk analysis of natural hazard events. The field of literature on the integration of disaster risk management, reduction and climate change adaptation has also gained popularity, with a similar commitment to address redundancies and deconstruct siloed thinking (Kelman, 2015; Urban and Nordensvärd, 2023).

For practically consolidating the issues of complexity and challenges of governance, literature on knowledge co-production has produced some promising outputs. Cultivated in sustainability sciences following Elinor Ostrom (see Miller and Wyborn, 2020), the promise of co-production has been introduced as a transdisciplinary and practical bridge between science, practice, and policy for addressing sustainability challenges (Djenontin and Meadow; Wyborn, et al., 2019; Howarth, et al., 2022; Norström, et al., 2020) in systemic risk research and management (Hochrainer-Stigler, et al., 2024), climate services (Daniels, et al., 2020; Bharwani et al., 2024), and governing complexity (Cosens, et al., 2021). Often discussed as a means of inspiring transformations by involving more stakeholders in the design of societal transitions to better incorporate the socio-economic context, and to address issues such as power and politics (Wyborn, et al., 2019; Miller and Wyborn, 2020), co-production in this context can be defined as the "iterative and collaborative processes involving diverse types of expertise, knowledge and actors to produce context-specific knowledge and pathways towards a sustainable future" (Norström, et al., 2020:183).

However, all these approaches – co-production included – are shaped by practical challenges hindering their implementation, particularly in real-world settings. Issues begin with scientific tradition; facing uncertainty and complexity, approaches to risk management tend to reflect a biased analysis of causality, and tend to veer toward reductionist quantification of nature as a determinant at the expense of the socio-political, legislative, and biophysical contexts that also underpin risks (Weichselgartner and Sendzimir, 2004). Altering these dynamics continues to be difficult, especially within the complexities inherent in short-term project cycles (e.g. time-boundedness, disciplinary constraints, staff turnover, etc). The integration of knowledge across disciplines is also a slow process: integration of risk management and climate change adaptation has been found to be hindered by siloed working cultures, chaotic institutional arrangements and limited coordination, lack of political will, as well as ad-hoc or haphazard funding (Dias, et al., 2021). Linking to this, technical information also often falls short in reaching its intended audiences. Due to differing technical capacities, lack of shared understanding, language or terminology, competing priorities and scope, limited knowledge transfer, and other issues, actors often fall short in producing contextually appropriate knowledge that would connect different system scales, in a manner that is useful for decision making (Weichselgartner and Breviere, 2011; Lemos, et al., 2012; Daniels, et al., 2020; Sillmann, et al., 2021). In terms of knowledge co-production (potentially addressing many of these issues), approaches are limited by lack of empirical and practical evidence supporting implementation and demonstrating real world impacts (Jagannathan, et al., 2020).

Importantly, conflicts and disagreement may also arise from, or underpin collaborative efforts. For instance, the deployment of Real-World Laboratories for research on the German mobility transition has shown that various points of contention arise from decisions regarding the authority over decision-making, questions about who benefits, and who is to represent which group (Klaever et al. 2024). The challenge of conflicting interests and goals is further exacerbated through potentially unequal levels of power and influence in the decision-making process. While the set-up of co-production processes can be developed in a comparatively procedurally just manner and on an egalitarian playing field, any decision in the real world is inevitably shaped by asymmetric power relations, levels of responsibility, and accountability. Of these, accountability is particularly relevant for risk governance purposes, used across governance and legal literature as an intertwined indicator and mechanism for understanding and evaluating risk governance and stakeholder engagement. Accountability can elaborate standards for the evaluation of the behaviour of (public) actors (such as transparency, decision-making rules, and stakeholder participation), but can also be seen as a mechanism, i.e., an institutional relationship or arrangement in which an agent can be held to account by another agent or institution (Bovens, 2010). Naturally, these affect the ability of actors to collaborate and co-produce knowledge toward transformative solutions or incremental change (in some cases, limiting the ability of actors operating below national levels to advance solutions).

By neglecting these issues, contemporary risk governance approaches, tools and frameworks may therefore fall short in terms of active inclusion of stakeholders across scales, ignore competing knowledge systems, and thus fail to generate trust, relationships, and useful systems-scale information across local to global interactions – all required for knowledge integration, and the management of systemic risks amidst a complex governance landscape (Schweizer and Juhola, 2024; Hochrainer-Stigler, et al., 2024). Connecting these aspects into an overarching framework, with an emphasis on governance processes, transdisciplinarity, stakeholder engagement, knowledge integration, and relationships is seldom presented in a practical setting, thus providing a reasoning for the Risk-Tandem framework.

3. Selected frameworks for supporting (systemic) risk governance, knowledge integration and co-production

In sum, the complexity of risk governance has increased alongside the complexity of risks themselves, generating diverse and sometimes competing approaches to management. This has resulted in the creation of siloed fields such as disaster risk management, disaster risk reduction and climate change adaptation (not to mention differing temporal and spatial information and data scales), which share goals but vary in their focus, priorities, underpinning theories, institutional and policy frameworks, terminology, funding, and output (Street et al., 2019). Evidently, a new way of thinking is needed, aimed at capturing the dynamic and multifaceted nature of risks and risk governance, making use of existing knowledges. Importantly, as pointed out by Coetzee, et al. (2019) the issue is less about the number of tools, but rather about the way of doing and thinking about risk management beyond products, mechanistic approaches and moving beyond data and information products to transdisciplinary knowledge integration processes that promote use and "working solutions" vis-à-vis complex challenges (Daniels et al., 2020; Berkes, 2017).

Therefore, cautious of introducing yet another "new" method, we rather propose a framework that builds upon existing knowledge, and promotes new ways of thinking and working with existing methods, toward building a comprehensive understanding of complexity and risk management. Recognising the crux of the issue (a lack of a shared consensus, and mechanisms for its generation), we introduce frameworks with a focus on stakeholder engagement and knowledge co-production, both crucial for enabling integrated risk management and climate change adaptation facing a complex governance landscape. The frameworks were chosen due to their empirically evidenced application in case studies, but also with consideration of their individual gaps: we seek to combine them to address these weaknesses, and to advance their transdisciplinary implementation in a manner informed by the context. Due to space restrictions we only provide the most important ideas of each framework and refer to the Supplementary for more details.

3.1. IRGC Risk Governance Framework

The first framework introduced is the International Risk Governance Council (IRGC) Risk Governance Framework (2005; 2007; 2018). It provides a conceptual and normative basis for dealing with uncertain, complex and/or ambiguous risks (Klinke and Renn, 2012). The framework's comprehensive, multi-disciplinary and multi-stakeholder approach also helps in understanding, analysing, and managing risk issues through outlining, supporting, and enhancing existing risk governance structures and processes (Florin, 2013). The Framework (see Supplementary A) includes**:**

- **Four interlinked elements (Figure 1):** Pre-assessment (identifying and framing risk issues); Appraisal (developing and synthesising knowledge for decision making, identifying options for management; Characterisation and evaluation (making judgements about the risk and needs to manage it); and Management (deciding and implementing risk management options).

- **Three cross-cutting aspects:** stakeholder engagement, risk communication, and contextual understanding (accounting fully for the societal context of the risk management decisions). These aspects are crucial for the holistic management of complex risks, and align well with the needs discussed in the previous section.

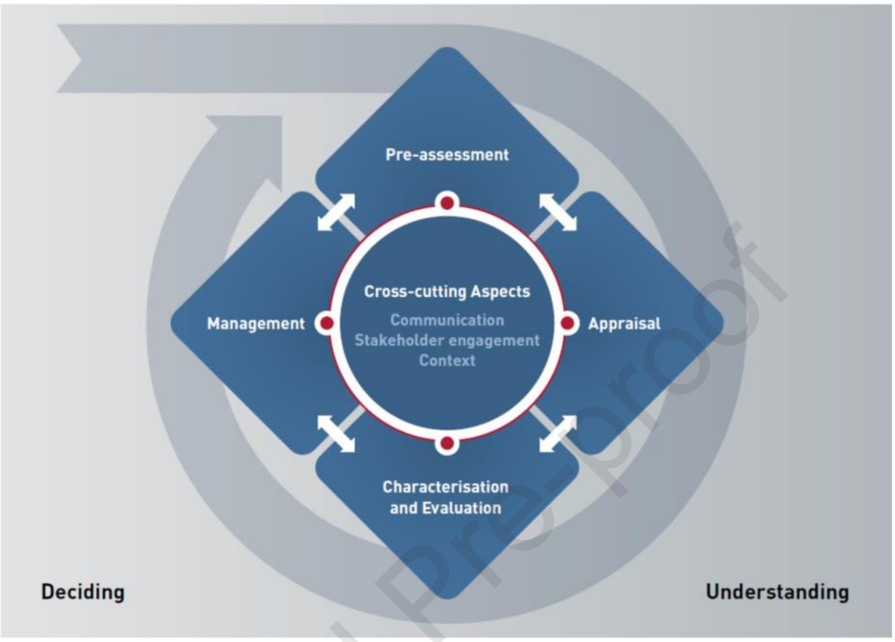

Figure 1. IRGC Risk Governance Framework (IRGC, 2019)

The IRGC Risk Governance Framework serves as both initial guidance for participatory risk governance and as a foundation for developing the tailored Risk-Tandem Framework explained further below. However, given the limitations of the IRGC Risk Governance Framework as a generic device (Boholm, et al., 2012), designed malleable enough to suit a range of risk-related problems from pandemics to accidents, there is a need to complement it with approaches specifically designed to support risk governance in the context of integrating knowledge across disciplines – in this case, across actors involved in DRM and CCA activities.

3.2. SHIELD Model

The SHIELD Model offers a set of guidelines for enhancing risk management capabilities developed through various research and participatory activities in the ESPREssO Project (Lauta et al. 2018). The model (Supplementary B) illustrates the synergies between governance of DRR and CCA, recognising the complexity of systems. It is framed around the Disaster Risk Management Cycle and its associated phases (i.e., response, recovery, prevention, preparedness) but recognises how these phases are dependent on various institutions, policies and structures and the need to support new sets of skills, such as cross-sectoral coordination and public engagement. The guidelines are organised around six themes (Figure 2), highlighting the key issues regarding integration of disciplines (including communication, coordination, capacities, and investments), associated recommendations and case study examples, as well as follow-up questions that form a checklist for implementation. The following list of themes are paraphrased from Lauta et al. (2018): Sharing knowledge; Harmonising capacities*;* Institutionalising coordination; Engaging stakeholders; Leveraging investments; and, Developing communication. The SHIELD model also emphasises the need for data sharing across DRR/CCA responsible institutions and building technical capabilities for risk assessment and management. It was selected to guide and support knowledge integration in key interest areas of the framework, otherwise absent from the IRGC Framework and Risk-Layering.

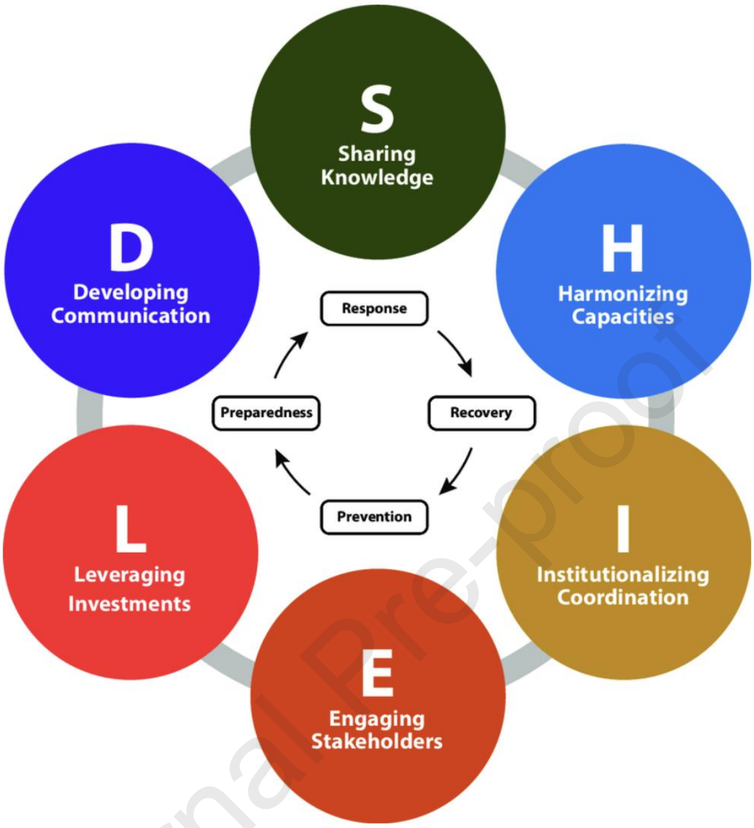

Figure 2. The SHIELD Model, arranged around the four phases of disaster management (Lauta, et al., 2018).

3.3. Risk-Layering

Although helpful in framing the issues and opportunities for managing risks in an integrated manner, including outlining thematic focus areas requiring support or capacity, both aforementioned frameworks still fall short in detailing a suitable approach for identifying and managing systemic risks, and addressing the issues of risk reduction and risk financing in detail. In other words, they do not provide practical support for establishing boundary conditions, nor aid in the process of contextualising risk management interventions. Thus, it is useful to look toward risk-layering which can be used as either a fully probabilistic or a storyline-based device to structure and examine complex risk issues as a tool within any risk governance framework. Risk-Layering (Supplementary C) builds on the quantification and management of inherently random phenomena, for example through approaches that focus on assessing damages and losses corresponding to hazards (Woo, 2012).

In this framework (Figure 3), related frequencies of disaster events are grouped into risk-layers (e.g., low, middle, high) and further related to generic risk instruments (e.g. risk reduction, risk financing and assistance). It should be noted that losses in this context can be tangible or intangible, they can be measured in monetary terms based on market methods or not (Hochrainer-Stigler et al. 2023). Either way, the approach relies on the principle that different risk bearers or stakeholders—e.g., in households, businesses, and the public sector—are experiencing different contexts, and each of them should therefore adopt the most appropriate strategy given their probabilistic hazard exposure, the cost efficiency of the risk-mitigating solutions they can use, and their access to financing instruments. Hence, through risk layering, gaps in individual risk measures as well as most appropriate instruments to increase resilience can be identified, both from a quantitative as well as a governance perspective (Hochrainer-Stigler et al. 2024). It can also reveal possible frictions, overlaps and gaps across different stakeholders' priorities, when arranged around a shared risk issue requiring decisions. It thus becomes immensely valuable as a tool to drive discussions around the complex notions of uncertainty and probability (which are partly entertained within the IRGC [2017:20] approach as well).

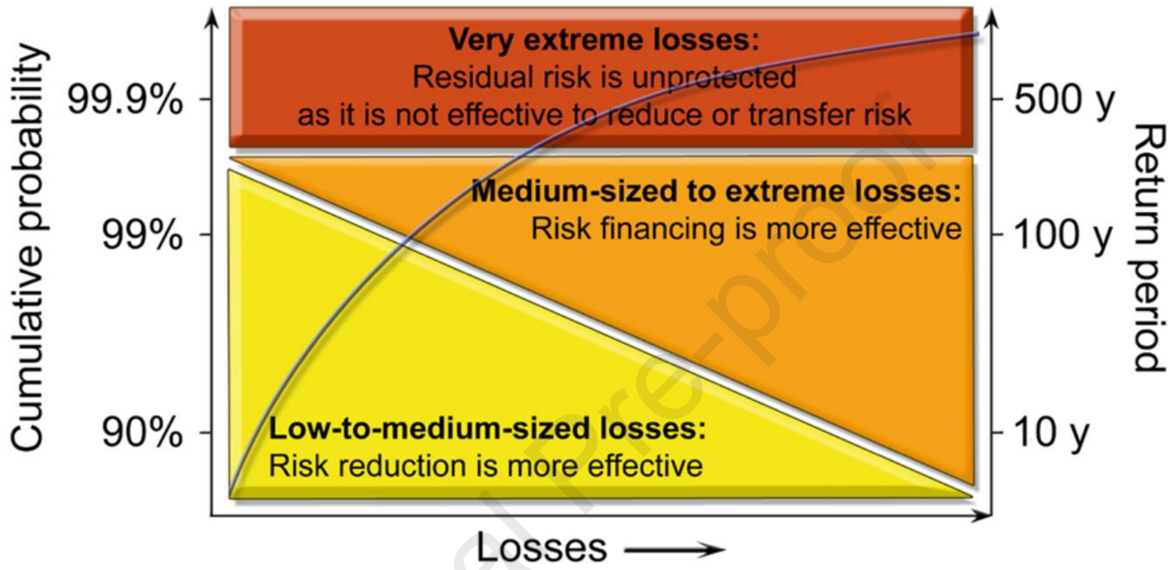

Figure 3. Risk layering approach for risk reduction and financing based on loss distributions (i.e. a cumulative distribution function of losses) (Hochrainer-Stigler, et al., 2020).

3.4. Tandem Framework for transdisciplinary knowledge co-production

Finally, one should consider transdisciplinary engagement and knowledge integration, required to enable collaboration across sectors, disciplines and scales of governance. The frameworks above do not guide such processes, nor provide perspectives on applying their methods in a manner that resists mechanistic, reductionist or expert-led approaches that may generate tunnel vision vis-à-vis complex risk dynamics and socio-economic context. For this purpose, transdisciplinary knowledge co-production is introduced, structured via the application of the Tandem framework (Figure 4 below). As an iterative, practical, and non-prescriptive tool (Supplementary D), built upon the conscious desire to avoid both social and techno-scientific determinism (Jasanoff, 2004) co-production can simultaneously increase the accuracy of knowledge when describing risk issues whilst broadening the scope of available solutions, as well as building trust and bridging actors involved in the process, thus helping to neutralize issues of power and hierarchy. The Tandem itself includes approaches to identifying and addressing users' needs in a proactive and inclusive way that is responsive to local dynamics and power imbalances, in consideration of different knowledge types. Practically, it can incorporate considerations for the informality and complexity of policy and planning processes to understand both horizontal and vertical governance, to address the common lack of coordination and collaboration between and within siloed institutional departments (Daniels, et al., 2020; Bharwani, et al., 2024). The guiding questions seek to examine and co-explore these dynamics, to promote the creation of multi-stakeholder partnerships, platforms and networks in consideration of the issues of power.

These aspects are often overlooked by technical frameworks, but are needed in efforts to support and improve their contextual appropriateness, revise them based on emerging needs, and to better navigate conflicts between existing processes and structures (Verwoerd, et al., 2022).

Initially designed to support the co-production of climate services (Daniels et al., 2020), Tandem seeks to address the gaps between science, policy and action by facilitating and guiding just, iterative, and semi-structured collaboration for knowledge co-production whilst adaptively responding to stakeholder needs and the social context through expert facilitation. By focusing on stakeholder engagement beyond the development and provision of data and information products, it improves the coordination, collaboration, and communication between stakeholders (such as policymakers, planners, researchers, engineers, or modellers), and guides co-working by building relationships and trust (Bharwani et al., 2024). Tandem also provides structure in conceptualising and implementing co-production amidst a vague field of literature – an issue that often limits its application in practice (Bandola-Gill, et al, 2022). The process has been divided into iterative phases (Supplementary D) that can be adapted to local context and needs based on associated guiding questions. These will be further discussed within the next section, in relation to the proposed Risk-Tandem framework.

The acknowledged benefits of knowledge co-production in relation to the other frameworks are also worth reiterating here. For instance, if utilised to co-produce knowledge regarding systemic risk through the mapping of interdependencies, layers, networks or actors within a system and its subsystems, it may produce more contextually accurate risk pictures by integrating 'non-traditional' or competing ways of knowing (Hochrainer-Stigler, et al., 2024). Using the language of systemic risk management, co-production can help to bridge the 'data-policy gap' (Sillmann, et al., 2022:20) by integrating the multiple languages and perspectives of actors to mitigate the fundamental differences in understanding, data collection methods, datasets and information sources used in describing risk. This need is well-aligned with the 'usability gap' discussed in the context of climate services (Lemos, et al., 2012), which explains how useful climate information often goes unused since it is either not understood or does not match the needs of its users. Knowledge co-production can thus be used to patch data-policy and usability gaps by bridging participants and their knowledge systems together in a purposefully designed transdisciplinary knowledge integration process supporting interoperability, collaboration, and communication (Daniels, et al., 2020). Co-production under Risk-Tandem represents a mode of research seeking to create a more inclusive, socially robust and deliberative approach seeking to respond to contextual challenges (Verwoerd, et al., 2022; Nordström, et al., 2020), structured via the application of the Tandem framework.

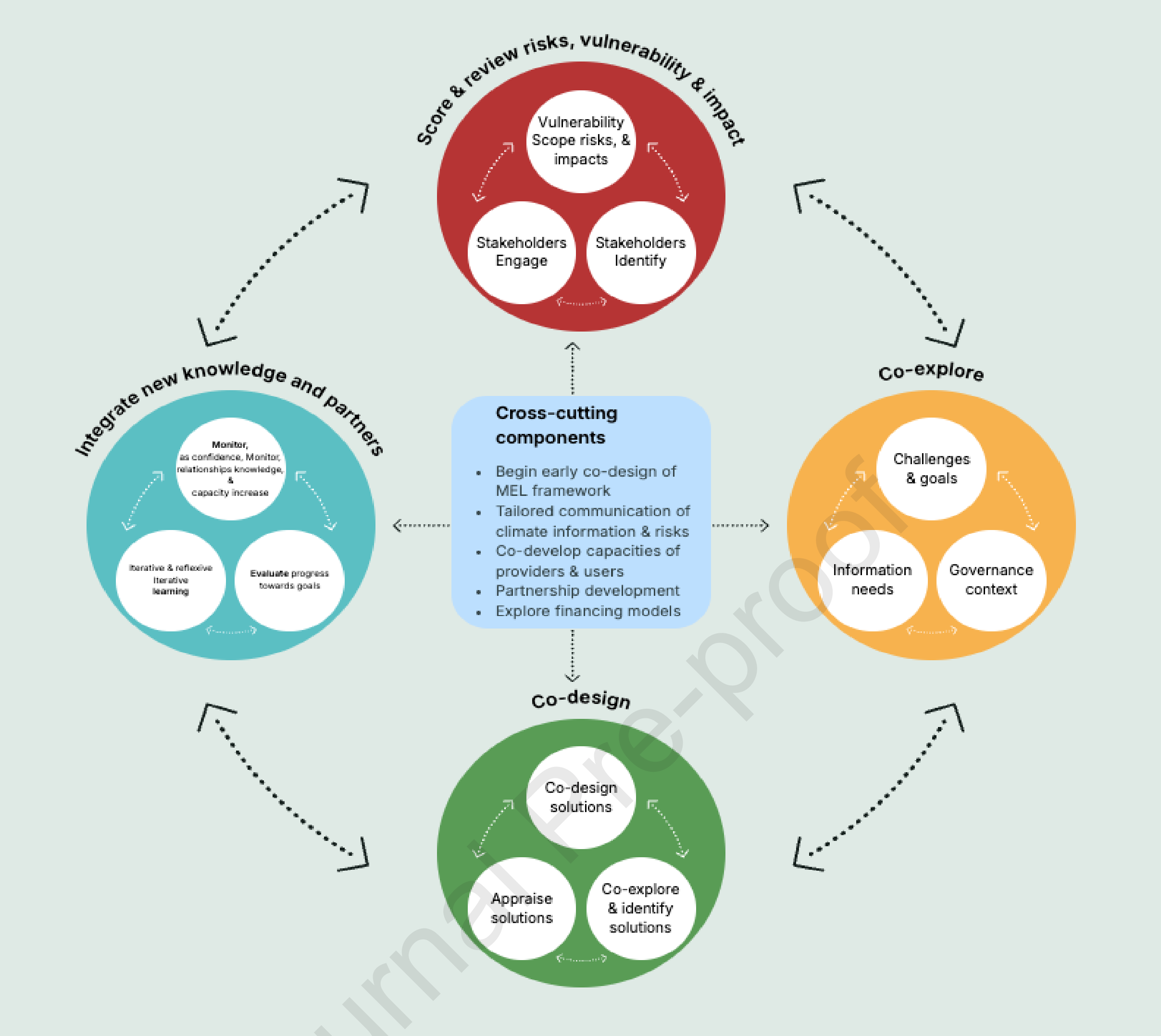

Figure 4. Tandem Framework for transdisciplinary knowledge co-production (Bharwani, et al., 2024)

4. The Risk-Tandem Framework

Integrating key aspects of these frameworks, the conceptual Risk-Tandem Framework establishes a comprehensive approach to address complex risk challenges, based on and informed by existing capacities, governance structures, and processes. The frameworks selected share similarities, synergies, and have the potential to fill gaps that using each alone may result in. By adapting and incorporating components from each, we propose ways forward that can simultaneously aid in identifying and outlining complex risk issues, determining entry points for their assessment and management, as well as supporting and exploring governance settings and mechanisms to promote the practical operationalisation and institutionalisation of these ambitions. In addition, to move beyond an expert-led, top-down, and product-based mechanism that rarely aligns well with real-world challenges.

At its core, the Risk-Tandem builds upon transdisciplinary and participatory governance, seeking to engage researchers, modellers, decision-makers, and practitioners to integrate disciplines, theory, and practical knowledge regarding risk governance context through knowledge co-production. As such, it goes beyond stakeholder engagement, and the range of definitions for transdisciplinary research that already emphasize complexity, cross-scale knowledge integration and unity of knowledge, participatory approaches, and the linking of theoretical and case-specific knowledges for solving complex problems (see Lawrence, et al., 2022). Indeed, co-production will be leveraged to promote the examination of relationships and institutions, co-exploration of the research/project context, and the leveraging of interactive, creative methodologies that seek to promote non-hierarchical collaboration (Norström, et al., 2024; Daniels, et al., 2020). Although complimentary (and sometimes considered within literature on transdisciplinary research), co-production has been selected here to emphasize the relationships underpinning research, and to reorient the process of research away from programming led and defined by scientists alone.

4.1. Overlapping aspects and connectivity between frameworks

Acknowledging the IRGC Risk Governance Framework's core commitments to communication, stakeholder engagement and context, the Tandem Framework is introduced as a process to mainstream the principles of co-production in a structured manner within all IRGC phases from risk pre-assessment to their management. In other words, Tandem is used to apply 'traditional' risk governance approaches (including problem-framing methods such as risk-layering and multi-risk methodologies) with a commitment to non-hierarchical and non-structured transdisciplinary collaboration that encourages engagement, innovation, and commitment to the local risk governance context. In addition, the logical synergies between these two frameworks are leveraged to maintain internal coherence. For example, the process of scoping, identifying relevant stakeholders and co-exploring the (risk) context align well with the phases of 'pre-assessment' and 'appraisal', seeking to frame the problem and characterize risks, respectively. By leveraging these (with a focus on elaborating interconnectedness of risks and vulnerability issues), the outputs are more likely to produce contextually accurate risk information, produced with and by stakeholders. It is also important to build on available data and knowledge to avoid replication of past efforts or redundancy of resources (Bharwani et al., 2024).

Similarly, it is possible to align the Tandem stages of co-exploration with the IRGC phases of characterisation and management, comprising the outlining of risk reduction options, judging the tolerability or acceptability of the selected measures, and option identification and assessments. These are also flexible enough to accommodate contextual priorities, as determined by the participants throughout the co-production process. For management, it is also useful to leverage some Tandem steps in efforts to integrate knowledge, distilling relevant information and data, and making it accessible to stakeholders which is central for supporting the implementation of selected risk management solutions.

To help set focus and objectives, the Risk-Layering method can be used either as a probabilistic representation of hazards identified, or as a storyline-based structuring mechanism, in efforts to clarify and maintain the momentum of co-production toward selected challenges and ambition vis-à-vis expected risk probabilities, available finances, and feasibility. While originally developed for the quantitative assessment and management of risks (see section 3.3) within the Risk-Tandem Framework, it is expanded to be applied in all phases as a structuring device especially between the quantitative modelling efforts to assess, measure and model risks (Pflug and Römisch 2005) and practical risk governance aspects as well as information needs (Schweizer and Juhola, 2024; Schweizer and Renn, 2019). This is achieved through the suggested categorization of loss distributions and risk management options into the different risk-layers (Figure 3), that should help to reduce complexity (e.g. by selection of which risk-layers are considered important, IRGC Framework), enhance co-production (e.g. by identifying risk-layers across scales and actors, Tandem Framework) as well as integration and coordination (e.g. aligning risk-layers for determining what risks should be assessed and managed, SHIELD model, see the discussion below).

The framework will then be aligned with the SHIELD Model, which provides thematic focus areas and capabilities to guide the integration of DRR and CCA across the four different phases of the DRM cycle from response to recovery, prevention, and preparedness. It also provides practical guidance on issues such as mapping the field of relevant actors, leveraging cross-sectoral investments, balancing national and local scales, exploring coordination mandates, mapping of capacities, and so on – methods that are otherwise absent from the IRGC Framework. Taken together, these approaches can thus form a foundation for managing complex and systemic risks, beginning from the principles of co-production, expanding towards risk governance and multi-level collaboration, fit for the European context. Figure 5 visualizes how the Framework, approaches and processes – IRGC Risk Governance Framework, Tandem, Risk-Layering and SHIELD – connect and complement each other, with stakeholder engagement and co-production as the common thread helping to connect them all.

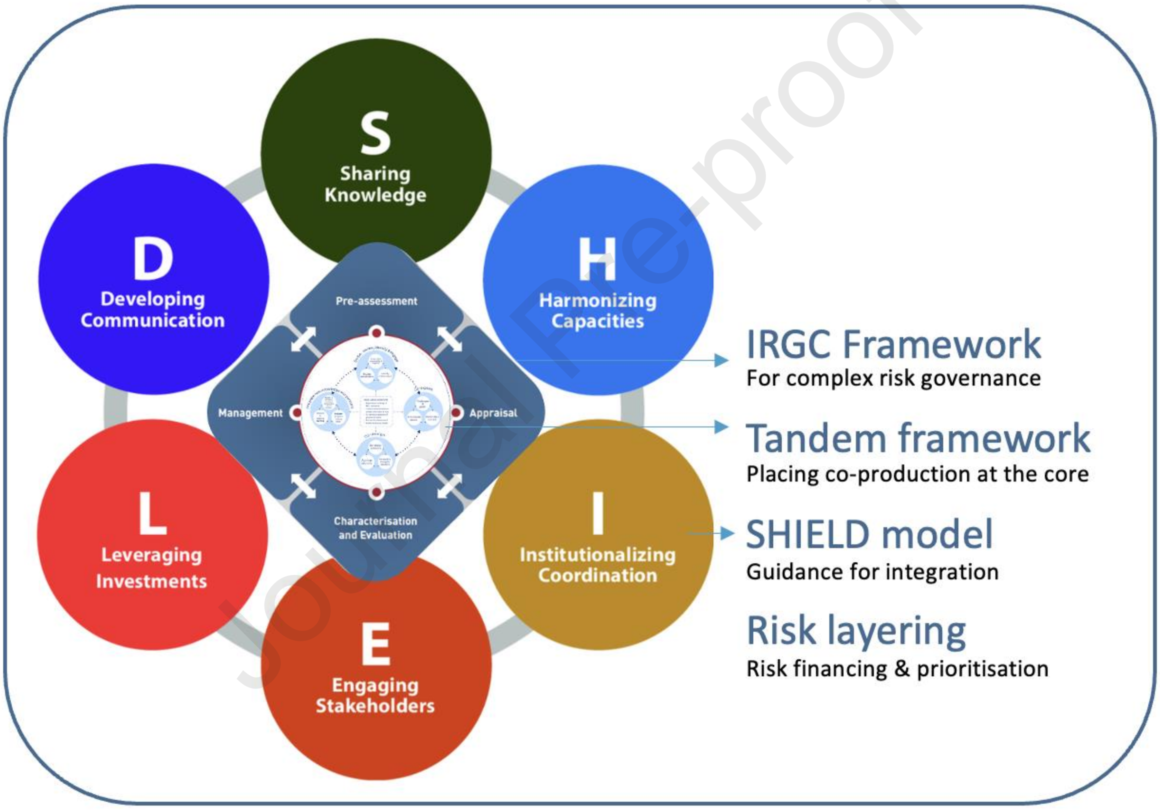

Figure 5. The overlay of existing frameworks and their connections – IRGC, SHIELD, Tandem and Risk-Layering

4.2. An iterative framework for risk governance and knowledge co-production

By bridging gaps and existing knowledges, the Risk-Tandem Framework harmonizes existing methodologies in a more concise and approachable manner, with an emphasis on aims and challenges regarding the interoperability of data, knowledge, communication, resources, and governance systems at different levels. It comprises two main components as represented in Figure 6. Stakeholder engagement is placed at the centre considering the connection between the SHIELD Model theme on engaging stakeholders, the IRGC Risk Governance Framework's focus on stakeholder engagement and Tandem Step 1 on scoping.

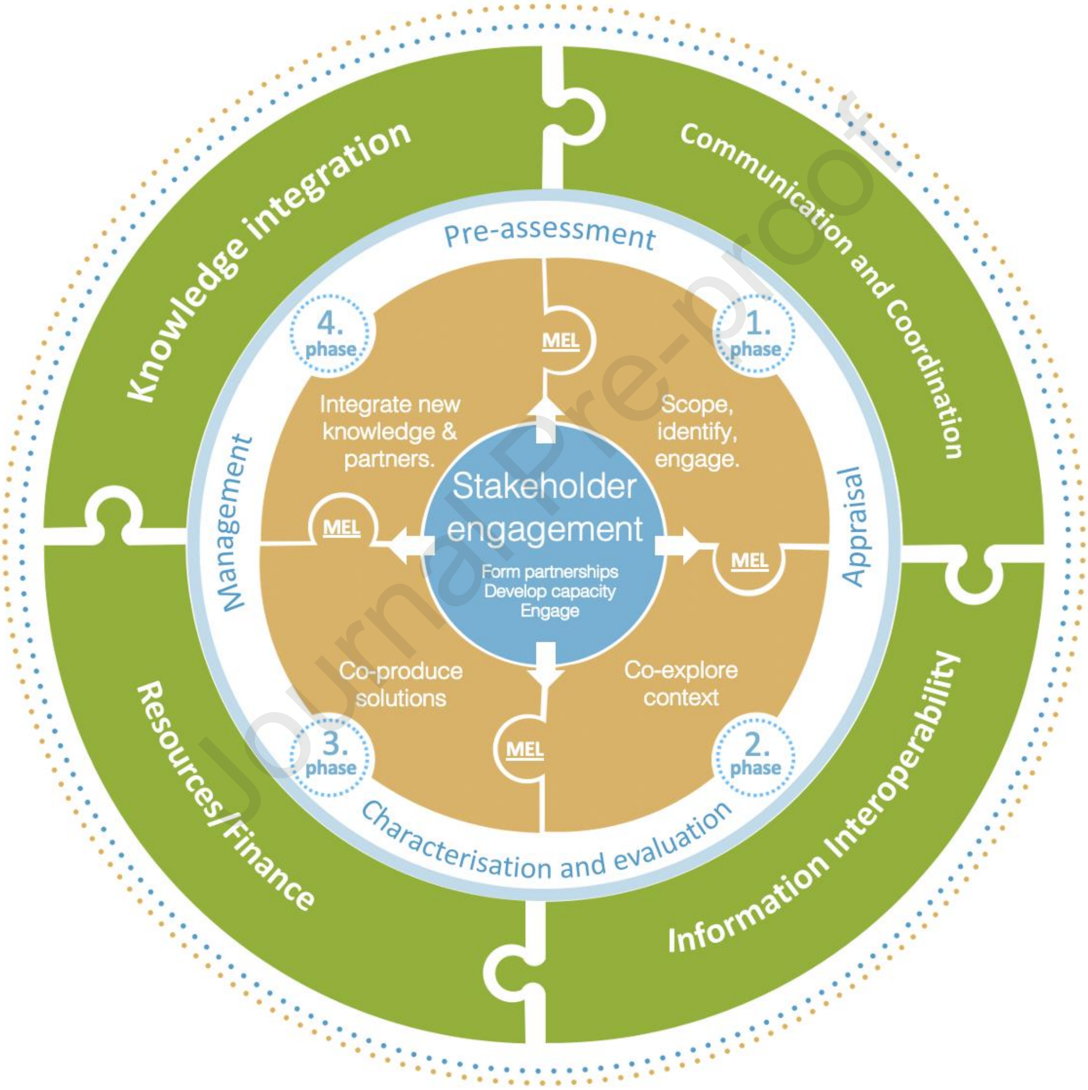

Figure 6. Risk-Tandem Framework

The orange puzzle pieces show the iterative progression of the Tandem process, surrounded by the phases of the IRGC Risk Governance Framework which will embed Risk-Layering and the general categorisation scheme of frequent, infrequent, and catastrophic risks as part of the analysis and co-production process. In the outer green circle, some of the SHIELD themes supporting the integration of DRM and CCA have been restructured to better align with the Risk-Tandem Framework, but its principles and guiding questions will continue to apply. The framework (and associated tools, under development at the time of writing) can identify the key entry points for embedding and sustaining the outputs and solutions generated through the knowledge co-production process and into practice or policy. This can relate to improving risk governance and knowledge co-production through improved communication and coordination, model/data/information interoperability, financing and resources distribution or their mobilization, and developing or sustaining institutional capacity and skills for DRM and CCA.

Importantly, Risk-Tandem Framework is designed to be applied by a range of actors through an iterative process that supports local ownership and enables the co-exploration of contextual risk governance challenges. It is evolving based on previous work and practical lessons (with associated tools and methodologies currently under testing and development), which therefore increase the capacity and confidence of actors by involving them in the process. As such, the framework contributes to incremental change through capacity development, engagement and learning over time (integrating Monitoring, Evaluation and Learning (MEL) throughout the process).

4.3. Phases of application

Application of the Risk-Tandem Framework begins with Real-World Labs, referring to four different European case study sites in which it is implemented and refined with local risk governance stakeholders (through workshops, capacity development, research, and continuous consultations). For the specific purposes of the DIRECTED project, the phases have been separated into four years based on the Tandem (however, different timelines can be established depending on the context, challenges, and project purpose) with distinct goals and objectives, all leading toward institutionalisation and up-scaling of the processes as introduced and refined during the project phases. Importantly, and since the Risk-Tandem Framework is designed to be locally implemented within the DIRECTED Real-World Labs, much of the timeline relies on capacity development for that supports the ability of Real-World Lab hosts to enable co-production in their risk governance contexts through workshops and other stakeholder engagement and apply risk governance methods and approaches as introduced by partners in a co-productive manner. A generic timeline is presented in figure 7.

Phase 1 (Foundation) involves scoping, identification of relevant stakeholders and mapping, and early workshop engagement toward transdisciplinary Real-World Labs, structured following Tandem, IRGC Framework and SHIELD guidance. In detail, this step seeks to outline relevant challenges in terms of data usability, interoperability, and practical risk management issues (pre-assessment) that may provide opportunities to promote the integration of risk reduction and climate change adaptation. Related to this, the framework provides guidance for identifying and engaging relevant stakeholders in a transdisciplinary and co-productive mode, including methods for stakeholder identification and mapping to build Labs that mirror their real-world context, and capacity development for enabling knowledge co-production and the examination of risks from a systems perspective. This is complemented by supporting research (including scoping interviews) and review of secondary literature to begin the process of establishing “baselines” in terms of risk governance and knowledge co-production (upon which further interventions can be developed).

Phase 2 (Growth) seeks to promote the deeper co-exploration of issues identified during scoping, examining the risk governance context, relevant hazards and climate risks, and data/user needs, in efforts to identify windows of opportunity for the co-design of governance solutions. Introduced methods will build on the SHIELD Model, IRGC Framework, and other tools promoting collaboration and interactivity. Co-exploration seeks to unpack issues such as communication, coordination, risk management, knowledge integration and financing through transdisciplinary collaboration, going beyond the status quo. The capacities for RWL hosts to enable knowledge co-production will be assessed and developed, and creative methodologies for unpacking contextual risk issues will be introduced through Risk-Tandem workshops. This involves the appraisal and temporal categorisation of risks with the support of Risk-Layering, and the development of storylines to address uncertainty associated with climate change. The storylines, referring to description of a historical or virtual multi-hazard event and its anticipated outcomes) are also used to structure gained knowledges into accessible and shareable formats to support planning, helping local/regional partners to identify priorities for specific user groups (e.g. emergency management authorities, municipalities, water boards, local responders) for shared opportunities for holistic risk governance. Continued research will expand the risk governance baselines to support co-designed MEL and Theories of Change (further discussed in section below).

Phase 3 (Learn) aims toward action and the co-design of risk governance “solutions”, which refers to tools, methods, processes, platforms, and technological innovation that can support holistic risk management. Wholly dependent on the encountered problems and stakeholders’ priorities, this phase of the Risk-Tandem Tandem gears toward enabling co-design, and co-produces innovative guidance for their management across the disaster management cycle. This phase will be supported by Risk-Layering to prioritise solutions, and complemented by evaluation that seeks to assess their economic, environmental, and human feasibility (as well as impact). Here, the production of tailored risk information services can begin, following the co-exploration of user needs, and the capacity development will gear toward supporting co-design and implementation.

Phase 4 (Sustain) will aim to up-scale lessons learned, institutionalize knowledge co-production approaches, and sustain knowledge exchange across actors involved in DRM, CCA and risk governance. This involves capturing the learnings from the application of the Risk-Tandem Framework as a whole and using these experiences to cultivate a knowledge base and tested tools for integrating co-production in risk governance contexts. For achieving this, a robust approach to MEL is necessary throughout the process, developed jointly with partners and local stakeholders, to identify indicators that can capture incremental changes and how they have produced benefits for those involved.

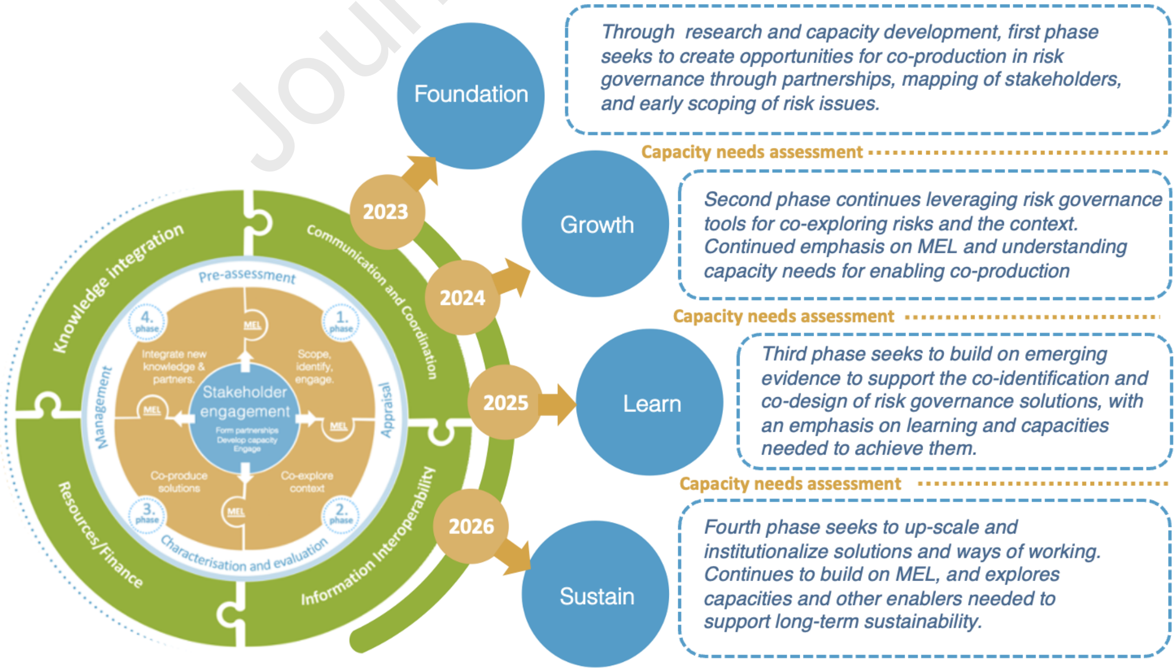

Figure 7. Timeline for applying Risk-Tandem Framework

As indicated, the framework is now being applied, tested, and refined for different DRM/ CCA integration challenges across four multi-stakeholder Real-World Labs (RWL), including regions in Denmark, Germany, Italy as well as the Danube region (Figure 8). Thus far (between 2023 and 2024), the Risk-Tandem Framework phases applied in the Real-World Labs have been the Foundation Phase and the Growth Phase which focused on stakeholder identification, mapping, and co-exploration of the risk and governance contexts building on knowledge co-production and pre-assessment methodologies, as well as setting priorities for action, learning and capacity development.

Insights from the Foundation Phase demonstrated that the Risk-Tandem Framework helped Real-World Lab hosts to guide the initial set-up of their labs to involve multiple diverse stakeholders across levels and sectors of government, especially municipalities, civil protection and sectoral actors (e.g. environment, water boards), while recognising the challenge to include citizens and volunteers. Guiding questions on risk governance were provided to the Real-World Lab hosts, who used this to develop tailored questionnaires or workshop activities for their stakeholders. Real-World Lab hosts were able to engage with their stakeholders around the governance, communication and data/modelling capacities and needs for integration or interoperability to capture synergies across institutions. The capacity development activities related to knowledge co-production for Real-World Lab hosts included a guidance on interactive workshop exercises, an online training module on complex risks, in-person training on use of World Cafes, serious games, and creative co-exploration exercises, as well as workshop preparation and debriefing calls to ensure a supportive and reflexive approach to respond to their needs.

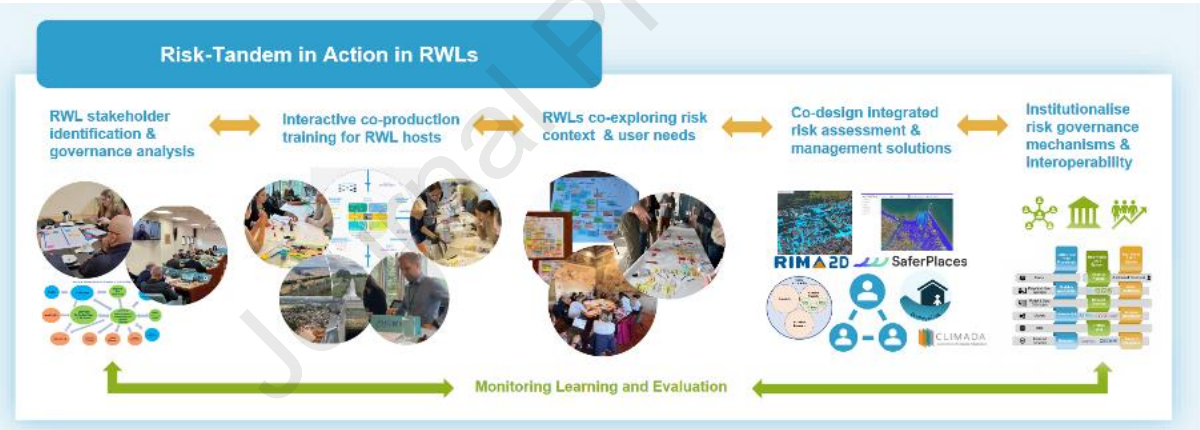

Figure 8. Application of the Risk-Tandem Framework in the RWLs

Research from partners supports the implementation and revision of the framework, including by the mapping of capacities for knowledge co-production (to guarantee locally led implementation), and to examine issues of the Real-World Lab risk governance, in alignment with the thematic interest areas of the framework (and local priorities). These build on evidence such as interviews with stakeholders, workshop outcome reports, and scoping consultations. Research is also conducted under each phase to identify and unpack user needs across Labs, and to build on case studies/past disaster events as an opportunity to respond to lessons learned based on past experiences. Under scoping and co-exploration, this involves (1) stakeholder analysis and objective framing; (2) examination of the institutional, multi-level governance and policy setting, including the dimensions of accountability; (3) risk communication and coordination; (4) risk knowledge and management; as well as (5) critical enablers and factors hindering the integration for DRR and CCA. Alongside risk governance methods, research approaches and guidance (such as methods for identifying stakeholders) will be refined and introduced in later iterations of the framework to promote practical uptake, beyond academic reflections that provide reasoning for its design.

4.4. Approach to monitoring, evaluation, and learning

Implementation of the Risk-Tandem Framework is a continuous process of reflexive evaluation and learning to effectively manage risks, and to monitor impact of the process. Given its locally led nature, the MEL and associated indicators are therefore not static, but instead co-designed for each RWL. Building upon components of the IRGC Risk Governance Framework and the SHIELD Model, the Risk-Tandem Framework will be evaluated in five primary dimensions, with a specific set of outcome indicators that are to be developed with stakeholders.

The first overarching MEL category seeks to assess institutions, and the formal/informal rules that underpin decision-making, to ascertain whether change has been achieved in decision-making structures following the implementation of the Risk Tandem Framework. The second aspect will assess developed risk governance strategies building on the IRGC Risk Governance Framework (IRGC, 2007), in efforts to determine the (human, economic, and environmental) feasibility of proposed solutions, and; the inclusivity and equity of solutions. Third category for MEL builds on knowledge integration and the SHIELD model, to assess the synergies cultivated as a part of the process. These include indicators on goals and aims, and the synergies (or trade-offs) emerging from the efforts that suggest change. Participation is also central to knowledge integration, and the inclusion of different knowledges involved. The fourth MEL dimension seeks to assess the boundary conditions for risk management by expanding on the Risk-Layering approach, to determine whether proposed solutions (whether technical, or relating to communication, coordination, or financing) align with the available risk information, and whether information has been used effectively vis-à-vis local risk perceptions and capabilities (as an effectiveness indicator for the Risk-Tandem Framework). This requires further sub-indicators that will be contextualized in each Real-World Lab.

Finally, and given that the Risk-Tandem Framework seeks to enable, improve, and learn from knowledge co-production processes, the fifth MEL dimension has been established for monitoring the quality of the co-production process and capacity development. Although contributing to impact and outcomes, this strand of MEL will measure and evaluate the contextual accuracy of the process; stakeholder engagement and its plurality, including in the dimensions of trust and new relationships; interactive methods and the difference they have made in terms of non-hierarchical collaboration, and; how the framework contributed to creation of shared goals and priorities between actors. This work builds further on the Tandem Framework (Daniels, et al., 2020) and the work of Norström et al. (2021) on the “good principles” knowledge co-production. This combined MEL will be further refined based on stakeholders’ inputs and published separately, due to the vast scale and detail required for discussing the approach more thoroughly.

Overall, MEL will contribute to the revision and testing of Risk-Tandem methods and tools that will evidence its impacts based on lessons learned, and promote its replicability in other contexts.

5. Discussion

While our suggested approach has several advantages it should be noted first that there are numerous practical and theoretical limitations affecting the operationalization of the framework as presented here. To begin with, facilitating knowledge co-production and stakeholder engagement is a time-consuming process, its application in science-policy contexts is not self-evident (Verwoerd, et al., 2022) or necessarily valued in the same way, and it suffers from different cultures of evaluation between the two domains (Cvitanovic et al., 2015). Often, approaches suffer from the conflation of meanings and practices from different collaborative research traditions across disciplines (Williams, et al., 2020). In addition, outcomes of the process seldom align with theoretical expectations (Jagannathan, et al., 2020; Flinders, et al., 2016), and may require constant revising as theory continues to engage with needs (Verwoerd, et al., 2022). In the case of our Real-World Labs, we have continuously engaged in discussions regarding expectations and feasibility, in efforts to better align theory with practice of risk governance. However, this affects the conceptual ambition as presented in the Risk-Tandem Framework; it cannot be applied in a homogenous manner, but instead is tailored and adapted to support the needs of local stakeholders. This will reshape the conceptualisation of the Risk-Tandem Framework, and by the end of the DIRECTED project, will be compiled to provide practical and real-world guidance for advancing integrated risk management in complex risk contexts.

The issue of context also affects facilitating change in governance systems (often underestimated in theoretical approaches). Indeed, the efforts to enable knowledge co-production in any setting is often shaped by the contextual limits, normative assumptions, underpinning values, and institutional structures that affect how well the idea of co-production can evolve within real-world settings (Verwoerd, et al., 2022). In other words, the "ideal" approach may fall short in achieving its promises when facing the scale of contextual issues that may, in some cases, actively work against them (Turnhout, et al., 2020; van der Hel, 2016). As such, it is essential that knowledge co-production incorporates thorough analysis of the institutional context (including beliefs, values, issues of gender, and unequal power relations between stakeholders). These are currently being developed and applied by project partners to generate information "behind the scenes" of the Risk-Tandem Framework.

There are also practical limitations that affect the operationalization of the framework. To date, despite some exceptions (e.g. Carter et al., 2019; Daniels et al., 2020; Bharwani et al., 2024) the application of co-production suffers from limited practical guidance and empirical evidence (Jagannathan, et al., 2020; Miller and Wyborn, 2020). Further, even less evidence is available regarding the mainstreaming of knowledge co-production in risk governance processes. Therefore, our approach continues to evolve through practical application of a concept as suggested here, alongside supplementary material developed to support its implementation. In addition, since the process is locally led (implemented via a Training of Trainers approach), actors and researchers involved have limited spheres of influence for operationalizing co-production in the wider multi-stakeholder context.

6. Conclusion

This paper began from the complex and multifaceted landscape of contemporary risks, with an emphasis on the interconnected and systemic nature of all environmental risks. We emphasized how the challenges of disjointed risk governance contexts, siloed disciplines and inaccessible data may hinder the ability of actors to coordinate their actions and knowledge repositories around shared priorities. We have outlined some theoretical and practical issues underpinning these, including 1) differing priorities across scales of governance; 2) lack of integration between disaster and climate spaces, practice and research; 3) diverse and competing ways of knowing across scales and disciplines; 4) data usability and interoperability, and; 5) lack of practical methods for addressing these problems in real-world settings. Consequently, we argued that siloed or overly technical approaches are not enough to tackle these complex challenges – holistic and comprehensive ones are needed instead.

As a proposed solution, we presented the Risk Tandem Framework (combining systems thinking, knowledge co-production and tools of risk governance), which can offer a solution for thinking about risk issues and applying existing tools in new ways, led by priorities of local stakeholders. In particular, we have suggested that knowledge co-production processes are essential for generating a deeper understanding of issues at hand, cultivating new relationships, and sustaining existing collaborations for their management in practice. On the other hand, these collaborations and knowledge integration processes require technical approaches ranging from understanding probabilities and event distributions to prioritizing available options based on well-informed risk assessments that all involved stakeholders can agree upon. To achieve balance between integrated risk management and adaptation, we thus combined the IRGC Risk Governance framework, SHIELD Model, Risk-Layering and Tandem framework for co-production.

These, however, cannot offer a panacea. As pointed out in our limitations, the implementation of Risk-Tandem through a Real-World Lab setting is a resource intensive task, requiring complementary research, monitoring, evaluation and learning approaches, as well as the constant revising of the Framework's activities to respond to emerging needs – all the while balancing its implementation between theory and practice as it is primarily implemented by local stakeholders. Therefore, our suggestions are not to be considered as a final "product", but rather a theory-informed framework and an approach which we suggest can cultivate new information and new ways of thinking around shared challenges through knowledge co-production in risk governance contexts. Therefore, its outputs are heterogenous and context dependent, and cannot be fully predicted here. Through this engagement, however, the framework will be further developed to support practical implementation, including guidance and activities. The ultimate aim is to provide an iterative, reflexive and process-based approach to transdisciplinary co-production in risk governance contexts, versatile enough to be used by stakeholders, practitioners and decision makers at various scales navigating complex risk governance challenges.

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• Supplementary A: IRGC Risk Governance Framework

The IRGC Framework informs and guides holistic approach to risk governance, with consideration for interconnected and systemic risks (IRGC, 2017). Importantly, it recognises the centrality of multidisciplinary and multi-stakeholder approach to risk management, with normative principles that promote transparency, effectiveness, efficiency, accountability, strategic focus, sustainability, equity and fairness, law, and the feasibility of the proposed interventions in their political, legal and ethical dimensions (ibid). Inclusive and open communication are placed at its core, to ensure that stakeholders make informed choices about risks, and that they remain able to balance evidence alongside their own interests, concerns, and resources (figure 9). As such, societal context is also emphasized, in consideration of the needs of those involved.

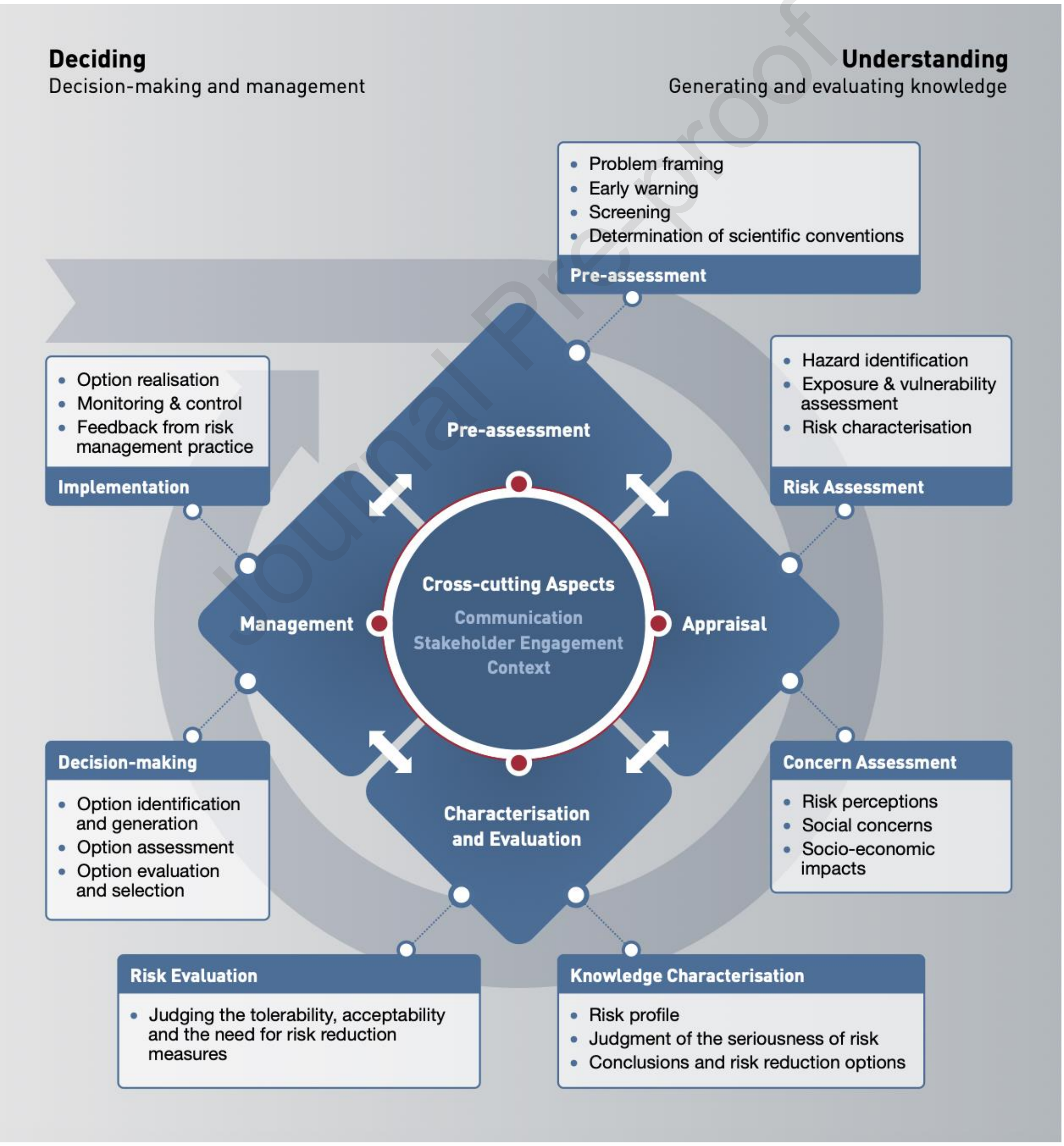

Figure 9. The IRGC Risk Governance framework (IRGC, 2017).

Figure 9. outlines the IRGC approach to early identification and handling of risks, comprising four interlinked elements and their cross-cutting aspects. Based on IRGC's guidance (2017) these include:

Pre-assessment, clarifying questions and perspectives on risks, aids in defining the issues, and forms baselines on their management. Some of the questions include:

- What are the risks and opportunities to be addressed?
- Who are stakeholders relevant to framing and managing the problem?
- What are the socio-political or environmental dimensions of risk?
- How are the boundaries of the evaluation defined?
- What are the current legal and regulatory systems, and how do they affect the problem?
- What are the organisational capabilities of relevant actors involved?

Appraisal, developing and synthesising knowledge regarding risk, and what are the options for preventing, mitigating, adapting to, or sharing it (or, whether or not it should be taken at all). This stage goes beyond conventional risk assessments, comprising both risk assessments and concern assessments. The latter refers to stakeholders' opinions, perceptions and priorities associated with the risk and its perceived consequences. Potential questions for risk assessment include:

- What are the potential damages or adverse effects associated with the risk?
- What are the processes that create risk (or control it)?
- What accident scenarios can occur (probability, severity, etc)?
- Can the risk be quantified, and how reliable are probability estimates?

Questions for concern assessments may include:

- What are the stakeholders' opinions, values and concerns about the risk?
- Are there biases that affect risk perception?
- What is the social response to the risk? How would people react?
- Are there constraints affecting the actors' ability to manage risk?
- What role do existing institutions and governance structures play?

Characterisation and evaluation aim at comparing the outcome of risk appraisal with specific criterion, in efforts to determine the acceptability of the risk, and to design interventions. For this purpose, The questions of complexity, uncertainty, and ambiguity are highlighted, in efforts to inform evaluation by stakeholders. Evaluation, however, should be also informed by probabilities, in efforts to help evaluation in the dimensions of acceptability, tolerability and intolerability. Other ey considerations for evaluation include:

- Ethical issues that must be considered
- Societal values and norms that affect tolerability and acceptability
- Commitment of stakeholders to want certain outcomes from risk governance processes
- What are the constraints?
- What is the political or strategic appreciation of the societal, environmental or economic benefits?

Management focuses on the tolerable risks that should be met with adequate risk reduction and management measures. The process involves design and implementation of actions to reduce (prevent, adapt, mitigate), transfer, or retain risks. Key questions include:

- Who are the actors and stakeholders that should be engaged in risk management processes? What are their responsibilities in decision making?
- What management options should be chosen? How are they evaluated and prioritised?
- What are the likely impacts and benefits of risk-reduction options?
- What are the potential trade-offs?
- Is there appropriate support for international/regional cooperation and harmonisation for global systemic risk dynamics?
- What measures are needed to ensure effectiveness of proposed solutions?

Cross-cutting aspects apply to all phases of the framework, adding three that are critical for the success of any risk governance process. These include communication, stakeholder engagement, and the social context. Questions for developing communications include:

- Is there a facilitator in charge of the communication process?
- How can it be organised among stakeholders within organisations?
- How can it be facilitated across multiple disciplines and stakeholders?
- How can communication support two-way sharing information?
- Does communication take risk perception into account?
- What is the role of the media?

To assess how and when engage different stakeholders, and emphasises that both those affected and those managing risk should be involved (incorporating a wide range of perspectives). For this purpose, the framework provides a “stakeholder engagement escalator” (figure 10).

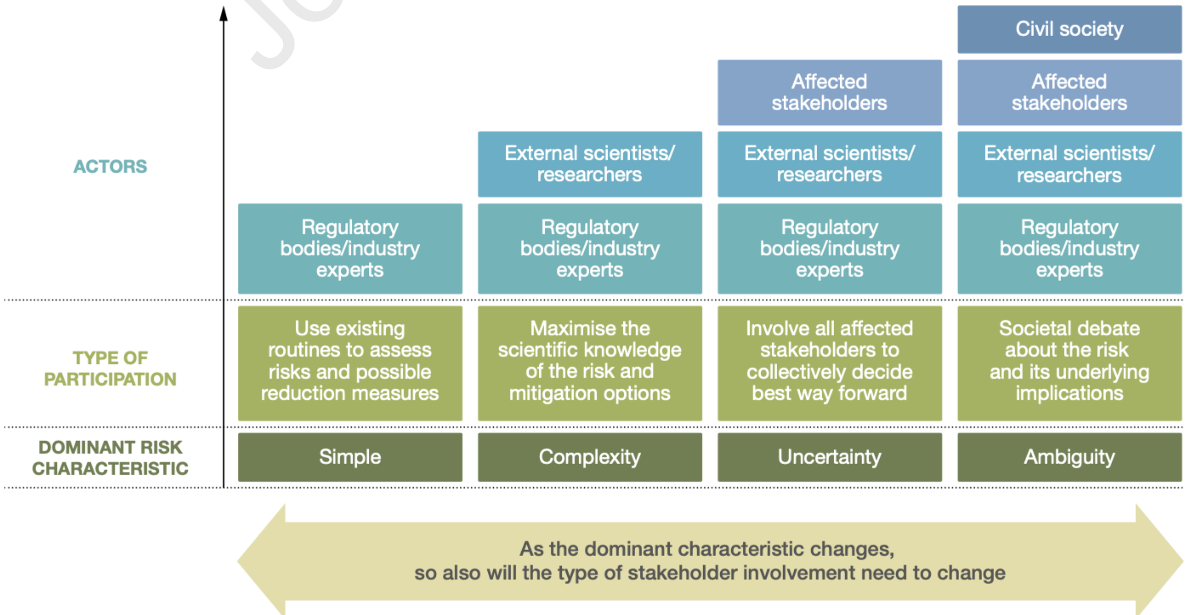

Figure 10. Stakeholder engagement escalator (IRGC, 2017).

Context provides guidance for incorporating elements of the social, institutional, political and economic contexts that affect risk governance processes. Given that they frame risk-related decision-making, and affect the capability of key actors to fulfil their roles and mandate, these elements are central when assessing risks and options for their management (figure 11).

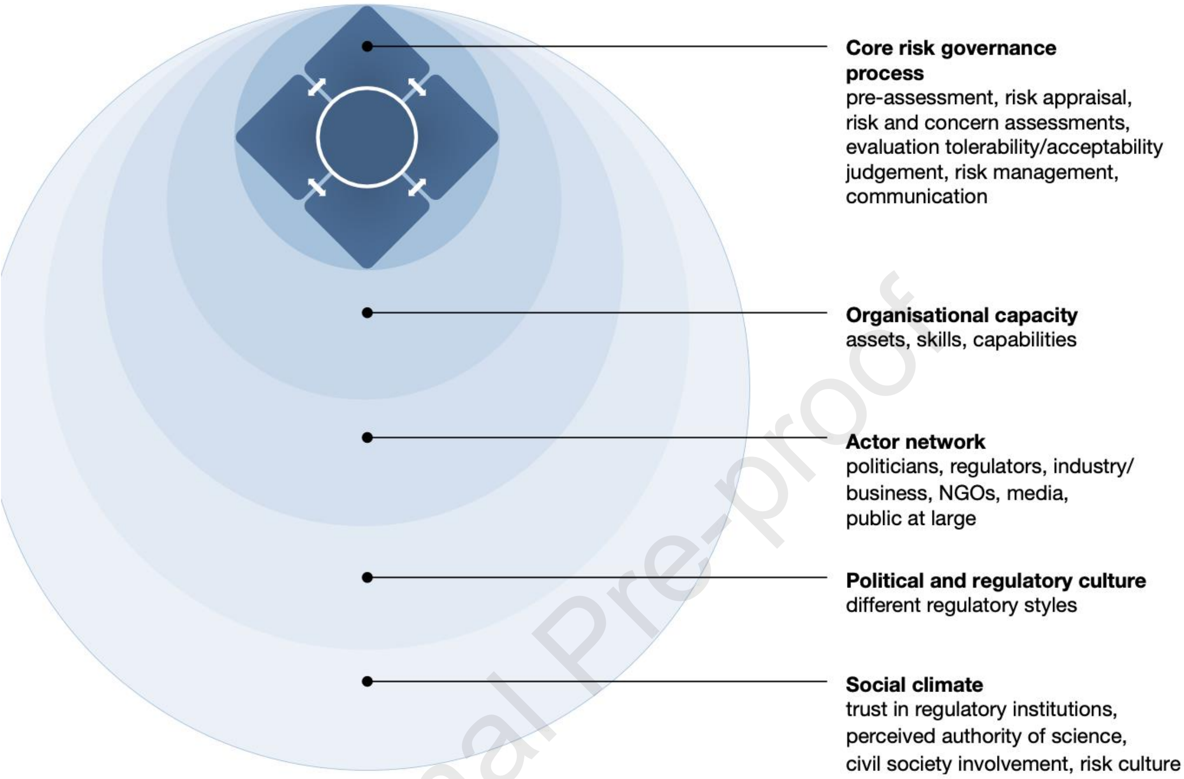

Figure 11. Risk governance in context (IRGC, 2017).

● Supplementary B: SHIELD Model

Developed under the ESPREssO (Enhancing Synergies for Disaster Prevention in the European Union) project, the SHIELD model proposes a guideline for enhancing risk management capabilities (Lauta, et al., 2018). Its primary focus is to integrate climate change adaptation and disaster risk reduction, integrate science and legal issues to enhance capabilities, and to improve national regulations to prepare for transboundary crises. It revolves around the four phases of disaster management (figure 2). Following Lauta, et al., (2018) its components can be summarised as follows (full list of guiding questions not included here):

1. **Sharing knowledge** seeks to key issues affecting communication between DRR and CCA actors, and during the phases of DRM. Guiding questions were developed to respond to is challenges of 1) knowledge transfer between sectors and institutions; 2) Information overload and lack of synergies between existing platforms; 3) Limited data and information access due to issues such as licensing and the value of data; 4) Knowledge siloes that prevents effective communication. Based on these, it provides suggestions for:

   - Mapping and engaging relevant actors, who should give and receive knowledge and information about DRR and CCA
   - Bridging knowledge gaps between science and policy
   - Building diverse networks for knowledge sharing
   - Providing incentives for knowledge sharing
   - Balancing national and local scales to support flows of information.

2. **Harmonizing capacities.** This step seeks to identify and harmonize capacities between actors working within risk governance, in efforts to support collaboration between sectors, disciplines, and levels of governance. Primary identified issues informing suggestions include 1) Lack of skilled employees at different government levels; 2) Changing landscape of risks, vulnerabilities and hazards; 3) Transboundary events, and; 4) Lack of continuity. Suggestions to harmonize capacities include:

   - The mapping of existing capacities that already exist, and can be strengthened
   - Assess and balance capacities to advance the management of risks from a shared starting point
   - Match capacities to risk issues
   - Evaluate and learn from the process, and to improve operations where possible.
   - Creating partnerships to relieve strain on individual stakeholders and organisations (between public and private sector, for instance).

3. **Institutionalising coordination.** This stage seeks to advance coordination between sectors and disciplines toward integrated risk management, and throughout the phases of the DRM cycle. Highlighted challenges include: 1) Professional and legal mandates that limit the ability of actors to coordinate response, recovery and risk reduction or climate change adaptation; 2) limited coordination between levels of governance, and disconnect in between; 3) Limited coordination of tasks between DRR and CCA; and 4) Limited coordination between EU member states. As a recommendation, SHIELD proposes:

   - Clarifying mandates for coordination through a comprehensive stock take

- Acknowledging the need for balance and flexibility, sometimes through informal relationships
- Practicing and exercising roles, including training for emergency response
- Setting up forums for coordination
- Aligning and streamlining priorities among stakeholders
- Building partnerships for transboundary crisis management

4. **Engaging stakeholders** seeks to inform multi-stakeholder engagement, in recognition of the limitations of "traditional" command-and-control approaches. Identified priorities that require addressing include: 1) Lack of clarity regarding relevant stakeholders across levels (who should be involved?); 2) Lack of common understandings regarding risk issues, and competing terminologies; 3) Competing interests that limit the possibility of building shared priorities; 4) Lack of sustained engagement, and; 5) Barriers affecting stakeholder engagement. Suggestions include:

- Clarifying the role of stakeholders, including their motivations and interests
- Creating incentives for stakeholder participation
- Creating online platforms for multi-stakeholder engagement
- Locating mediators and experiment with roles
- Utilizing local stakeholder knowledge for DRR action
- Ensuring sustained commitment

5. **Leveraging investments** is highlighted due to the centrality of funding for response and planning of DRR and CCA. SHIELD identifies key issues that require solutions; 1) Lack of clarity regarding the ownership of risk, and who should pay for its management; 2) Short-term political commitment; 3) Narrow focus on funding for preparedness and response; 4) Damaging investments. Responding to these, the model suggests:

- Increasing the visibility of DRR investments
- Connecting politicians and affected communities
- Innovating existing disaster risk financing structures
- Creating partnerships for DRR investments with the private sector
- Making long-term political agreements
- Identifying overlaps for CCA and DRR

6. **Developing communication** seeks to guide risk management in the information age, in efforts to improve how knowledge is transferred and communicated between actors (and the public). Identified issues include: 1) Lack of risk awareness among the public; 2) Lack of media expertise in public entities; 3) Priorities of the media industry; 4) Social media and big data trends. Suggestions highlighted are:

- Creating multi-media platforms for risk awareness
- Cooperating with media partners
- Strengthening and streamlining early warning platforms
- Innovating risk awareness campaigns
- Bringing risk management into classrooms

● Supplementary C: Risk Layering

As previously indicated, the risk-layer approach was initially developed within insurance applications (Hochrainer-Stigler and Reiter 2021). Already here one can implicitly distinguish between frequent and infrequent events as the primary insurer usually focuses on smaller losses which occur with higher frequencies and transfers more infrequent events with larger corresponding losses to reinsurers. Losses from rare but catastrophic (very extreme) events cannot be managed through insurance and assistance is needed, e.g., the government steps in as an insurer of last resort. Not only risk financing but also risk reduction can be included in such risk-layering approaches with the assumption that risk reduction may be especially useful for tackling frequent risks (Linnerooth-Bayer and Hochrainer-Stigler 2015). The risk layer approach was expanded to include different types of risk management options, especially risk reduction, risk financing and assistance for different layers of risk (Mechler et al. 2014), figure 12.

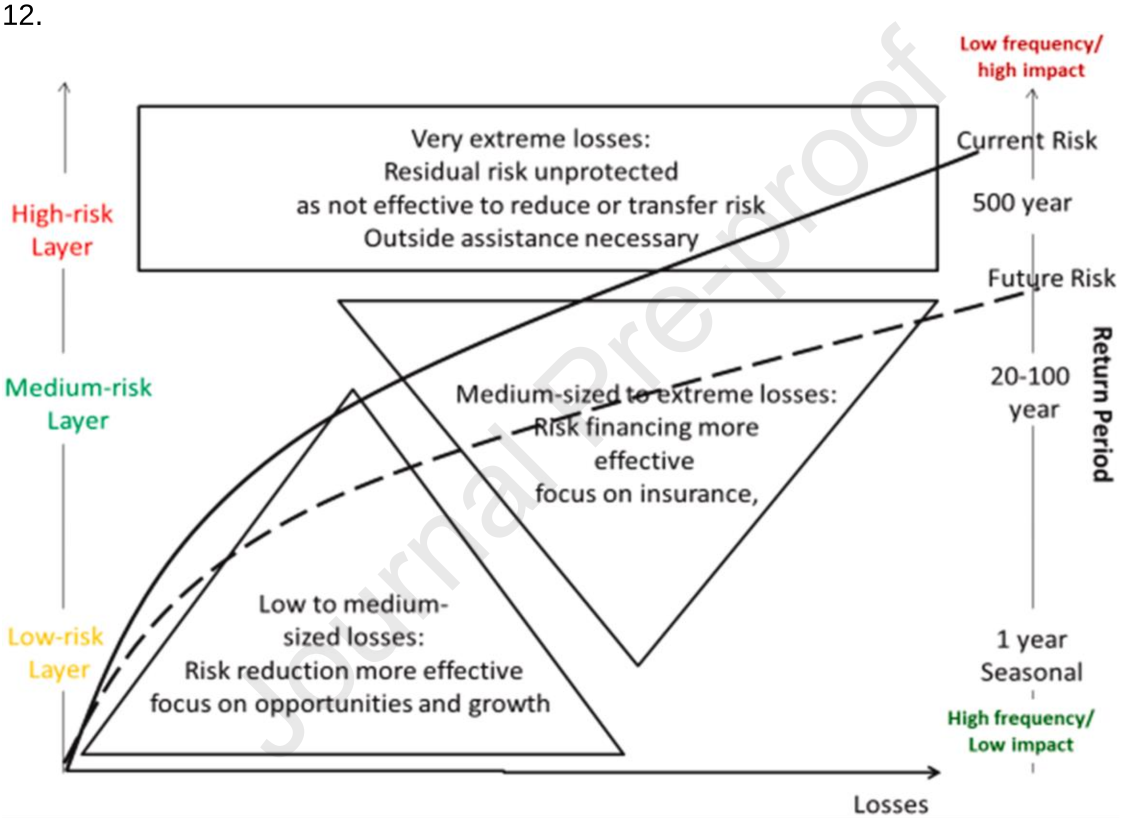

Figure 12. Layered disaster risk management (Hochrainer-Stigler et al., 2021).

For each of these risk layers, different risk metrics may be used to represent such kind of events. For example, for frequent events one may use average losses while for infrequent events one may use Expected Shortfall or Tail measures. Sometimes these events cannot be quantified but are seen by the risk bearer to belong to a given category, both in terms of events/risks as well as instruments to reduce them. Due to the inclusion of assessment and management aspects within risk-layering it can be applied to all the IRGC Risk Governance Framework's steps within the Risk-Tandem Framework and can be related not only to quantitative dimensions (models and data across scales) but also to governance processes and policies (as shown and related to the other circles). It especially also should show possible frictions as well as overlaps and gaps across different stakeholders in the complex system under study. In that regard, the question of how an event cannot be coped with, either due to the lack of risk management measures or due to insufficiency of the resources to cope with, may have effects on other risks of different stakeholders that may be exposed and can be identified therefore as well.

● Supplementary D: Tandem framework

The Tandem framework seeks to inform the co-design of climate services (Daniels, et al., 2020), providing practical questions and guidance for enabling knowledge co-production in diverse contexts, based on learnings and good practice. It is intended to be tailored in its application contexts and remains non-prescriptive, in efforts to support local ownership (Bharwani, et al., 2024). Its most recent updates (Figure 4) has been informed by its application in case studies in Southeast Asia, Sweden, and Latin America, in efforts to support its applicability across geographic and socioeconomic contexts (ibid.). In summary, steps and associated guiding questions inform:

Scoping, identifying and engaging stakeholders who are responsible for, or affected by the adaptation challenges/risks. Guiding questions associated with this step inform:

- Scoping of risks, challenges and the decision context, including initial scope and relevant challenges (that may not be climate focused)
- Identifying relevant actors and champions (to nurture collaborations and partnerships)
- Engaging relevant actors and champions

Co-explore, phase which advances deeper cross-sectoral and transdisciplinary examination of climate challenges and related socio-economic issues. This process is also likely to reveal context-led indicators for monitoring progress toward shared ambitions for resilience. It is sub-divided into three thematic areas:

- Co-exploring vulnerability and adaptation challenges, including from the perspective of those affected
- Co-exploring governance landscape and issues that affect (or enable) the design of solutions (such as climate services)
- Co-exploration of information needs and knowledge domains across stakeholders (including specific climate data and information required by users, and the capacity building interventions need to interpret and apply them).

Co-produce seeks to inform the process of building shared solutions upon the results of co-exploration, with a focus on creating a consensus regarding priorities, and a sense of ownership among stakeholders for long-term sustainability. This stage informs:

- Co-exploration and identification of solutions based on the identified challenges and issues.
- The co-design of solutions, including considerations and guidance for the process.
- Appraising solutions, to assess related uncertainty, maladaptation potential, synergies, trade-offs as well as co-benefits.

Integrating new knowledge and partners aims to distil lessons learned from the MEL process, and solidify relationships between stakeholders. This step also provides guidance evaluating progress toward goals, and includes considerations for reflexive learning that can sustain the process beyond projects' timelines.

Cross- cutting elements include guidance for integrating MEL throughout the co-production process (including feedback mechanisms), tailored communication of information (in consideration of differing understandings and terminology), capacity development and partnerships (on-going by-products of the co-production process), and financing (to support the operationalizing and institutionalising proposed solutions and climate services.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: