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New approaches to local climate change risk analysis

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New approaches to local climate change risk analysis

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Editorial: New approaches to local climate change risk analysis

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Editorial on the Research Topic
New approaches to local climate change risk analysis

This special Research Topic presents results from the project ≪Unpacking climate impact chains: A new generation of action- and user-oriented climate change risk assessments≫ (UNCHAIN) consisting of 11 local cases in seven European countries (cf. Figure 1). The overall objective of the UNCHAIN project was to improve climate change risk assessment frameworks aimed at informed decision-making and adaptation action. The research approach was based on the existing concepts of Impact Chain (Fritzsche et al., 2014) and insights from practices on the co-production of knowledge (Dannevig and Aall, 2015).

Despite the increasing sophistication of climate projections, their translation into adaptation decisions and actions is often not optimal (Klein and Juhola, 2014). The primary barrier is that climate information providers frequently lack a full understanding of the contexts in which the decisions they aim to inform are being made (McNie, 2007; Klein and Juhola, 2014). Even when climate information is available, barriers to its accessibility and effective utilization in decision-making persist, a phenomenon often referred to as the "usability gap" (Lemos et al., 2012). The prevailing inability of existing climate information to catalyze the necessary policy and action (Daniels et al., 2020) has spurred a growing body of scholarship on how scientific knowledge production should be conducted to better inform policymaking and facilitate climate change action (Gerger Swartling et al., 2019). A fundamental lesson from this body of work underscores the importance of how climate change knowledge is generated, communicated, translated, and customized to align with the requirements of users (Chiputwa et al., 2020). While substantial efforts have been dedicated to producing usable climate information for adaptation and other interconnected human-environmental issues, climate services have often been skewed toward a supply-based perspective (Lourenço et al., 2015). To bridge the current usability gap (Lemos et al., 2012; Vincent et al., 2020), future models and platforms for a science-user interface on climate change risk and adaptation must mirror the complexity of real-world needs and situations faced by policymakers and practitioners vested with the authority to make policy decisions and act (Daniels et al., 2020). This necessitates a heightened focus on interaction, co-ownership, and a recognition of the dynamics of power in researcher-politics-community relationships, alongside strategies to surmount these challenges, thereby empowering all involved stakeholders to drive effective action toward a more climate resilient future.

The UNCHAIN cases highlight five research innovations presented in the project plan for UNCHAIN: (1) Societal transformation: testing approaches to capture both short and

FIGURE 1
The geographical and thematic distribution of UNCHAIN case studies (Petutschnig et al.).

long-term climate change risk and adaptation; (2) Co-production: integrating participatory methods into impact modeling and adaptation assessment; (3) Incorporating societal trends into scenario analysis: accounting for socioeconomic developments as well as climate projections in addressing societal vulnerabilities and adaptation options; (4) Addressing uncertainties: combining qualitative and quantitative methods of impact assessment to test the Impact Chains approach; and (5) Transboundary climate risks: Expanding the logic of the impact chains approach to encompass transboundary climate risks and to link adaptation and mitigation response. Below we summarize the 11 articles of this Research Topic.

An increasing number of countries are recognizing the importance of addressing transboundary climate risks in their national adaptation policies. Aall et al. examines the potential for sub-national levels of governance addressing such risks in three case studies: Paris, France, focusing on issues related to migration and integration; Klepp, Norway, centered on agriculture and livestock production; and the river harbors in the Upper Rhine region of France, addressing concerns related to freight transportation and river regulation.

Sun and sea tourism play a pivotal role in the economies of southern European countries. This economic sector faces significant threats from climate change, including anticipated challenges such as the depletion of beaches, diminished thermal comfort, water scarcity, and extreme weather events, among other consequences. Agulles et al. illustrate an approach to evaluating climate-related risks affecting sun and sea tourism, using the case study of Mallorca.

There is a growing recognition that effective climate risk assessments greatly benefit from well-structured processes of knowledge co-production that actively involve key stakeholders and scientists. André et al. presents an improved methodology for co-producing climate services to support risk-informed decision-making and adaptation actions.

It's widely acknowledged by academia, funding agencies, and decision-makers that involving stakeholders in co-producing knowledge is essential for ensuring effective decision support. Englund, André et al. presents a Research Topic of methodological guidelines to assess co-produced climate services effectively.

When evaluating flood risk, it is crucial to extend the analysis beyond its climatic and technical aspects to encompass its differentiated impact on society. Englund, Vieira Passos et al. offers a practical example of how to quantify and map social vulnerability at a sub-municipal level in Sweden, specifically within Halmstad Municipality.

In the article titled "*Rhine low water crisis: from individual adaptation possibilities to strategic pathways,*" Gobert and Rudolf discusses the unprecedented low water crisis that gripped the Rhine transport sector in 2018, rendering large cargo vessels incapable of navigating certain segments of the river. This crisis severely disrupted inland waterway transport operations.

As the climate crisis accelerates, the resilience of Europe's aging critical infrastructure systems becomes an increasingly focal concern. Lückerath et al. introduces an innovative approach for assessing the climate vulnerability and risk within value applied in a case study set in a German metropolitan area situated along the Rhine River.

As the rail sector grapples with the unprecedented challenges posed by climate variability and change, there is a growing emphasis on generating pertinent climate data and information. Attoh et al. analyses the nature of climate risk information services required to support the rail sector's adaptation needs.

Contemporary scientific discussions surrounding the evaluation of loss and damage resulting from climate change predominantly center on quantifiable factors. However, the spectrum of potential harm caused by climate change extends far beyond these tangible aspects, especially in the context of residual risks that surpass the limits of adaptation. Menk et al. proposes an approach for assessing the risk of loss and damage from climate change.

The use of composite indices is prevalent across various fields of knowledge. However, a recurring challenge associated with these indices is how to incorporate uncertain knowledge into their construction. Melo-Aguilar et al. propose the utilization of a probabilistic framework which enables the integration of uncertainty considerations into the computation of composite indicators.

The last contribution brings together insights across all UNCHAIN-cases and discusses advancements in the methodological toolset used in Impact Chain-based climate risk and vulnerability assessments (CRVA), and new application fields (Petutschnig et al.). The authors propose several advancements in the stakeholder engagement process, including methods to capture dynamics between risk factors, resolve contradictory worldviews of participants, uncover hidden vulnerabilities, use scenario-planning techniques, and retain consistency between Impact Chains across policy scales. Furthermore, the authors examine IC-based CRVAs' applicability to address transboundary climate risks and climate risks for industry stakeholders. They conclude that the modular structure of IC-based CRVA enabled the integration of various methodological advancements from different scientific disciplines and that, even after a decade in use, the method still offers possibilities to further its potential to understand and assess complex climate risks.

The insights garnered from the UNCHAIN project offer a solid foundation for proposing the broad implementation and ongoing refinement of the Impact Chain-based approach. This approach aims to streamline existing climate risk assessment strategies across EU member states, various levels of governance, and sectors. Furthermore, it seeks to enhance cross-border collaboration and the sharing of knowledge.

By adopting this approach, Europe can speed up the process of achieving more effective adaptation. It achieves this by enhancing comparability between countries and regions, facilitating the transfer of knowledge and best practices, reducing ambiguity related to terminology and methodology, and fostering knowledge exchange and collaborative learning.

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Conflict of interest

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Four Methodological Guidelines to Evaluate the Research Impact of Co-produced Climate Services

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As climate change impacts unfold across the globe, growing attention is paid toward producing climate services that support adaptation decision-making. Academia, funding agencies, and decision-makers generally agree that stakeholder engagement in co-producing knowledge is key to ensure effective decision support. However, co-production processes remain challenging to evaluate, given their many intangible effects, long time horizons, and inherent complexity. Moreover, how such evaluation should look like is understudied. In this paper, we therefore propose four methodological guidelines designed to evaluate co-produced climate services: (i) engaging in adaptive learning by applying developmental evaluation practices, (ii) building and refining a theory of change, (iii) involving stakeholders using participatory evaluation methods, and (iv) combining different data collection methods that incorporate visual products. These methodological guidelines offset previously identified evaluation challenges and shortcomings, and can be used to help stakeholders rethink research impact evaluation through their complementary properties to identify complex change pathways, external factors, intangible effects, and unexpected outcomes.

Keywords: climate adaptation, climate services, decision support, knowledge co-production, transdisciplinary research, participatory research, evaluation method, research impact

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INTRODUCTION

As climate change unfolds across the globe, growing attention is paid toward producing climate services that supports adaptation decision-making (Papathoma-Köhle et al., 2016; Adger et al., 2018). Despite recent advancements in risk and vulnerability assessments, climate impact studies, and adaptation research, the use of such knowledge remains limited in practice (Klein and Juhola, 2014; Bremer and Meisch, 2017; Palutikof et al., 2019). Academia, funding agencies, and decision-makers are increasingly adopting knowledge co-production in order to transcend the divide between academia and practice, and take advantage of potential intangible co-benefits, for example mutual learning, social capital, and institutional capacity (Hansson and Polk, 2018; Bremer et al., 2019; Cvitanovic et al., 2019). This indicates a shift in the role of science in society (Jasanoff, 2004) in which science is held accountable for providing applicable and useful research of societal relevance (Barry et al., 2008; Wiek et al., 2014). The question, however, remains whether co-produced climate services fulfill these accountabilities as evaluations remain rare (Vincent et al., 2018; Daniels et al., 2020). It is still unclear how such co-produced climate services contribute to societal change (Lourenço et al., 2016; Wall et al., 2017). Consequently, funding agencies and decision-makers lack information to make sound decisions regarding where, or if, to spend their often limited resources to improve co-produced climate services (Vaughan and Dessai, 2014; Lemos et al., 2018; Visman et al., 2022). Evaluation can bridge this gap by contributing to a broader evidence base that can inform future climate service practices to maximize their impact. Hence, evaluations can support and improve climate risk-informed decision support, in the long run increasing the efficiency and effectiveness of climate risk management as a whole (Vaughan and Dessai, 2014; Daniels et al., 2020; Salamanca and Biskupska, 2021).

In this vein, scholars have recently started to outline evaluation practices that are fit for appraising co-produced climate services (see for example Vogel et al., 2017; Wall et al., 2017; Tall et al., 2018; Bremer et al., 2021; Salamanca and Biskupska, 2021; Visman et al., 2022). Many, however, continue to employ traditional evaluation procedures that solely focus on assessing academic outputs, thus failing to capture the many co-benefits that may emerge when co-producing climate services (Sarkki et al., 2015; Schuck et al., 2017). Tracking pathways to the impact of co-produced climate services remain equally limited (Jones et al., 2018), and further research is required to better design evaluation practices to capture long-term impacts and intangible benefits (Daniels et al., 2020). Novel approaches are, therefore, called for. Hence, this paper aims to address this limitation in current research by identifying methodological guidelines that outline approaches fit for evaluating co-produced climate services. We investigate the following research question: What methodological guidelines can be used to evaluate co-produced climate services more effectively? To this end, we review 25 scientific papers in-depth, followed by a survey study targeting actors with experience in co-producing knowledge.

CONCEPTUAL LANDSCAPE

Climate services first emerged when the World Meteorological Organization (WMO) in collaboration with various UN agencies initiated the World Climate Conference-3 (WCC-3) in 2009 to improve information for decision-making (WMO, 2009). Although still in its infancy, climate services, as a concept, is gaining prominence in the adaptation discourse (Vaughan and Dessai, 2014; Tall et al., 2018; Bremer et al., 2019; Hewitt and Stone, 2021). Climate services are commonly understood as efforts seeking to support climate risk-informed decision-making by providing timely, tailored, and usable knowledge and information (Vincent et al., 2018; Gerger Swartling et al., 2019; Daniels et al., 2020). Although many international organizations present definitions of climate services (see for example WMO, 2009; European Commision, 2015; IPCC, 2018), in practice, climate services tend to be confused with weather forecasts and climate research (Vaughan et al., 2018).

Other constraints further inhibit climate services to fulfill their stated aims, including, for example, a disconnect between stakeholders' expectations, inadequate consideration of stakeholders' differing realities, and data issues (Porter and Dessai, 2017; Ernst et al., 2019; Vogel et al., 2019). Many scholars attribute these shortcomings to the one-directional delivery of climate services from providers to users, which continue to dominate the field (McNie, 2007; Steynor et al., 2016, 2020). Climate services are supply-driven as to which decision-makers' demand for specific knowledge and information remains lacking (Lourenço et al., 2016), in the end inhibiting decision-makers to take ownership over the climate information and apply it in practice (Dilling and Lemos, 2011; Vaughan and Dessai, 2014). In addition, climate services tend to emphasize tailored products despite that other more intangible outcomes and impacts can be far more important (Daniels et al., 2020; Norström et al., 2020).

For this reason, knowledge co-production is considered a promising approach for making climate services more accessible, relevant, and actionable (Vincent et al., 2018; Bremer et al., 2019; Carter et al., 2019). As a wicked problem, climate adaptation cuts across sectors and disciplines, which calls for a collaborative and interdisciplinary approach that fosters knowledge exchange and action across different stakeholder groups (Cash et al., 2003; Jones et al., 2018; Harvey et al., 2019). Accordingly, academia, decision-makers, and funding agencies suggest that knowledge co-production deserves a central role in the environmental governance discourse (Vincent et al., 2018; Romina and Gerger Swartling, 2019). In broad terms, co-production refers to the process in which researchers and decision-makers collaborate when producing knowledge (Blackstock et al., 2007; Heink et al., 2015; Belcher et al., 2016). Norström et al. (2020) provides a more encompassing definition, in which knowledge co-production implies a collaborative research process involving diverse types of expertise and actors, to solve real-world problems and produce situation-relevant knowledge. In the literature, many benefits are associated with knowledge co-production such as better adaptation decision support, strengthened cross-sectorial networks, improved trust and confidence, increased institutional capacity, and better scientific quality (Bremer et al., 2019; Cvitanovic et al., 2019; Daniels et al., 2020).

There is, however, little existing evidence showing if co-produced climate services deliver on these potential benefits, and whether they are utilized in practice (Swart et al., 2017; VanderMolen et al., 2019). Research impact evaluation can bridge this gap. Numerous definitions of research impact evaluation exist (see Alla et al., 2017 for a review of definitions). For the purpose of this paper, we apply the definition suggested by Reed et al. (2021, p. 3): "the process of assessing the significance and reach of both positive and negative effects of research." Looking at the evaluation literature at large, three main typologies emerge, namely: *summative evaluation* that takes place at the end of an intervention to assess its overall merit; *formative evaluation* that is embedded into the project life cycle to enhance learning with intent to improve project performance; and *developmental evaluation* that offers an ongoing process supporting adaptive management in complex social interventions (Patton, 2006, 2010; Dozois et al., 2010; Mitchell and Lemon, 2020). Research impact evaluation may handle one or more of the following effects: *outputs*, which are the tangible products of the process; *outcomes*, as the less tangible effects and results of the co-production process; and *impacts*, as the long-term effects of the co-production process (Hassenforder et al., 2015; Wall et al., 2017). In the context of co-produced climate services, scientists and users may have contrasting views on measures of achievement, hence what outcomes and impacts to evaluate. It is, therefore, imperative to consider this multitude of perspectives when evaluating co-produced climate services (Roux et al., 2010; Fazey et al., 2014).

MATERIALS AND METHODS

To identify methodological guidelines for evaluating co-produced climate services, we first carried out a literature review exploring previous attempts to evaluate co-production processes. We paid special attention to challenges and good practices. We extracted lessons identified, that later were transformed into methodological guidelines. Lastly, through an online survey, we shared among actors with previous experience in co-producing knowledge our proposed methodological guidelines and validated them.

Literature Review

We first performed a literature review. To do so, we drew inspiration from the systematic snowballing approach outlined by Wohlin (2014) with methodological additions from Haddaway et al. (2015) and Dawkins et al. (2019). Previous research shows that snowballing is equally reliable as the traditional systematic review methods that rely on database searches (Badampudi et al., 2015). Snowballing, however, tends to have higher precision and therefore retrieve much fewer studies to be analyzed, which, therefore, arguably mitigates the risk of human error in comparison to database searches (Felizardo et al., 2016). This adapted approach consisted of five steps, as illustrated in **Figure 1**: (i) determine eligibility criteria, (ii) identify a start set, (iii) literature search applying backward and forward snowballing, (iv) coding and analysis, and (v) synthesis.

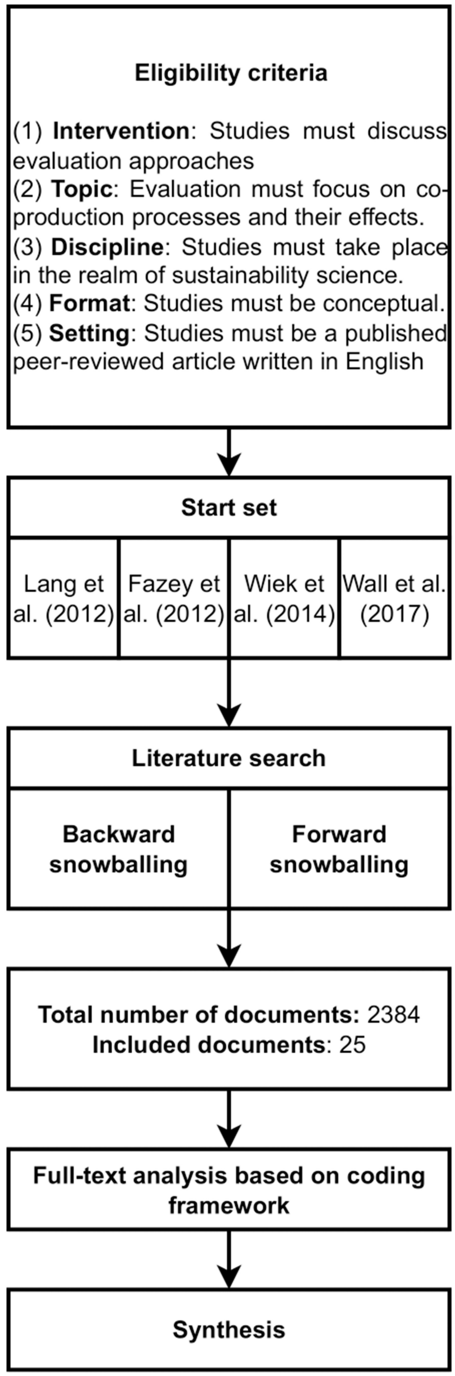

FIGURE 1 | Literature review process.

As an initial step, we developed a set of eligibility criteria that determined the basic conditions that a document must fulfill for inclusion in the final sample. This represented our attempt to ensure repeatability and reliability (Haddaway et al., 2015; Dawkins et al., 2019). We identified five criteria. First, documents were included if the studies suggested *an evaluation framework*, *approach, or method*. Second, documents were included if the studies concerned *evaluating knowledge co-production* or adjacent research practices like transdisciplinary research, participatory methods, and science-policy interface. Third, documents were included if the studies were related to *sustainability science*. The sole focus on climate services proved insufficient due to the lack of previous academic literature. Although considered as separate disciplines, climate services and sustainability science share many characteristics due to the many challenges invoked by complexity, uncertainty, and long time horizons. Fourth, documents were included if the studies were *conceptual*. Case studies were at first included, but it turned out that most focused on the co-production initiative itself rather than the evaluation approach. Case studies were, therefore, excluded. Some papers were both conceptual and empirical, as they developed and tested a novel evaluation approach. These papers were included to gain a better understanding of potential practical challenges and good practices that may arise when evaluating co-production initiatives. Fifth, documents were included if they were published in *peer-reviewed journals* written in *English*.

Next, we selected a start set compliant with the eligibility criteria. We first performed a preliminary literature search to gain a quick overview of available research. We used a simple search string that reflected the key concepts of interest: TITLE-ABS-KEY (evaluating *AND* knowledge *AND* co-production). The preliminary literature search yielded 32 documents, of which four documents were tentatively included. Thereafter we added six documents that were known among the authors but missing from the preliminary literature search. The start set was then reduced in size. Documents with the most citations were selected, in order to provide a larger input for the snowballing. A broad representation of academic journals was also considered. In total, four documents were included. The documents that were initially excluded were later included as they were identified in the literature search. For more details, see the **Supplementary Material**.

We thereafter began the literature search, applying backward and forward snowballing in iterations. Backward snowballing reviewed the reference list of the documents in the start set, whereas citations were considered during the forward snowballing (Wohlin, 2014). Only one author was involved in the screening process. Meetings were held with the remaining co-authors on multiple occasions to ensure consistency. Citations and references lists were identified using the well-regarded database Scopus in October 2020. Documents were included if titles and abstracts met the eligibility criteria. Documents found during the initial iteration were added to the start set, and subject to snowballing during the next iteration. The process continued until no additional documents were found. In total, the literature search generated 2384 documents, of which 70 were screened a second time. In the end, 25 documents were included for full-text analysis (see **Supplementary Material** for more information).

Once selected, documents were coded. A deductive approach was employed, using a pre-defined coding form to ensure consistency and replicability (Haddaway et al., 2015). Three types of codes were considered. First, basic citation information was noted. Second, conceptualizations and approaches to knowledge co-production were registered to avoid any terminological ambiguity. Third, the proposed evaluation design was considered, paying special attention to challenges and good practices. An overview is provided in **Table 1**.

TABLE 1 | Coding form.

Code	Type of code
Author(s)	Descriptive text
Title	Descriptive text
Year	Descriptive text
Abstract	Descriptive text
Research design	Descriptive text (case study, literature review, etc.)
Discipline	Descriptive text (sustainable development, natural resource management, climate change adaptation, etc.)
Country/Region/Sub-national	Country/Region/Sub-national area
Empirically tested	Yes, no
Term used	Descriptive text (transdisciplinary, participatory, co-producing, etc.).
Definition	Descriptive text
Theoretical approach	Descriptive text
Effects	Output, outcome, impact
Typology	Summative, formative, developmental
Timing	Pre-assessment, monitoring, retrospective, all
Design	Descriptive text (e.g. qualitative, quantitative, mix-method, participatory, etc.)
Data collection	Descriptive text (workshops, surveys, interviews, knowledge tests, etc.)
Evaluation framework	Descriptive text explaining how the evaluation is approached
Evaluation criteria	Descriptive text presenting and explaining evaluation criteria
Success factors for evaluation	Descriptive text
Challenges for evaluation	Descriptive text
Other useful information	Descriptive text

Findings were then synthesized narratively, by taking a textual approach to summarize the findings (Popay et al., 2006). Information was synthesized for each code. Data was clustered into classes of similar objects, which revealed key themes and patterns. We performed some simple statistical analysis for those codes to be easily quantifiable.

Next, we identified methodological guidelines for evaluating co-produced climate services based on the findings from the literature review. We paired all identified challenges with potential solutions outlined in the reviewed literature. Solutions were clustered into groups based on what methods they suggested. Four themes emerged, which were labeled and translated into methodological guidelines. Some additional literature was added at this stage to collect more information about the methods and approaches outlined in the methodological guidelines. Here it is worth noting, in line with Hassel (2010), that there are an infinite number of solutions to a single problem. We, therefore, refrained from making any claims on presenting an optimal solution. Instead, we aimed to find one possible solution that addresses the methodological challenges that arise when evaluating co-produced knowledge.

Survey

To increase the reliability of our findings and validate the emerging methodological guidelines, we distributed an online survey to actors with previous experience in co-producing knowledge. Survey responses also provided an in-depth understanding of practical barriers. Before its launch, the survey was tested to identify potential ambiguities. The survey was thereafter launched in February 2021, and remained open for a month. The survey included both qualitative and quantitative questions. Respondents were given the option to answer the questionnaire in Swedish or English, depending on what they felt the most comfortable with.

Respondents were identified through existing networks at the Stockholm Environment Institute (SEI) as well as personal networks through LinkedIn. Three groups were targeted: (1) previous project participants, (2) staff at SEI, and (3) personal networks. Respondents were also asked if they could recommend any other people to respond to the survey. In total, 61 complete responses were collected. 91% of the respondents self-identified as fulfilling multiple roles when co-producing knowledge – including users, providers, intermediaries, financiers, and evaluators. Respondents represented research institutes or universities (64%), non-governmental organizations (20%), governmental agencies (10%), municipalities (2%), and private consultancies (2%). Among the respondents, different geographical regions were represented – including Europe, Africa, Asia, Latin America, and North America.

We first asked some introductory questions to better understand the respondent's background, role, and experience in co-producing climate services. Subsequently, the survey asked questions that reflected the emerging methodological guidelines, with a focus on understanding potential benefits and barriers in applying the methodological guidelines in practice. For a detailed description, see the **Supplementary Material**.

Once collected, the data was analyzed using Excel. Quantitative data was summarized and visualized in different types of graphs. All numbers were rounded to the nearest integer. Statistical analysis was avoided, as most of the data was structured on an ordinal scale which eliminated most statistical methods (Bryman, 2012). The qualitative data was treated as one cohesive dataset, meaning that significant patterns were identified across the entire dataset rather than for the single questions alone (Braun and Clarke, 2019). We applied an inductive approach in line with Thomas (2006), in which we reduced the data by developing themes based on our interpretations and previous research. We noted the following for each theme: category label, short description, direct quotes, and potential links.

RESULTS

Results are presented in three parts. First, we present findings from the literature review focusing on current evaluation practices, challenges, and good practices. Based on these findings, we identify four methodological guidelines for evaluating co-produced climate services. Lastly, we present the survey responses to validate the methodological guidelines.

Literature Review

The 25 studies reviewed in our full-text analysis represent a wide variety of disciplinary fields: sustainability research (24%), natural resource management (20%), environmental science (20%), climate adaptation (4%), socio-ecological research (4%), and climate science (4%). The remaining studies (24%) take an interdisciplinary approach focusing on complex societal and environmental problems in general. None of the reviewed literature focus on climate services.

Following the eligibility criteria, all studies relate to knowledge co-production processes, although the conceptualization of knowledge co-production diverges. The reviewed studies refer to knowledge co-production as transdisciplinary, participatory research, communities of practice, knowledge exchange, joint knowledge production, science-policy interfaces, and knowledge integration.

Evaluating Co-produced Knowledge

Traditionally, research evaluations employ reductionist procedures solely focusing on assessing academic outputs, thus inadequately capturing the broad range of effects that can emerge when co-producing knowledge (Sarkki et al., 2015; Zscheischler et al., 2018). The reviewed literature seems to acknowledge this shortcoming, and suggests evaluation approaches that appraise all or a combination of outputs, outcomes, and impacts. None proposes a sole focus on outputs.

Most scholars suggest a formative approach when evaluating co-production endeavors (Jones et al., 2009; Lang et al., 2012; Sarkki et al., 2015), which in turn affects the timing of the evaluation. Integrating evaluation practices into the co-production process allows for reflection and learning, thus providing an opportunity for influencing the direction in which the co-production processes are heading (Roux et al., 2010). It also allows for trust to emerge among the involved actors (Wall et al., 2017). However, ex-post evaluations may be necessary to capture those outcomes and impacts that emerge after the end of a co-production process (Walter et al., 2007).

A systematic review performed by Ernst (2019) shows the many methods used in evaluating co-production initiatives, such as questionnaires, interviews, document analysis, and observation. Looking at the literature, most suggest using a Likert scale questionnaire. These studies tend to also employ evaluation criteria (Walter et al., 2007; van der Wal et al., 2014; Zscheischler et al., 2018; Hitziger et al., 2019; Fulgenzi et al., 2020). Others propose a mixed-method approach sequencing data collection methods to serve a specific purpose at different points of time, arguing that the strengths of one method can offset the weaknesses of another (Jones et al., 2009; Wiek et al., 2014; Holzer et al., 2018). Moreover, some studies advocate for participatory evaluation methods, in order to use the evaluation as an opportunity to further strengthening knowledge exchange (Fazey et al., 2014; Norström et al., 2020).

Evaluation criteria are contested subject, as explained by O'Connor et al. (2019, p.2): "developing evaluation criteria for knowledge co-production remains a challenge because of its variety of forms, contexts, and participants who may have differing views of what is valuable". Moreover, evaluation criteria are inappropriate when appraising complex systems, as it attempts to fit complexity into a few variables and consequently tends to fall into narrow ranges (Jones et al., 2009; Hassenforder et al., 2015). However, 12 studies present evaluation criteria as they can indicate signs of change and allows for comparison across contexts. Looking at the literature, some studies propose evaluation criteria that assess research quality in terms of relevance, credibility, legitimacy, and effectiveness (Sarkki et al., 2015; Belcher et al., 2016; Knickel et al., 2019). Others suggest evaluation criteria representing the co-production process, its effects, and the context in which it operates (Blackstock et al., 2007; Hassenforder et al., 2015; Jahn and Keil, 2015; Wall et al., 2017; Hitziger et al., 2019). Fulgenzi et al. (2020) identify good practices in knowledge co-production and outline evaluation criteria accordingly, whereas Lang et al. (2012) outline evaluation criteria for assessing the co-production process itself. Lastly, Roux et al. (2010) outline evaluation criteria assessing to what extent funders, researchers, and end-users fulfill their accountabilities when co-producing knowledge.

An overview of the evaluation criteria mentioned in the reviewed literature are presented in **Tables 2–4** and organized

TABLE 2 | Criteria for evaluating co-produced knowledge – the enabling environment.

Citeria	Description	References
Access to resources	The support to participants for them to meet their responsibilities (competence, time, scientific disciplines in research team, budget, adequate infrastructure, practical information, staffing)	Blackstock et al. (2007), Roux et al. (2010), Lang et al. (2012), Sarkki et al. (2015), Belcher et al. (2016), Wall et al. (2017), Hitziger et al. (2019), Knickel et al. (2019), Fulgenzi et al. (2020)
Drivers	Incentives - demand-driven or supply-driven	Blackstock et al. (2007), Hassenforder et al. (2015), Sarkki et al. (2015), Knickel et al. (2019)
External context	Characteristics of the system in which the co-production process operates, with a focus on complexity, boundaries, synergies, and catalyzing events	Blackstock et al. (2007), Roux et al. (2010), Hassenforder et al. (2015), Jahn and Keil (2015), Belcher et al. (2016), Wall et al. (2017), Hitziger et al. (2019)
Expectations	Whether participants are confident that the process will yield positive effects	Hassenforder et al. (2015)
Institutional memory	Safeguarding mechanisms to protect the acquired collective knowledge	Jahn and Keil (2015), Hitziger et al. (2019), Knickel et al. (2019)
Preexisting relationships	Preexisting professional relationships between involved actors	Wall et al. (2017)
Willingness to learn	The capacity and personal motivation to participate in the co-production process	Blackstock et al. (2007), Walter et al. (2007), Roux et al. (2010), Lang et al. (2012), Jahn and Keil (2015), Sarkki et al. (2015), Wall et al. (2017), Hitziger et al. (2019), Knickel et al. (2019)

into the following: (i) criteria assessing the enabling environment, (ii) criteria assessing the process, and (iii) criteria assessing the effects.

Challenges

A major challenge in evaluating knowledge co-production is the *complexity* of the process itself and of the system in which it operates (Roux et al., 2010; Lang et al., 2012; Fazey et al., 2014). Complex systems are characterized by non-linearity, multi-pathways, emergent properties, dynamic change, and interdependencies (Zscheischler et al., 2018), which in combination with the *long timeframes* in adaptation decision-making makes it *difficult to establish causality* (Jahn and Keil, 2015; Hitziger et al., 2019; Norström et al., 2020). Making mono-causal connections are further inhibited by the ongoing influence of *unforeseeable external factors* (Zscheischler et al., 2018). Trying to fit complexity into a few variables can cause distortion as complex problems are greater than the sum of their parts (Jones et al., 2009; Hassenforder et al., 2015). Tensions arise when trying to apply linear frameworks to capture change that occurs in a messy and complex reality (Walter et al., 2007).

Co-production is subject to *uncertainty* as objectives and practices tend to adapt as the process evolves (Laycock et al., 2019). In addition, uncertainty is inherent to the problem, namely climate change, which is being addressed (Hegger et al., 2012). This poses significant challenges for research impact evaluation, as success is defined in relation to formulated objectives.

In addition, the *intangible* nature of many key elements in knowledge co-production, such as learning, empowerment and trust, further complicates evaluation efforts. These intangible effects are difficult to objectively judge, and therefore tend to rely on subjective estimations (Blackstock et al., 2007; Hassenforder et al., 2016).

Moreover, evaluations are expected to yield different results depending on their timing (Wall et al., 2017; Fulgenzi et al., 2020). Outcomes and impacts emerge at different points in time (Roux et al., 2010; Ernst, 2019). There are significant *time-lags between causes and effects* as societal impacts evolve over a long period of time (Blackstock et al., 2007; Jahn and Keil, 2015; Wall et al., 2017), making them difficult to capture within the timeframe provided in an externally funded project (Norström et al., 2020).

Furthermore, co-production initiatives involve *stakeholders with different backgrounds* (Jones et al., 2009; Roux et al., 2010; Hitziger et al., 2019), which may complicate evaluation practices due to at times contrasting values, epistemological beliefs, educational background, professional jargons, and objectives. Motivation can also vary among involved stakeholders. Some might consider evaluations as a burden that distracts from the main co-production activities, especially if they are struggling with limited financial resources (Knickel et al., 2019).

Good Practices

Flexible practices are considered key when evaluating co-production processes (Lang et al., 2012; van der Wal et al., 2014; Knickel et al., 2019). Evaluation frameworks must be adapted to the needs of the intended users, considering timing, purpose, scale, and context (Belcher et al., 2016; Knickel et al., 2019). Furthermore, evaluation strategies should adapt and adjust as new insights arise (Blackstock et al., 2007; Carew and Wickson, 2010; Belcher et al., 2016). Evaluation objectives should be revisited and adapted as new information emerges (Norström et al., 2020).

Walter et al. (2007) call for novel evaluation approaches, of which *participatory evaluation* is a promising alternative (Fazey et al., 2014; Norström et al., 2020). Participatory evaluation encourages learning, ultimately transforming the evaluation into a learning activity in itself (Lang et al., 2012). In relation to this, stakeholder engagement is especially important when deciding on evaluation objectives to encourage ownership and buy-in from the involved stakeholders while ensuring contextual relevance (Wiek et al., 2014). It is also suggested to involve stakeholders

TABLE 3 | Criteria for evaluating co-produced knowledge – the process.

Citeria	Description	References
Awareness	The extent to which participants can identify available resources and possible gaps	Fulgenzi et al. (2020)
Capacity development	The process of developing skills, knowledge, and awareness	Blackstock et al. (2007), Roux et al. (2010), Sarkki et al. (2015), Wall et al. (2017), Fulgenzi et al. (2020)
Co-location	Whether involved actors are willing to host junior researchers	Roux et al. (2010)
Conflict resolution	The degree of conflicts between participants, and the ability to manage such conflicts	Blackstock et al. (2007), Roux et al. (2010), Lang et al. (2012), Wall et al. (2017), Hitziger et al. (2019), Knickel et al. (2019)
Continuity	The consistency in participation, in terms of recurring participants	Wall et al. (2017)
Cost effectiveness	Cost of achieving identified objectives	Blackstock et al. (2007), Jahn and Keil (2015)
Effective collaboration	Mechanisms promoting collaboration (research plan, documentation, agenda, roles and responsibilities)	Belcher et al. (2016), Wall et al. (2017), Knickel et al. (2019), Fulgenzi et al. (2020)
Effective communication	Appropriateness, relevance, clarity, and accessibility of communication efforts	Walter et al. (2007), Roux et al. (2010), Jahn and Keil (2015), Sarkki et al. (2015), Belcher et al. (2016), Wall et al. (2017), Hitziger et al. (2019), Knickel et al. (2019)
Ethical aspects	Whether research adheres to ethical standards	Belcher et al. (2016)
Inclusion of all relevant perspectives	The creation of a safe space for participants to voice their opinions and influence the decision-making process	Blackstock et al. (2007), Walter et al. (2007), Hassenforder et al. (2015), Hitziger et al. (2019), Knickel et al. (2019), Fulgenzi et al. (2020)
Involvement	At what stage of the process different participants are engaged	Knickel et al. (2019)
Leadership	A leadership figure facilitating the process	Blackstock et al. (2007), Walter et al. (2007), Roux et al. (2010), Lang et al. (2012), Jahn and Keil (2015), Sarkki et al. (2015), Wall et al. (2017), Hitziger et al. (2019), Knickel et al. (2019)
Methods	Appropriateness of the selected disciplines, epistemology, methods, approaches, and theories	Blackstock et al. (2007), Lang et al. (2012), Hassenforder et al. (2015), Jahn and Keil (2015), Belcher et al. (2016), Wall et al. (2017), Hitziger et al. (2019), Knickel et al. (2019)
Objectives	Whether goals are established for the co-production process	Blackstock et al. (2007), Walter et al. (2007), Lang et al. (2012), Hassenforder et al. (2015), Jahn and Keil (2015), Sarkki et al. (2015), Belcher et al. (2016), Wall et al. (2017), Hitziger et al. (2019), Knickel et al. (2019)
Practicalities	Frequency of events, number of participants, and setting of exchange	Hassenforder et al. (2015), Hitziger et al. (2019)
Reflection	Opportunities to reflect upon the collective experience and adjust the plan accordingly	Lang et al. (2012), Jahn and Keil (2015), Sarkki et al. (2015), Belcher et al. (2016), Wall et al. (2017), Hitziger et al. (2019), Knickel et al. (2019), Fulgenzi et al. (2020)
Relationships	The improvements in social capital, and the development of new social networks	Blackstock et al. (2007), Walter et al. (2007), Lang et al. (2012), Sarkki et al. (2015), Knickel et al. (2019), Fulgenzi et al. (2020)
Representation	The genuine inclusion of a diverse set of actors	Blackstock et al. (2007), Lang et al. (2012), Hassenforder et al. (2015), Jahn and Keil (2015), Sarkki et al. (2015), Belcher et al. (2016), Wall et al. (2017), Hitziger et al. (2019), Knickel et al. (2019), Fulgenzi et al. (2020)
Theory of change	The development of a theory of change that matches the objectives and clarifies any underlying assumptions	Jahn and Keil (2015), Belcher et al. (2016), Hitziger et al. (2019)
Transparency	The extent to which participants and observers can understand the process	Blackstock et al. (2007), Knickel et al. (2019)

when developing evaluation criteria to ensure that effects perceived as important are being considered (Fazey et al., 2014).

Additionally, scholars suggest considering the *evaluation as a process*. It is proposed to integrate the evaluation from the start to allow for social learning and trust to emerge (Roux et al., 2010; Wall et al., 2017). The evaluation should aim to be *comprehensive* to capture both the co-production process itself, and its expected and unexpected outputs, outcomes, and impact (Fazey et al., 2014; Belcher et al., 2016; Wall et al., 2017). Intangible aspects should also be assessed, despite being difficult to measure (Norström et al., 2020).

It is recommended to develop a *theory of change,* which is a logic model supporting project management, stakeholder engagement, and evaluation practices which seeks to describe how change is expected to occur. Theory of change offers greater flexibility in comparison to other logic models and can capture complexity, clarify causal linkages, and bridge conflicting interests (Fazey et al., 2014; Wall et al., 2017; Knickel et al., 2019; Norström et al., 2020). Others suggest using visual products to encourage meaningful discussions among involved stakeholders, as it can help to overcome barriers like differences in educational backgrounds and language preferences

TABLE 4 | Criteria for evaluating co-produced knowledge – the effects.

Citeria	Description	References
Accountability	The extent to which participants have satisfied their personal core responsibilities	Blackstock et al. (2007),
Inspiration	The motivation to pursue follow-up projects	Wall et al. (2017), Fulgenzi et al. (2020)
Outcomes	Whether desired change is achieved	Lang et al. (2012), Wall et al. (2017)
Outputs	The timely delivery of the tangible products (peer-reviewed articles, workshops, meetings, reports)	Roux et al. (2010), Hassenforder et al. (2015), Wall et al. (2017), Knickel et al. (2019)
Quality of decision-making	The implementation, integration, and maintenance of findings	Blackstock et al. (2007), Roux et al. (2010), Jahn and Keil (2015), Knickel et al. (2019)
Quality of research product	Validity of the final research product, considering its legitimacy, transferability, credibility, comprehensiveness, and robustness	Blackstock et al. (2007), Sarkki et al. (2015), Wall et al. (2017)
Recognized impacts	Perceived changes associated with the co-production process (unintended effects, changes in perspectives, and improved organizational performance)	Blackstock et al. (2007), Hassenforder et al. (2015), Jahn and Keil (2015), Fulgenzi et al. (2020)
Relevance to society	Whether research findings are used in practice to solve the targeted problem	Roux et al. (2010), Lang et al. (2012), Jahn and Keil (2015), Sarkki et al. (2015), Belcher et al. (2016), Wall et al. (2017), Knickel et al. (2019)
Social learning	Changes collective culture and values	Blackstock et al. (2007), Jahn and Keil (2015), Wall et al. (2017), Hitziger et al. (2019), Knickel et al. (2019)

(Lang et al., 2012). Evaluation practices should also allow for *maximum participation*, and *adjust for potential memory distortion* (Wiek et al., 2014).

Methodological Guidelines

Reviewing the literature, many insights strike as relevant although none addresses climate services. Challenges associated with complexity, long time horizons, uncertainty, and stakeholder diversity are inherent to many co-production processes, and thus cut across disciplinary boundaries. Drawing from the literature review, we identify four methodological guidelines fit for evaluating co-produced climate services. An overview is provided in **Table 5**.

Engaging in Adaptive Learning by Applying Developmental Evaluation Practices

As its name suggests, developmental evaluation puts emphasis on development rather than accountability or improvement (Mitchell and Lemon, 2020). Developmental evaluation seeks to support adaptive management, allowing practices to adapt as new insights emerge or circumstances change (Patton, 2010). Developmental evaluation rests on the same assumptions that underpin knowledge co-production initiatives. Co-production builds on the assumption that change is complex, non-linear, and emergent (Norström et al., 2020), and developmental evaluation is designed to understand such complexity. Drawing inspiration from complexity theory, developmental evaluation sets to support adaptive management in social innovation initiatives, like when co-producing climate services, characterized by complexity, emergence, stakeholder diversity, long time horizons, and uncertainty (Dozois et al., 2010; van Tulder and Keen, 2018).

Developmental evaluation is per design flexible, thus offsetting challenges encountered when applying summative and formative assessment approaches. Summative evaluations aim for predictability by using a linear cause-effect model and rigid methods (Fazey et al., 2014), which is considered unfit for evaluating co-produced climate services as they require flexible practices that can adapt as uncertainties and complexity unfold (Salamanca and Biskupska, 2021). Similarly, formative evaluations also prove inadequate in terms of flexibility, as they seek to support improvements toward a pre-defined objective

TABLE 5 | Overview of the methodological guidelines.

Methodological guidelines	Justification
Engaging in adaptive learning by applying developmental evaluation practices	• To handle complexity and uncertainty by engaging stakeholders in adaptive management. • Continuous evaluation process to capture change as it emerges.
Building and refining a theory of change	• To capture complexity. • Easy to update as outcomes unfold over time. • To take a system perspective to capture external factors. • To allow stakeholders to reflect upon causal linkages.
Involving stakeholders using participatory evaluation methods	• To develop a shared problem understanding. • To ensure that all perspectives are equally considered and represented. • To allow stakeholders to draw attention to unexpected outcomes. • To develop a shared vocabulary to overcome any professional jargon.
Combining different data collection methods that incorporate visual products	• To create a robust data set for analysis. • To provide a more comprehensive understanding of the problem at hand. • To capture both tangible and intangible effects. • To make it easier to grasp complexity.

(Patton, 2010). Co-production initiatives tend to change their objectives and practices as the process evolves (Blackstock et al., 2007), thus making it unfeasible to try to measure success against a set of pre-defined objectives. Instead, developmental evaluation promotes adaptive management in order for evaluation practices to adapt to changes in objectives, research design, or stakeholder constellation. In practice, developmental evaluation support adaptive management by engaging stakeholders in an ongoing evaluation process in which an embedded evaluator provides actionable feedback to facilitate continuous learning (Patton, 2006, 2010).

Adaptive management can serve as a vehicle for joint action, in which stakeholders can bring their experience and feedback into action and adjust evaluation practices accordingly (Reynolds, 2014; Gerlak et al., 2018). Developmental evaluation supports a shift from linear single-loop thinking toward transformative double-loop learning in which adaptive management allows evaluation practices, objectives, or metrics of success to change in response to experience. Double-loop learning is fit if adapting to uncertainty or complexity, as it supports transformation rather than retainment (Shea and Taylor, 2017). Arguably, climate services can benefit from adaptive management and double-loop learning by helping the involved stakeholders to navigate the inherent uncertainty, complexity, and long time horizons associated with adaptation decision-making, as it allows stakeholders to adjust their evaluation practices to emerging and changing contexts.

Building and Refining a Theory of Change

Theory of change is increasingly used to inform baseline studies, organizational design in complex and multi-stakeholder settings, and to facilitate adaptive learning from a systems perspective throughout a project life cycle (van Es et al., 2015). Theory of change is designed to support interventions subject to complexity and uncertainty, which makes it fit for co-production processes that address climate risks. Furthermore, climate services cannot be considered in isolation from the context they operate in as decision-makers combine different sources of information when planning for adaptation (Zscheischler et al., 2018; André et al., 2021). Theory of change acknowledges these external influences by identifying and monitoring them, ultimately strengthening any causal claims (van Es et al., 2015).

Climate risks operate on long timescales and so is adaptation decision-making, meaning that benefits emerging from climate services might appear far in the future. We, therefore, argue for considering the theory of change as a living entity that can track progress at different temporal scales. It is iterative, thus expected to be revisited and refined on a regular basis as new information emerges. In this way, the theory of change become more informed over time, as it enjoys continuous refinement (van Tulder and Keen, 2018). When employed or applied iteratively, the theory of change can capture development that occurs over long periods of time and help involved stakeholders, if resources allow, to continue their evaluation efforts after the end of the co-production process. The theory of change is widely, although not exclusively, used to support ex-post evaluations in explaining how change has happened, as it puts a structure in place for stakeholders to continue evaluating impacts as they unfold (Vogel, 2012; van Es et al., 2015; Mayne, 2017).

Involving Stakeholders Using Participatory Evaluation Methods

In short, participatory evaluation is an approach for involving stakeholders in the evaluation process (Trimble and Plummer, 2019). Stakeholders can be involved at any stage of the evaluation (Guijt, 2014; Reed et al., 2021). Participatory evaluation and knowledge co-production have the same theoretical and epistemological underpinnings. Our study reveals many overlaps, where participatory evaluation can reinforce many of the positive outcomes and impacts that emerge when co-producing knowledge. Benefits include helping diverse stakeholder groups to form a shared vision and vocabulary (Plottu and Plottu, 2011; Fazey et al., 2014); enhancing motivation and buy-in among involved stakeholders (Fazey et al., 2014); drawing attention to unexpected outcomes and impacts (Norström et al., 2020); and validating evaluation findings among involved stakeholders (Guijt, 2014). In addition, stakeholder participation can improve overall robustness by incorporating multiple sources of knowledge and realities (van Es et al., 2015).

Evaluation findings can have a transformational capacity if being integrated in iteration. Participatory evaluation methods can be instrumental in strengthening the evaluation's utilization. Participatory methods encourages ownership by stakeholders involved in the generation and use of climate services. This ownership contributes to sustainability beyond the limited time span of climate service projects (Patton and Horton, 2009; Fazey et al., 2014; van Es et al., 2015).

Combining Different Data Collection Methods That Incorporate Visual Products

Mixed-method approaches combine qualitative and quantitative methods, in order to take advantage of their respective strengths while counterbalancing any potential weaknesses (Ernst, 2019). Methods can be sequenced to serve a specific purpose at different points in time (Jones et al., 2009; Holzer et al., 2018), thus forming a comprehensive understanding of the process itself and its outputs, outcomes, and impact. On the one hand, qualitative methods are well suited to explore the many intangible effects that emerge when co-producing knowledge, such as social learning, empowerment, and trust (Fazey et al., 2014). Qualitative methods expect the unexpected, and allow the involved stakeholders to draw attention to any unexpected positive or negative effects (Bryman, 2012). On the other hand, quantitative methods can assess how change unfolds over time by employing longitudinal data (Fazey et al., 2014), which is especially appropriate considering the long time horizon that characterizes adaptation decision-making. Quantitative methods can also improve the generalizability of the evaluation findings, and thus identify transferable lessons. Additional benefits of using mix-methods include allowing for triangulation; increasing robustness; enhancing comprehensiveness; improving credibility and validity of findings; and generating unexpected insights (Reed et al., 2021).

In addition, art-based methods generate tangible products for expression and analysis, which can enhance mutual learning among the involved stakeholders (Chambers, 2008). Visualization complements text and dialogue (van Es et al., 2015). Art-based methods can generate products that act as boundary objects, thus helping to bridge diverging stakeholders' interests, goals, epistemologies, expertise, and languages (Wyborn, 2015). Boundary objects, such as visual products, can enhance meaningful participation (Nel et al., 2016; Reed et al., 2021). Discussing while drawing can create an informal and inclusive setting for knowledge exchange (van Es et al., 2015). As phrased by Chambers (2008, p. 100), "Hands are freer to move tangibles than mouths are to speak words." Visual products can stimulate discussions on the topic of interest, ultimately improving both the quantity and quality of the collected data (Petheram et al., 2012). In addition, visual products can disentangle and represent the complexity present when co-producing climate services, and thus provide a better understanding of causal linkages and change pathways (Chambers, 2008; van Es et al., 2015; Reed et al., 2021). Lastly, visual products can help communicating evaluation findings to a broader audience including new project members (Petheram et al., 2012).

Validation – Survey Results

To a great extent, the survey responses confirmed the methodological guidelines. However, the survey study revealed a number of benefits and challenges if the respondents were to apply the methodological guidelines. An overview is provided in **Table 6**.

In the open-ended questions, respondents refer to good practices in line with developmental evaluation. Frequently mentioned examples include:

- Utilization-focused approaches to ensure usefulness for intended users;
- Adaptive management to support continuous improvement and social learning; and,
- Importance of reflexive practices.

As such, developmental evaluation presents many benefits when evaluating co-produced knowledge. Barriers related to time allocation and funding are, however, noted.

Overall, 66% are familiar with building a theory of change of which around half recommend it in the case of co-production endeavors. Many benefits are identified, including clarifying underlying assumptions, mapping cause and effect pathways, disentangling complexity and context, and defining objectives. Challenges do, however, exist. Many respondents are unfamiliar with the concept. Others argue that the theory of change is "too abstract," "too academic," "bulky," and even "pointless." Others compare the theory of change with the logical framework approach, criticizing it for being donor-driven and reductionist.

In total, 97% of the respondents recommend using participatory evaluation methods. Participatory evaluation can yield many benefits, including forming a common understanding and vision, building trust, validating evaluation findings, and increasing buy-in and ownership among involved stakeholders. Survey responses indicate that stakeholder engagement is possible at all stages of the evaluation process, in particular when defining the objectives, developing indicators, and reporting the findings. Nonetheless, some challenges are mentioned. One respondent claim that personal involvement can create biases. Others note that stakeholder involvement is time-consuming, and that extensive participation paradoxically can lower engagement. There are also trade-offs between validating findings on one hand, and building ownership and buy-in on the other.

Many methods are considered useful when evaluating co-production initiatives, including interviews, mixed-methods, group discussions, questionnaires, written reflections, indicators, and document review. 98% agreed that visual products can clarify complex issues.

TABLE 6 | Overview of survey responses.

Methodological guidelines	Main points from survey responses
Engaging in adaptive learning by applying developmental evaluation practices	**Benefits** • Utilization-focused approach can increase usefulness • Adaptive management can promote learning • Reflexive practices are important **Challenges** • Time allocation and funding
Building a theory of change	**Benefits** • Clarify assumptions • Understand causal linkages • Disentangle complexity • Define objectives **Challenges** • Difficult to use • Donor-driven • Reductionist
Involving stakeholders using participatory evaluation methods	**Benefits** • Forming a shared understanding and vision • Build trust • Validating findings • Increase buy-in and ownership among involved stakeholders **Challenges** • Biases • Time-consuming • Trade-offs between validating findings and building ownership
Combining different data collection methods that incorporate visual products	**Benefits** • Clarify complex issues

DISCUSSION

Research Implications

Despite recent advances in climate services, research is thus far paying little attention to the evaluation of such services. Many methods exist for evaluating research impact. However, few consider climate services and their impact on adaptation policy and action. Usability is rarely assessed. We address this gap by introducing four methodological guidelines that may serve as stimuli for further discussions on how to evaluate co-produced climate services. In line with previous research (Sarkki et al., 2015; Belcher et al., 2016; Zscheischler et al., 2018), we argue that novel evaluation practices are needed to capture the broad array of effects that emerge when co-producing knowledge. The proposed methodological guidelines support a shift of evaluation approach from traditional practices emphasizing academic outputs to one that capture the many, often intangible or unexpected, effects that emerge, when co-producing climate services.

Our methodological guidelines add to the body of research that seeks to evaluate research impact and co-produced climate services, and shed light upon the need to rethink evaluation practices. Most previous research has focused on suggesting criteria for evaluating co-produced climate services and adaptation (Wall et al., 2017; Visman et al., 2022) as well as their quality (Bremer et al., 2022). Methodological choices remain understudied. In line with previous research (Walter et al., 2007; Jones et al., 2009; Hassenforder et al., 2015), we acknowledge that metrics and criteria themselves are insufficient when evaluating co-produced climate services. Objectives and strategies tend to change as the co-production process evolves (Laycock et al., 2019), and stakeholders may have contrasting views on what constitutes "success" depending the context in which they operate (Vincent et al., 2020). In this vein, the proposed methodological guidelines support flexible practices and address the challenges that arise when using predefined metrics and criteria in value laden and complex co-production processes.

We believe that the methodological guidelines are applicable in co-production processes that are developed for different purposes from climate services. The methodological guidelines draw on evidence from the broader sustainability literature (Blackstock et al., 2007; Carew and Wickson, 2010), suggesting that they also may prove applicable in such contexts. Sustainability science faces similar challenges as climate services when being evaluated, including complexity, uncertainty, and long time horizons. The methodological guidelines can offset these challenges, and thus support the many science-policy interfaces taking place amid complex socioenvironmental systems.

Applicability of the Four Methodological Guidelines

The four identified methodological guidelines are designed to fit a broad array of contexts, which enable effective application in a variety of climate service initiatives regardless of their scope, topic, and resources. As demonstrated in the survey responses, applying the methodological guidelines could improve evaluation practices by yielding multiple benefits, such as capturing both tangible and intangible effects; managing complexities and uncertainties; monitoring external factors; bridging stakeholder interests; and better representing causal linkages.

While the methodological guidelines can be applied in isolation, we suggest combining them as they are designed to complement each other. Together, they address all identified challenges that emerge when evaluating co-produced knowledge (see **Table 5**). Moreover, significant overlaps exist between the guidelines, suggesting they can reinforce and perpetuate one another's positive impacts. For example, developmental evaluation can be introduced to support an adaptive use of the theory of change, allowing it to be refined as change unfolds. A theory of change is better constructed when taking a participatory approach as it allows stakeholders to form a consensus representing the multitude of perspectives involved. Furthermore, a theory of change is best presented as a visual product together with qualitative or quantitative indicators. Visual products tend to be participatory by nature, allowing stakeholders to engage around a boundary object.

Challenges Applying the Methodological Guidelines

The survey responses shed light on some new challenges not being addressed in the reviewed literature. There appears a significant gap between theory and practice, indicating that current evaluation practices tend to neglect the contextual realities faced by involved stakeholders.

Looking at the survey responses, many are unfamiliar with the theory of change evaluation approach while others regard it as being difficult, academic, reductionist, or donor-driven. The theory of change approach seems to encounter the same shortcomings as other logic models in its practical application, although the reviewed literature makes a clear distinction between the two (Fazey et al., 2014; van Es et al., 2015). A probable reason for this, supported by findings from the survey, is the limited time and budget allocated for reflection and learning. van Es et al. (2015) argue that reflection is key when building a theory of change. Nevertheless, in practice, stakeholders face budgetary and time constraints that inhibit such critical reflection. Arguably, in line with developmental evaluation, there is a need to embed the reflection process into the evaluation cycle to encourage reflexive learning, ultimately stimulating the many benefits associated with building a theory of change.

It is evident in our study that challenges also arise in relation to stakeholder engagement. Participatory evaluations are no silver bullet, and must be adapted to the context at hand. As noted in the survey responses, participatory evaluations are time- and resource-intensive. Extensive participation can cause fatigue and lower engagement. Our findings indicate that funders sometimes require extensive stakeholder participation without fully grasping the research context and conditions, while researchers and practitioners express a lack of budget and time to engage in such activities. There seems to be a disconnect between funders' expectations and practical realities, highlighting the importance of flexible funding conditions that stimulate adaptive management.

CONCLUSION

As climate change continues to alter weather patterns, there is a growing need for climate services to support adaptation policy and action. Climate services are, however, rarely evaluated. This paper addresses current evaluation challenges and opportunities, by identifying methodological guidelines that outline methods and approaches fit for evaluating co-produced climate services. Based on a literature review and survey responses, the following methodological guidelines are identified: (i) engaging in adaptive learning by applying developmental evaluation practices, (ii) building and refining a theory of change, (iii) involving stakeholders using participatory evaluation methods, and (iv) combining different data collection methods that incorporate visual products. Our study indicates that the proposed methodological guidelines can offer significant benefits when evaluating co-produced climate services, such as helping stakeholders to map complex change pathways; capturing external influences; measuring the intangible; bridging conflicting interests; identifying unexpected effects; enhancing usefulness and learning; clarifying underlying assumptions; increasing ownership and buy-in; understanding causal linkages; and building trust.

Our study makes a significant contribution to a better understanding of what methods can be used when evaluating co-produced climate services, hence, marks a step toward improved research impact evaluation. Future empirical testing is, however, required to assure that the proposed methodological guidelines are feasible in practice. We recommend applying these guidelines in an array of empirical contexts to test their applicability in various stakeholder constellations and situations, and thus stimulate further refinement. Future research can engage with a growing body of developmental evaluation literature for cross-learning of methodological challenges and good practices.

Our study shows that evaluation is essential to enhance research impact of climate services, as it can reveal strengths and weaknesses of the current approaches and pave the way for more effective, user-oriented, and demand-driven climate services. Improved evaluation practices can ultimately increase the effectiveness and efficiency of climate services, thus equipping decision-makers with improved climate risk information and assessments. Most importantly, this can better inform the adaptation efforts urgently needed to combat climate change.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

ME: conceptualization, methodology, investigation, and writing—original draft preparation. KA, ÅGS, and JI-J: conceptualization, writing—review and editing, and supervision. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Risk of loss of tourism attractiveness in the Western Mediterranean under climate change

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The sun and sea tourism is key for economy of the southern European countries. This economic sector is expected to be severely affected by climate change due to the projected loss of beaches, loss of thermal comfort, water restrictions or extreme events, among other impacts. Thus, adaptation strategies need to be developed urgently. To do so, it is necessary to first conduct an assessment of the risk of loss of tourism attractiveness to guide the development of such strategies. Furthermore, uncertainties in the different factors are considered into the risk analysis. In this study we analyze the risk of loss of tourism attractiveness due to climate change in the Spanish Mediterranean destinations, in the Western Mediterranean, as a case study. To do so, the Vulnerability Sourcebook methodology is adopted and modified to incorporate the uncertainties in the different elements of the impact chains. The increase in heat stress and the loss of beach availability have been identified as the climate change induced hazards that will affect the most the region attractiveness. Also, the impact chains have been constructed and several climatic and socioeconomic indicators have been considered after a knowledge co-production process with selected stakeholders. The weights assigned to each indicator have been obtained from an analytic hierarchy process based on the results of a consultation with sector experts. The results of the impact chain operationalization have shown that exposure and vulnerability in all the touristic destinations in the region are very similar and that the hazard will largely increase in the next decades, specially under the future scenario SSP585 or the RCP8.5. However, the final risk does not seem to suffer a large increase because of the relatively small weight assigned to the hazard. In other words, the exposure (e.g., typology of the tourists and touristic activities) or the vulnerability (e.g., capacity to put in place adaptation strategies) would be more important than the projected change in the hazard (e.g., heat stress increase or beach reduction). The benefits and limitations of the methodology are discussed and some suggestions for the validation of the assessment are proposed.

KEYWORDS

impact chain uncertainties, risk, tourism attractiveness, climate change impacts, AHP

Introduction

In recent decades, the tourism sector has become one of the most important global economic activities mainly due to technology, information and reduction of boundaries (Peric, 2005). Tourism is a major global economic sector that has undergone tremendous growth over the last 50 years (UNWTO, 2018) and the global economic contribution of the tourism sector has continuously increased since then. The World Travel and Tourism Council (WTTC) estimates the sectorial contribution to global economy in 2015 was US$7.2 trillion (9.8% of the global GDP) and 284 million jobs (9.1% of jobs worldwide) (Wttc, 2016). In this context, the western Mediterranean is one of the favorite tourism destinations (Rovira Soto and Anton Clav, 2017) and the tourism activity has a great impact in the economy of the region (Coccossis and Koutsopoulou, 2020).

Climate change is one of the key future challenges for both developed and developing countries, and therefore for their economic activities, including tourism. With a growing population and a consequent rise of the demand for food, water and energy, and a gradually diminishing natural resource base, climate change will act as a "threat multiplier" (Board, 2007), aggravating resource scarcity and putting further stress on socio-ecological and economical systems. Severe floods, storms, droughts and heat waves as well as groundwater scarcity may change the socio-economic system of a region or country as we know it currently (Fritzsche et al., 2014).

The interaction between the tourism activity and climate change could be assessed from different points of view. From the one side, the global tourism system is currently almost entirely dependent on fossil fuel energy and directly contributes to an important share of greenhouse gas (GHG) emissions that interfere with the climate system (Scott et al., 2012; Gössling and Peeters, 2015). Between 2009 and 2013, tourism's global carbon footprint has increased from 3.9 to 4.5 GtCO2e, four times more than previously estimated, accounting for about 8% of global GHG emissions (Lenzen et al., 2018). Furthermore, the reliance on CO2 emissions offsetting would expose the sector to extensive and continued carbon liability costs along the century, and could be perceived as climate inaction which is contrary to sustainable tourism development (Scott et al., 2016). From the other side, there is a growing sectorial awareness of the vulnerability of tourism to climate change (Gössling and Scott, 2018). However, in spite of that vulnerability and the economic importance of the sector, the investigation of climate-induced impacts on tourism has not received sufficient attention and substantial knowledge gaps still remain (Enríquez and Bujosa Bestard, 2020). In particular, the differential climate change impacts faced by the tourism sector at a regional and destination country scale remains uncertain (Scott et al., 2019).

To reduce those knowledge gaps is not an easy task. For instance, differences in institutional settings, including divergent objectives, needs and priorities, represent a major barrier for the transfer of knowledge from academia to practice (Weichselgartner and Kasperson, 2009). Moreover, researchers look for models that are generalizable, whereas decision-makers require tailored answers, highlighting a disconnection between knowledge production in academia and the need for practical solutions by industry. Such discrepancies affect feedback loops among domains, leading to knowledge gaps, inaccessibility and lack of exchange (Loehr and Becken, 2021).

Regarding tourism in the Mediterranean, a large part of it is based on the "sun and sea" model with a clear seasonality peaking in summer. This type of tourism is potentially vulnerable to the global rise of temperatures that have led to an increase of heat waves in the last years (Lindsey and Dahlman, 2020; Miller et al., 2021). In fact, some authors have concluded that the Mediterranean region will become "too hot" for tourist comfort in the peak summer season by as early as the 2030s (Rutty and Scott, 2010). In addition, a permanent coastal flooding is expected due to the mean sea level rise in the Mediterranean (Agulles et al., 2021; Ciampa et al., 2021) which would reduce the beach resource. Water availability is also expected to be reduced in the coming decades which potentially could strongly affect the tourism activities which are responsible of a large part of water consumption in Mediterranean destinations (Garcia et al., 2022). Finally, the Mediterranean coastal zone is severely impacted by extreme climatic events (e.g., storm surges) coupled with human-induced pressures (e.g., uncontrolled building on coasts), resulting in a growing vulnerability (Satta et al., 2017). All these threats are particularly damaging in the archipelagos due to their high dependence on source markets and tourism economy (Mackay and Spencer, 2017; Vara et al., 2020; León et al., 2021).

In spite of the hints that climate change could have an impact on the tourism activity in the Mediterranean, it is important to produce actionable information for the stakeholders and to assess those impacts in a systematic way. The goal of this paper is to produce a holistic view to the risk of loss of touristic attractiveness due to climate change in Mediterranean coastal destinations. In order to produce a risk assessment useful for the design of adaptation policies and to reduce the above mentioned gap between academia and industry, we propose to follow the Vulnerability Sourcebook (Fritzsche et al., 2014; Zebisch et al., 2017) and the TANDEM framework for the co-production of knowledge (Daniels et al., 2019, 2020). Moreover, in the framework of the UNCHAIN project (https://www.unchain.no), funded by the EU JPI-AXIS program, the methodology has been extended to explicitly quantify the uncertainties associated to the risk computations.

This work is organized as follows. The conceptual framework for risk analysis and the sources of data are presented in section Material and methods. The results in section Results are organized following the module structure of the Vulnerability Sourcebook. The discussion is

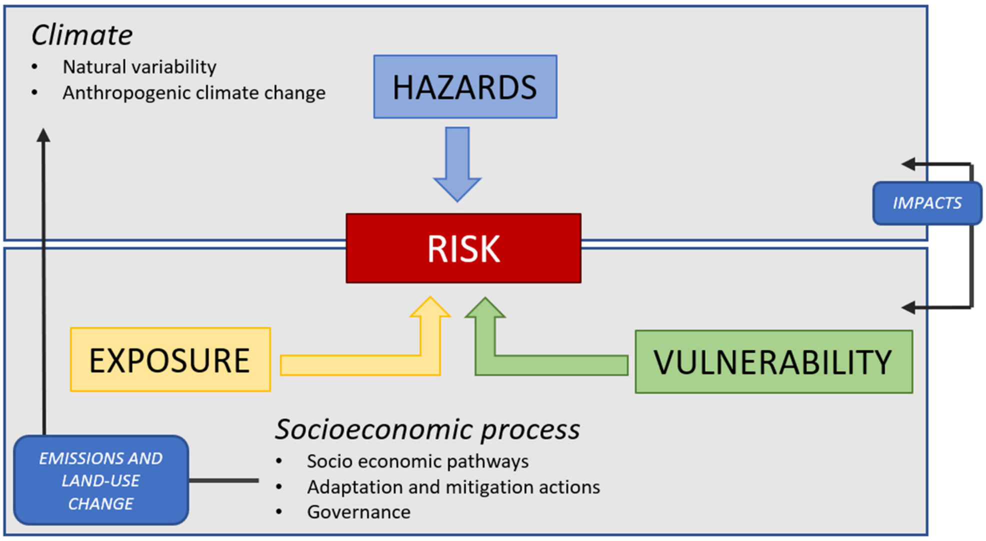

FIGURE 1
Illustration of the core concepts of the IPCC WGII AR5. The risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems.

developed in section Discussion followed by the conclusions in section Conclusions.

Materials and methods

Conceptual framework for risk analysis

Following the IPCC AR5 (Mach et al., 2016), in the context of climate-related impacts, risk is defined as a combination of three interacting components: (1) climate-related hazards (including hazardous events and trends), (2) exposure in places and settings that could be adversely affected and (3) vulnerability of human and natural and socio-economical systems (see Figure 1). So, the risk concept is defined by "the potential for consequences (impacts) where something of value is at stake and where the outcome is uncertain" (Zebisch et al., 2017). Then, it is not enough to identify climate hazards (i.e., floods, heat waves, water scarcity etc.,) but also the grade of affection to the socio-economic system of the region under evaluation. That is, to quantify the possible consequences depending on the exposure and vulnerability components. (Mastrandrea et al., 2010; Fritzsche et al., 2014; Toimil et al., 2017; Leis and Kienberger, 2020).

In this study, the risk assessment follows the approach proposed in the Vulnerability Sourcebook (Fritzsche et al., 2014), which is based on the concept of Impact Chain (IC). The impact chain is an analytical tool that helps to better understand, systemize and prioritize the factors that drive risk in the system of concern (Zebisch et al., 2017), so it lays the foundation for the entire risk assessment. Nine modules (from m1 to m9) sequentially built are required to complete the assessment (Figure 2). Here we present the results for the first seven modules. In those parts of the assessment where an interaction with stakeholders is required (modules 1 to 3), the TANDEM framework for co-production of knowledge (Daniels et al., 2019, 2020) has been applied. The Tandem framework provides a holistic approach for the co-design of climate services. The framework proposes iterative steps that the three parties (science, industry and police makers) can collectively follow to inform, guide and structure the transdisciplinary interaction for climate-resilient planning based on science knowledge (Daniels et al., 2019).

In the framework of the UNCHAIN project, a new extension of the IC approach has been implemented in order to take into account the uncertainties linked to each element of the risk assessment (Melo-Aguilar et al., 2022). This will be briefly described here, and the reader is referred to Melo-Aguilar et al. (2022) for further details. In the IC framework, the risk is formulated as the weighted combination of hazard, exposure, and vulnerability indicators. A typical choice is to assume an arithmetic combination, although it could be any other:

$$R = W_H{*}H + W_E{*}E + W_V{*}V; \quad (W_H + W_E + W_V = 1) \quad (1)$$

where W_H, W_E and W_V represent the relative weight in the final risk of the hazard (H), exposure (E) and vulnerability (V), respectively. At the same time, those three components are defined from a set of indicators:

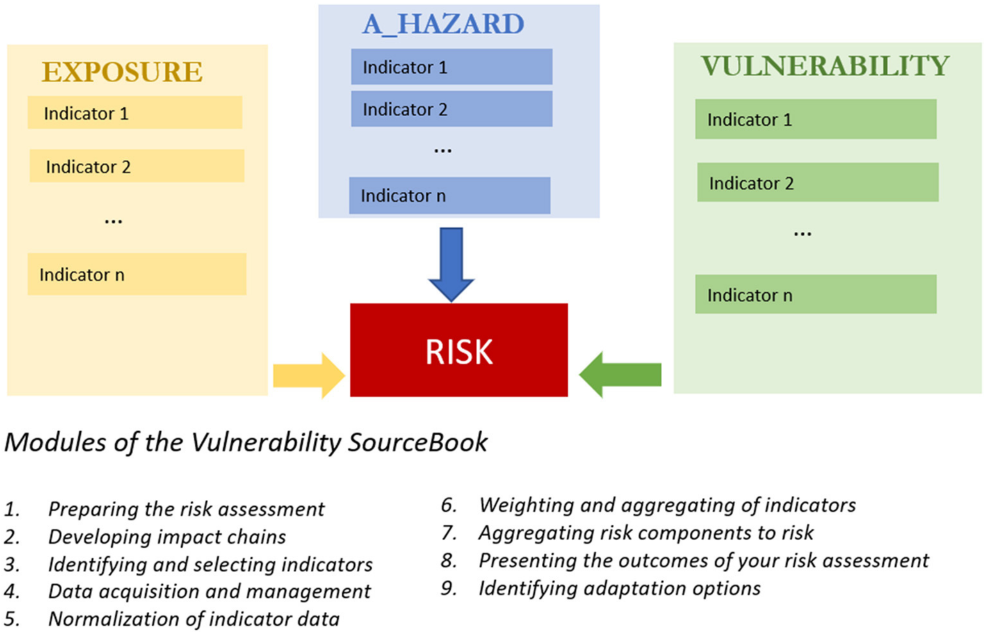

FIGURE 2
Structure of an impact chain following the vulnerability sourcebook modules.

$$H = \sum w_i * h_i;\ E = \sum w_j * e_j;\ V = \sum w_k * v_k;$$
$$\left(\sum w_i = 1; \sum w_j = 1; \sum w_k = 1\right) \tag{2}$$

where h_i, e_j and v_k are the normalized indicators that determine the total hazard, exposure and vulnerability, respectively, and the w's represent the corresponding weights. So, the final risk can be formulated as a combination of scalar quantities:

$$R = W_H * \sum w_i * h_i + W_E * \sum w_j * e_j + W_V * \sum w_k * v_k \tag{3}$$

The proposal of Melo-Aguilar et al. (2022) is to substitute all the scalar quantities by probability density functions (pdf's) that will describe not only the median value of the quantity but also the associated uncertainty. In consequence, the final risk will not be described by a scalar quantity but by a pdf assigning a probability to each value.

In practice, to implement this approach some choices have to be made to define the pdf's. For all those indicators from which enough information could be retrieved, we use a Gaussian function with an amplitude defined by the estimated uncertainties:

$$P(X) = e^{-\frac{(X - X_0)^2}{2\sigma^2}} \tag{4}$$

Where P represents the probability of having an indicator or weight value, X_0 is the central most likely value as provided by the databases or the expert opinions and σ is the range of uncertainty. The uncertainty associated to the indicators could be inferred from the characteristics of the databases (e.g., spread of climate model results or temporal variability of indicator time series).

For those indicators from which a central value could not be identified or even from which there is no information, a homogeneous pdf is used:

$$P(X) = \frac{1}{x_{max} - x_{min}};\quad \forall\, x_{min} \le x \le x_{max} \tag{5}$$

where x_{max} and x_{min} determine the maximum and minimum possible values.

Regarding the weights assigned to the indicators, they can be derived from existing literature, stakeholder information or expert opinion. In our case, we derive them from expert opinion following the Analytical Hierarchical Protocol (AHP; Saaty, 1990), which is widely used in risk assessment studies (Lamata and Pelaez, 2002; Hsu et al., 2017; Tascon-Gonzalez et al., 2020). This method is based on the comparison by pairs between different choices, which is easier than to consider

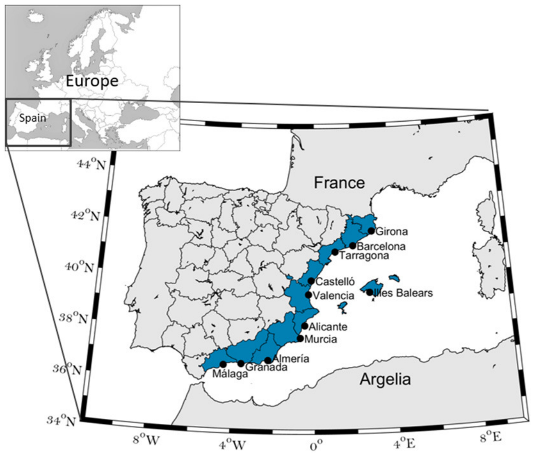

FIGURE 3
Study site with the provinces included in the study (blue area) and the main cities (black dots).

multiple variables. In particular we have developed an on-line poll to be answered by a wide variety of people with questions aiming at comparing the different indicators by pairs. In the end, from each answered poll we obtain a value for each weight, and the spread of values among all the answered polls define the range of uncertainty of that weight.

Once all the indicator and weights are compiled with their associated uncertainty, the risk is computed using the UNTIC tool (https://untic.pythonanywhere.com/) which is a friendly open-source web tool that do the required computations to propagate the uncertainties.

Study site and data sources

The study area includes the 11 Spanish provinces located in the western Mediterranean (Figure 3) which include some of the most important sun and sea tourism destination in the world (Lanquar, 2015). The source of information for most exposure and vulnerability indicators has been the Instituto Nacional de Estadística (INE; https://www.ine.es/), which is the responsible institute for statistics development in Spain. Detailed information is presented in Table 1. Regarding the climate hazards, two of them have been considered based on the stakeholder's feedback, the increase of heat stress and the loss of sand beach availability (see Section Developing impact chains). Regarding the former, the chosen indicator is the Heat Index (Schwingshackl et al., 2021), which combines relative humidity with the air temperature and is more representative of the perception of heat stress than only using the air temperature. Daily fields of Heat Index during summer months are obtained from an ensemble of 4 global climate simulations (CNRM-CM6-1, CNRM-ESM2, MIROC-ESLL and UKESM1-0-LL) which are part of the 6th phase of the Coupled Model Intercomparison Project (CMIP6, https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-extreme-indices-cmip6?tab=overview). Regarding beach availability, the hazard indicator considered is the percentage of beach surface loss with respect to the total beach surface. The data for this indicator has been retrieved from Agulles et al. (2021). Note that Agulles et al. (2021) focus on the Balearic Islands and not all the provinces considered here. However, all the provinces have a similar typology of sand beaches and sea level rise projections are very similar for all the region (Cramer et al., 2020). Thus, it is safe to assume that the beach loss in all the provinces will evolve similarly to the Balearic Islands.

All indicators have been aggregated to the province level. The hazard indicators have been computed for the present conditions (2000–2020) and for the end of the century (2080–2100) under the SSP245/RCP4.5 and the SSP585/RCP8.5 greenhouse gas emission scenarios (GHG, https://www.ipcc.ch/report/emissions-scenarios/). Note that the heat index is computed using the more recent SSP scenarios while the beach availability is derived from RCP scenarios as there has not been an update of the Agulles et al. (2021) work with the new scenarios. Nevertheless, the chosen scenarios are very similar in terms of global warming. The exposure and vulnerability indicators have been kept constant to the present conditions in order to highlight how the change in the climate would modify the risk.

Results

Preparing the risk assessment

Following the TANDEM approach (Daniels et al., 2019, 2020), peer to peer interviews have been designed for the co-production of knowledge with experts of the tourism sector coming from academia, industry and regional government. Aiming at having a productive exchange to obtain the most reliable information from them, the interviews were designed to fit the background of the interlocutor and had an average duration of 1 h. Also, all the interviews had the same initial structure, but they were flexible enough to be adapted depending on the feedback from the stakeholder.

The structure of the interviews was designed as follows. First, we briefly introduced the research team to the expert in order to break the ice and to define the position of the interviewer and the interviewee. I.e., to let him/her know that his/her expertise was required to fill some knowledge gaps in a relevant issue that also affects he/she. Some initial questions about the tourism sector status were included in order to have a first unbiased opinion of how climate change was placed among

TABLE 1 Overview of the indicators selected for the impact chains.

ID	Indicator	Definition	Data source
Hazard			
A1 (CS1)	Heat Index (°C)	Apparent temperature. What the temperature feels like to the human body when relative humidity is combined with the air temperature.	https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-extreme-indices-cmip6?tab=overview
A1 (CS2)	Loss of beach area (%)	Loss of beach area at the end of the century (2080–2100) with respect to the current available area (2000–2020), due to mean sea level rise.	Agulles et al. (2021)
Exposure			
B1	Age of tourists (%)	Tourist >65 years old during the year 2019	https://www.ine.es/jaxiT3/Tabla.htm?t=12441&L=0
B2	Purchasing power (euros/day/person)	Daily average spends per person (euros/day/person) during year 2019	INE (https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736177002&menu=ultiDatos&idp=1254735576863
B3	Tourist profile (%)	% of tourist arrival that are family	No data
B4	Comfort level	Number of hotels ≥3 stars available	www.booking.com
B5	Tourist origin		No data
B6	Quality of beaches services	Number of beaches with blue flag with respect to the total number of beaches of the region	https://www.banderaazul.org
Vulnerabiltiy			
C1	Health system	Life expectancy (reliable indicator of health system quality)	https://www.ine.es/ss/Satellite?L=es_ES&c=INESeccion_C&cid=1259926380048&p=1254735110672&pagename=ProductosYServicios/PYSLayout
C2	Quality of information for tourists	Grade of frustration when tourist arrives to the destination.	https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736176996&menu=ultiDatos&idp=1254735576863
C3	Long term planning	GDP per capita (reliable indicator of the capacity to adapt for future socio-economic threats)	https://www.ine.es/jaxiT3/Tabla.htm?t=9947
C4	Offer of alternative activities	From 0 to 1. 0 = no alternatives apart from sun and sea, 1 = many alternatives apart from sun and sea	Expert assessment
C5	Dependence of source markets	From 0 to 1. 0 = low dependence of source markets, 1 = high dependence of source markets.	No data
C6	Overcrowding	Number of tourist/number of residents for the year 2019	https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736176996&menu=ultiDatos&idp=1254735576863
C7	Deseasonalization		No data
C8	AC measures	Parks, shallow zones, air conditioning.	Expert assessment

the expert concerns. After this, the threats for the society linked to climate change were presented from a technical point of view, but at the same time understandable and complemented with observational evidence from the last years in the region of interest. Then, the UNCHAIN project goals and the concept of risk were introduced.

Following the introduction, several direct questions were asked to figure out what aspects of climate change may have the largest impact on the sector (e.g., "would water scarcity be a problem? do you foresee any problems linked to the increase of temperature"?). Depending on the hazards that were identified by the expert, several questions were prepared to identify what aspects could play a role in the tourist perception of destination attractiveness (e.g., "do you think all the tourists will be similarly affected by temperatures higher than normal? "Do all types of tourists value the beach quality?"). Also, other questions were prepared to identify the vulnerability aspects and what factors may help for adaptation or mitigation (see the document "List of questions for stakeholders" in the Supplementary Information).

In a final part, some questions were included to get information about what indicators would be the most useful to operationalize the impact chains once defined. To conclude the interview, a final discussion was prepared to rethink about what was discussed and to identify strengths and weaknesses of the sector in front of future adaptation strategies.

Developing impact chains

The peer-to-peer interviews were conducted with eleven experts, four from the administration (a general director from the regional government, a tourism councilor and two technicians), six from the industry (hotel managers, coordinators from hotel associations) and one member from the academia. From the analysis of the interviews, two main hazards potentially affecting the tourism attractiveness were identified: the increase of heat stress and the loss of beach surface. Accordingly, based on the experts' inputs, two impact chains were defined (see Figures 4, 5).

Regarding to the first Impact Chain: "Risk of loss of attractiveness due to an increase in the heat stress" 14 indicators have been selected (Figure 4). Regarding the exposure of the tourists to the increase of heat stress, all the experts agreed that in order to quantify the comfort level of the tourist when a heat wave is happening during their holidays, the status of the hotel is relevant (B4), since they can stay in the hotel premises enjoying the services provided (AC, pool, bar, spa etc.,), to avoid the outdoors high temperatures. Also, the perception of discomfort is related to their purchasing power (B2). The age of the tourist (B1) is another obvious indicator when the tourist faces a heat wave, as heat has a stronger impact on older people with respect to younger ones (Zhang et al., 2018). Also, the origin of the tourists can modify the perception of heat (B5, e.g., tourists from Mediterranean countries are more familiar with the warm events). Finally, the type of activities the tourists are conducting could also affect (B3, e.g., only beach related activities, sightseeing, hiking, biking,).

Concerning the vulnerability part, the experts agreed on considering that the quality of the health system and the level of safety (C1) may affect the attractiveness. The quality of the information provided to the tourists (C2, e.g., early-warning systems) can help to reduce the negative feelings induced by heat stress. Long term planning (C3) and coordination among different administrations and the industry is a key aspect that is needed for a successful implementation of adaptation strategies. The capacity to offer alternative activities less affected by heat (C4) can improve the tourist perception as well as the availability of AC measures (C7, e.g., fountains, green areas, projects of fresh air recirculation in buildings, etc...). Conversely, the level of overcrowding (C6) can have a negative impact as the massification of touristic areas can add up to the feeling of discomfort. Finally, two vulnerability aspects were pointed out as potentially relevant. The first one was the dependency on source markets (C5), as a strong dependence on a few foreign markets, reduce the flexibility to attract tourists from countries less sensitive to heat stress. The second one was the level of seasonality in the tourist arrivals (C8). A tourist destination strongly dependent on the arrivals during the hotter summer period would suffer more than another one which is able to shift a significant part of the arrivals to other cooler seasons.

For the second impact chain (IC2): "Risk of loss of tourism attractiveness due to the reduction of beach availability", the experts identified almost the same indicators as potentially relevant for the risk assessment (see Figure 5). The only difference is that they have considered that the quality of beach services (B5) should be taken into account as an additional element of exposure. Conversely, the vulnerability indicator related to the availability of AC measures was obviously discarded.

Identifying and selecting indicators

The heat stress can be defined in many ways (e.g., from raw temperature, physiological parameters, heat wave indices, etc...). In our case, for this hazard indicator, we have chosen the Heat Index (Schwingshackl et al., 2021), which combines relative humidity with the air temperature and is more representative of the perception of heat stress than only using the air temperature. The average of the heat index for the summer period (June, July and August) is considered as a measure of the heat stress. For the beach availability, the hazard indicator considered is the percentage of beach surface loss due to sea level rise with respect to the total beach surface in present conditions.

Concerning the characteristics of the tourists, several indicators have been defined. The age of the tourists (B1) is represented by an indicator measuring the percentage of tourists older than 65 years with respect to the total number of tourists. This gives a reasonable view of the share of exposed population to heat stress and beach availability. The averaged wealth of the tourists in a destination (B2) is quantified by the daily average spend per person. Finally, the origin of the tourists (B5) is represented by the percentage of tourists from warm countries (i.e., with temperatures similar to the destination) with respect to the total number of arrivals.

The characteristics of the destination are also represented in the impact chains. The level of accommodation comfort (B4) in a destination is defined as the fraction of hotels with more than 2 stars. The quality of beach services (B6) is described by the number of beaches with blue flags with respect to the total number of beaches in the region. The quality of the health system at the destination (C1/ is represented

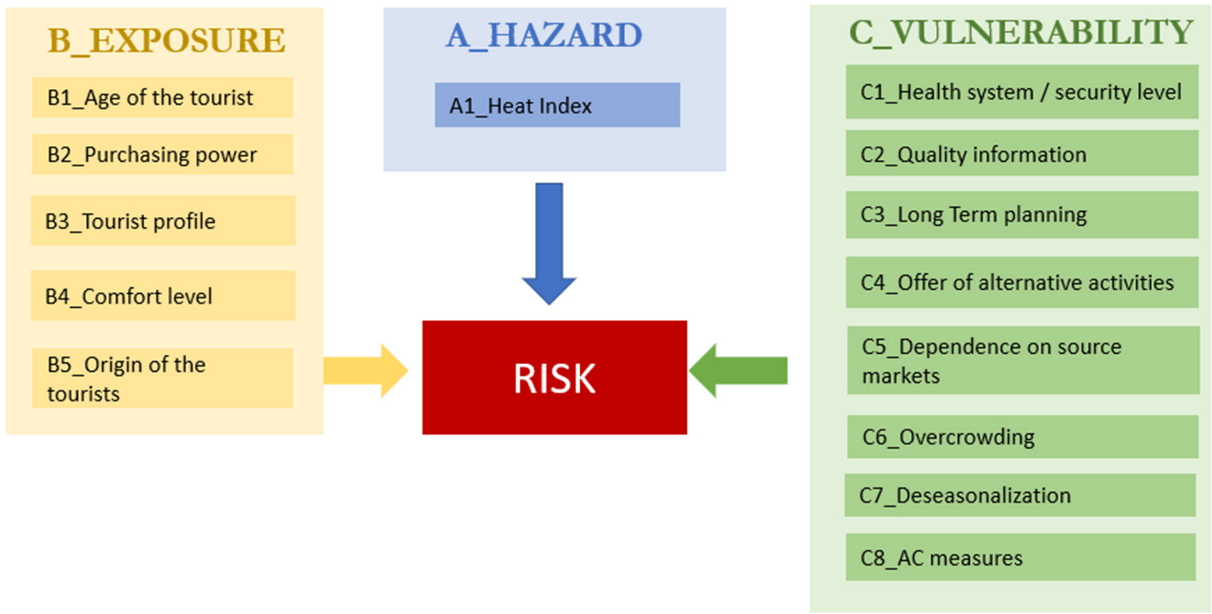

FIGURE 4
Impact chain 1, corresponding to the "Risk of loss of attractiveness due to an increase in the heat stress".

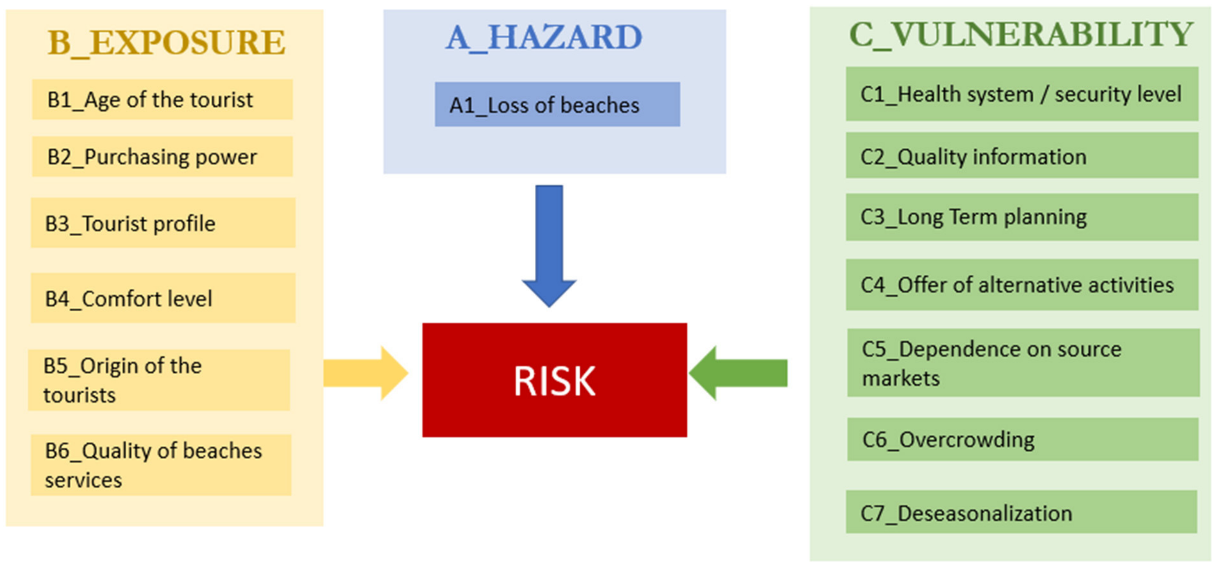

FIGURE 5
Impact chain 2, corresponding to the "Risk of loss of attractiveness due to a reduction of beach availability".

by the life expectancy and the long-term planning capacity (C3) is measured by the GDP per capita, as it is commonly related (i.e., countries with higher GDP have the political structures that allow long-term planning). An overcrowding index (C6) is defined as the number of tourists over the number of residents and the tourism seasonality (C7) is defined as the ratio of summer tourists over the annual average of tourist arrivals.

There are other elements of the impact chains that could not be quantified objectively. For those elements qualitative indicators have been developed based on expert opinion. These are the type of activities conducted by tourists (B3), the quality of tourist information (C2), the offer of activities not related to sun and sea tourism (C4), the dependence on source markets (C5) or the existence of cooling infrastructures (C8).

Data acquisition and management

The data required for the above identified indicators have been obtained from the databases described in Section Study site and data sources and Table 1 and aggregated to province level (see Supplementary Table 1). For those indicators where no information was available at all, the associated pdf is set to a homogeneous pdf where all values between 0 and 1 are equally likely (i.e., maximum uncertainty).

Normalization of indicator data

In order to homogenize the different indicators, which are expressed in diverse units, the original data has been normalized to a scale from 0 to 1. For the quantitative indicators, this has been done using a linear transformation. Data below a pre-defined minimum threshold correspond to a value of 0, data above a pre-defined maximum threshold correspond to a maximum value of 1 and for the values in the middle the following formula has been applied:

$$N = \frac{I - I_{\min}}{I_{\max} - I_{\min}} \tag{6}$$

where I is the original value of the indicator and $I_{\min}$ and $I_{\max}$ are the minimum and maximum thresholds, which have been subjectively set by the experts (Table 2).

For qualitative indicators based on expert opinions four categories were set (low, mid-low, mid-high, and high). The experts were asked to fit the indicator value into one of those categories. Then, they were transformed to a numerical value (0.12, 0.37, 0.62, and 0.87, respectively) with an associated homogeneous uncertainty of 0.25.

Finally, it must be noted that all indicators have been defined in a way that higher values imply higher risk.

Weighting and aggregating of indicators

The AHP based on the results from the polls described in Section Conceptual framework for risk analysis, has allowed to quantify the weight associated to the indicators along with their uncertainties. It must be noted that the participatory poll (see the document "List of questions for stakeholders" in the Supplementary Information) has been designed to obtain the weights among indicators (level 2, weights in equation 2), and also the relative importance among the risk components (level 1, weights in equation 1, see next section).

In the IC-1 ("risk of loss of attractiveness due to an increase in the heat stress"), all the exposure indicators have similar weights with values ranging from 0.16 to 0.24. The associated uncertainties are relatively small being between 0.02 and 0.07, which represents a noise-to-signal ratio below 0.4 in all cases (i.e., the magnitude of the uncertainty is less than a 40% of the weight value). For the vulnerability indicators, the weights are also very similar, with values between 0.09 and 0.15. The associated uncertainty ranges from 0.02 to 0.06 and represents a noise-to-signal ratio also below 0.4 in all cases except for indicator C3 (Capacity for long term planning), which reaches a noise-to-signal ratio of 0.7 (see Table 2).

In the IC-2 ("Risk of loss of attractiveness due to a reduction of beach availability"), most of the exposure indicators have a similar weight, although the indicators B3 (related to the type of tourist activities) and B2 (related to the tourist wealth) have slightly higher weights. Conversely, the indicator B6 (country of origin) is the one with the lowest weight. The associated uncertainty ranges from 0.02 and 0.07 and the noise-to-signal ratio is lower than 0.25 except for B1 (tourist age) for which the uncertainty is about half of the weight value. The weights obtained for the vulnerability indicators are similar for most of them with some exceptions. The weights for C1 (quality of the health system) and C7 (presence of cooling infrastructures) are relatively small while C6 (overcrowding) is the one with the largest weight. The associated uncertainties are larger in this case, with values ranging from 0.04 to 0.07, which represents a noise-to-signal ratio between 0.35 and 0.65 (see Table 2).

The aggregated indicators for each impact chain are presented in Figures 6, 7 for present conditions and for the end of the century under the two GHG scenarios. The value of each indicator is presented in Supplementary Table 1.

Regarding the IC-1, the hazard in present climate is low everywhere, as the summer average of heat index is below 31°C in all provinces. Under scenario RCP4.5 the index increases through the XXI century reaching a range of values between 32.2 and 35.4°C, which is equivalent to medium threat for heat disorders. Under scenario RCP8.5 the values reach a range between 37.5 and 40.5°C which implies a high threat for heat disorders. The lowest value (0.30) is found in the Balearic Islands and is driven by the higher comfort of the accommodation (B4) and the profile of the tourists choosing that destination (B3). The higher values (0.55) are obtained in Valencia and Almeria. In the former, the age of the tourists (B1) pushes toward higher values while in the later the comfort level (B4) of the accommodation drives the exposure to lower values. Concerning the vulnerability, the values are more homogeneous ranging from 0.42 to 0.55. The reason for this homogeneity is that all destinations show very similar values in most of the indicators. The exception is on the quality of the information provided (C2) and the overcrowding (C6), which is very

TABLE 2 Normalization thresholds and weights assigned for each indicator in the two ICs.

Indicator	Sign	Normalization		Weight in IC1	Weight in IC2
		Minimum	Maximum		
% Loss of beach area respect to the present	+	0%	100%	–	1.00 ± 0.00
Heat index (°C)	+	32°C	52°C	1.00 ± 0.00	–
% Tourists older than 65 years	+	0%	100%	0.24 ± 0.02	0.14 ± 0.07
Tourist wealth	−	100 €/day	300 €/day	0.20 ± 0.07	0.21 ± 0.05
% Family tourism	−	No data	No data	0.19 ± 0.05	0.22 ± 0.02
Comfort Level (n° hotels ≥3 stars)	−	33	1376	0.21 ± 0.03	0.17 ± 0.02
Quality of beaches services (n° blue flags/ overcrowding)	−	4	48	–	0.17 ± 0.04
Origin of the tourists		No data	No data	0.16 ± 0.07	0.09 ± 0.03
Heath system (life expectancy)	−	83 years	95 years	0.13 ± 0.05	0.05 ± 0.04
Quality information for tourists	−	0.9	11.9	0.12 ± 0.02	0.14 ± 0.06
Long term planning (GDP per capita)	−	18.9	31.7	0.09 ± 0.06	0.12 ± 0.07
Offer of alternative activities		No data	No data	0.12 ± 0.02	0.14 ± 0.05
Dependence of source markets	+	No data	No data	0.11 ± 0.04	0.13 ± 0.06
Overcrowding (% tourists/residents)	+	0.9	11.9	0.15 ± 0.02	0.19 ± 0.07
AC measures		No data	No data	0.15 ± 0.03	–
Deseasonalization		No data	No data	0.14 ± 0.02	0.14 ± 0.05

The sign (−) indicates that the indicator values have been inverted in order to reflect that higher values imply higher risk.

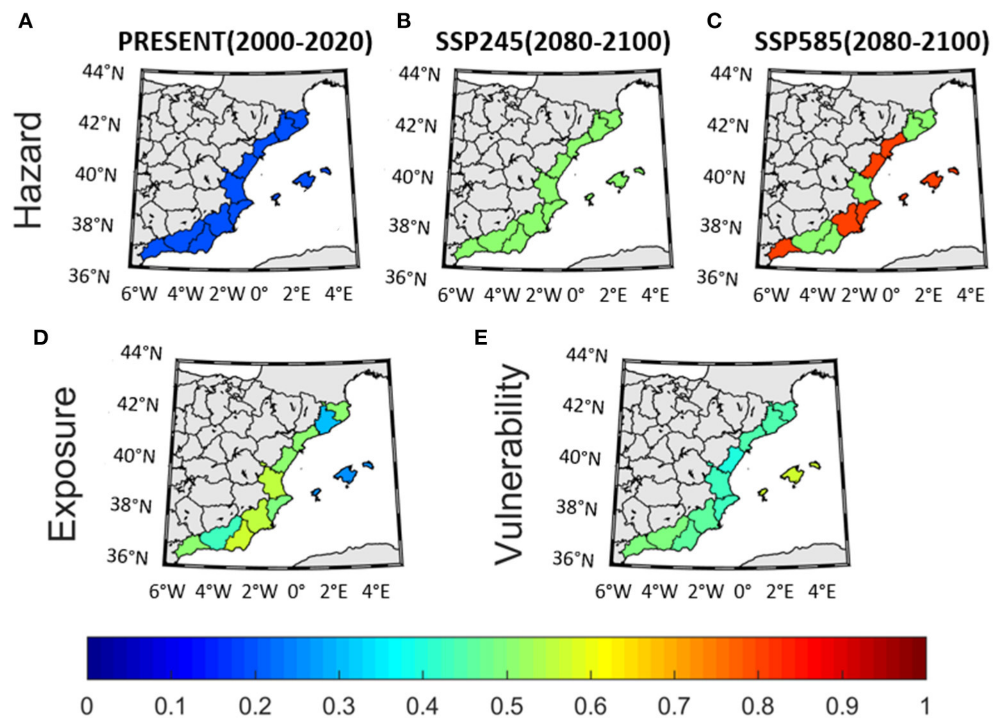

FIGURE 6
Aggregated indicators for impact chain 1, corresponding to the "Risk of loss of attractiveness due to an increase in the heat stress". **(A)** Hazard value in present conditions (200–2020), **(B)** at the end of the century (2080–2100) under SSP245 and **(C)** under SSP585. **(D)** Exposure and **(E)** Vulnerability. Note that **(D,E)** have the same values for present and future.

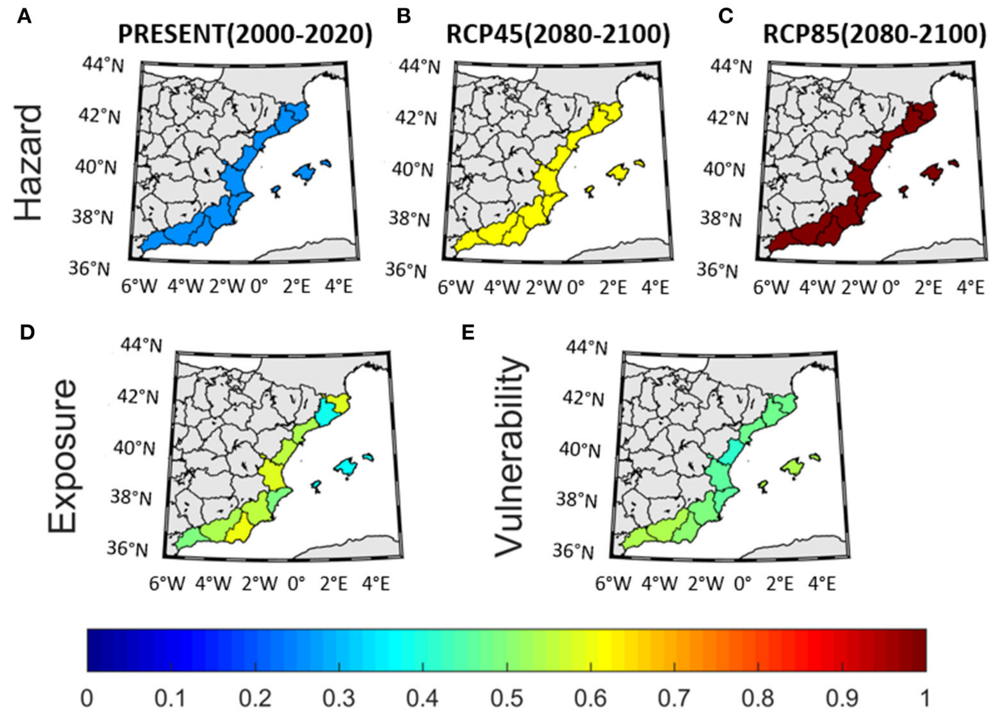

FIGURE 7
Aggregated indicators for impact chain 2, corresponding to the "Risk of loss of attractiveness due to a reduction of beach availability". **(A)** Hazard value in present conditions (200–2020), **(B)** at the end of the century (2080–2100) under RCP45 and **(C)** under RCP85. **(D)** Exposure and **(E)** Vulnerability. Note that **(D,E)** have the same values for present and future.

diverse among the destinations. The associated uncertainties (see Supplementary Table 2) are lower than a 10 % of the aggregated values and the distribution shape is close to a Gaussian distribution (see Supplementary Figure 1).

For the IC-2, the hazard values are very homogeneous in all the destinations at any temporal horizon (see Supplementary Table 3). The reason is that the sandy beaches in all the region have very similar characteristics (i.e., grain size, beach slope) and the projected changes in sea level and waves in the whole region are expected to be fairly homogeneous. In consequence, the hazard at the end of the century in all destinations will reach medium values under scenario RCP4.5 and will be very high under scenario RCP8.5. The exposure in the Balearic Islands is again the lowest (0.39) and in Valencia and Almeria the highest (0.58) for the same reasons that in IC-1. The vulnerability is again rather homogeneous and similar to what was found in IC-1. Concerning the uncertainties (see Supplementary Table 3 and Supplementary Figure 2), they are lower than a 10% keeping an almost Gaussian shape.

Aggregating risk components to risk

Concerning the weights of the risk components, the results are similar in the two impact chains (Table 3). The weight of the hazard on the final risk is 0.13 and 0.21 for the IC-1 and IC-2, respectively. The exposure is more relevant in the IC-1 with a weight of 0.52 and a weight of 0.38 in the IC-2 while the vulnerability is more influential in IC-2 (0.41) than in IC-1 (0.34). The associated uncertainties are smaller in the IC-1, with values around 0.10, than in IC-2 with values ranging from 0.15 to 0.23.

Using those weights to combine the aggregated indicators presented above, we obtain the final risk for present conditions and for the end of the century under GHG scenarios (Figures 8, 9 and Table 4). Concerning the IC-1, the risk associated to the heat stress increases with time under both GHG scenarios. In present conditions it takes values in the range of 0.37–0.49 and goes up 0.40-0.52 under scenario RCP4.5 and to 0.40–0.55 under scenario RCP8.5. The relatively small change is linked to the low importance experts gave to the heat stress in front of the exposure and vulnerability. In other words, they considered that the potential loss of attractiveness of the destination depends more on the typology of the tourists and the activities they perform than to the actual magnitude of the heat stress.

For the risk associated to the loss of beach availability, we find that the risk increases from mid-low present values (0.40–0.47) to mid-high values at the end of the century under scenario RCP 4.5 (0.47–0.54) and under scenario RCP8.5 (0.53–0.60). Despite the large increase in the hazard, the final risk does not

TABLE 3 Weights and uncertainties among level-1 components of the risk for both impact chains.

IC1 heat stress	Weight	Uncertainty	IC2 beach flooding	Weight	Uncertainty
Hazard	0.13	0.11	Hazard	0.21	0.15
Exposure	0.52	0.11	Exposure	0.38	0.23
Vulnerability	0.34	0.09	Vulnerability	0.41	0.22

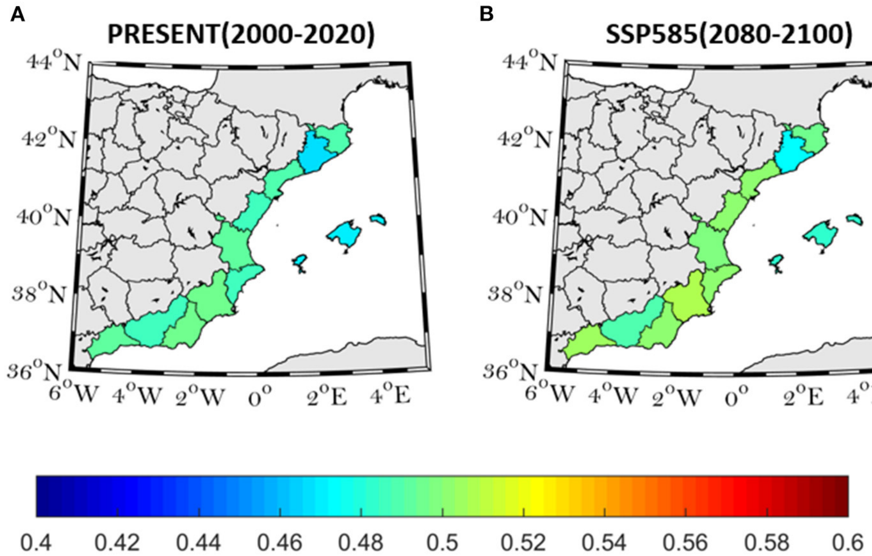

FIGURE 8
Final risk of the impact chain 1, corresponding to the "Risk of loss of attractiveness due to an increase in the heat stress". For **(A)** present conditions (2000–2020) and **(B)** for the end of the century (2080–2100) under SSP585 scenario.

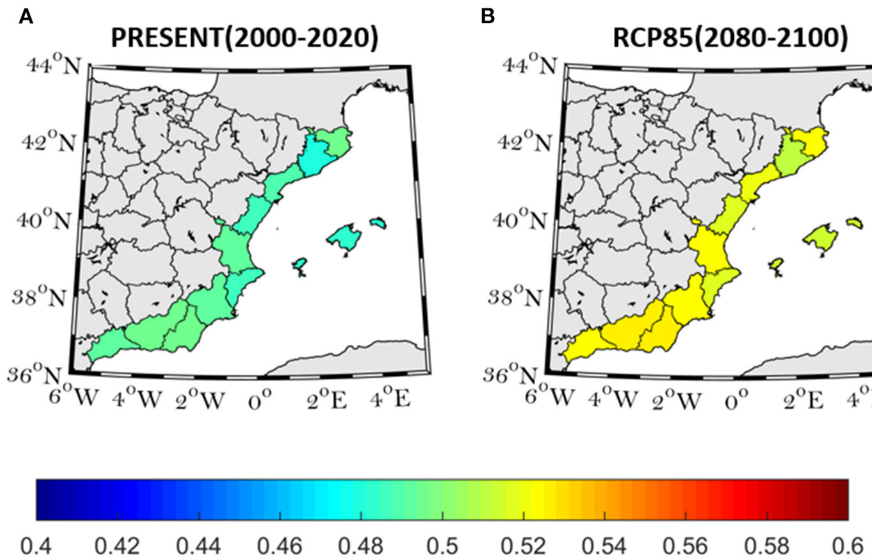

FIGURE 9
Final risk of the impact chain 2, corresponding to the "Risk of loss of attractiveness due to a reduction of beach availability". For **(A)** present conditions (2000–2020) and **(B)** for the end of the century (2080–2100) under RCP85 scenario.

TABLE 4 Final risk (R) and uncertainties (U) for each province (in rows) and for the two study cases, IC-1 and IC-2 for the present climate and under GHG scenarios (columns).

RISK	IC-1: Risk due to heat stress						IC-2: Risk due to beach loss					
	Present		SSP245		SSP585		Present		Rcp45		Rcp85	
Region	R	U	R	U	R	U	R	U	R	U	R	U
Girona	0.45	0.03	0.49	0.02	0.49	0.02	0.46	0.05	0.53	0.04	0.59	0.07
Barcelona	0.37	0.03	0.40	0.02	0.40	0.03	0.40	0.03	0.47	0.04	0.53	0.07
Tarragona	0.46	0.03	0.49	0.02	0.52	0.03	0.45	0.04	0.51	0.03	0.57	0.07
Castelló	0.45	0.03	0.48	0.02	0.51	0.03	0.43	0.04	0.50	0.04	0.56	0.07
Valencia	0.47	0.03	0.50	0.02	0.50	0.02	0.45	0.04	0.52	0.04	0.58	0.06
Alicante	0.45	0.03	0.48	0.02	0.51	0.03	0.43	0.04	0.49	0.03	0.55	0.07
Murcia	0.48	0.04	0.51	0.02	0.55	0.03	0.46	0.04	0.52	0.04	0.58	0.07
Almería	0.49	0.03	0.52	0.02	0.52	0.02	0.47	0.05	0.54	0.03	0.60	0.06
Granada	0.44	0.03	0.47	0.02	0.47	0.02	0.47	0.04	0.54	0.03	0.60	0.06
Málaga	0.47	0.03	0.50	0.02	0.53	0.03	0.45	0.04	0.52	0.03	0.58	0.06
Balears	0.38	0.03	0.41	0.02	0.44	0.04	0.44	0.05	0.51	0.04	0.57	0.07

These results are obtained after aggregating components of the IC (equation 3).

change that much because of the relatively low weight experts assigned to the hazard in front of the exposure and vulnerability.

For both ICs, the propagated uncertainties remain relatively low, suggesting the results are little affected by the lack of information in some of the indicators or to the uncertainties associated to the weight estimates.

Discussion

Risk assessment of the loss of attractiveness of touristic destinations due to climate change has provided some unexpected results. First, experts have only identified the increase of heat stress and loss of beach availability as relevant climate change associated impacts that would have an effect on sun and sea tourism. In particular, the projected reduction of water availability has not been considered as a threat. Climate projections suggest a reduction of 10–20% of water availability due to the reduction of precipitation and the increase of evapotranspiration (Cramer et al., 2020). Most experts have not considered this quantity as a significant change compared to the impact that water management and/or the total number of tourists have on the water availability.

Another unexpected result is that the risk estimates for the end of the century do not show big changes with respect to present conditions under any of the scenarios. This is although, at the end of the century and under scenario SSP585, all the regions would be under quasi-permanent heat wave conditions during the whole summer or that more than 60% of the area of sandy beaches will be lost. The reason for this result is that experts considered that the exposure and vulnerability of the region have more importance than the increasing hazard (about four times more in the case of the heat stress and twice in the case of beach loss). In other words, the underlying idea is that the tourist typology (e.g., age, origin, activities) and/or the socio-economic characteristics of the destination are more influential on the attractiveness than the environmental changes. In any case, there was a broad agreement considering that despite that, loss of beach surface was of more concern than the increase in heat stress.

Another aspect that is interesting to explore is the sensitivity of the risk to changes in the different indicators. In particular, it is worth analyzing what would be the potential reduction in the risk if changes in the sensitivity or the exposure occurred. This can be done with the UNTIC tool (Melo-Aguilar et al., 2022) to propagate the uncertainties to the sensitivity analysis. However, a first simplified approach could be to directly derive the sensitivities from the risk definition. Namely, the sensitivity to a given indicator ($\frac{dR}{dE}$ or $\frac{dR}{dV}$) of a risk defined by (equation 2) would simply be:

$$\frac{dR}{dE} = W_E; \qquad \frac{dR}{dV} = W_V \tag{7}$$

with W_E and W_V the weights computed in Table 3. Therefore, in order to infer the potential reduction in risk induced by a change in the aggregated indicators, it would be enough to multiply that change by the corresponding weight. For the IC1, and provided that averaged aggregated exposure and vulnerability are 0.48 and 0.47, respectively, the risk associated to the increase in the heat stress could be reduced up to 0.25 and 0.16. In other words, a maximum reduction in the exposure or vulnerability (indicators going to 0) in the region would reduce the risk up to those values.

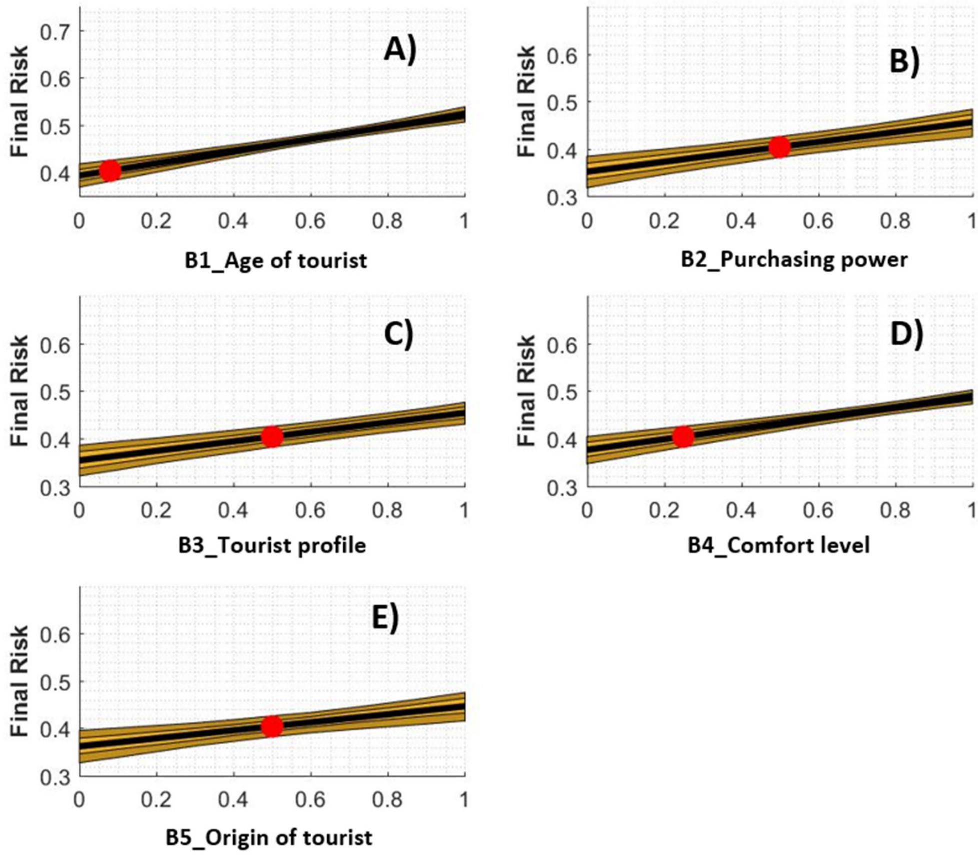

FIGURE 10
Sensitivity of the risk of loss of tourism attractiveness due to heat stress (IC1) in the Balearic Islands to changes in single exposure indicators (black lines), represented in each subplot by **(A)** Age of tourist, **(B)** Purchasing power, **(C)** Tourist profile, **(D)** Comfort level, and **(E)** Origin of tourist. The red dot indicates the present value for each indicator and the orange patch represents the range of uncertainty. Note that the vertical axis is different in each subplot. Values normalized from 0 to 1.

Doing the same computation for the IC2, we found that the maximum risk reduction that could be reached through the reduction of the exposure or vulnerability would be 0.19 and 0.18, respectively.

This potential reduction in the risk is relatively big and opens the door to the design of adaptation strategies ahead the threats the tourism sector faces because of climate change. The downside of this is that getting a reduction in the exposure and vulnerability is far from being a simple issue. Both components are composed by a variety of indicators covering from the typology of tourists to the quality of the heath system. Thus, actions should be taken in multiple aspects. In order to illustrate this, we have computed the sensitivity of the final risk in the IC1 to each individual exposure indicator (Figure 10) for the Barcelona province. Reducing any of the indicators to 0 (i.e., maximum reduction of one of the aspects of the exposure), would not change the final risk more than 0.05. Also, some of the indicators have more room for improvement (e.g., B2, increase of the tourist's wealth) than others (e.g., B1, age of the tourists). In any case, the analysis helps to anticipate in which of the exposure or vulnerability aspects the benefits of action would be potentially larger.

Regarding the methodology used for the risk assessment, the application of the UNTIC methodology (Melo-Aguilar et al., 2022) has proven to be very convenient in order to accommodate uncertainties in the impact chain framework. In particular, those aspects that were poorly known (i.e., indicators for which no information was found) could be also included in the computation. The absence of knowledge was then translated to an increase in the uncertainty associated to the final risk. In our case, the final uncertainty was low enough to question the conclusions, meaning that the lack of information did not jeopardize the study.

Another important aspect is the critical role that the weighting has on the final quantification of the risk. A small change in the weights of the aggregated indicators can dramatically change the conclusions of the assessment. In order to minimize this issue, we have opted to use the AHP to include in an optimal way the expert knowledge. However, even the AHP does not prevent the fact that some biases can exist in the expert's answers. For instance, they have given their opinion about tourist reaction in face of extreme heat. But in practice, this is a situation that has barely happened in the past, so they may be underestimating the role of heat stress in the tourist perception. This critical dependence of the risk assessment on subjective judgement is a common feature in all the approaches.

Melo-Aguilar et al. (2022), have suggested that a way to partially overcome this limitation would be to do a retroanalysis of the risk in the past, or in analog situations, in order to see if the results of the assessment matched the observed impacts of the hazard. In our case, for IC1, this could be done through the analysis of long time series of satisfaction surveys. Comparing the survey results in periods when the tourists have experienced heat waves with the results in normal periods, could give us an estimate of the sensitivity of risk to changes in the hazard. This in turn, would allow to validate the weights used and the risk assessment in general. For IC2, as the beach availability has not changed much locally in the last years, the satisfaction surveys between different regions could be used for the same purpose. Unfortunately, up to our knowledge, there are no such homogenized and long enough time series that would allow such analysis, therefore the results could not be validated until such data will be generated.

Conclusions

A risk assessment has been conducted on the potential loss of tourist attractiveness for sun and sea tourism in the western Mediterranean due to climate change. Through a participatory process following the Vulnerability sourcebook (Fritzsche et al., 2014) and the TANDEM framework for co-production of knowledge (Daniels et al., 2019, 2020), the main relevant hazards have been identified. These are the increase of heat stress and the loss of beach availability. Then, the corresponding impact chains have been developed to consider the exposure and vulnerability aspects that may shape the final risk. The weights of the different indicators have been determined based on expert judgement through the analytical hierarchy process (Lamata and Pelaez, 2002). Also, uncertainties in the indicators and the weights have also been considered thanks to the implementation of a new extension of the risk methodology developed in the framework of the UNCHAIN project (Melo-Aguilar et al., 2022).

The results showed that exposure and vulnerability in all the touristic destinations in the region are very similar, and the hazard will largely increase in the next decades, specially under the GHG scenario (SSP585/RCP8.5). However, the final risk does not seem to suffer a large increase because of the relatively small weight assigned to the hazard. In other words, the exposure (e.g., typology of the tourists and touristic activities) or the vulnerability (e.g., capacity to put in place adaptation strategies) would be more important than the projected change in the hazard (e.g., heat stress increase or beach reduction). Translated to the consequences climate change may have on the tourism sector, our results suggest that the sun and sea tourism would be resilient up to certain extent to the increase in temperature and the loss of comfort in the beaches. If the sector ensures the exposure and vulnerability remain low, the impacts of climate change would be reduced. However, it is worth noting that the sensitivity analysis performed shows that keeping low values for the exposure and vulnerability could only be done through combined actions in all the individual aspects of those components, which may be complex in practice as they would require the commitment and collaboration of different actors (i.e., government, industry, and academia).

The methodology applied has proven to be robust and allows to accommodate in a natural way the gaps of knowledge in the indicators or weights. Therefore, it could also be applied to any risk assessment in which uncertainties may play a relevant role. Additionally, it must be noted that the assessment lacks a formal validation, as it is common in similar assessments. In our case, the establishment of long-term series of tourist perception of tourist attractiveness (i.e., through homogenized satisfaction surveys) would help to calibrate and validate the results of the assessments. It is also worth highlighting that the main conclusion of this work is mainly driven by the relative low importance experts give to extreme heat or low beach comfort in front of other aspects that drives the attractiveness of the destination. However, this may be a biased result as this is a situation that has barely happened in the past, so they may be underestimating the role of those hazards in the tourist perception. The above proposed long-term series of tourist perception could help to reassess our results when periods of extreme heat or reduced beach will be considered in the surveys.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

MA, GJ, and CM-A designed the study and the experiments, were responsible for data processing and analysis. GJ organized the structure of the manuscript and MA and GJ wrote the manuscript. All authors reviewed, contributed to the article, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2022.1019892/full#supplementary-material

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Introducing uncertainties in composite indicators. The case of the Impact Chain risk assessment framework

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The use of composite indices is widespread in many fields of knowledge but a common problem associated to those type of indices is how to introduce uncertain knowledge on them. One example would be the Impact Chain framework for risk assessment. This methodology has proven to be a robust and effective approach to set up the conceptual framework associated to a given risk allowing to naturally consider the different components that shape that risk. However, the operationalization of the impact chain may not be straightforward, in particular due to the inherent uncertainties associated to the selected indicators and the assigned weights. In this paper, we propose to use a probabilistic framework that would allow to consider uncertain knowledge in the composite indicator computation. Moreover, in the framework of the UNCHAIN project, a web-based tool has been developed to ease the task of implementing that methodology. This web-based application is designed as a multidimensional tool to consider uncertainties in any type of composite indicator, thus, its scope goes beyond the Impact Chain and risk analysis framework. For illustrative purposes, the tool has been applied to a case study on the risk of loss tourist attractiveness due to heat stress conditions on the Balearic island, Spain. This case study is used to show how uncertainties in different components of the impact chain can affect the robustness of the final risk assessment. Also, the tool provides an estimate of the sensitivity of the final risk to each component, which can be used to guide risk mitigation strategies. Finally, a proposal for the validation of the risk assessment is presented.

KEYWORDS

uncertainty, climate risk assessment, impact chains, climate change risk, tourism risk management, heat index, composite index

1. Introduction

Natural disasters related to extreme climate conditions are one of the main threats that human society faces nowadays and are expected to become more frequent in the coming decades due to global warming (Seneviratne et al., 2022). In fact, the effects of a changing climate are currently emerging in different parts of the world. One example is the devastating early heat wave that hit Northwestern India and Southern parts of Pakistan during March and April 2022, which was the hottest in India since records began

122 years ago (Zachariah et al., 2022). In addition, extremely dry conditions in both India and Pakistan favored local heating of the land surface. This situation reduced India's wheat production, limiting global wheat stocks. In the future, climate-related impacts may become more severe, as they are shaped not only by changes in the climate state, but also by many societal factors, like a growing population, socioeconomic development, or a rising demand for food, water, and energy, which underlie physical and social vulnerability, and the social responses themselves (Ara Begum et al., 2022).

Accordingly, climate risk assessment at local to national and regional levels has become an important tool for the development and implementation of adaptation strategies to support decision-making that limit the consequences of climate-related impacts on the natural and socioeconomic dimensions. Climate risk assessment includes identifying the frequency and intensity of climate hazards (droughts, floods, heat waves, etc.), but also evaluating the level of impact on the socioeconomic system and the natural ecosystems (Reisinger et al., 2020; Ara Begum et al., 2022). This, in turn, depends on the exposed elements and how vulnerable they are (Mastrandrea et al., 2010; Toimil et al., 2017; Leis and Kienberger, 2020). In this regard, the concept of impact chains (IC; Fritzsche et al., 2014) has emerged as an important analytical tool that helps to understand, systemize, and prioritize the drivers of climate risk. Impact chains are conceptual models that describe climate impacts as cause–effect relationships within a socio-ecological system (Aall and Korsbrekke, 2020), focusing on identifying and describing important linkages between the different components of climate related risks.

To quantify the level of risk imposed by a certain physical disturbance on a natural or socioeconomic system, the three components of risk defined in the ICs framework (i.e., hazard, exposure, and vulnerability; Reisinger et al., 2020), are combined in climate risk models (Kropf et al., 2022). In these types of models, indicators are defined for the hazard (i.e., climate stressor), the exposed elements (e.g., population, infrastructure, buildings, ecosystems etc.), and the vulnerability components. These indicators are then aggregated using different approaches, from simple weighted arithmetic/geometric methods (Fritzsche et al., 2014) to more complex impact functions that estimate the level of damage (Aznar-Siguan and Bresch, 2019) and the potential risk. An important feature of climate risk models is that they may enable quantitative data (e.g., evidence of observed and modeled evolution of the climate system) to be combined with qualitative information (e.g., expert judgment), thus, providing an integrated climate-risk assessment across multiple lines of evidence (O'Neill et al., 2017). However, the different nature of the input data complicates the quantification of the final risk. Particularly, obtaining robust verification data for the exposure and vulnerability components can be quite challenging (Kropf et al., 2022), since these elements are sometimes identified from subjective methods (Zommers et al., 2020).

Moreover, dealing with uncertainties in the selection, quantification, and weighting (i.e., the relative importance among the three components of risk) of the input indicators remains central in the debate on climate change risk due to the inherently complex nature of climate-related phenomena. Particularly, assessing the risk under future climate change conditions involves dealing with different sources of uncertainties, including those from climate model projections, in addition to future changes in demographics, human development, economy, lifestyle, and policies (O'Neill et al., 2017). The way uncertainties related to climate-risk analysis are traditionally handled in the climate science field is too strongly associated with statistical measures of the magnitude and frequency of the hazard (Aven, 2020), while the concept of uncertainty should be also applied to the exposure and vulnerability to any given hazards (Reisinger et al., 2020).

Incorporating a systematic treatment of uncertainty into the framework of climate risk analysis has become an important task to improve the quality of such analyses and provide useful results for risk management. This will assist policymakers to develop more informed adaptation measures taking into account the full range of uncertain aspects inherent to climate risk analysis. However, the implementation in practice of the uncertain aspects of climate risk assessments still faces some limitations. For instance, translating qualitative sources of information to a quantitative measure of uncertainty, and integrating them with hazard model-based output that can be incorporated into risk analysis is challenging (Adler and Hirsch Hadorn, 2014). Some attempts have been done in this direction, like the probabilistic impact risk model softwares packages CLIMADA (Aznar-Siguan and Bresch, 2019) or CAPRA (Cardona et al., 2012). However, although they are valuable tools that provide a way to consider a measure of uncertainty in the different components of risk, they tend to be designed to address a limited range of climate and other natural events (e.g., tropical cyclones, river flood, or earthquakes). Therefore, their use is restricted to those specific cases, limiting its application to a wider range of potential climate-related events. Furthermore, using these types of software may require some level of expertise, thus, limiting its implementation by some users.

One of the goals of the UNCHAIN project ("Unpacking climate impact chains") funded by the AXIS-JPI EU funding mechanism (http://www.unchain.no/) is to develop and test a standardized analytical framework for addressing uncertainties involved in local decision-making on climate change adaptation. In this work, we contribute to this goal by proposing an extension to the Impact Chain framework that allows to consider uncertainties in the different components of the risk assessment. The basic idea is to consider that any component of the IC (indicators and weights) is defined not as a single value, but as a probability density function (PDF) that describes the uncertainty associated to that component. As a result, a PDF for the final risk is obtained. The methodology can also be used to assess the sensitivity of the risk to different factors, thus helping the policymakers in the development of adaptation strategies.

In order to simplify the application of the method, a very simple, user-friendly interactive web application has been developed, the UNTIC (Unchain Tool for Impact Chain uncertainties) tool, which can be easily adapted to any climate-related risk evaluation or even extended to other fields. The reason is that climate risk assessment can be though of as a composite index (CI), as it reflects a complex relationship between multiple dimensions and indicators (e.g., natural phenomena and socioeconomic components). Essentially, a CI combines multiple indicators using various normalization and weighting schemes (Wu and Wu, 2012) to allow better interpretation of the connections between its different dimensions rather than reducing it to its "isolated parts" (Rosen, 1991). In fact, CIs are widely developed in several fields, such as, economy, in which they are very popular tools to assess and rank countries and institutions (e.g., Human Developing Index; UNDP, 2022), sustainability (e.g., Ecological Footprint; Huang et al., 2015), environment (Wiréhn et al., 2015), and others. However, despite the widespread and interdisciplinary nature of CIs, there remain criticisms surrounding their development. In particular, the lack of uncertainty and sensitivity analyses in the development of many CIs is a shortcoming that may limit the delivery of a more robust message on the CI conclusions (Greco et al., 2019). Considering the broad scope of CIs, the UNTIC tool is designed as a multidimensional application to introduce uncertainties in any type of CI. That is, it is not limited to the aggregation of the three components (i.e., hazard, exposure, and vulnerability) considered in the Impact Chain and risk analysis framework. Instead, users can include as many components and indicators as necessary, and the application automatically expand uncertainties to each component and to the aggregated CI.

Herein, we describe the methodology and the practical application of the UNTIC tool to a case study on the risk of loss of tourist attractiveness due to heat stress increase on the Balearic Island, Spain. We encourage researchers in the field of climate risk assessments and other disciplines to incorporate the quantification of uncertainties when computing CI (e.g., using the UNTIC tool or other similar software).

2. Materials and methods

2.1. The Impact Chain formalism

The probabilistic approach for composite indices was originally developed for the risk assessment in the Impact Chain framework. Therefore, for clarity, the methodology is presented in that framework. However, the same background applies to the estimation of any type of CI. i.e., in practice, any type of CI can be described as a combination of different dimensions and indicators, and the aggregation scheme described here could be extended to CIs of any complexity.

Following the IPCC AR5 (Burkett et al., 2014), in the context of climate-related impacts, risk is defined as a combination of three interacting components: (1) climate-related hazards (including hazardous events and trends), (2) exposure in places and settings that could be adversely affected, and (3) vulnerability of human and natural and socio-economical systems. Then, it is not enough to identify climate hazards (i.e., floods, heat waves, water scarcity, etc.) but also the grade of affection to the socioeconomic system of the region under evaluation. That is, to quantify the possible consequences depending on the exposure and vulnerability components (Mastrandrea et al., 2010; Toimil et al., 2017; Leis and Kienberger, 2020). This can be done following the approach proposed in the Vulnerability Sourcebook (Fritzsche et al., 2014) which is based on the concept of impact chain. The development of a climate-risk assessment under the IC approach involves the combination of the hazard, exposure, and vulnerability components via identifying and describing connections between them. The interactions between these factors, are controlled by the different indicators that make up each of the IC components, which ultimately shape the final risk magnitude. Accordingly, in the IC approach, the risk is defined as:

$$R = W_H \sum_{k=1}^{K} w_k H_k + W_E \sum_{j=1}^{j} w_j E_j + W_V \sum_{i=1}^{i} w_i V_i \quad (1)$$

where H, E, and V, are the components that describe the Hazard, Exposure, and Vulnerability, respectively. The Ws refer to relative Weight/Normalization factor applied to transfer these three components to risk value, and w represents the weight of the indicators for each risk component. It must be noted that here we have assumed the typical choice where the three components are arithmetically combined, but the whole formalism presented below can easily be translated to any type of combination. For instance, the risk components could be aggregated geometrically (multiplicative aggregation), where Equation (1) takes the form:

$$R = \left(\prod_{k=1}^{K} H_k^{w_k} \right)^{W_H} \times \left(\prod_{j=1}^{j} E_j^{w_j} \right)^{W_E} \times \left(\prod_{i=1}^{i} V_i^{w_i} \right)^{W_V} \quad (2)$$

The selection of the aggregation method depends on a "compensability" effect among the different indicators. That is, the existence of trade-offs between high- and low-score indicators. While a weighted arithmetic aggregation allow for "full compensability," meaning that a high score for one indicator can offset a low score of another indicator, the weighted geometric aggregation, only allows partial

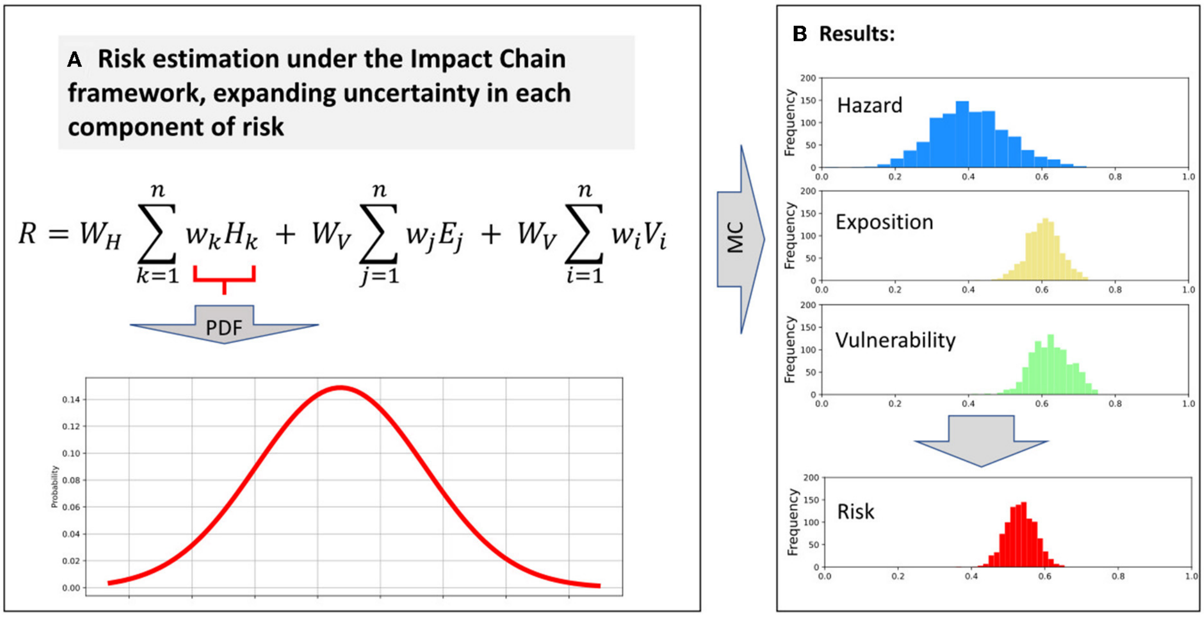

FIGURE 1
Sketch of the methodology proposed to accommodate uncertainties in the impact chain framework. **(A)** Risk estimation under the Impact Chain framework, expanding uncertainty in each component of risk. **(B)** Results.

compensability (Nardo et al., 2008). The latter means that a very low score for one indicator can only partly offset a very high score of another indicator. It is important to recall that by definition all weights must add up to 1 (e.g., $W_H + W_E + W_V = 1$, or $\sum w_k = \sum w_i = \sum w_j = 1$).

The identification of the indicators for each of the risk components (either quantitative or qualitative), the normalization and the determination of the weights is not straightforward. It requires literature review, brainstorming process, compilation of historical data regarding past events of the analyzed phenomenon, expert judgement, and the interaction with the different stakeholders involved in the field (Fritzsche et al., 2014). The latter is one of the most important tasks in linking academia with practitioners and to promote the adoption of the results by the final users and policymakers as they actively participate in the co-generation of knowledge. However, participatory approaches such as workshops and other, add uncertainties to the climate-risk assessment as they tend to be subjective methods.

2.2. Addressing uncertainties in the impact chain framework

Three main types of uncertainties of different nature that influence the results of the risk assessment can be considered. First, existing datasets are uncertain, leading to uncertain indicators. Second, the relative importance of each element of the IC (the weight) has a profound impact on the final risk. However, that is usually defined based on subjective expert knowledge, which is inherently subject to uncertainties. Finally, a third level of uncertainty exists when some key elements of the actual chain of impacts may not be included in the theoretical IC. This would lead to a biased estimate of the final risk, so the problem must be bounded in some way. All these types of uncertainties should be quantified and propagated to the final risk, so the risk is provided along with a level of confidence. Here, we propose a standardized probabilistic framework in which the basic idea is to consider that any component of the IC (indicators and weights) is defined not as a single value, but as a PDF. The PDF provides a full representation of all the possible values that a quantity can have with its probability of occurrence. A sketch of the approach is presented in Figure 1.

In practice, to implement this approach, some choices have to be made to define the PDFs. For all those indicators for which enough information on the uncertainty could be obtained, a frequent choice is to use a Gaussian function with an amplitude defined by the estimated uncertainties:

$$p(x) = e^{-\frac{(x-x0)^2}{2\sigma^2}}$$

where p represents the probability of having an indicator or weight value, $x0$ is the central most likely value as provided by the databases or the experts opinions, and σ is the the standard deviation of the distribution, which is often used as a measure of the level of uncertainty. The uncertainty associated

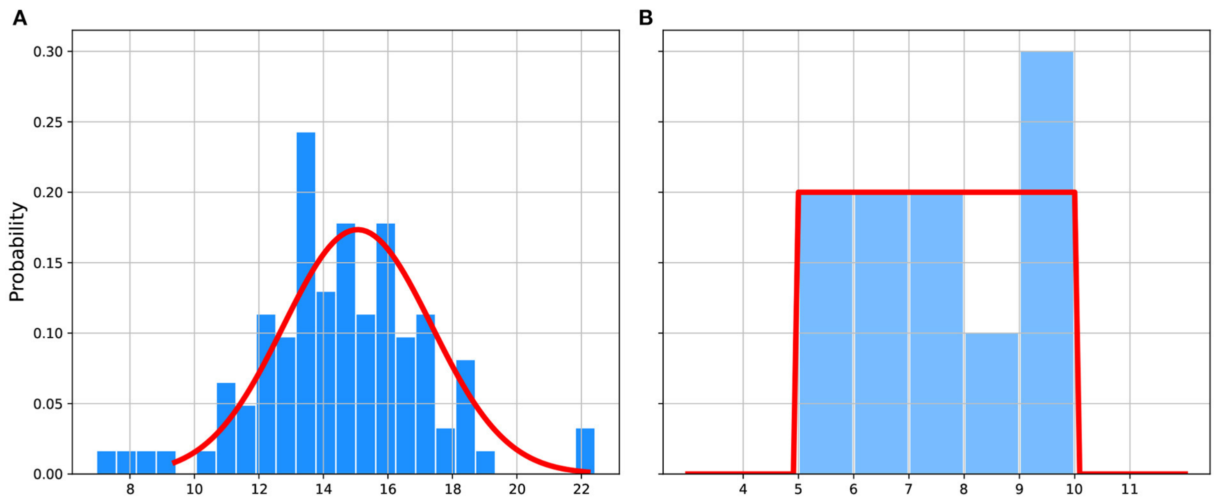

FIGURE 2
(A) Example of the fitting of a Gaussian function to the outputs of an ensemble of climate models providing the heat index in the Balearic Islands. **(B)** Example of the fitting of a homogeneous pdf to the outputs of a poll to experts about the quality of information for tourists.

to the indicators will be inferred from the characteristics of the databases (e.g., spread of climate model results).

For those indicators for which a central value could not be identified or even for which there is no information, an homogeneous PDF can be used:

$$p(x) = 1/(x_{max} - x_{min}, for x_{min} <= x <= x_{max})$$

where x_{max} and x_{min} determine the maximum and minimum possible values.

For instance, in the case of the hazard, the type-1 source of uncertainty (i.e., those related to the datasets used to define the different indicators) is typically determined by the probability of occurrence of a climatic driver. This can be measured from sample observations of the climate state or from physical model outputs. An example is the case of climate change projections, which are based on climate model simulations. Model outputs are inherently uncertain due to our incomplete knowledge about the climate system (Maher et al., 2019), including the internal variability (e.g., El Niño) and external variations in the forcing factors outside the climate system (e.g., solar activity or volcanoes). In addition, scenarios of global development describing societal futures and greenhouse gases emission are developed from assumptions of different socioeconomic developments and future societal conditions, which are made to span a range of possible futures of warming (O'Neill et al., 2017). The assessment of these types of uncertainties is usually done with the use of ensembles of simulations that provide a range of possible future scenarios of the climate state in a probabilistic framework (Taylor et al., 2012). In this case, the hazard indicator would be computed as the ensemble average while the uncertainty would be computed from the ensemble spread (see Figure 2A). In other cases, the number of inputs is not large enough to fit an analytical function (e.g., the results of a poll to a limited number of experts). In this case, we propose to keep all the expert opinions using a homogeneous PDF with the limits defined by the range of values obtained in the poll (see Figure 2B).

Furthermore, it is possible that for some indicators there is no clear information about the associated uncertainty. An example could be when the information is retrieved from databases that do not specify the methodology followed or a measure for the reliability of the data. A possible alternative would be to use the temporal variability of the indicator as a measure of the uncertainty associated to the mean value provided.

It is important to remark that this formalism naturally accommodates the gaps of knowledge. It should be kept in mind that the IC is a conceptual framework that does not require all all information to be available. Thus, if no information is found for any of the indicators defined in the IC, they can simply be set to a value of 0.5 with a range of uncertainty of $\pm$ 0.5 following a homogeneous PDF. This would be equivalent to assume that the indicator may have any value between 0 and 1. This will propagate through the risk computation and enlarge the final uncertainty. If that missing information was from an indicator with little weight, the consequences will be negligible. Conversely, if that piece of information corresponded to something that experts considered was important, and thus had a strong weight, will result in a large uncertainty in the final risk.

Finally, it is also worth mentioning that qualitative information can also be naturally included in this approach. It would be enough to discretize the expert's judgement to a limited number of classes and to assign a numerical value to each class with a corresponding uncertainty. For instance, if the experts have to assign a low, mid or high value to a certain indicator, this can be transformed to 0.16, 0.5, and 0.84 with a homogeneous uncertainty of $\pm$ 0.16.

Regarding the level-2 uncertainties, those associated to the weights, the same approach can be followed if they are based on expert judgement. In our case we propose to use the Analytical Hierarchal Protocol (AHP; Saaty, 1990) although other approaches are also valid as long as a range of uncertainty is provided for all the weights used in the IC. Analytical Hierarchal Protocol is widely used in the risk assessment (e.g., Hsu et al., 2017; Tascón-González et al., 2020) and aims at deriving ratio scales from paired comparisons. It allows converting subjective opinions to a numeric scale that can be used in the risk assessment process. To do so, a pairwise comparison of either the risk components or between indicators in each group is presented to the expert. The former provides an estimate of the overall weight, while the latter indicates the weights among indicators of each type. For each pairwise comparison, the expert selects the option he/she considers to be more important, using a numeric scale. Then, the results are organized in a matrix and the weights are obtained by computing the normalized principal eigenvector (Saaty, 1990). As this is repeated for several experts, an ensemble of values is obtained for each weight. Thus, the average is used as the final weight and the spread of the values as the uncertainty (e.g., the standard deviation of the values can be used as a measure of the uncertainty). If the number of experts is large, an analytical function (e.g., a Gaussian function) can be fitted. If not, an homogeneous PDF should be preferred, as mentioned above.

Once all the indicators and weights are defined, they are combined using Equation (1)/(2) with the functional form chosen for the IC (weighted arithmetic aggregation, geometric aggregation, conditional combinations, etc...). To propagate the uncertainties to the final risk, we use a classical Monte-Carlo technique. Namely, each indicator and weight is transformed from a single value to a range of values randomly sampled from a distribution described by the chosen PDF. All these values are used to compute a large number of risk estimates. As a result, a PDF for the final risk estimate is obtained (see Figure 1B).

Another important aspect of the risk assessments is to evaluate the sensitivity of the final risk to the single indicators. This can help to guide the adaptation strategies by focusing on those indicators that have the largest impact on the final risk, so a reduction of them would lead to a meaningful reduction of the final risk. To illustrate this, we can assume a linear form for the IC and neglect by the moment the uncertainties in the weights or the indicators, as in Equation (1). The sensitivity to the indicator $I(S(I))$ can be formulated as:

$$S(I) = \frac{dR}{dI} = W * w$$

In other words, the relative change of the final risk with respect to a change in the indicator I can be estimated as the product between the weight of the indicator w and the weight of the aggregated component W. By multiplying $S(I)$ by the expected change in a given indicator ΔI one can obtain what would be the change in the final risk:

$$\Delta R = \frac{dR}{dI} * \Delta I = W * w * \Delta I$$

This has been shown for a relatively simple linear case without uncertainties. In our case, the sensitivity is numerically computed using the Monte Carlo approach and thus the associated uncertainty is also provided. Moreover, more complex functional forms for the risk can be easily considered when computing the sensitivity.

2.3. A web-based tool

In the framework of the UNCHAIN project, a web application has been developed to simplify the application of the described methodology, the UNTIC tool, hosted in: untic.pythonanywhere.com. The UNTIC tool has been designed as a very simple and user-friendly interface, in which the final user is only required to fill in an Excel spreadsheet with the information of Equation (1)/(2) (i.e., the overall weights, the aggregation formula, the weights for the indicators within any risk component, and the value of the indicators with their associated uncertainty). The web tool also helps in the generation of a template for the Excel file once the number of components and indicators are defined by the user. Once the file is uploaded to the web, the Python code generates the PDF for each element in the composite index based on a Monte Carlo approach and provides numerical and graphical outputs. Figure 3 shows a schematic representation of the UNTIC structure for the case of a Risk assessment. The box on the left-hand side (Figure 3A) represents the input spreadsheet, in which the user is asked to provide the value (V), the uncertainty measure (U), and the shape of the probability distribution (S) for each element of Equation (1)/(2), and for each location or timeframe in which the assessment is conducted. The UNTIC tool reads in this information and randomly generates the samples based on the user-defined S to be used in the MonteCarlo simulation. Then, the final composite index is estimated using the functional form chosen for the risk [i.e., arithmetic/geometric aggregation; Equation (1)/(2), respectively] while uncertainties are propagated to provide the risk in a probabilistic framework. The UNTIC tool will automatically generate some outputs (Bottom box;

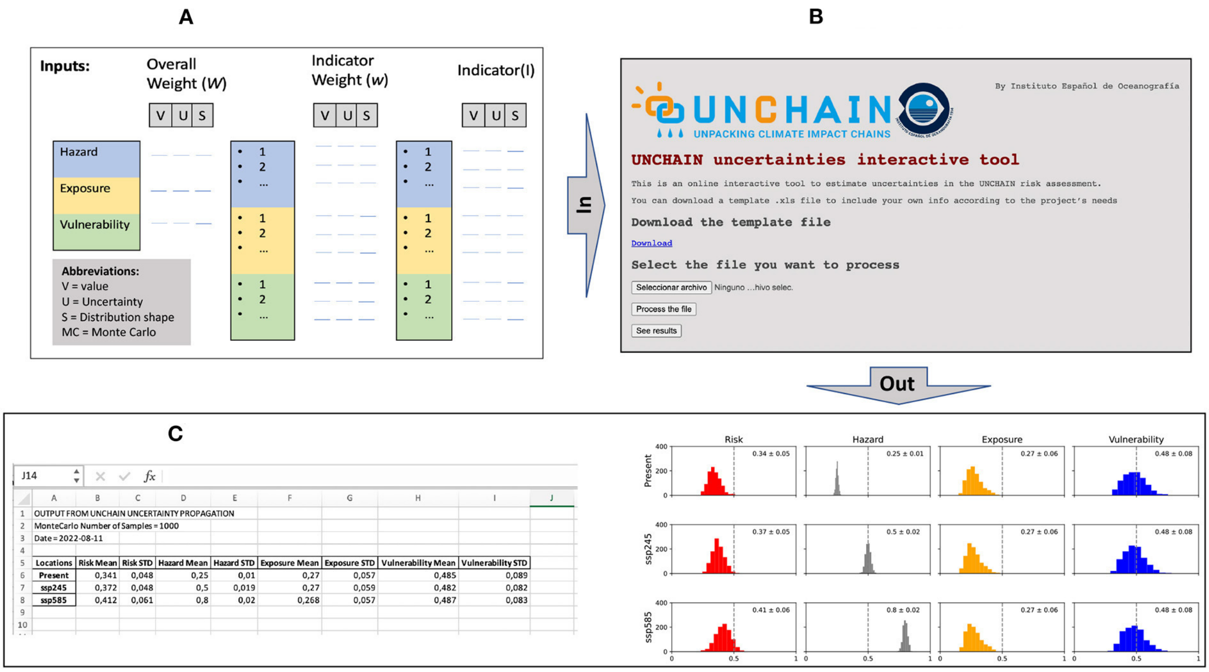

FIGURE 3
Schematic representation of the UNTIC tool. **(A)** Panel illustrates the required input fields that are provided in the Excel spreadsheet. **(B)** Web interface. **(C)** Outputs: the UNTIC tool provides numerical and graphical outputs for the index composite and each of its components.

Figure 3C) including a report in Excel format and a set of plots illustrating the main results. The former includes the results of the composite index (i.e., mean and standard deviation values of the composite index and each component) and those of a sensibility test in the final risk estimate to variations in the values of individual indicators (i.e., the minimum and maximum risk values that would be obtained if the indicator ranged from 0 to 1).

In the following, we describe the practical implementation of the formalism for the specific case of the risk of loss of attractiveness by heat stress in the Balearic Island, Spain. This implies the aggregation of three components (i.e., Hazard, Exposure, and Vulnerability), but, as mentioned before, the UNTIC tool has been designed for any type of composite index, regardless of the numbers of components and indicators.

3. Example of application

In this section, we illustrate the application of the above-mentioned concepts using a case study for the risk of loss of attractiveness by heat stress on the Balearic Island, Spain. The full description of the development of the IC is included in a companion paper ("Risk of loss of tourism attractiveness in the Western Mediterranean under climate change." Agulles et al., this issue), thus, here we focus on detailing the process of dealing with uncertainties in the final risk assessment and only a brief overview of the case study is presented. The results presented herein have been generated with the UNTIC tool; the input Excel spreadsheet can be accessed from untic.pythonanywhere.com.

The IC has been defined from expert knowledge through participatory activities with relevant stakeholders in the tourism sector in the Balearic Islands, involving people from academia, government, and industry. This was a user and stakeholder-centric, process-oriented, and demand-driven approach, commonly referred to as "co-production of knowledge," which has been recognized as a key factor to promote sustainable development outcomes (Norström et al., 2020).

The resulting IC contains indicators for each of the three risk components that were identified by working interactively with the stakeholders, mainly through online meetings due to the restrictions associated to the COVID pandemics. Once the IC was defined, the indicators were selected. Regarding the hazard, it is represented by the National Oceanic and Atmospheric Administration (NOAA) heat index (HI), which is a heat stress indicator used for issuing heat warnings. For the Exposure and Vulnerability components, a total of five and nine indicators are included in the IC, respectively (see Table 1).

Data to quantify the HI under present and future conditions have been obtained from global climate model runs in the framework of the sixth phased of the Coupled Model

TABLE 1 List of indicators for the hazard, exposure, and vulnerability components and their respective normalized values and corresponding uncertainty.

Indicator	Present (2000–2020)	ssp245 (2080–2100)	ssp585 (2080–2100)
Hazard			
Heat index (HI)	0.30 ± 0.01	0.50 ± 0.02	0.80 ± 0.02
Exposure			
Age of tourist (%>65 years)	0.08 ± 0.01	0.08 ± 0.01	0.08 ± 0.01
Purchasing power (Daily expenditure/pers)	0.5 0 ± 0.03	0.50 ± 0.03	0.50 ± 0.03
Tourist profile (% of tourist arrival that are family)	0.25 ± 0.02	0.25 ± 0.02	0.25 ± 0.02
Comfort level hotel (num hotels ≥3 stars)	0.25 ± 0.02	0.25 ± 0.02	0.25 ± 0.02
Quality of beaches services (num blue flags/num beaches)	–	–	–
Vulnerability			
Health system (life expectancy)	0.50 ± 0.04	0.50 ± 0.04	0.50 ± 0.04
Quality of information for tourists	0.25 ± 0.01	0.25 ± 0.01	0.25 ± 0.01
Long term planning (GDP per capita)	0.25 ± 0.03	0.25 ± 0.03	0.25 ± 0.03
Offer of alternative activities (grade of offer no beach %)	0.50 ± 0.05	0.50 ± 0.05	0.50 ± 0.05
Dependence of source markets (grade of dependence %)	0.75 ± 0.05	0.75 ± 0.05	0.75 ± 0.05
Overcrowding (tourists/residents)	1.00 ± 0.03	1.00 ± 0.08	1.00 ± 0.08
AC measures (parks, shallows, air conditioning)	–	–	–
Deseasonalization	–	–	–

The indicator values for the present conditions represent their average value over the 2000–2020 conditions, whereas for the future, the ssp245 and ssp585 scenarios are considered for the hazard indicators. The dash symbol indicates that no information is available for that indicator.

Intercomparison Project (CMIP6; Eyring et al., 2016). The data have been retrieved from Schwingshackl et al. (2021) for the present climate and projections for the end of the century under two Shared Socioeconomic Pathways (SSP245 and SSP585; Riahi et al., 2017). The hazard indicator for present and future has been obtained as the model ensemble average and the uncertainty as the ensemble spread (Figure 4).

For the exposure and vulnerability, the information to quantify the indicators is obtained from official statistics services at regional and national levels. These data are usually provided as yearly values, but we were unable to find details on the associated uncertainty. Therefore, the indicators were computed as the average for the period 2000–2020 and the temporal standard deviation is considered as a measure of the uncertainty associated to these values. It has to be noted that no future projections have been done for the exposure and vulnerability indicators (i.e., they are set constant in time), as the goal was to assess how changes in the hazards may impact the risk. This represents the risk if adaptation measures were not considered. Although this is an unrealistic case, it will provide a first-order view of the risk for the tourism sector if no actions are considered to deal with the projected climate change hazards.

The following step has been to normalize the indicators in order to make them comparable. In our case, we have chosen a linear transformation where data below a predefined minimum threshold correspond to a value of 0 and data above a pre-defined maximum threshold correspond to a maximum value of 1. For the values in the middle, the following formula has been applied:

$$N = (I - I_{min})/(I_{max} - I_{min}),$$

where I is the original value of the indicator and I_{min} and I_{max} are the minimum and maximum thresholds, which have been subjectively set by the experts. It must be noted that all indicators have been defined in a way that higher values imply higher risk. The values for the indicators along with their associated uncertainties are presented in Table 1.

The computation of the weights has been done using the AHP. Table 2 contains the results of the AHP evaluated by one stakeholder involved in the process for the weighting of the exposure indicators as an example. The same procedure was applied to the vulnerability components, as well as to obtain the overall weight between risk components. In this example, the

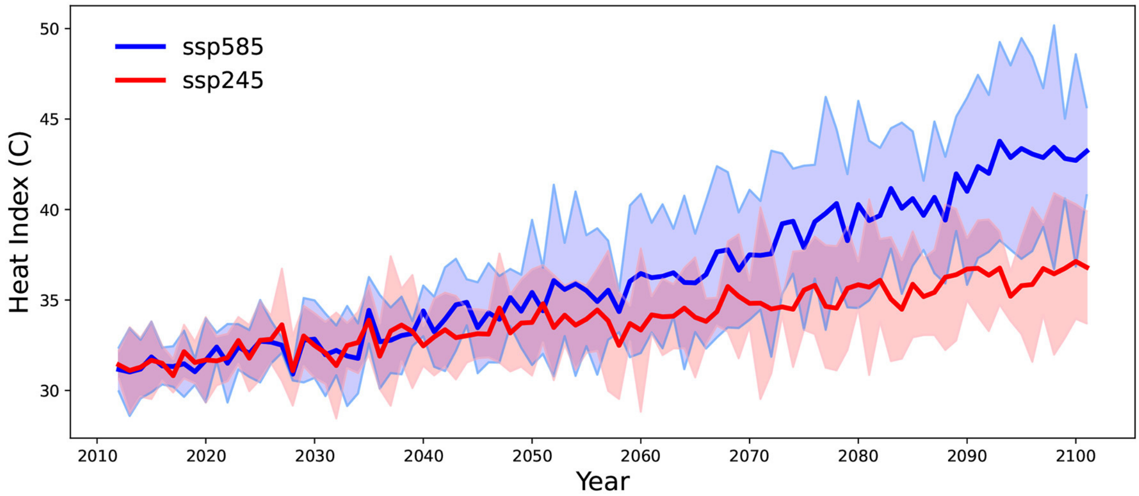

FIGURE 4
Evolution of heat index over the 2015–2100 period for the ssp585 and ssp245 scenarios. The thick line shows the ensemble mean, whereas the shaded area illustrates the uncertainty estimate (± std).

tourist age emerges as the most important indicator of exposure (45%) followed by the origin of the tourists (17%). The same procedure was applied to all the participating stakeholders. The final weight was obtained as the mean value of those results, while the spread in the values of the weights (i.e., the standard deviation) was used as a measure of the uncertainty (see Tables 3, 4 for the resulting weights).

The estimation of the final risk is done by combining the normalized indicator values with the weights of each of the risk components, following Equation (1). The uncertainty in the final risk estimation is analyzed by performing a Monte Carlo-based simulation with 1,000 samples. Figure 5 illustrates the resulting histograms for the risk estimation distribution, as well as for each component for present conditions and two future scenarios. As expected, the hazard increases in the future, specially under scenario SPS585. The exposure has a mean value of 0.3 and vulnerability of 0.55. Note that the largest source of uncertainty is represented by the vulnerability component (last column in Figure 5). The final risk ranges from 0.38 under present conditions to 0.41 and 0.45 in the future under scenarios SPS245 and SPS585, respectively. Despite the large increase in the hazard, the final risk estimate is not affected as the hazard weight is relatively small (see Table 4).

The sensitivity of the final risk to each individual indicator as well as for the aggregated hazard, exposure, and vulnerability has also been assessed (Figure 6). It can be seen that variations in the aggregated exposure would translate into large variations of the final risk, while variations in the hazard produce the smallest contribution to the risk. This is an expected result as it reflects the weight of each component (Table 4). The sensitivity analysis also highlights that some indicators could not be used to reduce the risk, as they are already contributing little to it (e.g., Indicator "age," whose lower end is close to the red line in Figure 6). Conversely, the same indicators could significantly increase the final risk if they were increased. Also, it is interesting to notice that if a risk reduction is aimed at through a reduction of the exposure, for instance, that would require a reduction in several indicators. In other words, acting on a single aspect of tourist typology would not be enough to reduce the final risk.

Discussion

In this study, we propose a flexible framework for incorporating uncertainties into the computation of composite indices under a probabilistic approach. By considering that any component of the CI (indicators and weights) can be described through a PDF, uncertainties are easily propagated through the CI computation. Our approach to perform this propagation is to use a Monte Carlo method to randomly simulate *N* number of samples based on the prescribed probability distribution function. This has been shown to be a good approximation of the true distribution (Johansen, 2010) and provides a PDF for the final index. In the test case used to illustrate how the method works, we use a relatively simple function to combine the weights and the indicators and two types of PDF (e.g., Gaussian and homogeneous). However, any functional form for the combination of indicators or any definition of the PDFs could be easily implemented. Moreover, the inclusion of qualitative indicators can also be done by simply assigning a numerical value to each qualitative value (e.g., low, mid, or high) along with a range of homogeneous uncertainties.

TABLE 2 Matrix containing the AHP evaluation process to obtain the weights associated to the exposure components from the survey with a single stakeholder as an example.

Pair wise comparison matrix (Exposure)

Indicator	Tourist age	Purchasing power	Tourist profile	Comfort level	Beach services	Normalized matrix					Average
Tourist age	1.00	5.00	5.00	2.00	5.00	0.48	0.64	0.50	0.15	0.49	**0.45**
Purchasing power	0.20	1.00	3.00	1.00	2.00	0.10	0.13	0.30	0.08	0.20	**0.16**
Tourist profile	0.20	0.33	1.00	2.00	2.00	0.10	0.04	0.10	0.15	0.20	**0.12**
Comfort level	0.50	1.00	0.50	1.00	0.14	0.24	0.13	0.05	0.08	0.01	**0.10**
Origin of the tourists	0.20	0.50	0.50	7.00	1.00	0.10	0.06	0.05	0.54	0.10	**0.17**
Total	2.10	7.83	10.00	13.00	10.14						**1.00**

TABLE 3 Normalized weight of indicators for the hazard, exposure, and vulnerability components obtained from the AHP procedure and their corresponding uncertainty.

Indicator	Normalized weights
Hazard	
Heat index (HI)	1.00 ± 0.1
Exposure	
Age of tourist (%>65 years)	0.24 ± 0.02
Purchasing power (Daily expenditure/pers)	0.20 ± 0.07
Tourist profile (% turismo familiar)	0.19 ± 0.05
Comfort level hotel (num hotels ≥3 stars)	0.21 ± 0.03
Quality of beaches services (num blue flags/overcrowding)	0.16 ± 0.07
Vulnerability	
Health system (life expectancy)	0.13 ± 0.05
Quality of information for tourists (proxy Overcrowding)	0.12 ± 0.02
Long term planning (GDP per capita)	0.09 ± 0.06
Offer of alternative activities (grade of offer no beach %)	0.12 ± 0.02
Dependence of source markets (grade of dependence %)	0.11 ± 0.04
Overcrowding (tourists/residents)	0.15 ± 0.02
AC measures (parks, shallows, air conditioning)	0.15 ± 0.03
Deseasonalization	0.14 ± 0.02

TABLE 4 Normalized values of the relative weights among the three risk components (i.e., hazard, exposure, and vulnerability) and their corresponding uncertainty, obtained from the AHP procedure.

Component	Normalized weights
Hazard	0.13 ± 0.11
Exposure	0.52 ± 0.11
Vulnerability	0.34 ± 0.09

The UNTIC tool can be used to evaluate uncertainties in any type of composite index without any limitation in the number of components and indicators. To do so, the user is simply required to modify the default template file that can be downloaded from the web application, or create a custom template automatically from the web application. The tool has also been designed as a very simple web-based application written in Python, where users do not have to learn or master any specific software. Thus, the UNTIC tool can be implemented by a wide community of users. Among all the potential applications of UNTIC, it can be employed to assess any type of climate-related risk, from local to regional scales, or even be extended to other fields as long as the three components of risk (i.e., hazard, exposure, and vulnerability) can be characterized. Due to the inclusion of uncertainties, it would potentially contribute to improve the way climate risk is communicated to the general public and to policymakers, and, ultimately to contribute to the development of more informed adaptation strategies.

In addition to its flexibility and ease of use, one of the main strengths of our proposed approach is that gaps of knowledge in some of the aspects of the CI are also naturally incorporated in the assessment. For instance, the impact chain approach is often view as a conceptual description of a system and does not necessarily require that all the components can be quantified. For instance, experts may consider that hotel services may affect the tourist perception of attractiveness, but that is difficult to quantify. In previous assessments, those indicators that could not be quantified were discarded, so strongly jeopardizing the relevance of the assessment. Now, such unquantified indicators can be incorporated by simply assigning a very large uncertainty to it. This would propagate to the final risk, increasing its uncertainty. As an example, in Figure 7 we show the results of the IC under three cases. The first one is assigning values to all the components of the IC (reference); in the second

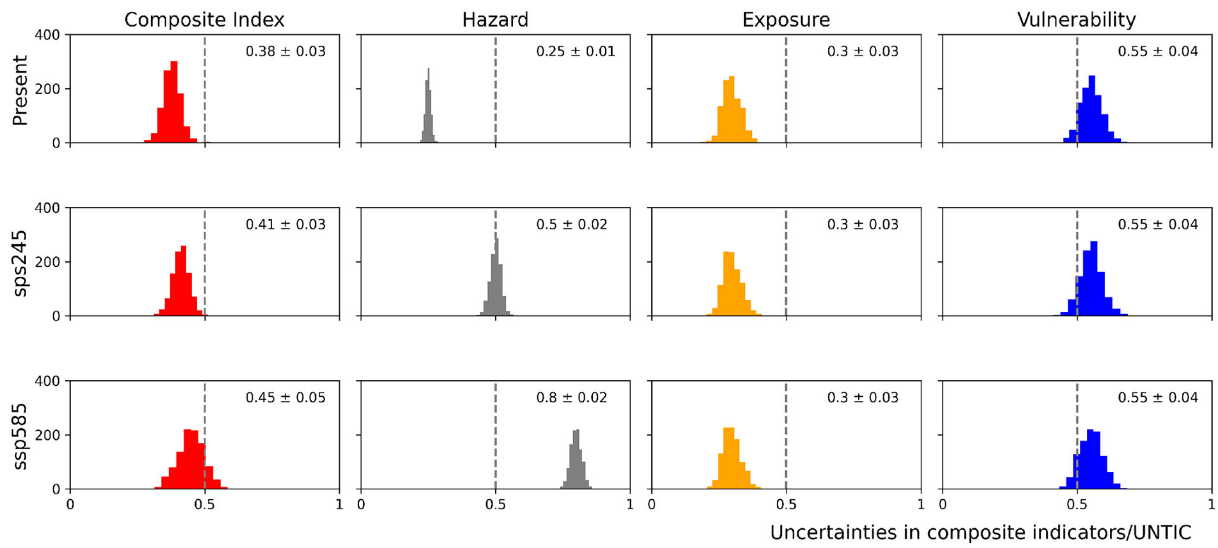

FIGURE 5
Probability distribution function for the risk estimate, the hazard, exposure, and vulnerability components under present conditions **(top)**, SSP245 scenario **(middle)**, and SSP585 scenario **(bottom)**. The mean and the standard deviation are indicated in the inset.

one 4 out of 14 indicators have been considered as unknown (low uncertainty); and in the third one 8 out of 14 indicators have been considered as unknown (high uncertainty). It can be seen, that increasing the knowledge gaps makes the aggregated components to be more uncertain. The exposure uncertainty shifts from 0.03 in the reference case to 0.12 and 0.15 in the second and third case, respectively. The same happens with the vulnerability. Consequently, the final risk distribution becomes wider as more gaps of knowledge are included, going from a standard deviation of 0.04, to 0.07 and 0.09 in the second and third cases, respectively.

The sensitivity analysis included in the UNTIC tool can help to design adaptation measures and to foster better-informed decision-making. Herein, we have evaluated the risk of losing tourist attractiveness due to global warming, setting the exposure, and vulnerability indicators constant. That is, no future change or investment in the touristic sector are considered to cope with climate change impacts. However, let us suppose that a high investment is projected to improve the air conditioning measures or to expand the offer of alternatives tourism activities focused on reducing the dependance on sun and beach tourism. These types of measures would reduce the value of some exposure and vulnerability indicators, which in turn, may reduce the estimate of the final risk. The opposite case in which no investments are planned, leading to worsen the conditions of some of the indicators, such as overcrowding or safety levels could be also evaluated. The sensitivity analysis provides a quantification of up to what extent those actions would affect the final risk. Some of the indicators may have little room for improvement (e.g., lower bound close to the red line in Figure 6) or have a little impact in the final risk. In those cases it would not be worth dedicating much efforts on reducing them.

A word of caution is also needed regarding a shortcoming of all composite index: the strong dependence of the final value on the definition of weights (i.e., the importance that is given to a certain indicator). We have proposed a way to reduce the subjectivity of the weight selection by applying the AHP. However, we recognize that this is not the final solution as it may be subject to biases. For instance, experts may underestimate the importance of a climate hazard (e.g., quasi-permanent heat waves) that are not that frequent in present climate.

Additionally, there is the third-level of uncertainty, mentioned in section 2.2, which is related to incomplete impact chains. That is, experts may have not identified some aspects that may play a role in the actual risk. Therefore, a calibration/validation process should be carried out to ensure the relevance of the assessment. Unfortunately, this is not easy at all. A possible option would be to analyze analog situations in time or space to infer a pseudo-risk that can be compared to the computed risk. To do that, a measure of a cost (C) should be defined. In our example this can be the degree of satisfaction the tourists have after their stay in a given location. Then, long time series of C can be analyzed comparing them with the hazard levels at that time (e.g., in our case the heat stress suffered by the tourists). After this, a measure of the probability of changes in C due to a certain hazard can be computed and compared to the estimated risk. The same could be done by comparing different locations where the corresponding IC is the same.

In our case study this calibration step was not possible since the historical record does not contain the required information

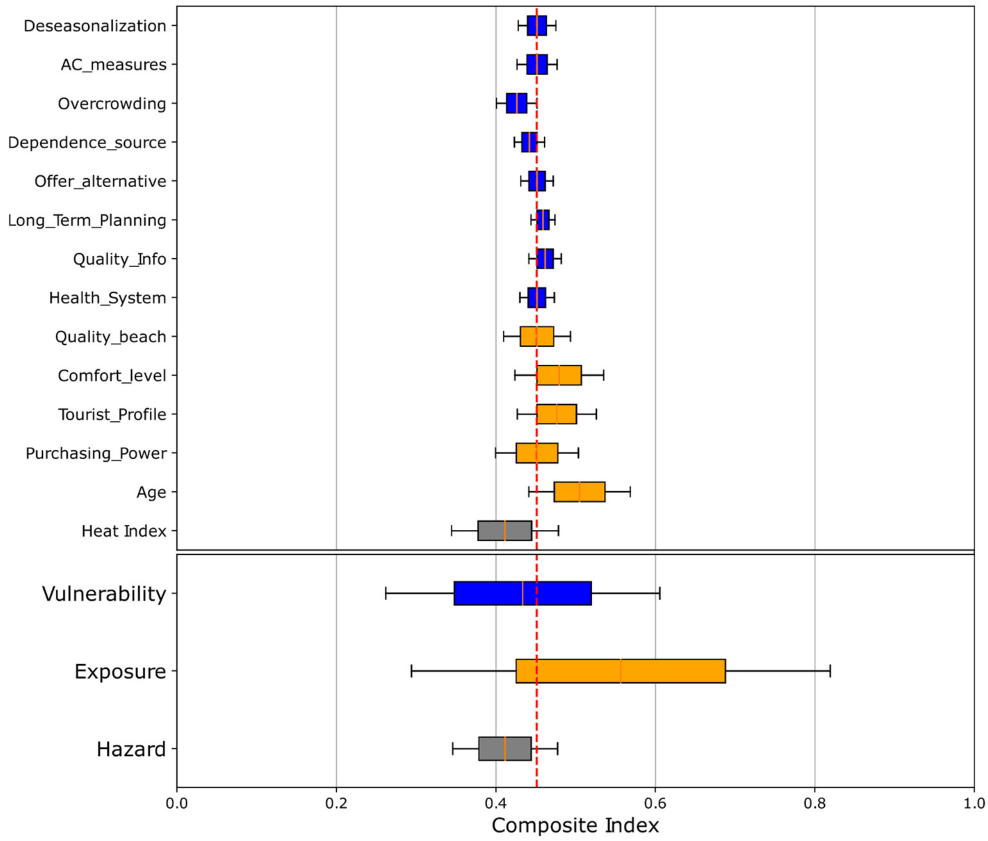

FIGURE 6
Sensitivity of the final risk under future scenario SSP585 to different values of each indicator and the aggregated indicators. The vertical red line indicates the computed risk while the bars denote the range of risk values that could be obtained for the whole range of values of a given indicator.

or it is not homogenized. However, that is not the case for other climate-related risks, where historical data certainly contains information on this relationship. For instance, let us suppose one is analyzing the potential risk to agricultural production of droughts. Even if this type of climatic event is expected to be more frequent and intense in the future (Seneviratne et al., 2022), there is evidence of agricultural losses induced by extreme drought condition in different parts of the world. The historical data can be used to constrain the hazard–exposure–vulnerability relationships and to calibrate the final risk. Such "calibrated risk" can be used to communicate climate change knowledge to the final users, which is still one of the main limitations to effectively translate risk analysis into decision making (Vaughan and Dessai, 2014).

Conclusion

In this study, a probabilistic framework for the computation of composite indices is proposed. As an example, the framework has been applied to the risk assessment based on the impact chain approach (Fritzsche et al., 2014). The new framework allows to accommodate in a natural way the gaps of knowledge associated to the operationalization of composite indices. In particular, the different components of the index including the indicators and their corresponding weights are not described by scalar quantities but by PDFs. These PDFs can be defined as analytical functions (e.g., Gaussian or homogeneous) with parameters representing the uncertainties associated to a given quantity. These uncertainties can be quantified from the datasets used to retrieve the indicators (e.g., climate model ensemble spread) or from expert knowledge. Through this approach, gaps of knowledge in some aspects of the composite indicator (e.g., the impact chain definition) can be easily considered in the assessment. This allows to quantify how those gaps affect the reliability of the estimated index.

In the framework of the UNCHAIN project, UNTIC, a web-based tool has been developed to ease the task of implementing the proposed methodology. The tool has been applied to a study case to illustrate how the uncertainties in different components of the impact chain can affect the robustness of the final risk assessment. Also, the tool provides an estimate of the sensitivity

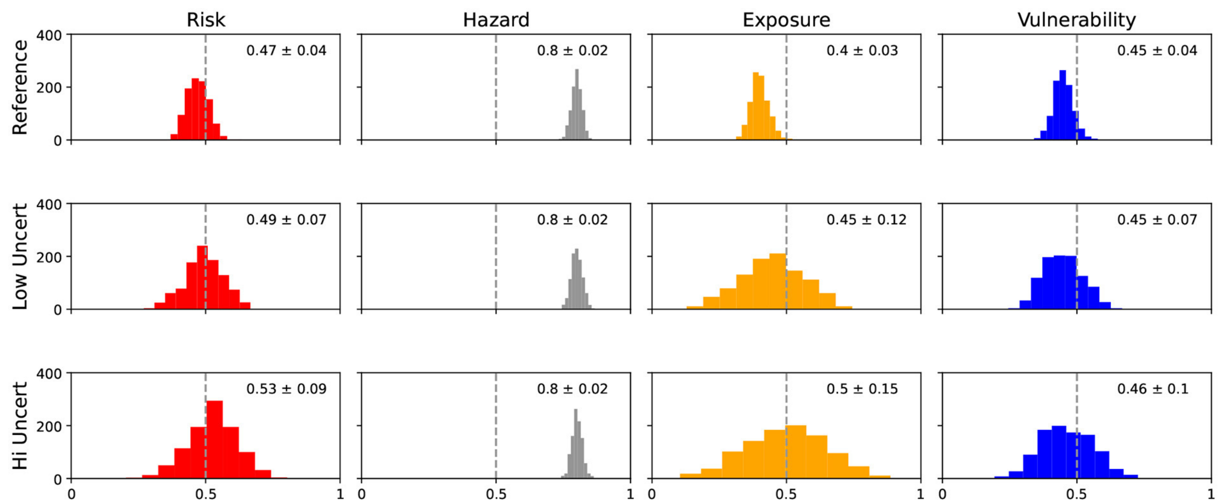

FIGURE 7
Sensitivity of the final risk under future scenario SSP585 to different level of incomplete knowledge of the indictors defined in the Impact Chain. The "reference" case **(top)** illustrates the case when values are assigned to all the indicators for the three components. In the "low uncertainty" case **(middle)** 4 out of 14 indicators have been considered as unknown, whereas the "high uncertainty" case **(bottom)** 8 out of 14 indicators have been considered as unknown.

of the final risk to each component, which can be used, for instance, to guide risk adaptation or mitigation strategies.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://untic.pythonanywhere.com/.

Author contributions

CM-A, MA, and GJ designed the study and the experiments, responsible for data processing and analysis, and reviewed the manuscript. GJ organized the structure of the manuscript. CM-A and GJ wrote the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Climate services for the railway sector: A synthesis of adaptation information needs in Europe

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Given that climate variability and change present unprecedented challenges to the rail sector, efforts to produce relevant climate data/information for climate risk management and adaptive decision making in the rail sector are gaining traction. However, inadequate understanding of climate change impact and information needs raises several concerns for the sector. This paper addressed the question: What climate risk information services are needed to support the adaptation needs of the rail sector? Data from interviews, literature reviews, and workshops were used. The results show that changes in precipitation, temperature, sea-level rise, and thunderstorms are the top drivers of climate risk in the sector. Additionally, the need for tailor-made climate information to manage these changes is in high demand. Although insufficient, rail organizations use special protocols to manage climate risk. Understudied countries have operational and design standards formulated in metrics and codes related to specific critical weather conditions as part of their Natural Hazard Management process. However, desirable adjustments in the standards are currently based on past events rather than future climate conditions. Future climate change information is relevant for medium- to longer-term decisions, strategy, and policymaking. For operational and design standards, weather and climate information provided by national weather service agencies are used but they also refer to the European standards and databases. National level data/information is preferred for developing thresholds for standards yet pan-European level information is also relevant in filling in missing data gaps. Therefore, rail organizations operate on flexibility and a "use of best available data" policy. Understanding how climate information is used to support decision-making in the rail sector is by no means an easy task given the variety of decisions to be taken at different spatial and temporal scales. However, stakeholder engagement proved to be an important step to better inform tailor-made information that is user relevant.

KEYWORDS

climate change, climate services, adaptation, railway, Europe

Introduction

Governments and organizations are concerned that extreme weather events caused by climate change will increase, and cause significant damage to infrastructure which undermines the development of many economic activities (Auld and MacIver, 2006). Globally, extreme weather events are recorded almost every year, causing frequent disturbances to railway organizations, affecting the safety, reliability, availability, and functionality of operations (Quinn et al., 2017). In addition to people's travel behavior, timing, travel modes, and travel routes are influenced by weather conditions (Sumalee et al., 2011). Meanwhile, the IPCC AR6 has stated that temperatures in Europe continue to rise, and the frequency and intensity of hot extremes have increased in recent decades. The report also indicates that they are projected to increase even further. In addition, extreme precipitation and pluvial flooding are expected to increase in all regions except the Mediterranean as global warming exceeds 1.5°C. The relative sea level will rise in all of Europe except the Baltic Sea and is projected to continue beyond the twenty first century irrespective of the level of global warming. This will increase the frequency and intensity of extreme sea level events leading to more coastal flooding. Severe windstorms at global warming of 2°C are also expected to increase (IPCC, 2021).

Given that the current and future climate changes endanger society and many sectors, the need for adaptation has gained increasing attention at the national and continental levels in Europe. This is particularly true for the transport sector where infrastructure and operations are more sensitive to extreme events such as storm surges, floods, and wind drafts compared to incremental changes in precipitation or temperature (Christodoulou and Demirel, 2018). Transport operations are however, more sensitive to climate change than infrastructure (Christodoulou and Demirel, 2018). Reports from past decades show that different weather conditions, exacerbated by climate change have caused severe damage to railway networks in different parts of Europe, affecting the functionality of the rail infrastructure and operational activities (Love et al., 2010; Nemry and Demirel, 2012; Schweikert et al., 2014). For instance, track warping due to uneven thermal expansion in the summer or build-up of snow and ice in the winter, lead to decreased speeds and causes derailment. Extreme cold causes brittle tracks and track separation while directly affecting the performance of rail operators (Xia et al., 2013). The severity of the climate effect is however, dependent on the type of design, age, and usage of the infrastructure (Baker et al., 2010).

Most weather-related failures in the rail sector are caused by high temperatures, rainfall, icing, storm, and lightning (Sabir et al., 2007). In Netherlands, 4–10% of all rail infrastructure failures have been attributed to adverse weather conditions (Duinmeijer and Bouwknegt, 2004; Xia et al., 2013). In 2018, 1,230 rail disruptions were caused by extreme weather in Netherlands (Scholten, 2020). Similar observations occurred in the UK where extremely high temperatures were associated with increased failures of rail buckles. In 2003 alone, 137 rail buckles cost £2.5 million in delays and repairs meanwhile buckling events are expected to be four to five times more frequent in the 2050s (Dobney et al., 2009; Jenkins et al., 2014). Also, 20% of all unplanned delays are due to adverse weather conditions (Thornes and Davis, 2002). More recently, it is estimated that ∼1.6 million delay minutes on the railway each year are caused by weather conditions (Dawson et al., 2016). In Austria, about 95% of all infrastructure damages are triggered by floods and rain (Bachner, 2017). These weather-induced impacts result in different kinds of costs including infrastructure, operation, and user costs (Doll et al., 2014).

Railways play an instrumental role in the European economy as they facilitate the production and distribution of goods and economic services and form the basis for the provision of basic social services (European Commission, 2010). The use of the railway transport system in Europe is expected to increase in the future because it can operate on low energy, making it environmentally friendly and necessary for the transition toward more sustainable and energy-efficient transport solutions (Rotaris et al., 2022). However, the combination of high future demand for rail and the need for long term planning and design raises many concerns about how climate change adaptation can be accounted for in the planning, design, and management of railways (Blackwood et al., 2022; Ferranti et al., 2022). Some studies have examined the implications of climate change on transport infrastructure networks including railways and concluded that climate change will alter the impact of weather-induced risk on the design rules, procedures for the operation, and maintenance of infrastructure (Armstrong et al., 2016; Adams and Heidarzadeh, 2021; Palin et al., 2021). A few case studies in Austria (Doll et al., 2014), the UK (Armstrong et al., 2016), and Netherlands (Scholten, 2020) have focused on building the resilience of the rail sector against the current climate hazards and future uncertainties. Additionally, another important research area is how to handle future climate risks and uncertainties with climate information services when planning adaptation for infrastructure (e.g., Wilson and Burtell, 2002; Auld and MacIver, 2006).

Climate information services are generally defined as the provision of science-based, user-specific high-quality data on climate variables such as temperature, rainfall, wind, soil moisture, and sea level. It also includes information on risk and vulnerability analyses, assessments, long-term projections, and scenarios to equip decision makers in climate-sensitive sectors to manage risks and explore opportunities created by climate variability and change. This helps society to become more resilient in coping with the increasing impacts of climate change (Vaughan and Dessai, 2014; Vaughan et al., 2016). Climate information services, therefore, involve the timely production, translation, and delivery of useful climate data and information. Climate knowledge is necessary for planning, societal decision-making, and climate-smart policy (Machingura et al., 2018). However, some challenges preclude the progress of climate information services. These challenges include lack of understanding of specific climate information, lack of capacity to use specific climate information, and use of information not locally relevant or fit-for-purpose. Information might also not be available on time or there might be reluctance to incorporate climate information into management practices. Poor understanding of scientific uncertainties and unrealistic expectations from end users cannot be addressed with the current state of knowledge (Dinku et al., 2014; Lackstrom et al., 2014). Other challenges are related to the multiple meaning of the services, the governing right which raises the tension between climate service as a public good or a business opportunity, funding structures, and mechanisms. Co-production as a pre-condition in climate services projects and initiatives have also been discussed (Bruno et al., 2019). Therefore, it is imperative to improve the provision of climate information services.

The application of climate information services for adaptative design, planning, and decision making is relevant in managing climatic risk and uncertainties [World Meteorological Organization (WMO), 2002]. This is particularly true for the rail sector given the numerous adaptation needs of the sector that requires climate information. However, only few studies focus on adaptation initiatives for European railway administrators (Lindgren et al., 2009; EEA, 2014). Copernicus Climate Change Service (C3S) is an example of such an entity that seeks to develop a sectoral climate information system to support infrastructure, transportation, and associated standards (https://climate.copernicus.eu/).

This paper, therefore, aims to address the question: what climate information services are needed to support the adaptation needs of the rail sector? In this regard, the paper focused on first, understanding how climate information is currently used within rail organizations and potential strategies to support access and use of climate information. Second, it identified the most important climate change impacts on the rail organizations and how climate risk information is handled by the railway organizations. Third, we elaborated on how climate information is represented in the design and operational standards of rail organizations. Finally, we explored the need for standardization of trans-national pan-EU rail trajectories and the logic of common standards regarding climatic extremes. The study also draws data mainly from Netherlands and UK rail organizations with some considerable inputs from Spain and Austria rail. Although the empirical data produced offers case-specific views and considerations, the findings of this study could serve as a template for researchers and policymakers in other European countries to develop proactive climate information services that improve the adaptive capacity and resilience of the rail systems.

Conceptual framework

Even with the ongoing extreme efforts toward greenhouse gas mitigation, scholars have concluded that certain climatic changes will be inevitable and as a result adaptation remains critical on the agenda of many scientists and policy makers especially large infrastructure managers (IPCC, 2021). Despite continuous advances in climate change adaptation for various sectors, the rail sector has not benefited enough from these adaptation efforts. This is largely because of significant knowledge gaps on the effects of climate change on the railway and the mismatch between adaptation needs and the information available (Bowyer et al., 2020). Rooted in the field of climate change adaptation, this research adopts a descriptive approach to explore the adaptation needs of the railway sector toward the development of effective climate information services that makes the railway system resilient. The study is based on the premise that if the right climate information is given in time, and in the appropriate format to the right stakeholders, good adaptation strategies can be implemented to avert the consequences of climate change.

More than ever, railways are exposed to harsh weather conditions due to climate change and thus the need for adaptation is growing. Different railway companies implement various strategies aimed at reducing the impacts of flooding, storms, intense rainfall, thunderstorms, and hot temperatures to survive the extreme weather conditions and to recover quickly. These strategies could be changes in operations and infrastructure design such as making changes to protective structures, erosion and drainage, material specifications, land use planning, early warning, and maintenance planning (Koetse and Rietveld, 2012; Ortega et al., 2020). For example, increased extremes in precipitation may demand an increase in drainage capacity, and wider temperature ranges will affect the rail tracks and thus demand proper maintenance. An adaptive railway organization, therefore, adjusts intelligently to the changing climate and delivers service sustainably with value for money (Quinn et al., 2017). Achieving this requires that adaptation needs be met with actionable climate information.

Climate change adaptation refers to the changes that are made to a system in response to actual or expected climatic effects to reduce harm and explore opportunities (McCarthy et al., 2001) Also, the term "need" as used in the context of this study refers to the "gap" between "what is" (current conditions) and "what should or could be" (desired conditions). The gap between "what is" and "what could or should be" must be measured to operationalize need. Therefore, we operationalized adaptation needs assessment as a systematic process for identifying, analyzing, and prioritizing current and future climate adaptation needs for the rail sector (Moore et al., 2018). The adaptation needs expounded in this study are not meant to be exhaustive because of the limited number of case studies, but rather, to represent the most commonly cited needs in the rail sector.

From existing literature, we also operationalize climate information services as the generation, translation, and transfer of timely and useful climate information for adaptative design, operational decision-making, and planning that makes the railway system resilient. Regarding the design of the rail system as used in this study refers to infrastructure and track engineering systems including earthworks, bridges, tunnels, steelwork, timber, and track systems which form the base upon which the railway runs. For example, to give a train a good ride, the track alignment must be set within a millimeter of the design. Operational decisions also include efficient passenger flow, ease of access, comfort of passengers, and healthy working conditions for personnel. Borrowing from the work of Quinn et al. (2017), resilience is defined as the ability of a rail organization to provide services effectively and sustainably as the climate changes. Further, the authors mentioned the need for a resilient rail organization to possess the element of (a) robustness: the ability to resist disruption, (b) redundancy: the ability to use backup facilities to provide service during disruption, and (c) recovery: the ability to rapidly return to service after a disruption.

This study, therefore, focuses on the interface of climate change impacts, emerging adaptation needs, provision of climate information, and data for the design and operations of the rail sector, as an interactive system that improves the resilience of the rail sector. The framework in Figure 1 starts by questioning how climate change impacts influence critical adaptation needs and affects the design and operations of the rail sector. This then demands effective climate information services that meet the needs and make the rail systems resilient. Analyzing such interaction in the different European case countries is expected to inform the development of a common pan-EU standard to meet the desired needs and make the rail organizations more resilient. According to Gharehgozli et al. (2019), even though standards will facilitate interoperability, quality, and safety of intermodal transportation for better performance, they have received little attention in literature. The authors argue that although many technical standards such as safety control systems for the electrical power network have been developed to improve the interoperability of the European rail network, these are not yet used throughout Europe. This is especially true for climate sensitive standards in the rail sector. Thus, results from this study will contribute to this effort.

The approach adopted in this study considers how the rail organization currently understands and deals with the impacts of climate change. The analysis identifies and describes various needs and data required to improve adaptation. This goes from incremental reactive adjustments that enhance resilience to current impacts, to significant transformations anticipating future changes (Matyas and Pelling, 2015).

Methods

This study uses data from document analysis, expert interviews, and stakeholder workshops (Figure 2) to address the main question: what climate information services are needed to support the adaptation needs of the rail sector? The study investigated; (a) how climate information is currently used within the rail organizations, (b) climate change impacts on the rail organizations, (c) how climate information is represented in the design and operational standards of rail organizations, and (d) the need for standardization of trans-national pan-EU rail trajectories and the logic of common standards regarding climatic extremes.

Literature review

The study adopted a traditional literature review approach to analyze and summarize relevant information required to answer the research question. According to Coughlan et al. (2007), a traditional literature review can help in refining, focusing, and shaping research questions as well as help in developing theoretical and conceptual frameworks. Thus, information from the literature was used to inform the background of the study, development of the theoretical framework, and preparation of the relevant questions to be asked during the interviews and workshop.

Aside from scientific articles, we used gray literature comprised of documents and reports produced by rail organizations including ProRail and Network rail (see references for the list of literature and documents consulted). For example, based on various documents from ProRail and Network Rail on the consequences of climate change, a list of the most important climate change threats was developed. These threats were further discussed during the interviews and workshop. However, the disadvantage of this type of literature review is that it has no standard study protocol and detailed search strategy. Also, the searches are conducted using keywords with no specific selection criteria and are usually subjective and non-exhaustive. Usually, well-known articles are selected for this type of review which is normally prone to bias (Fletcher and Fletcher, 1997; Demeyin, 2016).

Interviews

Prior to the workshop, representatives of ProRail in Netherlands and Network Rail in the United Kingdom were interviewed. A total of 15 interviews were conducted (9 from ProRail, 6 from network rail) with people from different departments in the rail organizations to identify the most important impacts. These individuals have expertise ranging from:

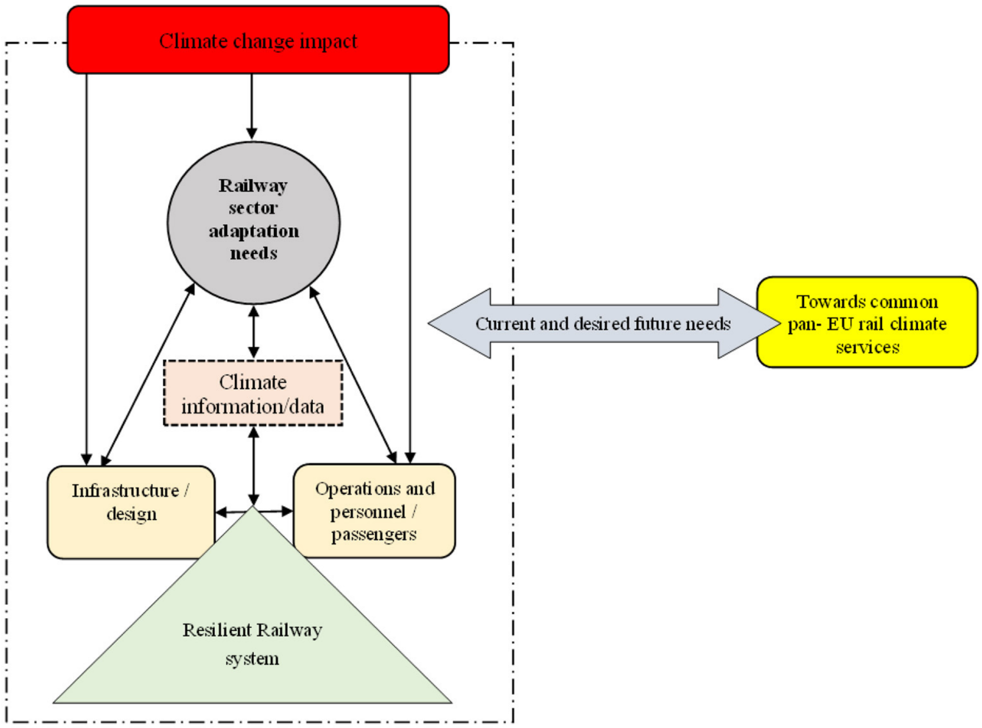

FIGURE 1
Conceptual framework of the study.

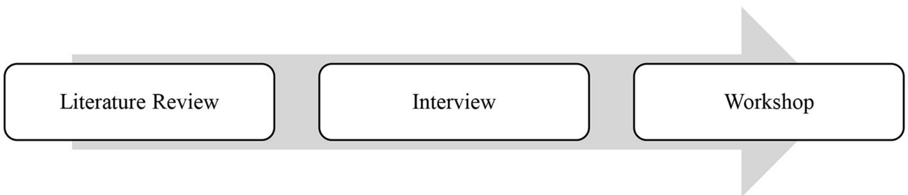

FIGURE 2
Methodology of the study.

- Station inspection and system safety.
- Contract and asset management.
- Signaling, switches specialist and system and civil engineering.
- Energy supply and electrical.
- Rail research and projects management.
- Infrastructure and maintenance work.

Interviewees were nominated by the main contact person of the rail organization and through a snowballing approach, where initial interviewers from each organization help recruit subsequent interviewees with specific relevant expertise. The selection of interviewers was based on individuals with skills and expertise relevant to the subject of discussion. We did not focus on large numbers but rather focused on the details of the discussions. It aimed to consult people with expertise on different aspects of asset management related to different climate hazards. We determined the sufficiency of the interview when it reached saturation; when interview responses yield no new or additional information or interview subject. The interview was structured to have a better understanding of the following issues:

a. How climate information is used within rail organizations.
b. Identify the most important climate change impacts on the rail organizations.
c. How climate information is represented in operational and design standards.

Based on the initial document analysis from ProRail and Network Rail, a list of the most important climate change threats was developed and discussed during interviews with 15 experts from different departments in the rail organizations. Subsequently, these impacts were fashioned into "impact schemes" indicating the relationships between climate hazards and impacts on specific parts of the rail system. Each interview was about 1 h, and the outcomes of the interviews served as a basis for the workshop.

Workshop

The workshop was organized at Amersfoort, Netherlands on 21st November 2019. Participants at the workshop included representatives from rail organizations, weather and climate service professionals, and standardization experts from the UK, Netherlands, Austria, and Spain. A total of 15 participants were purposively selected for the workshop: 7 from Netherlands (ProRail and ClimatAS and wageningen University); 4 from the UK (Network Rail and University of reading and John Dora consulting); 2 from Austria (Ubimet); and 2 from Spain (Tecnalia).

The workshop was divided into two sessions. The first session aimed at conceptualizing climate information in rail standards to understand how climate information is and could be represented (*current situation and desired future)* in rail standards across Europe. The discussions among participants were structured to focus on the design standards in one group and operational standards in the other group. A set of guiding questions were used to facilitate the group discussions (see Appendix A). The outcomes of each group discussion were presented on brainstorm posters.

The second session explored the climate change information demand from the rail organizations and supply from the climate data store using C3S. Based on participants' perspectives, climate change impacts were prioritized and projected using impact scheme posters. Every participant prioritized five impacts on the impact schemes based on the following:

1. Impact on the rail system.
2. Potential for developing indicators from the available climate datastore because data available may not be sufficient to develop relevant indicators to meet all information needs. For example, are there enough quality data to determine the number of days/years exceeding xx mm rainfall, as input for flood-related standards (matching demand with supply)?
3. Potential for integrating this information into rail standards.

Furthermore, participants discussed the needs and possibilities for relevant climate change information in the climate data store. Appendix B shows the guiding questions of the second session.

Results

Climate information use in rail organizations

Results of the interviews show that climate change impacts are a serious threat to railway infrastructure and operations. Thus, climate change information is relevant in managing these impacts. Rail companies are performing analyses to understand and address these impacts. For example, ProRail in Netherlands is currently performing climate vulnerability and risk analysis of the railway system and has developed guidance for integrating adaptation into new Rail projects. Network Rail in the UK has a special Weather Resilience and Climate Change program that guides weather and climate risk assessment for the design, construction, and maintenance of the rail system.

Potential climate change impacts

Results of the initial document analysis and interviews were aggregated into climate change impact schemes of precipitation (high and low precipitation), temperature (high and low temperature), thunderstorms, and sea-level rise as shown in Table 1. The design and operations of the understudied railway organizations are under serious threat of climate change impacts (Table 2). Changes in precipitation, temperature, sea-level rise and thunderstorms pose serious hazards to the railway systems.

Climate information on standards

Results show that rail organizations in the participating countries have their national standards but often make references to European standards. Operational standards of rail organizations use tailored made current weather information that is provided by weather service providers. In the *design* standards, however, different types of climate/weather information are used. Temperature for instance, is relevant for developing standards for European electrical equipment. There are national annexes to the Structural Eurocodes for snow and wind loads. Precipitation and flooding related standards are determined at the national and international levels. There are continuous efforts at the national level to update these standards. Table 3 shows ProRail and Network Rail examples.

Operational standards

Currently, individual countries have their operational standards that are related to specific critical weather conditions

TABLE 1 Identified climate change impacts.

Climate change	Hazard	Impact
Low precipitation	Increased fire risk	• Disruptions • Wooden railway sleepers catch fire • Burning of cables (for signaling energy supply)
	Low groundwater levels	• Rotting of willows in railways for stability • Rotting of wooden foundation infrastructure works • Insufficient water in wells for extinguishing the fire
	Low humidity	• Good impact: signaling fewer failures of electrical equipment
	Uneven subsidence	• The sag of station tracks, tunnels, and support structures (also: differences in foundation)
	High precipitation after drought	• Overhead line support structures sag
High precipitation	Flooding	• Railway saturated and become unstable • Flooded tunnels • Inaccessible platforms and stations • Rail erosion • Short circuits • Failing switches • Damage to electronic equipment (e.g., location cases)
Low temperature	Frost/freeze thaw	• Slip and fall accidents • Project planning threatened • Corrosion of materials due to salt sprinkling • Failing switches (freezing elements) • Overhead lines sag (frost on cables)
High temperature	Heat stress	• Overhead lines sag (expansion of cables) • Failing electrical equipment at stations (elevators) • Decreased lifetime conversation system steals bridges • Expansion of concrete works • Track expansion • Track buckling • Problems with moving elements: bridges, switches • False alarms occupied tracks • Discomfort travelers and workers • Thermal degradation of elements (e.g., copper)
	Change of climatic zones	• Health issues because of the processionary caterpillar (a moth or insect that causes diseases to workers on the rail lines)
Sea level	Storm surge	• Big impacts on the entire infrastructure e.g., high waves destroying rail lines and floods washing away or destroying assets
Thunderstorms	High winds	• Discomfort travelers (lack of shelter) • Moving overhead lines • Falling signposts • Decrease availability of movable bridges • Trees on track/overhead lines
	Lightning and electrical storms	• Damage and disrupt of electrical systems

as part of their Natural Hazard Management process. These standards focus on day-to-day operation of the railway and facilitate efficient passenger flows, ease of access, comfort of passengers, and healthy working conditions for personnel. Based on weather forecasts, the operations may be adjusted for the coming days while climate change information may be relevant to review the operational standards for climate resilient asset management. For instance, the indicators of heat stress for rail workers and passengers include temperature and humidity. This serves as input for operational standards related to working conditions or passenger comfort and health.

In Netherlands, rail weather service provides weather alarms according to the "Four Season Matrix." This Matrix provides critical thresholds for weather conditions that inform risk assessment and operational adjustment (Weijers, 2013). There are also weather alarms for temperature, wind, excessive rainfall, lightning, snow, frost, and freeze-thaw events. In addition, three weather codes with underpinning thresholds are used based on operational errors that have occurred in the past for these specific weather conditions. Code 1 describes temperature ranges that do not demand alterations in the operation. Code 2 describes a critical threshold that demands extra measures. Code 3 describes even more extreme weather events. The Austrian Österreichische Bundesbahnen (ÖBB) also known as Federal railway has a similar system. However, currently information on changing climatic conditions is not represented in operational standards. There are no efforts to screen the current operational standards for desirable adjustments anticipating future climate conditions. Yet, operational standards are changed incrementally through the weather changes that have occurred in the past decades.

TABLE 2 Prioritized climate change impacts/parameters for rail standards.

Actors/experts	Prioritized impacts/parameters
Actors from Netherlands	• Flooding (all impacts) • Uneven subsidence (all impacts) • Low groundwater levels (all impacts) • High temperatures (all impacts) • Electrical storms (all impacts)
Actors from the United Kingdom	• Surface water drainage overwhelmed • High temperatures (all impacts) • Objects on tracks/high winds • Sea level rise (all impacts) • Saturated earthworks, instability
Actors from Austria	• Increased fire risk • Extreme (wet) snow • Track expansion and buckling • Lighting and electrical storms • Saturated earthworks, instability
Experts on climate data supply	• High precipitation • Low precipitation • High temperature • Heat stress • Low temperature
Experts on railway standardization	• Flooding • Heat stress passengers and workers • Lighting and electrical storms • Storm surges

Looking at the expected conditions of the desired future, results show that future climate change information is relevant for informed decision making in rail organizations, especially for medium to longer-term decisions. Knowing expected changes in medium- and long-term climatic conditions is valuable to the rail organization at strategy and policy levels. If specific temperatures are frequently exceeded in 20 years, then rail organizations would have to revise their operational practices, change design and product specifications to minimize operational disruptions, or rethink their operational performance indicators.

The thresholds for weather conditions that relate to operational standards can be determined at the national, regional, or local levels. Such thresholds may be dependent on current climate conditions, robustness of the rail system, and level of tolerable and manageable operational failure. Therefore, it does not make sense to determine these thresholds at the pan-European level. Also, national level information is preferred if there is good quality climate information as this is more detailed and locally relevant. Moreover, climate change information from regional sources such as CS3 climate datastore has a resolution of 12 × 12 km and does not include local characteristics that are relevant for local scale impact assessments. Another reason for using more local climate change information is that national meteorological offices often develop specific downscaled climate projections. However, it is noted that the quality, availability, and relevance of climate change information at the national levels vary. Therefore, if the needed information is not available at the national level, the climate datastore could fill the gaps by providing services in two main ways:

TABLE 3 Use of climate information in standards.

Standards	ProRail	Network rail
Operational standards	Weather codes, "season matrix"	Managing weather operational risks—national control manual and supplementary standards
	Weather forecasts information by infoplaza	Weather service by MetDesk
Design standards	Internal "OVS" standards, often with references to Nederlandse Norm/European standards (NEN/ENs) norms.	Internal network rail (NR) Standards supplemental to ENs where appropriate
	Developed and maintained by asset management	Developed and maintained by the chief Engineer Team in asset discipline

1. Provide climate change data that national meteorological offices and weather services can use to model local impacts under future climates. This information could be used for climate stress tests, relevant to the operational and design standards of the rail system.
2. Provide a climate change information "dashboard" where rail organizations can find statistics for frequency, duration, and intensity of critical weather conditions under current and future climate conditions across Europe. The end-users would specify the climate variable and the thresholds they want to explore to make this dashboard sensitive to the various national contexts and needs. The dashboard then shows how often this weather event occurs in the current climate and how often it can be expected in future climates.

Design standards

Currently, ProRail and Network Rail are in the process of moving from using historical data to using climate projections for their design and operational policies. Network Rail also uses historical weather data and a guideline outlining projected changes to the baseline data based on UK Climate Projections. Similarly, ProRail uses historical data for railway design in addition to climate change projections. ProRail also has a guide for incorporating climate change projections into new projects though it is not yet officially part of their existing design standards nor the EN/ISO standards.

In the future, rail organizations would prefer flexibility and would adopt a "use of best available data" policy. European standards (EN) do not prescribe safety levels but rather provide information on different levels that can be used by national rail organizations to set their standards. EN standards should be flexible. For instance, it should not stipulate the use of the T100 hourly rainstorm but provide a range of rainstorms and their occurrence in Europe for the national organizations to use at their convenience.

As for the "best available data" policy, the desired situation would be one central NR/ProRail standard that can be used internally and when subcontracting work to engineering firms. This central standard should not contain data itself but rather refer to EN standards and United Kingdom climate projection (UKCP)/Royal Netherlands Meteorological Institute (KNMI) scenarios and data. It should abstractly describe the data to use. The EN standards should include information on relevant parameters (weather and climate variables/indicators) for specific climate risks that should be used and how they influence railway infrastructure. For instance, the number of days above a critical temperature threshold is relevant for track buckling.

Based on maximum hourly precipitation, a range of safety levels was significant to consider. The actual information for the location of the infrastructure can then be considered as the best available data source. For instance, UKCP does not provide data on maximum temperatures or extreme precipitation, at least these are not readily available in the Network Rail climate guidance note. Despite a reluctance to use anything that is not country-specific, providing such information could encourage railway organizations to use European scale information sources.

Climate change information needs for operational and design standards

Results of the participants' discussion on information needs and potential for rail operation and design standards are presented in Table 4.

Discussion

Generally, intermodal transport plays a vital role in the European Union (EU) policy on the future transport network. Road transport has remained the most dominant mode of movement in the last three decades because it is fast, flexible, and relatively cheaper. However, the use of road transport is reducing due to traffic jams, higher fuel prices, road taxes, and the increasing awareness of environmental issues. A shift to rail is considered the most effective way of reducing the pressure on European roads, saving money, and saving the environment (Gharehgozli et al., 2019). Unfortunately, rail transport faces several challenges including climate change impacts that obstruct the delivery of reliable, safe, affordable, and attractive rail services in the pan-European rail corridors. Hence the call for a Railway Standardization strategy in Europe and the sector vision for 2050 [European Railway and Infrastructure Companies (CER), 2013; International Union of Railways (UIC), 2016]. The role of climate services in meeting adaptation needs that will make the sector resilient to climate change impact is absent in these unified railway standardization documents. This paper, highlights the climate information required to support the adaptation needs of the railway sector.

We found that the participating railway organizations use climate information for different types of risk analysis that are intrinsically related to context and dependent on location. Some studies have observed that the relevance of weather and climate information is dictated by the nature of the risks being managed, the region of interest, the specific economic sector, the governance structures, and other context-specific realities (Adger et al., 2009; Goddard et al., 2010). This realization should drive the need for context specific climate services to assist decision-making in the rail sector. However, efforts to make climate information services actionable have rather concentrated on improving underlying prediction or observation systems with little attention to improving the

TABLE 4 Climate information needs.

Operational standards					
Impact/variable	**Indicators**	**Relevant for standard**	**Spatial resolution and coverage**	**Temporal resolution and coverage**	**Format**
Heat stress for rail workers and passengers	Risk ranges, e.g., low, medium, high	-Working conditions	Regional classes	-Time steps of 10 years, or user can define	-Graph or numbers indicating the risk for heat stress.
Variables: Temperature + humidity + clothing + age		-Passenger comfort and health		-Historical Conditions -Projections up to 50 years	-Dashboard allowing users to select clothing type, age, etc.
Temperature related impacts	-Number of days/years	-Multipurpose e.g., Checking for risk track buckling etc.	Regional classes	Historical and Future climate; users can define timesteps (e.g., based on lifetime assets)	The dashboard allows users to enter a temperature threshold and explore frequency or enter the type of lifetime asset
Variable: Air temperature	-Air temperature—above certain degrees Celsius				
Precipitation related impacts Variable: Precipitation	Two types of information: 1. Return periods of extreme rainfall events 2. Number of days/time period exceeding an amount of rainfall in mm.	Flooding related standards	Regional classes	-Historical and future climate -Thresholds for days, months, seasons and years. Flexible timesteps (e.g., based on lifetime assets)	Dashboard allowing users to explore: -Predetermined set of return periods extreme rainfall events -Thresholds for days, months, seasons and years (dashboard).
Drought related impacts	Number of days without precipitation.	Drought related standards	Regional classes	Historical future climate	Dashboard allowing users to for example e.g., enter the type of lifetime asset
Variable: precipitation	Number of consecutive days without precipitation			Flexible timesteps (e.g., based on lifetime assets)	
Wildfires	Indicator for fire risk (if possible). Intensity and frequency of fires	Fire related standards	Regional classes	-Historical and Future Climate -Temperature threshold wildfire events	Dashboards with different temperature thresholds for wildfire events
Design standards Lightning	Amount of lightning strikes per year	Regional classes	Distribution of lightning	Per decade	Map
Wind gusts	Max gusts	Wind related standards	Regional classes	Decadal	Map
Diurnal temperature difference	Diurnal temperature range	All Temperature related standards	Classes	Decadal	Map

(Continued)

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TABLE 4 (Continued)

Operational standards					
Impact/variable	**Indicators**	**Relevant for standard**	**Spatial resolution and coverage**	**Temporal resolution and coverage**	**Format**
Temperature range	Difference between maximum and minimum yearly temperatures	All T related standards	Classes	Decadal	Map
Heavy rain after drought	Heavy precipitation days after the dry period. E.g., number of times when the average maximum dry period is followed by T1 hourly rainstorm	Structural	Classes	Decadal	Map
Hottest and the coldest day per month	Average hottest day per month	T related	Classes	Decadal Map	Map
Coldest and the hottest night per month	Average coldest night per month	T related	Classes	Decadal	Map
Hot days	Days above 25 and 30 Celsius and days above current 90 and 95 percentile	T related	Classes	Decadal	Map
Max number of days w/o precipitation	T1, T2, T5, T10, T25, T50, and T100 events	Subsidence, sag, and stability	Classes	Decadal	Map
Precipitation deficit	T1, T2, T5, T10, T25, T50, and T100 events for cumulative rainfall anomaly for meteorological year	Subsidence and sag	Classes	Decadal	Map
Peak river flow	Change in 90, 95, and 99 percentile	Flooding of tracks, use of bridges	Classes	Decadal	Map
Hourly data on precipitation	Hourly T10, T25, T50, T100, T200, T250, and T500 rainstorms		Classes	Decadal	Map
Summer/winter precipitation	Change in seasonal precipitation		Classes	Decadal	Map

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acceptability and usability of climate information for decision-making (Lemos et al., 2012; Kennel et al., 2016). Consistently, the extent to which climate information is used to support decision-making in the railway sector is not clear. Understanding this is by no means an easy task given the different backgrounds of end-users in the rail sector and the variety of decisions to be taken at different spatial and temporal scales. However, stakeholder engagement implemented in this study proved to be an important step to better inform and tailor climate information to parameters and formats that are user relevant.

Access to useful and usable climate information is an essential step toward building a climate resilient rail sector where climate risks are anticipated and mitigated, and at the same time potential opportunities are exploited (Jacob et al., 2015; Goddard, 2016; Street, 2016). The different climate risk analysis and adaptation actions performed by rail organizations can be attributed to recent progress in the generation and provision of weather and climate information that has created opportunities to improve decision-making (Hewitt et al., 2012; Adams et al., 2015; Wilkinson et al., 2015). However, weather and climate information will become more relevant if they are tailored to match needs and are provided in formats that easily facilitate its integration into decision-making processes (Ranger et al., 2010; Daron, 2015).

Our results also show that the design and operations of railway organizations are under serious threat of climate change impacts. Changes in precipitation, temperature, sea-level rise, and thunderstorms pose serious hazards to the railway systems. Rail infrastructure is built to last a lifetime with many still expected to be functional by the end of the twentieth century (Auld and Maclver, 2006). However, some existing rail networks are located in areas that make them vulnerable to climate hazards such as floods. The degree of impact of the identified hazards however, varies among countries and largely depends on the design, age, and usage (Oslakovic et al., 2013). According to Auld and Maclver (2006), many of the rail infrastructures in Europe are aging at an unexpected and unsustainable replacement and maintenance rate. Consequently, these structures are increasingly vulnerable to climate extremes. Therefore, to address these impacts, historical and projected climate information is needed to perform risk assessments to guide infrastructure decision making and by extension develop the design and operational standards for the rail sector.

The use of climate information in the analysis of risk and development of potential adaption for the rail sector has improved in recent years. However, there are still significant gaps. Further improvements to transform this information into the design and operational standards are urgently required not only at the national but at the Pan-EU level. Technical guides produced by national rail organizations can be used as examples of good practice in developing climate sensitive Pan-EU rail standards. While the Pan-EU standards may serve as a relevant reference for developing rail infrastructure and related activities in the region, we suggest that it remains optional to allow individual countries the possibility to define their own nationally determined parameters to suit local geographical and climatic conditions. Currently, climate change resilience standards are yet to be introduced at the European level for the railway sector. The existing Eurocodes related to construction do not completely address all climate resilience issues such as flooding caused by intense and prolonged rainfall. Therefore, new guidance is recommended to address critical environmental impacts such as water action and flooding which pose a significant risk to infrastructure (Dora, 2018). Many standards have been developed already to improve the homogeneity of the European intermodal rail market. However, implementation of these standards has been problematic due to cost, hence taking several years for standards to be implemented throughout Europe (Gharehgozli et al., 2019). The main issues to overcome while implementing climate sensitive standards are to improve better communication and exchange of information between stakeholders. For example the language, timeliness, and accuracy of information communicated must be improved. The unit of measurement in which climate information is given must be standardized and well understood by end-users. Additionally, member states must have the required infrastructure to interpret and use climate information with ease.

In the face of a changing climate, the benefits of climate related standards for the design, operation, maintenance, and emergency responses of the rail sector are many. First, standards will increase awareness and understanding of climate-related risks and opportunities for railway organizations for better risk management, informed decision-making, and strategic planning. Secondly, they will serve as tools for designers, builders, operators, and users to ensure infrastructure safety, operability, and longevity of railway systems. Thirdly, standards can contribute to reducing costs when adopted throughout a project lifecycle due to retrofitting while building more resilient infrastructure.

However, many challenges also exist. These challenges include determining local thresholds in standards based on local climate conditions, the vulnerability of specific railway infrastructure (e.g., state of maintenance), and the local level of accepting failures. Moreover, the resilience of railway infrastructure is not only location-specific, but hazards may affect the entire network causing disturbances in operation. Another critical challenge is how to deal with trans-national railway design standards that intersect different climatic zones. The rail sector requires different climate data and information some of which are very ambitious. The questions that require attention are (a) which of the required data or information is feasible to generate at what level of uncertainty? and (b) what investment is required?

Quality data that is available in forms that are useable for local decision making is required to develop effective and useful climate sensitive standards. Copernicus Data Store could serve as a key data source, yet data currently available are coarse. This makes rail companies deem the data store useless for risk analysis and formulation of standards. Hence relying on weather and climate data from national sources. Nonetheless, Copernicus Data Store could meet the climate information needs of rail organizations by providing comprehensive data that is downscaled and bias-corrected to meet local specifications and needs.

To effectively develop climate information that meet adaptation needs of the rail sector, accurate appreciation of the problem through robust climate impact assessment needs to be conducted. In this regard, we recommend the use of digital technologies as they possess inherent abilities that ensure faster and more accurate evaluation of the conditions of assets relevant to decision-making and adaptation planning. According to Argyroudis et al. (2022), the deployment of emerging digital technologies supported by multi-stakeholder engagement accelerates the containment and recovery of infrastructure from multiple hazards in a sustainable manner making systems more resilient. The authors argue that although the traditional approach to infrastructure management whereby expert judgment is based on manual measurements and visual inspection are mostly used, it is limited in terms of responding in time to climate change impacts. Therefore, emerging digital technologies, such as the Internet of Things (IoT), Artificial Intelligence, and Building Information Modeling (BIM) (Sacks et al., 2020) can be leveraged for proactive decision making before, during, and after hazard occurrences. This will ensure a resilient rail system. Currently, the main digital technologies and solutions which have accelerated transformation in the railway sector include IoT, Cloud Computing, Big Data Analytics, and Automation and Robotics (Pieriegud, 2018). Furthermore, the development of vulnerability and restoration models is needed to quantify the risk and resilience of railway infrastructure exposed to climatic stressors. For instance, in Britain, scour has caused the failure of railway bridges crossing rivers due to flood events and as a result, Lamb et al. (2019) developed a probabilistic model to quantify scour risk in terms of passenger journey disruptions and associated economic costs. Also, given that climate change is expected to have an impact on the frequency and/or magnitude of flood events and thus on the restoration of bridges, Mitoulis et al. (2021) developed recovery models for traffic reinstatement and capacity restoration of flood critical bridges. These include restoration task prioritization, scheduling, inter-task dependencies, idle times, durations, and cost ratios for different damage levels, as well as the evolution of traffic capacity after floods.

We recognize that the method used in this study to identify the climate information required to support the adaptation needs of the rail sector may not be exhaustive. A limitation of this qualitative study is that it relies on perceptions collected from interviews and workshops which could be diverse depending on the knowledge level of individuals involved. This can cause differences in emphasis, though where possible it was supported with literature sources. Using a traditional rather than systematic literature review resulted in a broad overview of the research even so, the interviews and workshop offer more detail. A second limitation is that the respondents of the study were from a limited number of countries in Europe which may not be representative. However, it underscores the importance of co-production and collaborative efforts in identifying and understanding these needs. The different participating rail companies hold certain unique knowledge and understanding about climate impact and adaptation which could be useful to other companies.

Conclusion

This study is among a few that go a step further into the subject of climate adaptation and climate information services standardization in the European railway system. It combined a literature review and an empirical part based on interviews and a workshop. The study highlighted the most important climate change impacts on rail organizations, what climate information is needed, and how climate information is currently used for design and operational standards within rail organizations. In addition, we explored the need for a common pan-EU rail standard regarding climatic extremes. We found that weather and climate are the dominating factors that can shape not only the design but also the operational standards of railways when properly handled. Rail organizations from different countries have different approaches to dealing with extreme weather and climate impacts. For example Network Rail has a full program dedicated to weather resilience and climate change, with tools to perform climate risk assessments. ProRail has also developed various tools to map the rail systems' vulnerabilities, such as the national climate stress test for rail. The rail organization in Austria is specifically advanced in its natural hazard management, being able to recover quickly after extreme weather conditions. The organizations however, differ in their experiences about using the information on climate change to inform their operational and design standards. This is related to the availability and quality of climate change information at the national level. Nationally sourced information is preferred by railway organizations because such information is more specific and better for decision making at the local level. Nevertheless, across Europe, this kind of detailed weather and climate information is not always readily available, especially for rail relevant parameters. We suggest that the Copernicus Data Store can fill this data gap especially for "less mature" railway organizations or where data sources are less comprehensive. An example is frequency-intensity statistics for a set of weather conditions in the future climate. Also, we recommend the use of digital technologies, and probabilistic and recovery models in assessing climate change impact on railway infrastructure due to their ability to perform a faster and more accurate evaluation of the conditions of assets adaptive decision-making. To develop effective tailored climate information services for the railway sector, it is essential to engage relevant stakeholders such as researchers and railway decision-makers. The adaptation information needs identified in this study underscore the importance of collaborative efforts. Finally, there is high potential for knowledge exchange between rail organizations. Rail organizations that just started exploring climate risks can learn from organizations that are more experienced in addressing these risks.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

EA, MS, and EB conducted the research and wrote the first draft of the article. HG and FL assisted with the research question, framing, and writing of the article. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

APPENDIX A Questions for evaluating current and future situations of representing climate information in design and operational rail standards.

Current situation	Future situation
1. Where is climate information currently represented in standards? • In national standards and in/or European standards? • How do the national standards relate to European standards, and to other national standards?	1. Where should climate information be represented in standards? • In national standards and/or European standards • References to an external climate information source?
2. What climate information is currently used for standards? • National climate information? European climate information? What sources? • Historical climate? Future climate?	2. What climate information would be interesting to harmonize at an European level, and what information not? (e.g. temperature zones, precipitation events, wind, drought etc.) • For operational standards: Would it be relevant to project the weather codes/weather alarms for the future climate?
3. In what manner are design standards determined for specific climate conditions? • Absolute value for critical threshold? • Reoccurrence time? • Lifetime of an impacted object?	3. What should the climate change information - to be used in standards -look like? e.g. zones in Europe, different safety levels for climate variables, reoccurrence times / specific values.
4. How is climate information presented? • Graphs/Tables/Zones	4. In what format should it be presented? e.g. graphs, map viewer, tables, text
5. What are the shortcomings of current standards? E.g. regarding how they are organized? • Regarding the themes/ impacts that are addressed.	5. How could current shortcomings be overcome? Climate Information Need
6. Who is the user of the climate information in standards?	

APPENDIX B Guiding questions for climate information needs.

Information needs	Relevant questions
Impact	What information is needed to make climate robust standards for this impact? What are relevant national and European standards for this impact? (design, product spec. operation?)
Climate Variable and Thresholds	What would be relevant values for the climate variable (e.g. define different safety levels, specific values, reoccurrence time)? What information is available?
Geographical requirements	What would be the geographical resolution needed to include this information in design requirements? What spatial coverage?
Temporal requirements	What are relevant time steps for projecting this variable (think about the lifespan of the impacted object)? What should be the total time coverage? For which temporal resolution is this information needed? (e.g. daily, monthly, season, yearly) How often should this information be updated?
Quality requirements	What quality information is needed for this variable? e.g. uncertainty representation
Format requirements	In what format should this information be disclosed? E.g. dataset, map, graph, figure, table

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What's at stake? A human well-being based proposal for assessing risk of loss and damage from climate change

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Current scientific discourse on the assessment of loss and damage from climate change focuses primarily on what is straightforwardly quantifiable, such as monetary value, numbers of casualties, or destroyed homes. However, the range of possible harms induced by climate change is much broader, particularly as regards residual risks that occur beyond limits to adaptation. In international climate policy, this has been institutionalized within the Loss and Damage discourse, which emphasizes the importance of non-economic loss and damage (NELD). Nevertheless, NELDs are often neglected in loss and damage assessments, being intangible and difficult to quantify. As a consequence, to date, no systematic concept or indicator framework exists that integrates market-based and non-market-based loss and damage. In this perspective, we suggest assessing risk of loss and damage using a climate change risk and vulnerability assessment (CRVA) framework: the Impact Chain method. This highly adaptable method has proven successful in unraveling complex risks in socio-ecological systems through a combination of engaging (political) stakeholders and performing quantitative data analysis. We suggest expanding the framework's logic to include not only the sources but also the consequences of risk by conceptualizing loss and damage as harm to nine domains of human well-being. Our approach is consistent with the risk conceptualization by the Intergovernmental Panel on Climate Change (IPCC). Conceptualization and systematic assessment of the full spectrum of imminent loss and damage allows a more comprehensive anticipation of potential impacts on human well-being, identifying vulnerable groups and providing essential evidence for transformative and comprehensive climate risk management.

KEYWORDS

loss and damage, NELD, human well-being, risk assessment, indicators, climate change

Need for a holistic and human needs-oriented approach for assessing loss and damage

It is projected that climate change will have increasingly harmful impacts on the natural environment, as well as on human society and individuals (Field, 2014). These impacts are discussed under the umbrella term Loss and Damage. Policy and decision-makers worldwide are urged to act against climate change through mitigation and adaptation, to keep loss and damage from residual climate-related risks to a minimum. Nevertheless, current mitigation and adaptation trajectories indicate that residual risks are occurring and will become increasingly common globally (Nachmany and Mangan, 2018; Watson et al., 2019). Accordingly, decisions will increasingly be accompanied by the question: What is at stake once risks manifest into actual impacts? Therefore, there is a clear need for risk assessments of loss and damage beyond the limits of adaptation.

Assessing (potential) loss and damage is not a trivial task, as experienced harm can be intangible and not clearly quantifiable (Serdeczny et al., 2018; Chiba et al., 2019; McNamara and Jackson, 2019). Assessments, whether ex ante risk assessments or ex post impact assessments, are the much-needed base of evidence of what is at stake when climate risks manifest. However, existing assessments tend to focus on monetary valuation or other tangible aspects of loss and damage, such as the number of destroyed homes or casualties (Gall, 2015; Gawith et al., 2016). Such evaluations are heavily produced by, for one thing, the disaster risk community and secondly the insurance industry (Gall, 2015), whose interests lie in the first response to disasters and in resulting monetary damages respectively. Nevertheless, the straightforwardly quantifiable aspects alone do not reflect the full spectrum of harm experienced by those affected (Gawith et al., 2016; Serdeczny et al., 2018).

Climate risks and impacts may, for example, also entail mental health disorders, inaccessible sanitation, reduced mobility, disrupted school service, impaired collaboration between governments and communities and all its implications (Chiba et al., 2019), involuntary relocation (Pill, 2020), a lost sense of belonging to a place (Morrissey and Oliver-Smith, 2013). Moreover, it spans harm to cultural heritages, biodiversity, ecosystems or to indigenous and local knowledge (Fankhauser et al., 2014; Tschakert et al., 2019).

These consequences are referred to as non-economic loss and damage (NELD) or non-market based, as opposed to market-based loss and damage, and are regularly defined as harm to goods and services that are not commonly traded in markets (McShane, 2017; Serdeczny et al., 2018; McNamara and Jackson, 2019; van der Geest and Warner, 2020). NELD are often assessed explorative through first hand experiences, surveys and narratives and less often measured through indicators (Vincent and Cull, 2014; Van der Geest and Warner, 2015).

Neglect of NELDs in quantitative indicator-based assessments due to their intangibility and their resistance to systemization and quantification has led to the current lack of a systematic conceptualization of them. However, there is growing evidence of loss and damage in this category (Cissé et al., 2022). While some approaches have been developed to categorize and derive typologies from the loss and damage literature (Fankhauser et al., 2014; Tschakert et al., 2017, 2019; Boda et al., 2021), no holistic conceptualization exists at present. However, without a conceptual and applicable framework that overcomes the divide between market- and non-market-based loss and damage, much of it, especially in the non-market-based domain, might go unnoticed by authorities and remain unaddressed.

The indicator-based climate change risk assessment method "Impact Chain method" (Fritzsche et al., 2014; GIZ, 2017; Zebisch et al., 2021) became popular due to its ability to dismantle climate risks into its components vulnerability, exposure and hazard, to translate them into quantifiable indicators and to identify adaptation measures. The method employs a mixed-method approach that combines close stakeholder-researcher collaboration with operational, quantitative data analysis. The workflow is described step-by-step in the "Vulnerability Sourcebook" and the "Risk Supplement to the Vulnerability Sourcebook" (Fritzsche et al., 2014; GIZ, 2017). The method spans a set of tools to assess integrated risks within complex socio-ecological systems, and it is explicitly designed to consider locally specific conditions and needs. Further, it can raise awareness and foster risk ownership among policy- and decision-makers (Kabisch et al., 2014; Greiving et al., 2015; Kienberger et al., 2016). Especially important in this regard is that it provides strategies to systematize, weight and prioritize indicators that do not require monetary quantifications and, thus, enables weighting and combining straightforwardly quantifiable and less tangible factors into a single assessment.

In the Impact Chain framework, risk is, in line with IPCC framings, conceptualized as a function of vulnerability, hazard and exposure factors (IPCC, 2022). We argue that this logic can be extended to: Once risk manifests into impacts, loss and damage occurs. Loss and damage, in turn, needs to be conceptualized into its constituents, similar to risk being conceptualized as hazard, exposure and vulnerability.

Therefore, in this perspective we first discuss a possible conceptualization of loss and damage that supports indicator definition and does not require separating market from non-market based loss and damage. To this end, we build on reports and studies of occurred loss and damage and systemize them based on concepts of human well-being, which correspond to the evidence of already occurred loss and damage (Annex I).

Second, we explain how this conceptualization is integrable with the Impact Chain method and the wider IPCC risk framing.

A systematic conceptualization, integrable with an effective assessment method may enable better prioritization and systematic monitoring of what is worth protecting from potentially escalating loss and damage and at what cost. If we fail to prioritize and protect what we value, we may learn that "what is important, yet not sufficiently valued, may only become apparent when it is lost, at times irretrievably" (Tschakert et al., 2017).

Bringing loss and damage from climate change and human well-being together

The concept of human well-being is concerned with the question of what humans require to lead good lives, no matter the context, culture, or time. Human well-being is generally understood to consist of a range of non-substitutable or constitutively incommensurable determinants that must all be fulfilled to some degree (Fankhauser et al., 2014). While no one claims to have found the definitive set of these determinants, the concept is largely accepted and widely discussed. In fact, human well-being is considered by some as a promising candidate to replace economic growth as the new overall aim for sustainable development (Verma, 2017; Lutz et al., 2021). This concept is already influencing important development programs, such as the Human Development Index (UNDP, 1990), the Millennium Development Goals (UN, 2015), Sustainable Development Goal 3: Good health and well-being (UNDP, 2016), and more recently, the vividly discussed well-being indicator "Years of good life" (YoGL) (Lutz et al., 2021) and Project Drawdown (Jameel et al., 2022), which seeks to find synergetic solutions at the intersection between planetary and human well-being.

Table 1 presents a synthesis of well-being domains drawn from two central publications to systematically assess loss and damage from climate change. From a systematic assessment of more than 100 published case studies that "make visible and concrete what matters most to people and what is at stake," Tschakert et al. (2019) presents evidence for 18 NELD domains. Similarly, a working paper by Fankhauser et al. (2014) for the United Nations Framework Convention on Climate Change (UNFCCC), which is typically cited when referencing NELD domains, lists eight domains; however, these are only examples of a list of undefined length.

In addition to these two core pieces of literature, we build our conceptualization on two central concepts of human well-being. The first, the gross national happiness (GNH) index, is one of the best-known indicator frameworks for holistic assessment of human well-being. The GNH is known for its regular use in the Royal Kingdom of Bhutan as an alternative development indicator (Verma, 2017), and is used with modifications around the world at the national and sub-national levels. It challenges development framings based on gross domestic product (GDP) growth, which is in line with other recent tendencies to pull focus away from GDP and toward sustainable development framings in measuring human well-being (Costanza et al., 2014). The other human well-being concept we rely on for this study is laid out in Gough (2017): "Heat, Greed and Human Need–Climate change, capitalism and sustainable wellbeing." In this book, Gough defines domains of universal human need based on eudemonic psychology (autonomy, competence, and relatedness). These universal needs relate to a set of basic and intermediate needs and are sharply distinct from their respective satisfiers, which do differ by context, culture, and time (Gough, 2017; Max-Neef, 2017).

Assessing loss and damage with the impact chain method and conceptual embedding with the IPCC's risk framework

We propose to link these categories of loss and damage to the IPCC's risk framework, which is undergoing heavy use in assessments of current and future climate-related risk.

First introduced in the IPCC's Special Report on Extreme Events (Field et al., 2012) the risk framework has been further developed in recent years to include the concept of adaptation limits, which is of crucial importance for the discourse on loss and damage from climate change. The IPCC's 5th Assessment Report (Field, 2014) identified important biophysical, financial, social, institutional, and cultural barriers to adaptation, which can lead to soft and hard adaptation limits (Dow et al., 2013; Klein et al., 2015). The Special Report on Global Warming of 1.5°C (SR1.5) collected scientific evidence related to these limits for the first time (Roy et al., 2018). Moreover, the SR1.5 synthesis presented the first evidence that relates loss and damage to adaptation limits and residual climate-related risk (after adaptation), which has been substantiated by the contribution of WG II to the AR6 (IPCC, 2022c).

With the SROCC (Pörtner et al., 2019), the concept of adaptation limits has been embedded into the IPCC's risk framework (see Figure 1). The risk framework has been updated to explicitly consider limits to adaptation in these three risk domains (Mechler et al., 2020).

We embed our conceptual extension of a human well-being based categorization of loss and damage into this wider theoretical framing (Figure 1). Residual risks are risks that cannot be eliminated through actions to reduce hazard, exposure and vulnerability, i.e., they lie beyond the limits to adaptation. Once residual risks manifest we speak of impacts, which in turn cause loss and damage.

TABLE 1 Consolidated domain suggestions based on well-being and loss and damage domains as identified in Fankhauser et al. (2014), Gough (2017), Verma (2017), and Tschakert et al. (2019).

Loss and damage domain based on consolidated human well-being	Description
Physical and mental health	- Being alive (Fankhauser et al., 2014)
	- Getting through daily activities without fatigue or physical stress (Verma, 2017)
	- Being able to experience life satisfaction (Verma, 2017)
Material living standards	- Access to nutritious food and water (Gough, 2017)
	- Protective housing, asset ownership (Gough, 2017)
	- Income-generating activities (Tschakert et al., 2019)
	- Economic security (Verma, 2017)
Functioning ecosystems	- Supporting, provisioning, and regulating cultural functions (Costanza et al., 2014; Fankhauser et al., 2014; Tschakert et al., 2019)
Functioning communities and primary relationships	- Social cohesion between individuals, family, and community members (Tschakert et al., 2019)
	- Volunteering, solidarity, informal safety nets (Verma, 2017; Tschakert et al., 2019)
	- Sense of belonging to a place (Morrissey and Oliver-Smith, 2013)
Cultural heritage and identity	- Shared practices, narratives, and customs that provide meaning and structure to people's everyday lives (Tschakert et al., 2019)
	- Historic buildings (Fankhauser et al., 2014)
	- Traditional knowledge, festivals, norms, and creative arts (Fankhauser et al., 2014; Verma, 2017)
	- Help individuals to understand themselves and what is expected of them (Gough, 2017)
	- Language and socially specific skills (Gough, 2017)
Knowledge and education	- Local, indigenous, and community knowledge (Tschakert et al., 2019)
	- Formal education (Verma, 2017)
	- Values and skills (Gough, 2017)
	- Often strongly linked to the environment, and spiritual and cultural customs
	- Contribute to social cohesion and identity (Fankhauser et al., 2014)
Governance and participation	- Human dignity (Shultziner, 2004)
	- Being able to lead legal and just lives (Tschakert et al., 2019)
	- Being able to participate in government decisions (Verma, 2017)
	- Capacity to self-govern in a sovereign manner under the jurisdiction of a state (Fankhauser et al., 2014; Tschakert et al., 2019)
	- The "critical autonomy" to "compare cultural rules, to reflect upon the rules of one's own culture, to work with others to change them and, in extremis, to move to another culture" (Gough, p. 44).
	- Mobility, travel, no involuntary displacement (Fankhauser et al., 2014).
Self-determination and time-use	- Having the capacity to lead autonomous lives, have control over their lives (Gough, 2017)
	- Be valued, respected, and treated equally (Tschakert et al., 2019)
	- Balance between time spent on work, non-work and sleep (Verma, 2017)
A desirable future[a]	- Not having to apply "erosive coping strategies" such as selling productive assets or taking children out of school for additional household income (Van der Geest and Warner, 2015)
	- Having reason to believe that the future will be better than the present, that one's children will have it better, or that a life full of hardship will be compensated by a rewarding afterlife/rebirth

[a]During an exercise of assigning real-world loss and damage examples from Alston and Kent (2004) to the well-being domains, it became apparent that some examples were not satisfactorily assignable. In particular, these were the ones that are related to concerns about how the future will unfold and situations that require coping strategies that entail adverse future implications. Van der Geest and Warner (2015) call these "erosive coping strategies": Coping strategies with negative implications for future livelihood security, such as selling productive assets or taking children out of school for additional household income. To cover the impacts that take away from 'belief in a secure future', we have added the domain "A desirable future". The description column gives examples explicitly mentioned in the literature. The full table of domains given in the literature can be found in Annex I.

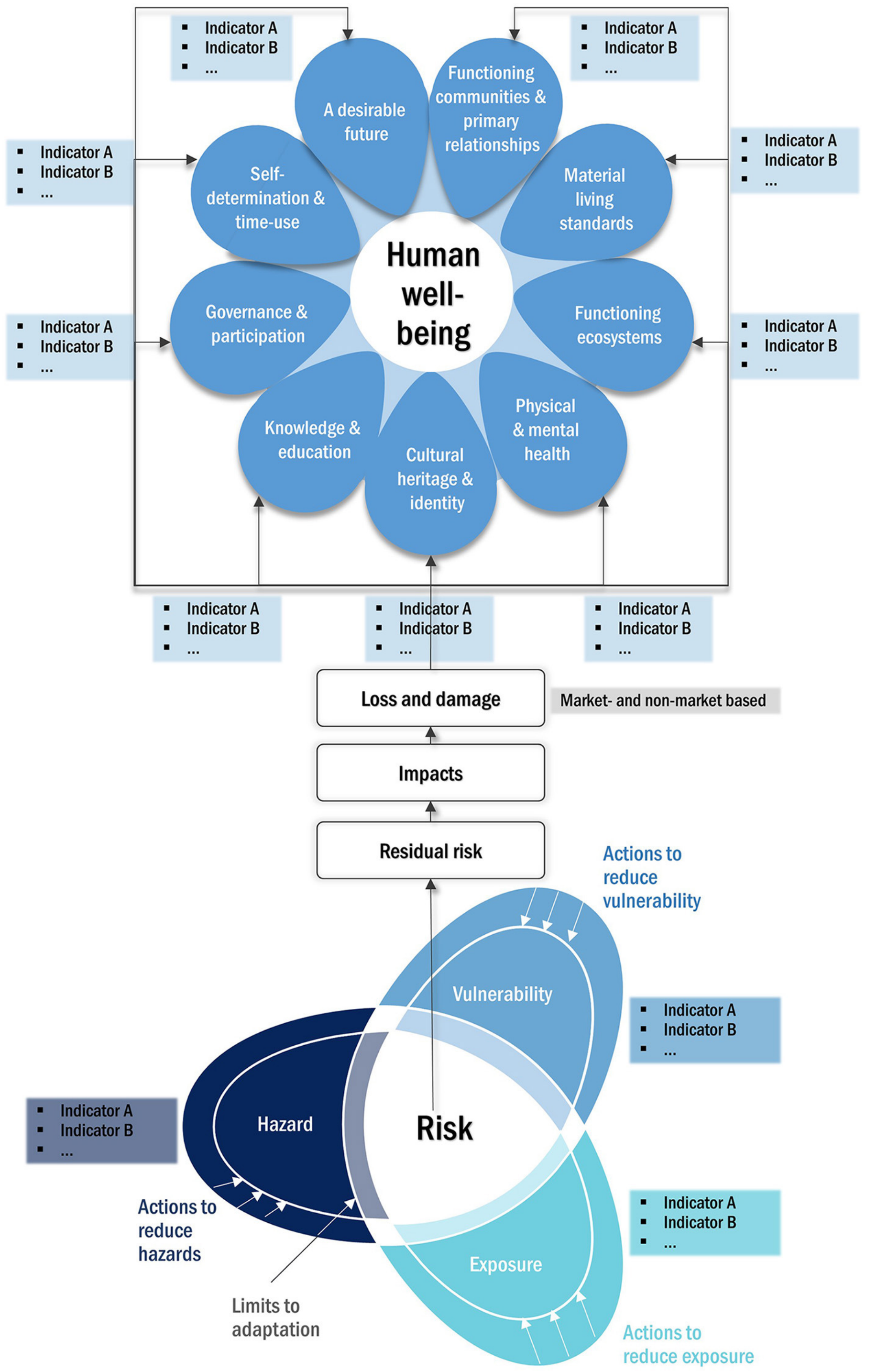

FIGURE 1
Human well-being as an approach to identify market-based and non-market-based loss and damage from climate-related risks. Climate-related risks manifest through a combination of three domains: hazard, exposure, and vulnerability. In all three dimensions, risk reduction measures may be taken, but simultaneously there may be limits to adaptation.

Loss and damage causes harm to human well-being. We propose to assess loss and damage and their respective relationships with domains of human well-being in an indicator-based manner.

In an operational risk assessment this could mean that instead of, or in addition to, identifying and quantifying risk contribution factors i.e., indicators to quantify hazard, exposure and vulnerability, the consequences of risk manifestations are identified and, where possible, quantified as well. Naturally, this is not a trivial task and requires a robust and extensive set of methods and tools. However, risk assessment strategies are continuously evolved and are becoming more sophisticate. Existing risk assessment methods, such as the Impact Chain method (Fritzsche et al., 2014; GIZ, 2017; Zebisch et al., 2021) offer ways to systemize tangible and intangible factors that contribute to a particular risk and provide quantification strategies away from monetary evaluations.

The Impact Chain method integrates the IPCC's risk framework and has proven that it can produce relevant and actionable insights for policy- and decision-making and is applicable in a broad range of contexts (Menk et al., 2022; André et al., forthcoming). The loss and damage related results produced by this method would in turn be integrable with comprehensive climate risk management approaches such as those given by Schinko et al. (2019) and Hagen et al. (forthcoming).

Discussion and conclusions

We proposed a systematization of loss and damage that builds on nine categories of human well-being. We understand loss and damage as harm caused by manifestations of residual risks beyond limits to adaptation. We propose this systematization to be operationalized within the context of climate-related risk assessments, in particular the Impact Chain method, building on the IPCC's risk framework. One of our aims was to lay out a path to narrow the gap between monetary assessments of loss and damage and qualitative NELD assessments. This is, because there is a need to synthesize both realms into one effective monitoring framework (Kurian et al., 2019). We argue that loss and damage indicators can be developed and monitored by the methods and tools already available to the Climate Change Adaptation, Disaster Risk Reduction and related communities. The indicators may be developed under nine "umbrella" categories that are for loss and damage what "hazard, vulnerability and exposure" is for risk. Through a close collaboration between decision makers and researchers, actionable, locally specific decision-support may be provided, aiming to reduce possible harm to human well-being. We draw on studies that describe loss and damage and studies that propose determinants of human well-being to systematize values shared by humans throughout space and time.

To pay due respect to planetary boundaries, we suggest that conceptualizing well-being is only possible between the planet's ecological ceiling and socially negotiated foundations that no one should fall below. Resilient and well-functioning ecosystems are an indispensable foundation to human well-being. Although the contribution of a component to the functioning of an ecosystem might not be scientifically understood yet, its disappearance can severely impact human well-being and must be avoided (Rockström et al., 2009). Thus, we argue that the disturbance of ecosystems be restricted to a degree that would foster well-being while not exceeding any planetary boundaries (Rockström et al., 2009; Steffen et al., 2015). This entails remaining within the "safe and just space for humanity to thrive" as indicated by Raworth's idea of "doughnut economics," bordered by the social foundation that must be ensured and the ecological ceiling that should not be exceeded (Raworth, 2017).

Taking this extended understanding of loss and damage based on human well-being, we aim to shift the discourse away from domination by monetary evaluation. Using simply cost-benefit considerations, poor and less-privileged communities tend to be deprioritized, and unjust or unsustainable structures tend to be reestablished (Preston et al., 2013). Furthermore, monetary evaluations provide the false impression that all loss and damage can be reversed if only enough money is allocated.

The well-being determinants presented herein are to be understood as a starting point for discussion, not a definitive answer to what universally defines human well-being. Harmed human well-being and social consequences in general through loss and damage from climate change are heavily underexplored, and detailed empirical studies are lacking.

We see three main challenges with this operationalization that need to be addressed by future research. The first is to determine a clear cause-effect relationship between a climate impact and an experienced impairment of well-being. Chiba et al. (2019) managed to attribute decreased mental health or trust in government to climate change loss and damage. However, the causal chain from climate impact to impaired well-being to adaptive action can be challenging to untangle, particularly for slow-onset/medium-onset processes, such as droughts. Future research efforts should therefore seek a way to attribute a clear cause-effect relationship between climate impact, harmed human well-being, and adaptive decision-making to explore other techniques to express decisions and their influencing factors.

The other conceptual challenge concerned thresholds and how to integrate them. We suggest that human well-being has a lower threshold, which we, in accordance with Raworth (2017), term the social foundation. When someone falls below the social foundation in any of the well-being domains, they experience loss and damage. To the contrary, the planet dictates a certain boundary to humanity: the ecological ceiling. At some point as we strive for well-being, we must reach a certain material living standard that we deem sufficient that is still well within the holding capacity of our environment. However, specifying such thresholds in actual real-world examples is challenging, as what should be considered above the social foundation is perceived differently between individuals and across cultures, and is continuously negotiated in society. Further research should seek a pragmatic means of conceptualizing the two thresholds for the purpose of assessing loss and damage.

The third challenge is the availability of data. While discussions about risk factors and their relationships can be solely based on expert or stakeholder knowledge, quantifying the indicators is heavily reliant on data. The absence of appropriate data has been found to be, to date, a major challenge in the application of the Impact Chain method (Menk et al., 2022). This challenge would be equally present when aiming to populate loss and damage indicators with data. However, the participatory awareness-building steps can be conducted even in the absence of quantitative data. To some extent, lacking data might be compensated through data-light approaches, such as utilizing expert knowledge to derive indicator weights or to integrate uncertainty (Melo-Aguilar, forthcoming; Kurian and Kojima, 2021). However, for a comprehensive indicator quantification, more research in the direction of utilizing citizen science, socioeconomic modeling or agent-based modeling would be necessary (Biggs et al., 2021; Kurian and Kojima, 2021).

We consider this perspective an opportunity to raise awareness for the widespread absence of data and knowledge about the possible consequences of residual risks manifesting. Some scholars warn that attempts to formalize and quantify harm in an indicator-like manner will lead to overshadowing factors that cannot easily be quantified (Tschakert et al., 2017). We do not challenge this, but we argue that attempting a quantification has the potential to increase awareness, and it also provides the opportunity to raise awareness for gaps in knowledge and data. We furthermore argue that collecting qualitative and quantitative data on harms to well-being could support sustainable development and decarbonization efforts, offering an evidence base for decision-making in addition to monetary valuations. Evidence of avoided loss and damage through mitigation and adaptation could also function as a performance indicator that could complement GDP. A robust and structured evidence base is crucial for policy and decision makers who seek to justify transformative risk management strategies that are not limited to gradual adjustments, but which seek to fundamentally alter systemic structures that lead to loss and damage (Kates et al., 2012; Deubelli and Mechler, 2020; Roberts and Pelling, 2020). Transformational risk management is moving away from adaptation practices that reconstruct vulnerable states of being and instead foster well-being and development (Wrathall et al., 2015). Viewed through this lens, prospective assessments of potential market- and non-market-based loss and damage from climate change constitute “an opportunity to scrutinize and address the root causes of vulnerability” (Roberts and Pelling, 2020).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, methodology, and writing—review and editing: LM, TS, VK, IH, and SK. Data curation: LM. Investigation: LM and VK. Funding acquisition and project administration: TS. Supervision: SK and TS. Visualization: LM, SK, and TS. Writing—original draft: LM and TS. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Rhine low water crisis: From individual adaptation possibilities to strategical pathways

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Introduction: In 2018, the Rhine transport sector experienced an unprecedented low water crisis, during which large cargo vessels were no longer able to navigate on certain sections of the river. This led to a major disruption in inland waterway transport. This article aims at questioning how the crisis acted as a stimulus for port authorities and their customers to consider the risks for their assets and operations and as a window of opportunity for creating a new collective and for defining "solutions."

Methodology: Inspired by the Impact Chain methodology, a step-by-step protocol integrating focus groups and interviews, was applied so that stakeholders affected by low waters can identify their individual and common vulnerability and define possible ways of acting (pathways).

Results: One of these pathways, the transitional infrastructural pathway, targets to increase the water level and overcome low water levels (use of Lake Constance as a water reservoir or creation of new water storage areas; deepening of the channel at Kaub and Maxau). It appears as the most suitable because it is a technical, well-controlled process that provides a comfortable solution in the short term. It exemplifies the lock-ins set by infrastructure.

Discussion: However, the participative approach also highlights the fundamental challenge of developing new processes and new intermodal organizations in the long term.

KEYWORDS

inland waterway transport, low water, adaptation pathways, infrastructural strategy, climate change

1. Introduction

The global trade in goods depends upon reliable transportation of freight along complex and long-distance supply chains (Curtis, 2009). However, these supply chains are highly dependent on infrastructures: ports, rail, road, river, canals, etc. The exposure of these infrastructures to hazards has severe consequences on world economies and societies, not only because they lead to an interruption in traffic and flows, but also because they have cascading effects on other sectors of society (Argyroudis et al., 2020; Shughrue et al., 2020). In the context of climate change, these hazards will increase and then undermine the organizations of stakeholders, which manage the logistics and transportation of goods, as well as infrastructure reliability (Chester et al., 2020). Understanding this vulnerability and the possibilities for action require not only scientific and technical knowledge, but also contextual knowledge and in-depth reflexion from the involved stakeholders (Jonsson and Lundgren, 2015).

Inland waterway infrastructure is one of these chokepoints; it is vulnerable to hazards and its disruption has local and transnational consequences (Bailey and Wellesley, 2017). The Rhine is one of the major European rivers, flowing from Switzerland through Germany, France and the Netherlands into the North Sea. It is a major corridor of inland waterway navigation. The organization of the commodities transport is based on the coordination of different firms and authorities (Figure 1), which have economic, social and political relations and will be named in this article "the Rhine transport sector." In 2018, this sector experienced an unprecedented low water crisis, during which large cargo vessels were no longer able to navigate on certain sections of the river. This led to a major disruption in inland waterway transport. The severity of this crisis was the result of several months of drought, reinforced by heat waves and low rainfall over the same period. Some of the traffic was absorbed by other intermodal providers and the wagon load rail system, but it was not sufficient. This crisis had cascading effects on the stock management of exporting and importing firms, customs regulation, and so on. This crisis was a confirmation of what was predicted by different researches: periods with low water levels are likely to occur more often and become more serious (Jonkeren et al., 2014; Klein and Meissner, 2016; Commission internationale pour la protection du Rhin, 2018). That is why some stakeholders, and particularly the Strasbourg port authority, decided to learn from this episode and to create a new arena of dialogue between stakeholders to define solutions. However, initiating a new thinking and working "community" results from a long process of different trials and confrontations of stakeholders' viewpoints (and sometimes their arrangement), which can be interpreted through pragmatic sociology (Lemieux, 2018).

In this context, we can consider that crisis acted as a stimulus for port authorities and their customers to consider the risks for their assets and operations and as a window of opportunity for creating new collectives and for defining "solutions" (Kingdon, 2003). As a matter of fact, major crises and disasters have the potential to change dominant ways of thinking and acting (Birkmann et al., 2010). They create new ways of considering the initial issue and the solutions to take, to push or to dismiss some ways of acting (Kingdon, 2003; Rudolf, 2007; Birkmann et al., 2010). But at the same time this impulse given by a crisis can reinforce some pre-existing ideas of adaptation solutions (Petitimbert et al., 2022). It can enlighten an already-existing solution, enabling "business as usual," which dissolves individual responsibility into the expected consequences of a project managed by national or international authorities. Crises can be then considered as opportunities to re-politicize projects, which were postponed or even abandoned, because of their environmental impacts, the economic costs and so on.

The increasing complexity and uncertainty in decision making due to climate change and the associated wicked problems (Head, 2022) make it necessary to better understand these possible levers of action (or inaction) and how the stakeholders react when faced with a crisis, how they try to define or impose strategies according to their capacity for action and their willingness to take their individual and/or collective responsibility to prevent risks (Meah, 2019). In the presented research, we then investigated how stakeholders after this low water crisis decided to work together, accepting the methodology proposed by researchers (social and engineering scientists) and the Strasbourg port authority and, through this process, made emerge conflictual or consensual visions of the low water problem and solutions.

This article more precisely attempts to understand the adaptation driving forces at the individual and collective levels for the inland waterway navigation transport and addresses two sub-questions: Are the stakeholders able to overcome their individual interests to create collective adaptive pathways? Why do they favor one form of adaptation pathways over the others?

Consequently, this article will present the results of a case study dedicated to the sensibilities and vulnerabilities of SMEs in the Upper Rhine Region where researchers and river transport stakeholders have striven to build common knowledge, to find sustainable adaptation pathways. A mixed methodology combining semi-directive interviews and collective brainstorming with the help of a collaborative methodology [particularly deployed in engineering design processes based on the use of specific software (TRIZ)] was used to help to take into account nuances between collective exchanges and individual representations. This methodology participates in opening the "black box" of the supply chain, the internal processes, the unsaid things. The third part exposes the results obtained at the individual and collective levels to apprehend the possibilities of adaptation, to tackle the situation of low waters. In the fourth part, the preferred adaptive pathway is discussed while exploring two dimensions: the necessary combination of technical and engineering and organizational rationale and the infrastructural choice as a way of delegating individual responsibility.

2. Climate change adaptation and pragmatic sociology: Basis of the theoretical framework

Addressing the increasing frequency and intensity of extreme weather events and natural hazards appears as a major challenge for humans and their activities. Climate change hazards have direct/indirect consequences for economic activities (losses and/or disruption of their routine functioning, decreasing productivity, infrastructure damages, capital assets weakening) (Thornton and Manasfi, 2010; Gobert et al., 2017;

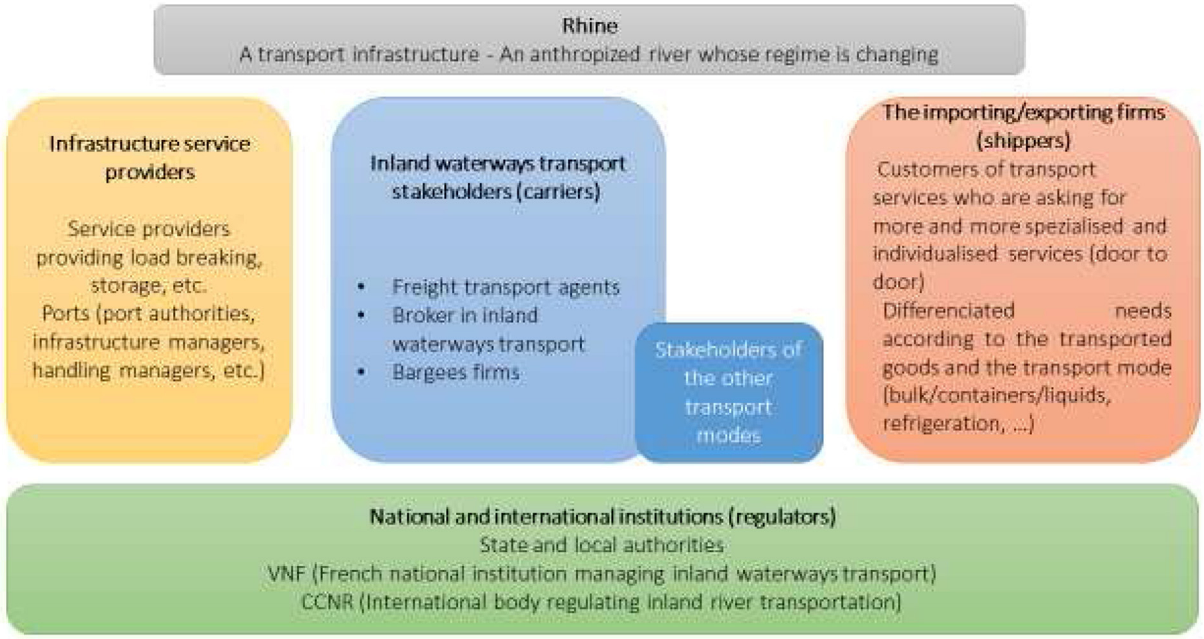

FIGURE 1
The different stakeholders involved in the process and impacted by low waters.

Chester et al., 2020; Averbeck et al., 2021). Climate change adaptation refers to the capability of a socio-technical system (and its stakeholders) to cope with risks, hazards, while integrating vulnerability (Smit and Wandel, 2006; Rudolf, 2008; Puupponen et al., 2015). Enhancing knowledge on risks, impacts and defining adaptation measures is more and more considered as a necessity (Thornton and Manasfi, 2010; Linnenluecke et al., 2012; Settele et al., 2014; IPCC, 2022). However socio-technical systems on which are organized economic activities like the inland waterway transport are embedded into different kind of lock-ins, which can prevent/slow down the implementation of coping measures (Winz et al., 2014; Berrang-Ford et al., 2015; Klitkou et al., 2015; Fazey et al., 2016; Burnham et al., 2018; Simoens et al., 2022). Then, adaptation measures differ depending on the sector of human activity and the vulnerability of the stakeholders and their assets (Harries, 2021).

Concerning the inland waterway navigation (Schweighofer, 2014), involving stakeholders in identifying the problems, their individual and collective vulnerability and the solutions are key steps, as international river navigation gathers numerous actors from different countries and activities (PIANC, 2020). Stamos et al. (2015) worked on adaptation measure roadmaps for the protection and resilience enhancement of transport infrastructure. Desquesnes et al. (2016) present the tools dedicated to design adaptive management strategies for the inland navigation waterway transport.

The theoretical framework deployed for this research is at the crossroads of two approaches. The first one is based on the literature on climate change adaptation: it aims at apprehending and explaining the pathways taken by stakeholders (through values, rules, knowledge, path dependency, levers of action, etc.). Different articles display typologies of adaptation strategies. Three main adaptation processes are often distinguished, although they may be named differently according to the authors (Hadarits et al., 2017):

- Incremental adaptation: A "entral aim of maintaining the essence and integrity of an incumbent system or process at a given scale" and founded in "the decision to continue responding to the same organizational objectives and within the same governance systems" (Park et al., 2012; p. 119). This adaptation attempts to fix the existing infrastructure: stakeholders progressively (sometimes unconsciously) adjust their behavior, their habits, because they are hit by a hazard, because they take into account a "natural" evolution, but without integrating this change into a strategic decision of adaptation. This appears as a reactive adaptation process or spontaneous adaptation (Godard, 2010).
- Transitional adaptation is "…an intermediary form or adaptation. It can indicate an extension or resilient adaptation to include a greater focus on governance or an incomplete form of transformational adaptation that

falls short of aiming for or triggering cultural or political regime change" (Pelling, 2011; p. 56). The stakeholders recognize the effects of climate change on their daily operations (and clearly attach the reasons to climate change) and build a well-considered action to anticipate hazards and to minimize impacts. This way of thinking intends to keep "business as usual" [for example, new freight schedule planning for river transport as illustrated by Zheng and Kim (2017)] and do not challenge the structural causes of the dysfunctions. The adaptation process is then intentional.

- Transformational adaptation (Kates et al., 2012; O'Brien, 2012). In line with Folke, we consider that it is not just a question of upscaling the adaptive answer, but of work on the causes of the system degradation (supply chain organization at the global scale, resource vulnerability, etc.). Then, it does not imply a simple relocation of economic activities, but a new organization of these activities to respect ecological rhythms. "The capacity to transform the stability landscape itself in order to become a different kind of system, to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable" (Folke et al., 2010).

These researches often outline that "business as usual" strategies that do not challenge the current system are privileged; because they do not question the current way of thinking and doing (cognitive comfort), they appear more "reachable" and less time-, money- and resource-consuming (Fedele et al., 2019). Climate change issues are often observed and addressed from fragmented points of view and by domain; this process tends to promote "techno-fixes," although they raise multi-scale, integrated and systemic challenges, mixing technical, individual, organizational and institutional dimensions, that are required to be dealt with simultaneously (Abson et al., 2017). Even when methodologies of knowledge production become more participative, from formalization of the issue until the proposition of solutions, as it was the case, they do not fundamentally transform this preference. Fedele et al. (2019) particularly study transformative adaptation, considering it aims to reduce the root cause of vulnerabilities to climate change, but many barriers hinder implementation: human, financial, time high investments, power imbalances between stakeholders (dominant actors can block the evolution, because their position may be disputed).

These pathways are defined by actors, who have each a vision of the world, a way of perceiving climate change and its impacts. It resonates with pragmatic sociology, which explores "the reasons for acting and the moral exigencies that these persons give themselves, or want to give themselves, if not by way of "ideals"" (Boltanski and Thévenot, 2000; p. 20). Human action is seen as deeply embedded in situations. Some stakeholders can use the opportunity of an event to enroll other stakeholders to share their perspectives and to define new actions. The ability to adjust between different rationalities may be the main social skill needed in response to environmental challenges of our time and the methodology deployed can help some boundary organizations/actors to reach this goal. That is to say they are able to translate the expectations and interests of other actors, even if they do not share the same apprehension of a problem, and to build a bridge, a consensus. That is why this understanding of the stakeholders' agency is the second dimension of our framework.

3. A co-production process based on a mixed methodology

3.1. A case study imbedded in the project UNCHAIN

This article is the result of one of the case studies, carried out for the project UNCHAIN ("Unpacking climate impact chains -a new generation of climate change risk assessments") in correlation with the INTERREG project, Clim'Ability Design. This project takes as reference point the concept "impact chain" (IC), first published by Schneiderbauer et al. (2013), and then "catalyzed" by the German cooperation (GIZ), in the Vulnerability Sourcebook (VS). As outlined by Zebisch et al. (2021) the "VS" was developed to address the need for an operational vulnerability and risk assessment. The VS—with its supplement and adaptations (Zebisch et al., 2022)—is a standardized methodological framework for climate change vulnerability assessments.

The Unchain project is consequently based on the postulate that CC adaptation requires a shared scientific knowledge (Bremer and Meisch, 2017; Nogueira et al., 2021). Therefore, a constructive dialogue between different professionals (researchers, public authorities, private sectors, NGO's, etc.) has to be completed, in order to build a collective understanding of the issues due to climate change and actionable knowledge. The project assumes that adaptation strategies could fail if they are not embedded in the perceptions, representations and experiences of individuals, in their specific context of action and interaction. As well, they do take into account the local adaptive capacities (Burnham et al., 2018).

In line with previous and complementary European projects developed in the Upper Rhine Region and dealing with climate change adaptation strategies (Interreg Projects Clim'Ability and then Clim'Ability Design), it was decided to focus our attention on the low water periods and their consequences on the river's international transport and to deploy the IC methodology while adapting it to the context.

It was decided to explore the consequences in Strasbourg of the 2018 crisis when the Rhine transport sector experienced a major disruption of inland waterway transport. Low and high waters are common periods integrated in the planning of the stakeholders. Water levels on the Rhine River fluctuate with seasonal rainfall[1], and both high and low water levels can create problems for barges. As such, barges need to adjust the amount of cargo they carry to balance bridge clearance and deep draft restrictions based on water levels. Low water levels mean barges must carry less cargo, increasing the freight rate per unit of cargo. Low waters are particularly impacting at certain water levels because many vessels can no longer move because they need a large draft for loading the goods they carry. Inland waterway transport can even be stopped to avoid accidents and groundings. This was the case in 2018.

That year, Strasbourg Autonomous Port recorded its lowest tonnage of goods for half a century. A drop in the commodities transported by river was observed (−35% for Upper Rhine French ports). Some sectors at the European level were particularly affected, like agriculture: crops could not be exported. The direct economic impact for firms had resulted in a difficulty in being provisioned and in increased barge freight rates. Low water surcharges are indeed applied at critical water levels. According to the goods transported and the transport modes[2], intermodal solutions had been rapidly considered (transferring goods from inland waterway to roads or rail). But the other transport modes also have their own inertia. First and foremost, transferring all containers on roads or rail was impossible because of the considered volumes and the types of goods. Alternatives to shipping products on the Rhine River are expensive for shippers. It also appeared complicated to change transport modes if the transport providers impacted by the crisis did not have previous contracts with rail or road transport companies. As Caris et al. (2014) outline it, Intermodal transport decisions need to be integrated in advance with supply chain decisions. Moreover, some resources may have been lacking. For instance, railways are considered as insufficient and too overloaded to assure the transferability. The lack of skilled drivers is also a European issue[3], which reveals itself as particularly symptomatic when a crisis breaks. That is why reacting in the face to this kind of crisis requires a collective agility and demands deeper and longer work between stakeholders: firms which have to transport goods or resources, carriers, port authorities.

In 2020, Strasbourg Port Authority proposed a process of collective brainstorming with researchers to better identify the different issues raised by low waters, the solutions which could be drafted, and the contradictions between them, so as to select the best solutions worth being explored.

3.2. A mixed methodology combining semi-directive interviews and guided collective workshops

The preparatory phase was based on the reading of the gray literature (literature produced by institutionalized stakeholders like the Central Commission for the Navigation of the Rhine, the port authorities, the national authorities managing inland waterway transport and flows, etc.), of academic literature (dedicated to the specific impact of droughts and lack of rainfall on river levels and then the capacity for transport providers and the associated supply chains) (Park et al., 1995; Thirel et al., 2015).

Moreover, after a long approach phase with Strasbourg Port Authority, a working relationship was built and enabled researchers to identify key stakeholders (transport providers, importers/exporters using inland waterway transport, etc.), and to immerse themselves into an existing network[4]. This immersion and consequently the understanding of the issues raised by low waters from operators' point of view were particularly noteworthy. It progressively opened access to the operators, not only to organize collective workshops, but also to facilitate the possibility to fix appointments for interviews.

A mixed method was then employed to understand the vulnerability of the firms and the territories to low waters: semi-directive interviews with stakeholders concerned by low waters, and the implementation of the Inventive Design Method (IDM) to stimulate a cooperative understanding of the collective vulnerability to the risk. This was a step-by-step approach,

1 Since the early 90s, it has been studied how climate change has changed the Rhine toward being a rain-fed river (Park et al., 1995). Winter discharge increases, which can have consequences for safety, and summer discharge decreases with consequences for shipping, industry, agriculture and ecology. The climatic and hydrological consequences of these unpredictable weather patterns include prolonged periods of heavy rainfall and dry conditions leading to drought, as well as the continuous melting of glaciers in the Alps that feed into the river. Increased rainfall and snowmelt in the Alps, with water levels rising, seasonally cause river shipping to be suspended at several sections between Karlsruhe and Koblenz. Low waters have consequences for inland navigation, where the river is shallow.

2 By dry cargo ships (for grain, scrap, etc.) and tanker ships (for transportation of oil, chemical liquid products, etc.), in container or in bulk.

3 A shortage of skilled drivers is affecting the freight and logistics sector at the European scale. This could affect the transport prices and is considered as a major challenge for national and international carriers.

4 The Port Authority had already organized groups of stakeholders concerning other issues and some of these collective workshops had already resulted in actions (and the transformation of these groups into coalitions for action) to work on industrial ecology and find synergies between firms for example.

similar to the method proposed by the Vulnerability Sourcebook (VS) (Figure A2 in Appendix).

Then, from September 2020 to March 2021, four workshops brought together inland navigation stakeholders according to their activities. They were prepared by researchers from the engineering and social sciences in order to apply the IDM to the problem of severe low water levels (using Triz software). The IDM is a participatory engineering approach that enables breakthrough solutions to be proposed to resolve problems in the industrial system especially for designing new products (Cavallucci, 2018; Coulibaly et al., 2022). The IDM highlights an overview of the logical links between these problems and the actions (already implemented or only envisaged) to try to solve them (Figure A1 in Appendix). The links between problems and solutions imposed by the software in the construction of the tree diagrams facilitate the understanding of the overall problematic situation[5]. Furthermore, one of its interests is to capture the positions built in interaction and obtaining the largest consensus (Zhou et al., 2022).

However, co-production of knowledge raises several challenges, since stakeholders have diverse expectations, worldviews and interests. Besides, during workshops, some processes of domination can take place and erase the diversity and subtlety of opinions. We noticed that the inland waterway transporters' interventions were more frequent, more developed and, in both groups, they were the ones who proposed to favor infrastructure development rather than another partial solution. The reasons for this imbalance may be explained by the ease of speaking.

To tackle this issue and to apprehend social representations concerning climate change, the challenges of adaptations at the intra-organizational level, since July 2020, semi-directive interviews had been conducted with river operators (infrastructure managers, shippers, transporters, etc.), specialists on the Rhine and operators of other transport modes (see Table 1). The interviews lasted between 90 min and 3 h each; and were fully recorded, transcribed, coded and analyzed (Lejeune, 2015). This qualitative methodology is based on a very patient reading of the interviews to better understand the processes at work and the resources used and to identify the narratives elaborated by each stakeholder and possible associations or contradictions between them. The interviews were also a way to enlarge the panel of involved stakeholders, while researchers also questioned cruise transport representatives, environmental associations, or firms located on the other side of the border, in Switzerland.

The semi-structured interviews conducted with Rhine transport operators make intelligible different dimensions of a complex field of activity; each actor gives insight into concrete practices situated in specific contexts. Compared to quantitative survey methods, and even compared to collective interviews (focus groups), the methodological interest of the individual interview is to make accessible the way in which the different actors understand the situation(s) in which they find themselves, the problems and issues they encounter in their activities and the margins of maneuver they have available.

4. Results: Adaptation possibilities—from individual involvement to strategical pathways

This section presents the results obtained at the individual and collective levels to apprehend the possibilities of adaptation, that is to say of adjustment to tackle the situation of low waters. The different combinations of technical, infrastructural and organizational solutions draw pathways of possible adaptation.

4.1. Individual vulnerability and adaptation possibility

Dependence on the river makes sensitivity and vulnerability to the hazard stronger. The Rhine is considered as a human-made infrastructure. The dependence on this infrastructural "resource" has a significant influence on the way stakeholders consider the effects of climate change and their willingness to act, to develop solutions. As a matter of fact, shippers (firms which export and/or import commodities or raw materials) are less sensitive to water level, than to prices and sometimes transport time, according to the commodities transported[6]. Other work has highlighted this different sensitivity in relation to the place occupied on the supply chain and the proximity to the resource affected more directly by climate change (Rudolf et al., 2019). Each link of the supply chain is then hit by

5 The Triz Inventive Design Method is a participative engineering approach that allows participants to propose breakthrough solutions to solve problematic situations or industrial impasses. The process is divided into six main steps: Collecting information from a sample of firms and operators impacted by the issue; building a "problem graph" whose root corresponds to the key problem. In this case, because of drought and a lack of rainfalls, navigation on the Rhine is hindered during low water periods and then stopped for inland waterway transport, which has consequences on different levels, at the international, local, and intra-firm scales; identifying evaluation and action parameters, which respectively allow the problems to be placed on a scale of intensity (severity) and the possible solutions to remedy them; constructing a graph of contradictions resulting from the evaluation and action parameters and action parameters; solving the contradictions (Solution Concepts); evaluation of the solution concepts in order to identify the most relevant that could be implemented.

6 For example, pharmaceutical products (high-value goods) cannot suffer from a break in the cold chain, because of their vulnerability to certain temperature.

TABLE 1 Sensibility, vulnerability and adaptation capacity according to the types of stakeholders.

Stakeholders by profession	Variables of sensibility	Level of vulnerability to low waters	Adaptation capacity and possible difficulties
Ship owners	- Water level (and singularly in Kaub and Maxau) - Fleet type: number of vessels, number of large vessels, vessel size, lifetime of the boats	Very strong because of water level dependency Tonnage limited by water level, even inability to move	Transforming the ship fleet ≠ Investment capacity ≠ Impossibility to "displace" the cost on the exporting or importing firms
Transport providers (carriers)	- Water level (and singularly in Kaub and Maxau) - Contract with different transport modes (flexibility)	Strong	Capacity to use other transport modes (horizontal coordination) ≠ Unavailable railways ≠ Not previous contracts/relationships with rail or road transport firms ≠ Not sufficient number of skilled truckers ≠ Not adapted to all products
Port authorities	- Water level - Storage capacities - Available infrastructure to facilitate the modal transfer (intermodal connectivity)	Medium	Capacity to develop new storage sites Capacity to promote multimodality while investing in new platforms and materials ≠ competition between ports (private and public transport)
Firms (exporters/importers) shippers	- Transport prices (comparing to the product price) - Volumes of goods - Types of goods transported - Conditioning mode (in bulk or in containers) - Optimisation of the supply chain (each little spanner in the work may be difficult to overcome)	Strong if their goods are rapidly degradable (edible, pharmaceutical goods) Medium if their goods are less sensitive to degradation	Capacity to adapt its contracts with carriers Storage possibility on the production location
Firms specialized in storage of bulk liquid products (proposing rental storage capacity)	- Storage capacity (number of storage sites) - interconnexion with different modes of transport	Medium	Capacity to increase the storage capacity in building more storage infrastructure on the port

a significant change of the water level, but to understand at which degree, the workshops and the interviews were explored to identify the variables of sensibility and the level of vulnerability (see the Table 1).

Individual actors have their own resources and ability to act through preventive, reactive or structural changes. They may develop an adaptation capacity as illustrated in the table, while transforming their internal organization, raising their infrastructural investment (as far as shippers are concerned, by increasing their storage capacity for example) or creating new bilateral relations with other professions. For instance, the transport providers may resort to other modes. However, this coping adaptability can be hampered by lack of resources (financial, cognitive, etc.) or the competition between firms (column 4) as the international freight transport market operates within a very competitive environment (Sys et al., 2020), exacerbated by the transnational character of the river. Side effects can also affect the credibility of some solutions. The crisis may disqualify the river transport mode, while demonstrating a reliability gap, and meanwhile rehabilitate other modes, considered as more reactive. That is why the promotion of multimodality and particularly the combination of rail and river modes, according to different stakeholders (port authorities, transport providers, etc.) have to be consolidated not just in the crisis period, but in the daily processes. Infrastructures have to be developed as well in this objective (new terminal, better linked to rail, improvement of rail capacities to maritime ports).

Not only do the different professions not have all resources available, but moreover, stakeholders, even if they are working in the same environment, have a situated rationale and socio-professionally constructed knowledge. Each profession has a good knowledge of its own weaknesses in the supply chain, but a limited apprehension of the impacts caused by low waters to other stakeholders and of the behaviors they will adopt. These "spaces of ignorance"[7] limit their capacity and their will to act, if they are not involved into a collective dynamic (like the Impact Chain approach and our methodological attempt to develop).

What appeared significant for almost all stakeholders is the possibility to have access to information about water levels but also about the operating of other stakeholders in order to identify the margins of individual and collective maneuver. For example, a modal shift is highly dependent on the rail capacity and the numbers of transport firms, which intend to use it at

7 This ignorance can also be a strategic behavior to minimize the individual cost of an action (High et al., 2012).

a precise moment. But the individual actor does not have this information. This need for information can be broken down into different variables: Degree of reliability of forecasts, and anticipation of water level changes in Kaub and Maxau (the narrowest stretches of the Rhine river, which raises navigation problems in case of low waters). This information is necessary so that stakeholders can be able to make useful decisions and work together to adapt the supply chain and the transport system at a given time. The stakeholders expect very precise information to be able to plan new transport solutions and to make predictions on travel time. They therefore can select suitable travel routes and modes. It appears this information system could result from a collective ability to define expectations and needs.

4.2. Adaptation strategies to low water

From the data obtained through the TRIZ IDM methodology, it was possible to study collective strategies, because the workshops create stages where conflicting rationales that do not always fit with the norms and ethics of the different professions that can be found in confrontation.

The stakeholders of a shared supply chain could have very different sensibilities and vulnerabilities (according to their proximity to the natural elements hit by a hazard, for instance) (Gobert et al., 2017; Averbeck et al., 2021) and then very strong or weak motivations to act. Some of them may push for action (and deploy an internal plan for action) whereas others may slow down. But when they discuss together, the analysis leads us to distinguish three main strategies. Each pathway is based on specific technical, organizational, institutional modalities and a certain degree of knowledge and know-how: That is why we firstly display the possible strategies and secondly the organizational and technical solutions which may be mobilized by the different strategies.

The **reactive adaptation pathway** corresponds to an immediate response to the crisis. This adaptive answer is limited to technical and organizational reactions (like short-time work, decreasing the volumes transported, etc.). Stakeholders may attempt during the crisis period to shift to another transport, but flexibility needs to be prepared for because of the lack of drivers, of railways, and because confidence between transport firms has to be structured through agreements.

This reactive adaptation is symptomatic of stakeholders and communities of stakeholders which are not very sensitive to climate change and specific hazards. They do not consider the issue as a regular one or suppose they can tackle it without more investment and involvement than necessary during a crisis. According to Burch et al. (2016) many SMEs tend to have a reactive position toward environmental initiatives that discourages environmental improvements, spurring the need for external engagement. Moreover, in certain firms, strategies are elaborated in headquarters, far from their local establishments and the difficulties they encountered. Then, the local entities have to fix problems according to the crises (Rudolf, 2015; Gobert and Brullot, 2017) and their limited means.

So, the trans-organizational dimension stays at micro level, because the concerned firms can take measures in their own organization, without expecting actions from others and without being solicited to act outside their own perimeter of competence. In crisis periods, this trans-organizational dimension can be requested (to find new transport modes) at a meso-level (between organizations). But this coordination during crises necessitates some preliminary preparation, as the 2018 crisis highlighted it.

The **transitional infrastructural adaptation** is the kind of solution which most convinces the stakeholders involved, as it involves planning strategies to increase the water level and overcome low water levels (use of Lake Constance as a water reservoir or creation of new water storage areas; deepening of the channel at Kaub and Maxau). This transformative change may only occur with intentional action in the realms of policy and practice. This requires lobbying from local authorities (ports, shippers, etc.) toward competent authorities, but does not lead to a reconfiguration of actor/system relations because it strives to maintain the current business path.

This solution extends the vision that "business as usual" is possible but with major changes. This adaptation pathway improves the existing situation, makes inland waterway transport and the associated logistics more efficient for all stakeholders (except the Rhine, as these solutions are considered as impactful).

The deepening of the channel (dredging) at Kaub and Maxau in order to increase the water level is frequently mentioned, but the difficulty of this decision to remove the two main bottlenecks is not under the responsibility of one or more French entities but of the German authorities, or even of an international agreement. In fact, deepening the Middle Rhine was already set on the agenda of the German Federal Transport Infrastructure Plan (BMDV, 2022) before the low water crisis of 2018. The decision process is very long, however, and depends on a myriad of environmental decisions.

Some less environmentally impacting solutions are mentioned: The creation of additional dams (e.g., rock dams) and locks. More specifically, the installation of movable (or flap) dams at Kaub and Maxau could limit the environmental damage caused by the channeling or deepening of the channel, but also the problem of stagnation and heating of the stored water.

The **radical (or transformative) adaptation** appears principally in the discourses of some regulators or representatives of the "river" as a natural component[8]

8 Even if in line with Actor-Network theory we recognize the non-human agency (Latour, 1997), non-humans may need in some political arenas translators and voices, which are often embodied by environmental NGOs.

when they are personally asked (during interviews). Changing transport and production systems at an international level would require a deep transformation of the "industrial" system (from production to consumption). This adaptation pathway strongly recognizes the agency of non-humans, including the Rhine and the natural components, as well as the limits of technical solutions. This adaptation was not discussed during workshops because representatives of environmental organizations were not invited and the exchanges between stakeholders did not grasp this possibility of global and systemic evolution, which does not directly rely on the individual or local responsibility.

5. Discussion

The results displayed above raise reflexion about the way in which the stakeholders of the Rhine navigation sector consider their ability to act and to adapt their socio-technical system to low waters. Even if the promise of technical fixes and infrastructure are strong and often privileged in the exchanges, because they are considered as the most suitable, the stakeholders are collectively obliged to combine technical and organizational procedures of adaptation (4.1.). The transitional infrastructural pathway appears as the most suitable because it is a well-controlled technical process that provides a comfortable solution in the short term and enables to delegate responsibility (4.2.).

5.1. Combination of technical and engineering and organizational rationale

The "technical solutions" focus at first on technical and engineering expertise to resolve a problem at a micro-, meso- or macro-scale. In our case, this could be: transforming ships and adapting boats to low waters (retrofitting), or designing lighter boats and widening mid-size boats at the micro-scale. These kinds of solutions can also aim at facilitating the information system and data sharing between operators. They are highly dependent on the intentions of transport providers and their investment capacities. However, some cooperative agreements can be signed to share the costs for studies and research. At the macro-scale, this would be the transformation of existing infrastructure or the siting of new ones, in order to prevent risks. Over-reliance on technical expertise and engineering solutions is a well-known phenomenon in the frame of risk prevention (Heazle et al., 2013). Luhmann outlined that in the absence of norms collectively validated and accepted, the technical temptation prevails (Luhmann, 1994). This perspective is named "techno-fix" bias by some authors (Thornton and Manasfi, 2010). The collective decision has to rely on precise technical data to legitimize policy choices, collective action and decision making, and to deliver a feasible and promising future (Joly, 2015). Moreover, infrastructures and infrastructural works give the impression the issue is taken into attention. They offer a feeling of security and the impression to act against climate change. They build a promising narrative. The construction and management of infrastructure continue to be a key technology of government (Joyce, 2003).

However, this technical reliance has been criticized for a few decades (Durand and Ferroudji, 2016; Rudolf, 2016). The promise of infrastructure (Anand et al., 2018) and technical engineering to limit the impacts of hazards and climate change has displayed some dysfunctions. A technical-driven solution may increase vulnerability. For example, dykes can strengthen vulnerability if they justify the siting of new populations in the "protected" areas behind them. Some experts and scientists underline the necessity to combine a technical approach with "soft" solutions (risk awareness, adaptation of the activities according to the risk and new governance system, etc.) (Pigeon, 2015; Wesselink et al., 2015; Petersson, 2021). Soft solutions require the interaction of different skills and oblige stakeholders to a certain humility against uncertainty.

Even when they prefer infrastructural solutions that enable the delegation of responsibility to others, in our case study, stakeholders have to admit a more balanced management configuration, where technical and infrastructural measures have to be combined with organizational and governance resolutions (Hoang et al., 2018). The organizational solutions are essentially based on inter- and multimodality. The principle is: when the water level no longer allows inland waterway traffic, the transport provider switches to another mode of transport. These solutions are based on a collective reflection, but do not need a global consensus. Arrangements can be made bilaterally or multilaterally, at the scale of transport providers or more broadly at a regional scale. The objective is to increase the cooperation between the different transport providers and to enable the recourse to one transport system or another (water, train or roadways), according to climate events and the availability of the given transport system. There is a need to access railways and to make railway management coherent between the different countries. Besides, the port and firms proposing storage capacities would have to create new storage facilities to create buffer zones and times and enable transfers when the water levels return to normal.

5.2. Privileging infrastructural response to redistribute and share the responsibility

Involving stakeholders impacted by the same hazard (low waters) into a process of discussion, issues definition, and evaluation of solutions does not substantially change the solutions that each actor appraises, and does not guide stakeholders to adopt more transformative solutions. This creates new arenas of dialogue, exchange of information, knowledge, which can be transformed into lobbying capacities toward regulatory authorities.

The process defined between Strasbourg Port Authority and the researchers can be analyzed as a step to structure a community of stakeholders sharing the same objectives: integrating climate change as a collective issue that can be tackled at different levels. Some solutions can be easily achieved (innovation for improving boats); others need to organize new rounds of negotiation, to enroll the national and international authorities, to make the dominant infrastructural narrative credible by way of new knowledge, by solidifying a coalition of Rhine ports.

The transitional infrastructural pathway appears as the most suitable because canalization is a well-controlled technical process that provides a comfortable solution in the short term. It exemplifies the lock-ins set by infrastructure (Klitkou et al., 2015) and infrastructural policies (Pierson, 2000), as the required investments are susbstantial and "irreversible" and community of incumbent stakeholders try to preserve the status quo (Winz et al., Trowsdale, et Brierley 2014). The incumbent way of managing an issue and a natural and artificial infrastructure such as the Rhine hampers thinking through the problem and the solution in another manner. This partly explains why radical strategies are not chosen. (Rip and Kemp, 1998, p. 338) characterize the regime as "the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artifacts and persons, ways of defining problems—all of them embedded in institutions and infrastructures." The regime of management of the Rhine is thought through controlled lenses (navigation rules, professional practices guiding the river navigation, inter-organizational links, infrastructures like ports, sluices, etc.). The Rhine could be considered as an artifact whose reliance and regularity is questioned, but not the way of considering it.

Moreover, these infrastructural solutions are a means to redistribute the responsibility between stakeholders and to release individuals from financially contributing and organizations from seriously changing. They may be considered as a way of temporizing and postponing investments. Delaying a soft solution and contributing to build the legitimacy of an infrastructural solution is a social strategy to play with the political time of the crisis, of the protest. Temporisation of a "complicated" solution enables the guarantee of a certain social opacity, because the decision is linked to a specific expertise, to very precise environmental processes, which take time and that are not really visible by an organization over the long term (Blanck, 2016). The infrastructural solution is both a temporary arrangement between viewpoints, the current situation (Boltanski and Thévenot, 2000) and the stakeholder's expectations, and a way to dismiss environmental issues raised by a human-driven intervention on the Rhine (Petitimbert et al., 2022).

6. Conclusion

The low water crisis of 2018 has revealed for supply chain stakeholders of Rhine inland river transport the need to gather the different stakeholders and define common visions on the ways of adapting this recurrent hazard. Three possible pathways have been identified on the basis of the collective work. Technical and infrastructural solutions prevailed (e.g., dredging of the Rhine river). Likewise, the fundamental challenge of developing new processes of discussion and new intermodal organizations appears significant. The actors were therefore obliged to put water in their wine, to take into account the limits of their action in a global market and a transnational natural "infrastructure," to extend their influence and, without doubt, to fall back on softer, but no less complex, solutions: those that combine new organizations and new infrastructures for the storage and circulation of flows.

This work shows to what extent a thorny subject and source of uncertainty such as climate change and the necessary adaptations requires new forms of interaction with operational actors, researchers and public actors. The apprehension of this problem on a transborder river, on which many goods circulate, shows even more that individual and collective action often implies the creation of spaces of common discourse that could allow for the combination of scientific, lay and professional expertise, and the emergence of coalitions of persuasion and action. Moreover, climate change issues demand the integration of new actors and dimensions into the decision process.

Finally, the combined methodology used does not create "new" solutions but new "collectives," which strive to produce tools for improving their knowledge of the situation, convincing and enrolling new stakeholders in their approach (transitional infrastructural adaptation pathway).

Future research should enlarge the perimeter of the involved actors. Even if solutions can emerge and be negotiated by stakeholders, they have to be submitted to the civil society and confronted to the non-human entities (Roelich and Litman-Roventa, 2020). As they are not incorporated in the discussion circles, both could resist.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JG: conceptualization, methodology, validation, formal analysis, investigation, writing—original draft, writing—review and editing, and supervision. FR: conceptualization, methodology, investigation, writing, project administration, and funding acquisition. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

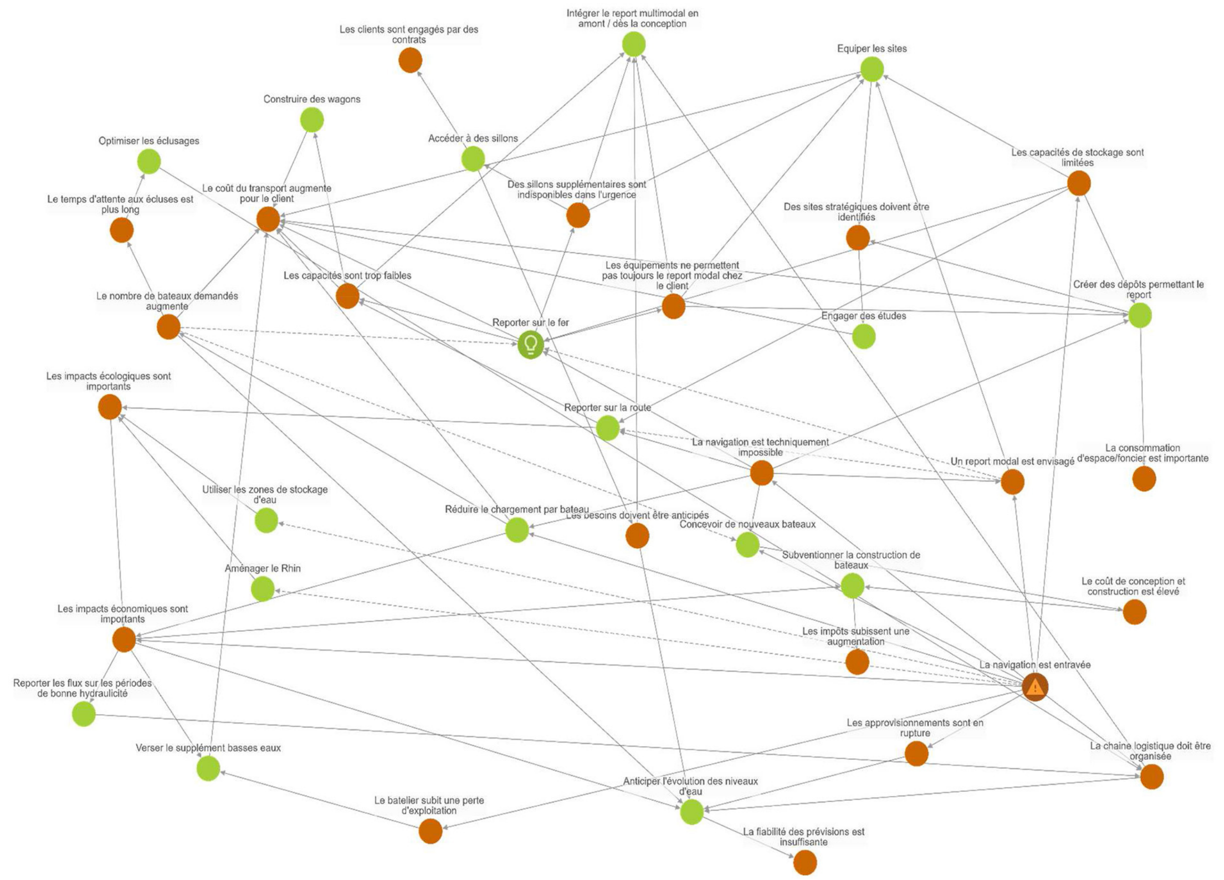

FIGURE A1
Problems graph worked by the group of in bulk carriers, storage providers and firms (TRIZ extraction).

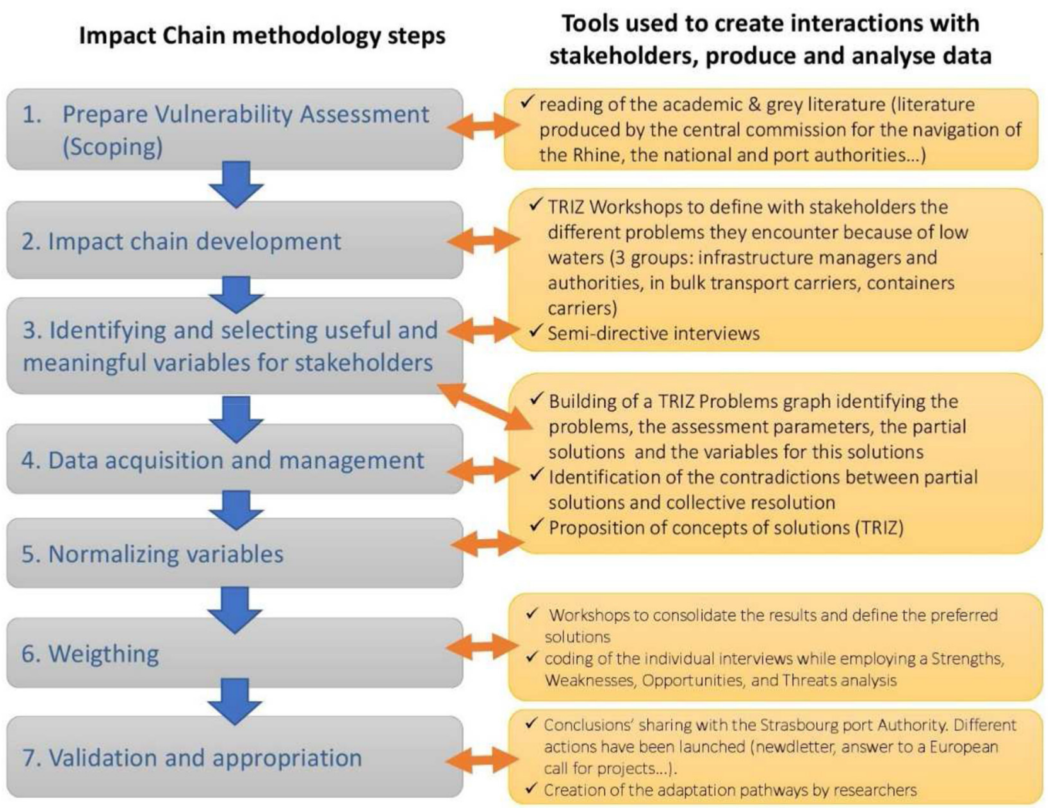

FIGURE A2
Methodology: Impact chain methodology in combination with TRIZ and semi-directive interviews.

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Using impact chains for assessing local climate risk—A case study on impacts of extended periods of fluvial low waters and drought on a metropolitan region

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As the climate crisis accelerates, the resilience of Europe's aging critical infrastructure systems shifts more and more into focus. However, the rising interconnectedness of critical infrastructure systems and the dependency of their operation on multiple stakeholders makes approaches that target the resilience of isolated infrastructures insufficient and might even result in a decrease of the resilience of the whole system. This need for more resilience thinking in interconnected infrastructure systems has resulted in advances in risk analyses of supply chains and analyses of interdependencies in infrastructure systems from a Critical Infrastructure Protection/Resilience perspective. However, results from such analyses on the level of interconnected infrastructure systems have seldomly be broken down to the level of individual corporate value chains, a necessity as national/regional resilience efforts need to be supported on the local level. In this paper we therefore propose a novel approach for value chain climate risk and vulnerability analysis that combines a participatory, indicator-based approach with a semi-quantitative risk matrix approach to allow linking analyses from national to local scale and supports economic assessment of climate change impacts for individual businesses. This approach has been developed and prototypically applied in a case study in a German metropolitan area located at the Rhine River. The results allow to identify where along the dependency chains of interconnected infrastructure systems, hazards and impacts might manifest, which cascading (economic) impacts result on the level of individual infrastructure operators, and where resilience measures should be taken to be most effective and (cost) efficient.

KEYWORDS

climate change adaptation, climate risk assessment, impact chains, supply chains, knowledge co-production, case study

1. Introduction

Critical Infrastructure is essential for everyday life and for the functioning of society; it is the backbone of vital societal functions as well as the social and economic wellbeing of people. Critical Infrastructure includes many types of public and private assets, like transportation, communication, electricity, and water networks, food production, supply chains, waste treatment, industrial facilities, governmental facilities, and cultural assets. At least 70 countries[1] have introduced definitions of what qualifies as and constitutes their Critical Infrastructure, but these definitions vary due to the differences in available infrastructure,

1 https://websites.fraunhofer.de/CIPedia/index.php/Critical_Infrastructure

abilities, and resources for protecting such infrastructure, as well as governance and political priorities. Therefore, we will use "infrastructure" and "Critical Infrastructure" synonymously in the remainder of this article. Over the last decades, infrastructure systems have transformed from widely isolated service providers to interdependent parts in a *"system of systems"* (cf. Eusgeld et al., 2011)—tightly organized networks that are carried by a multitude of actors, involve a myriad of physical and digital structures, and offer services to society through all sorts of physical and digital channels. Without these tightly organized networks, the international division of labor and global economy would not be possible. But it is also an inherent feature of this tight organization that risk, including climate risk, can propagate along dependencies in these networks and cause local, regional, national, and transboundary impacts.

The infrastructure sector is responsible for 79 percent of total greenhouse gas emissions and 88 percent of all adaptation costs (Thacker et al., 2021). It therefore takes on a key role to achieve the Paris 2015 goals and needs to be better adapted to the unavoidable impacts from climate change we are already experiencing. Physical climate-driven hazards such as heatwaves, droughts, wildfires, fluvial and coastal floods, as well as windstorms already have significant impact on the aging European infrastructure systems (European Commission, 2021a) and these impacts will increase even more in the coming years, especially in places already exposed to high temperatures and along coasts (cf. IPCC, 2022).

As infrastructure becomes even more connected, it becomes necessary to focus on the full spectrum of dependencies within the connected system of systems to fully address its climate mitigation and adaptation potential, and move to a "resilience thinking" approach for managing infrastructure systems (Forzieri et al., 2016, 2018). On a European level, several new or updated policies (European Commission, 2019, 2020, 2021b) acknowledge this fact and require measures for making infrastructures and "critical entities" more resilient to threats—including threats induced by climate change. While such policies become increasingly mutually consistent, the increasing interdependence of infrastructure systems raises several questions: Where along the dependency chains of interdependent infrastructure systems do climate hazards originate? Where will the impacts of these hazards manifest? Where will cascading impacts manifest? What risks result from these impacts? Where along the dependency chain should adaptation and mitigation measures against climate change risks be taken to be most efficient and effective? Who should be responsible for implementing these measures? And who should bear the costs of these measures, considering that multiple stakeholders along the dependency chains might benefit from their implementation?

A first step toward answering some of these questions would be to conduct a climate risk assessment that allows to locate impacts and risks along dependency chains of infrastructure systems and enables to quantify the socio-economic losses posed by climate change impacts as well as the potential benefits of adaptation/mitigation measures for different stakeholders. To do so, it would be necessary to understand the nature of the dependencies within the global system of systems: infrastructure systems and economic networks and their substructures. Contributions to advance such an understanding have been made in different fields. In the research area of Critical Infrastructure Protection and Resilience, numerous investigations on critical infrastructures, their dependencies, and cascading failures have been made (e.g., Luiijf et al., 2010; Setola et al., 2017). In economics, methods for analyzing commodity chains, supply chains, and value chains have been developed for specific analytical purposes in macro-economy or on business level. Some of these methods have been further developed to inform risk management, so it seems logical to integrate climate risk assessment into such established methods. However, despite the rising need to increase the resilience of infrastructure systems against extreme weather events, methods to assess climate risks along their corporate value chains are still lacking[2] and have become moderately popular only in the food industry (Oxfam, 2012). In addition, only few economic assessments of future infrastructure developments under different climate scenarios, like recently (Hänsel et al., 2020), have been developed.

To take a step toward closing these gaps, in this paper we propose a novel approach for value chain climate risk and vulnerability assessment (CRVA) that combines a participatory, indicator-based approach with a semi-quantitative risk matrix approach to allow linking analyses from national to local scale and supports economic assessment of climate change impacts for individual businesses. This approach has been developed and prototypically applied in a case study as part of the research project "Unpacking climate Impact Chains—a new generation of climate change risk assessments" (UNCHAIN). In UNCHAIN, ten research organizations and universities collaborate on a systematic study to improve a particular indicator-based CRVA approach using Impact Chains (ICs). The research and development took place in twelve case studies that the project partners conducted in seven countries, each covering different sectors, spatial scales, and innovation approaches. Some of the work originating from other UNCHAIN case studies, a more detailed presentation of the use of Impact Chains for CRVA, an overview and assessment of the achieved innovations, and a description of the research pipeline in UNCHAIN please find in other UNCHAIN related articles of this journal issue.

The case study, in which the work presented in this paper has been developed, addressed climate risk for a German metropolitan area located at the Rhine River, including critical infrastructure. Specifically, the case study focused on the major metropolitan region of Mannheim—a heavily industrialized region—the companies and residents located therein, as well as energy production and freight transport *via* the Rhine River as critical infrastructure systems. A specific goal of the case study was to connect the regional risk analysis to the more general national German climate Impact Chains (Umweltbundesamt, 2016) on the one hand, and to individual stakeholders' business continuity management on the other hand, spanning three levels of governance scale. In particular, we collaborated with the City of Mannheim and other regional stakeholders to assess the "Risk of negative impacts of extended periods of drought and low waters of the Rhine River on infrastructure, logistics and population in the metropolitan region of Mannheim," using climate Impact Chains. It should be noted that besides the research goals, it was also a goal to provide actionable decision support to the stakeholders participating in the case study for their climate risk assessments.

The remainder of the paper is structured as follows. After a brief introduction into participative, Impact Chain-based climate

2 On the level of individual organizations, risk analyses are usually part of business continuity planning, which is often confidential and cannot be shared publicly.

risk and vulnerability assessment (IC-based CRVA), we describe the background situation of the case study and introduce the applied value chain CRVA process. The "Results" section then describes the major outcomes of the case study, before we discuss the main insights from the case study and the achieved innovation of the value chain CRVA. We conclude the paper by providing hints for future work.

2. An introduction to participative, IC-based CRVA

Climate risk and vulnerability assessments can be conducted using different methods, depending on the aims and scope of the analysis. Quantitative methods, like quantitative risk assessments using damage functions or event tree analysis, are usually extremely data demanding, but allow detailed analysis from international to site-specific spatial scales that can support cost-benefit analysis and the identification of cascading effects. (Semi-) Qualitative approaches, like the risk matrix approach or the indicator-based approach, on the other hand, are less data demanding, allow the inclusion of expert judgements, and are usually easier to understand for a broader range of stakeholders. However, their results heavily depend on participating stakeholders, usually cannot easily support cost-benefit analysis, and—in the case of the indicator-based approach—are often not applicable at small (site-specific) spatial scales.

One well-known implementation of the indicator-based approach was developed by Eurac Research for studies on climate vulnerability in the Alps. First published in Schneiderbauer et al. (2013), it has been further developed for the national climate vulnerability assessment for Germany and the Vulnerability Sourcebook on climate vulnerability assessment in the context of international cooperation (Fritzsche et al., 2014). The Vulnerability Sourcebook provides a modular CRVA framework for understanding, systematizing, and prioritizing the factors that drive climate impact related vulnerability in a specific system of concern. The framework is known as the "Vulnerability Sourcebook method" and is divided in a highly participative, qualitative phase and a less participative, quantitative assessment phase. It has been applied in numerous cases, usually at national, regional, or local—i.e., city or county—scale. Since 2017, the framework was adapted to the new IPCC Assessment Report 5 (IPCC, 2014) concept of climate risk and was recommended for climate risk assessments in the context of Ecosystem Based Adaptation (Hagenlocher et al., 2018). At the same time, the framework was also adapted by Fraunhofer in the European research project RESIN for climate risk assessments of cities and infrastructures (Lückerath et al., 2018; Rome et al., 2018), also investigating the potential of combining indicator-based approaches with quantitative risk assessments and risk matrix approaches using damage functions (Rome et al., 2018). For applying the original Vulnerability Sourcebook method and its updates extensive guidelines are available (Fritzsche et al., 2014; GIZ and EURAC, 2017; Hagenlocher et al., 2018; Rome et al., 2018). In this introduction, we present only the basic underlying concepts of this family of IC-based CRVA methods.

At the core of the Vulnerability Sourcebook method lies the development of Impact Chains, cause-effect models that describe the relationship between climate change-induced hazards (e.g., a heavy rain event), exposed elements (e.g., businesses located in a specific area) and their vulnerability (e.g., availability of flood protection measures), and resulting impacts (e.g., erosion upstream that contributes to flooding downstream). According to the IPCC Assessment Report 5 (IPCC, 2014), the final risk "results from the interaction of vulnerability, exposure, and hazard." Works like (GIZ and EURAC, 2017) and (Rome et al., 2018) are first operationalizations of that IPCC definition of climate risk, using its *risk components* hazard, exposure, and vulnerability as defined by the IPCC. Both works look at risk components in more detail and subdivide them into (risk) factors: Factors of the hazard under consideration are climate signals and *direct physical impacts*, exposure factors are one or more entities exposed to the hazard, vulnerability factors are *sensitivities* and *capacities* of these exposed entities (GIZ and EURAC, 2017). Again, IPCC definitions are used for these terms.

Impact Chains are composed of all these elements: risk components, risk factors, and additionally, intermediate impacts. According to GIZ and EURAC (2017), "intermediate impacts are not a risk component by themselves but merely an auxiliary tool to fully grasp the cause-effect chain leading to the risk." Intermediate impacts can capture, for instance, cascading effects like infrastructure failures propagating after a first physical impact. The Impact Chain concept is depicted in Figure 1. An Impact Chain is represented in graphical form, which is typically a diagram like that in Figure 1, but with more and concrete elements. In some works, like (Rome et al., 2018), *stressors* are added as external factors that could aggravate impacts of a hazard, like a garbage worker strike during a heat wave.

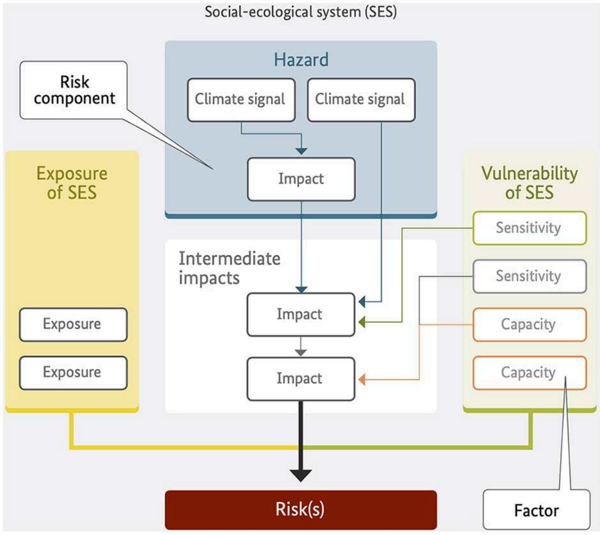

FIGURE 1
Structure and elements of an Impact Chain. Source: Hagenlocher et al. (2018). With kind permission of K. Renner, EURAC. Climate risk results from the interaction of the risk components vulnerability, exposure, and hazard (IPCC, 2014). Risk components are subdivided into (risk) factors: Factors of the hazard under consideration are climate signals and direct physical impacts, exposure factors are one or more entities exposed to the hazard, vulnerability factors are sensitivities and capacities of these exposed entities (GIZ and EURAC, 2017). "Intermediate impacts are not a risk component by themselves but merely an auxiliary tool to fully grasp the cause-effect chain leading to the risk" (GIZ and EURAC, 2017), including cascading effects like propagation of infrastructure failure.

Impact Chains are usually developed in participative settings with local stakeholders. A validation of an Impact Chain is conducted by gathering and integrating feedback of the participating domain experts until a final approval of the results by all stakeholders. A final validated Impact Chain captures the cause-effect relationships of the investigated climate risk in a structured way and provides pointers to first options for adaptation: increasing identified capacities, reducing identified sensitivities, and mitigating identified intermediate impacts. But Impact Chains also serve as the backbone for an indicator-based CRVA; they are the basis for the selection of appropriate indicators as well as a backbone for the aggregation of indicators to composite risk indicators. CRVA based on Impact Chains can combine data and model driven approaches with expert-based approaches. However, Impact Chains as a core modeling element are more versatile and can be the basis for different analyses, from the analysis of transboundary knock-on effects, like diminished local industrial or agricultural production, to the analysis of cross-sectoral local effects, for example, the disruption of local supply chains. In addition, Impact Chains are also a useful tool for communication of complex cause-effect relationships of impacts and risks.

The participative nature of IC-based CRVA has shown to be particularly effective in providing actionable results that are usable by relevant decision-makers and practitioners, compared to conventional CRVA approaches, in which researchers or industry professionals provide consultancy services as a "black box" or where isolated departments of single businesses conduct risk analyses in a top-down fashion (Klein and Juhola, 2014; Bremer and Meisch, 2017; Palutikof et al., 2019). This effect is especially pronounced in interdependent infrastructure systems and value chains, where a myriad of stakeholders from different backgrounds and institutions, each with differing expectations and agendas, need to collaborate to make the whole system and value chain more resilient in a cost-efficient and effective way.

The positive effects of transdisciplinary methods for knowledge co-production that include experiences from various points of views have been acknowledged by a growing number of scientists and policymakers, who argue for reconceptualizing the roles of experts, practitioners and citizens in the production and use of scientific knowledge (European Commission, 2009; Rodela and Gerger Swartling, 2019). The need for better collaboration and combination of knowledge and expertise is also emphasized in several European and national strategies. For example, the Recommendations for National Risk Assessment for Disaster Risk Management in the European Union (Poljansek et al., 2021), the new German resilience strategy (Bundesregierung, 2022), and the German guidelines for national and regional climate impact and vulnerability analyses, targeting national and regional authorities (Umweltbundesamt, 2017).

The Impact Chain-approach to CRVA is especially suited for such knowledge co-production approaches, as it makes extensive use of participatory workshops in which assessment goals, Impact Chains, and indicators are jointly defined between researchers, experts from municipalities, local businesses, Non-Governmental Organizations, civil society, and other local stakeholder groups, thus validating the results and ensuring ownership and sustainability. For more in-depth information on this assessment method, we refer the reader to the elaborated guidelines (Fritzsche et al., 2014; Rome et al., 2017; Hagenlocher et al., 2018), the publications (Schneiderbauer et al., 2013; Rome et al., 2018), the identification of challenges and opportunities of the approach (Menk et al., 2022), and the discussion on the value of innovating the method in another paper in this journal issue.

3. Case study background, process, and applied methods

In this section, we describe the regional and nationwide setting of our case study, characterize the case study process, and describe in detail how we applied IC-based CRVA on the regional level and how we combined IC-based CRVA with Value Chains on the corporate level.

For being able to properly conduct a climate risk assessment for the metropolitan region of Mannheim, we collected relevant background information from various sources to get an understanding of the situation in the region. The guiding questions for the research were:

- What is the economic importance of the Rhein River for Germany, what are its infrastructure functions, how was it affected by the weather extremes of 2018?
- What is the current understanding of the current and future situation regarding climate risk in general and drought and low water in particular in Germany and in the metropolitan region?
- What is the local situation in the Mannheim region in terms of infrastructure, economy, climate risk, exposure, adaptation policies, and action plans?

3.1. Case study background

3.1.1. Economic importance of the Rhine river

The Rhine is the most important waterway in Europe. It connects important industrial locations from Switzerland to the Netherlands. The transport of goods by inland waterway vessels *via* the Rhine is of great economic importance for many companies, for the riparian states and for Europe. In Germany, 80 percent of the goods transported by inland waterway vessels are shipped *via* the Rhine (IfW, 2018). Restrictions on the transport of goods *via* the Rhine can lead to considerable economic losses. In the summer of 2018, 132 low-water days were registered on the Rhine—a record since data recordings began. According to the Federal Statistical Office (Destatis, 2019, p. 11) and the Kiel Institute for the World Economy (IfW, 2018, p. 2), the low water of the Rhine caused a 0.2 percent decline in Germany's gross domestic product in the 3rd quarter of 2018. A study (Streng et al., 2020) by the Erasmus Center for Urban, Port and Transport Economics puts the economic damage of the low water level of the Rhine in 2018 at a nominal €2.4 billion for Germany and €295 million for the Netherlands.

Even if the share of goods transported annually by inland waterway in Germany is "only" about 6 percent of the total inland transport volume, 4.8 percentage points of which are on the Rhine alone, the share is considerably higher for certain types of goods, namely 28 percent for raw materials like coal, crude oil, petroleum, natural gas, and 21 percent for derivatives like coke, petroleum products (Ademmer et al., 2018). The Kiel Institute for the World Economy concludes: "*These goods tend to be at the beginning of* *many production chains, so transport-related failures could lead to production disruptions in downstream production stages"* (Ademmer et al., 2018; 15).[3]

The shallowest and most critical points of the Rhine River are near gauging station Kaub. All shipments from the ARA[4] seaports and the Nether and Middle Rhine ports to the Upper Rhine region—and vice versa—must pass Kaub. This includes a good part of the industrial production of the metropolitan region of Mannheim and the raw materials and derivatives needed for it.

But the Rhine River is not just used as transport infrastructure, it also provides water for many purposes, including cooling water for the industry, process water for the production industry, and water for firefighting. Low waters of the Rhine may lead to restrictions of water intake.

3.1.2. Current understanding of the national situation regarding drought and low waters and recent forecasts

The year 2018 brought several weather extremes to Germany, which influenced the choice of the hazards to be analyzed in our case study. By then it was the warmest recorded year since 1881, the sunniest year since the recording started in 1951, and it was too dry for 10 months in a row (from February through November)[5], resulting in an agricultural drought in most parts of the country.[6] The most recent comprehensive assessment of the situation in Germany with respect to drought, low water, and ground water recharge is provided in Umweltbundesamt (2021). The authors state that the accumulation of agricultural droughts that hit six European countries between 2014 and 2018 has not occurred in Central Europe for 250 years.

In Germany, the agricultural drought returned in 2019 and in 2020. Today, in August 2022, the soil in entire Germany is too dry again. Adaptation measures are already being taken, both in enterprises—including infrastructure operators—and in politics. Enterprises, for example, improve their business continuity management and health protection of workers, secure their water supply, and use renewable energy, as well as improved and intelligent logistics.

The year 2018 also brought an extremely long period–132 days—of extreme low waters of the Rhine River (hydrological drought), leading to significantly reduced freight transport volumes on Europe's most important inland waterway. In August 2022, the water levels of the Rhine dropped again to extremely low values (Bloomberg, 2022).

Regarding adaptation on the national level, the German Federal Ministry of Transport and Digital Infrastructure (BMVI) has issued an eight-point action plan "Low Water Rhine" (BMVI, 2019) for securing the freight transport on the Rhine River. A German specialty is the fact that the national government has included German national climate Impact Chains (Umweltbundesamt, 2016, 2019a) in the German Adaptation Strategy, structured into twelve national fields of action. The progress of implementing the national adaptation strategy is monitored on an annual basis and published in annual monitoring reports (Umweltbundesamt, 2019b).

3.1.3. Situation in the metropolitan region of Mannheim

The metropolitan region around Mannheim, the Rhein-Neckar region, is an agglomeration of three large cities—Mannheim, Ludwigshafen, and Heidelberg—five smaller cities and seven counties across three German federal states: Baden-Wuerttemberg, Rhineland-Palatinate, and Hesse. Since 2005, the region is a "European metropolitan region." About 2.4 million citizens live within this seventh largest industrial region of Germany.

The regional climate is warmer than the German average. The years 2018, 2019, and 2020 belong to the warmest years in the region since recording started in 1881 (KLIWA, 2021). For Mannheim, the recent city climate analysis (Stadt Mannheim, 2021) stated that the average temperature for the period 1990–2019 was 2°C above the average temperature for the period 1881–1910.

The recent second climate monitoring report of Baden-Wuerttemberg (KLIWA, 2021) also contains an assessment of past fluvial hydrological discharges in the federal state. Discharge patterns and quantities are regionally quite different and depend on many factors, like the number of gauging stations and the quality of data delivered by these stations. Nevertheless, the report concludes that for the hydrological water management summer semester (the months May–October), the number of gauging stations with significantly decreasing discharge trends rises clearly (KLIWA, 2021, p. 55).

Mannheim with its 300,000 citizens belongs to the most advanced cities in Germany regarding climate protection and adaptation. In 2017, the City of Mannheim signed the climate protection pact of the State of Baden-Württemberg and thereby committed to strong climate protection activities. The city has a municipal climate protection office responsible for the city-wide coordination and implementation of climate protection projects and is committed to bringing the climate protection strategy of the city "Mannheim on climate course"[7] into action.

For conducting the case study, we collaborated with a diverse group of stakeholders that were relevant for and interested in the case study: the state-owned Rhein-Neckar Port Authority that operates the inland ports at the Rhine and Neckar confluence in Mannheim; the City of Mannheim's municipal departments Climate Protection Office, Economic and Structural Development, Urban Development, Public Health Office, and Professional Firefighters; the logistics company Contargo; the sanitary paper production company essity; the Mannheim Large Powerplant; and experts from the German Federal Institute of Hydrology (BfG).

3.2. Case study process

The case study started with two preparatory phases to collect relevant information on the climatic and economic situation in Mannheim (desktop research), as well as establishing initial stakeholder commitment (in individual meetings with stakeholders).

3 Translated with www.DeepL.com/Translator (free version).

4 ARA: Amsterdam, Rotterdam, Antwerp.

5 German Weather Service (DWD), 28.12.2018 https://www.dwd.de/DE/presse/pressemitteilungen/DE/2018/20181228_deutschlandwetter_jahr2018_news.html.

6 German Drought Monitor at https://www.ufz.de/index.php?de=47252.

7 https://www.mannheim.de/de/service-bieten/mannheim-auf-klimakurs/abteilung-klimaschutz-klimaschutzleitstelle

A summary of the desktop research results can be found in the previous section and the Appendix "Case study background." A kick-off meeting with all involved stakeholders was then used to define the scope of the CRVA, establish a common understanding on the terms of collaboration, and clarify expectations from stakeholders and researchers. Afterwards, a first "test run" for the participative, IC-based CRVA (Rome et al., 2017; Hagenlocher et al., 2018) was conducted with a limited number of stakeholders from the Municipality of Mannheim. Here, the CRVA process was conducted partially to co-produce a qualitative IC that models the risk of extended heatwaves for vulnerable population groups in Mannheim (IC 1) and showcase how to use the German national ICs as a foundation for the IC development. Based on the experiences of this "test run", the main IC-based CRVA (IC 2) to examine the risk on prolonged periods of low water of the Rhine River was conducted. To be able to keep the focus of the activities and to keep participation time and workshop times to a tolerable limit, not all stakeholders were included in all activities. Table 1 provides an overview of the whole case study process in a chronological order and lists the applied methods, the participants, taken actions and outcomes, respectively. As the main innovation—the development of the IC-based value chain CRVA—took place during the second half of the case study process (creation of IC 2 and beyond), the following sections focus in detail on this part of the case study.

3.3. Case study methods

3.3.1. Impact chain co-production with stakeholders of the metropolitan region of Mannheim

For the regional climate risk assessment, we co-developed an Impact Chain with the full group of regional stakeholders. In addition, a researcher from the Institut National des Sciences Appliquées de Strasbourg, an UNCHAIN research partner, was also involved. This Impact Chain covered the risk of "Negative impacts of extended periods of drought and low waters of the Rhine River on infrastructure, logistics and population in the metropolitan region of Mannheim."

Prior to working together with the experts and local stakeholders, we prepared an initial Impact Chain for the workshop. This version contained extracted information from different climate Impact Chains of the German Environment Agency (Umweltbundesamt, 2016, 2019b) and was visualized—without causal connections—in a miro[8]-board and corresponding to the Impact Chain layout from the Vulnerability Sourcebook (Fritzsche et al., 2014). In this version, we already clustered consequences, sensitivities and capacities based on the "fields of action" of the German Adaptation Strategy (Bundesregierung, 2008) and added some questions and comments to guide the workshop (e.g., reference to further fields of action).

In a joint workshop (lasting approximately 4 h) with the above-mentioned stakeholders from Mannheim and the UNCHAIN project, the initial Impact Chain was systematically expanded. First, the Impact Chain method was explained before individual participants explained the relevant impacts of dry periods and summer low water on their companies and specialist areas based on their experience. Based on this exchange, the individual sections of the Impact Chain were further filled-in during a moderated working session. The workshop concluded with collecting sensitivities and capacities. This approach encouraged the participants to discuss with each other their individual or sector perspectives on and approaches to risk and adaptation, leading to mutual awareness of which adaptation measures are necessary for whom or are already in use.

In a next step, we analyzed the collected information and developed proposals for restructuring, simplification, and causal connections. This version was provided to the participants and their feedback was implemented. The process of finalizing the Impact Chain in feedback loops with the stakeholders until their consistent final approval for correctness and completeness—according to their points of views, respectively—leads to a validation of an Impact Chain. This has been implemented as an iterative process, starting with discussing and modifying the "raw" initial Impact Chain that resulted from the co-production workshop. The comments and replies of the participants regarding the elements of the IC and their relations have been documented. These minutes and the modified IC have been distributed to the participants for the next round of discussions. This process has been repeated until a final outcome has been agreed. The minutes and the intermediate versions are kept as documentation, including all arguments, such that the evolution of the IC can be understood even by persons who were not involved in the process. The result of this qualitative IC-based CRVA, a validated Impact Chain, is explained in the "Results" section of this article.

3.3.2. CRVA on corporate level using value chains

For preparing a more in-depth, quantitative CRVA on corporate level, we designed the assessment of the climate change risk for value chains of a company as a multi-step process. This procedure requires a regional or corporate Impact Chain as input and is based on methods of economics for the analysis of dependency chains.

3.3.2.1. Methods of economics for the analysis of dependency chains

In economics, methods for analyzing *commodity chains*, *supply chains*, and *value chains* have been developed for specific analytical purposes. Since these terms are often confused, we have depicted the ranges of and relations between these related concepts in Figure 2. Global commodity chain analysis methods shall yield insights in the organizational structure and dynamic processes of the globalized economy (Hopkins and Wallerstein, 1977; Wallerstein and Hopkins, 1993; Bockel and Tallec, 2005). On corporate scale, supply chain analysis is aimed at optimization in delivering a product or service, like minimizing costs, maximizing customer value, or strategic planning, and it informs supply chain management. Subjects of the analysis can be the entire supply chain or its manufacturing, service, or distribution parts (*distribution chains*). Value chain analysis (Porter, 1985, 1991) is aimed at identifying which elements of corporate business contribute to what extent to the corporate margin, for the purposes of raising the margin or getting advantage over competitors.

The international Association for Supply Chain Management promotes the supply chain operations reference (SCOR[9]) model as a standard method for supply chain analysis. Since its introduction in 1997, the process oriented SCOR model has been improved and extended. SCOR can now also be used for supporting supply chain

8 miro: web-based collaborative whiteboard software.

9 https://scor.ascm.org/processes/introduction

TABLE 1 Overview of the case study activities (optional: *methods*), participants, actions, and results.

Case study activity *(method)*	Participants	Actions	Output
Preparatory phase I	Researchers	Researching information on the situation in the case study region Planning	Collection of publications, reports, information, data; summary of desktop research Time plan
Preparatory phase II	Researchers, individual stakeholders	Acquiring case study participants, initial stakeholder information, stakeholder interest in CRVA	List of participants Additional stakeholder information
Kick-off	Researchers, all participating stakeholders	Clarifying research goals, scope of the case study, terms of collaboration, possible tangible outcomes for stakeholders	Documentation of agreements Action list with deadlines
IC 1 creation, consolidation, and validation *(participatory, qualitative local IC-based CRVA)* "Test run" for the regional assessment	Researchers, stakeholders from City of Mannheim	Co-production of a first, local IC based on German national ICs for assessing the "Risk of negative impacts of heat waves on the population (especially on vulnerable groups) of Mannheim" Commenting, discussing, editing the initial IC 1 until agreement on a validated IC 1 was achieved	Consolidated, validated IC 1 Documentation of the assessment IC 1 integrated in heat action plan of the City of Mannheim
IC 2 creation *(participatory, qualitative regional IC-based CRVA)*	Researchers, participating stakeholders and additional experts	Collaborative creation of a second, regional IC based on German national ICs for assessing the "Risk of impacts of more frequent periods of drought and summer low water of the Rhine on infrastructure and logistics in the Mannheim region"	Initial IC 2 Action list for next step
IC 2 consolidation and validation (*participatory, qualitative regional IC-based CRVA)*	Researchers, participating stakeholders and additional experts	Commenting, discussing, editing the initial IC 2 until agreement on a validated IC 2 was achieved	Consolidated, validated IC 2 Action list for next step
Assessing risk on corporate level using value chains (*participatory, qualitative and quantitative analysis combining IC-based CRVA and Value Chains*)	Researchers, stakeholders from energy producing utility	Eliciting the corporate value chain (VC) Pinpointing regional factors to VC elements Identifying additional corporate climate risk factors Determining suitable indicators for climate risk factors Checking data availability Validation of results Selecting one indicator for further analysis (low water transport surcharges) Realizing the decision support tool Presentation and validation of results of the quantitative assessment	Corporate value chain annotated with climate risk factors List of indicators for climate risk factors Decision support tool for analyzing and comparing transport surcharges under different low water scenarios

risk management (Wilkerson, 2011; Rotaru et al., 2014), a subtask of supply chain management that has become increasingly important (Wieland and Wallenburg, 2012). A prerequisite is that an overall corporate risk management is already in place.

American economist Michael E. Porter developed the concept of the value chain and introduced it in Porter (1985). Porter looks not just at business processes. He starts by roughly dividing a company's activities into primary and supporting activities. Value chain diagrams describe these company activities in graphical form (Figure 3). The task of value chain analysis is to get a clear picture which business activities and which units contribute to which extent to the business margin. The further division of a company's activities into areas and intertwining processes that take place in and across these areas offers various opportunities for analysis and optimization.

This type of modeling is also suited for informing risk management but can yield different or additional information compared to supply chain analysis. Also, value chain analysis helps identifying the "business fence lines", that is, which business activities and processes are fully internal, and which require external interaction, like input logistics, product delivery, and customer service. For managing risk, including climate risk, this modeling approach allows pinpointing risk factors to business processes, activities, and units, and, furthermore, could hint at which risk factors are within the business fence lines, and which go beyond them.

A fundamental prerequisite for being able to carry out such analyses at all is an in-depth understanding of the company's activities. For eliciting a corporate value chain, one must acquire knowledge from company experts on how their company operates. This can be done by means of interviews or by facilitated participative workshops with company experts.

3.3.2.2. The process of creating a value chain CRVA

The individual steps of the proposed procedure for eliciting a corporate value chain are adapted to the individual needs and the existing information and data situation of the company to achieve a result that is useful for the corporate stakeholders. Whenever possible, the process should build on existing results and information. In the final fifth step, the risk analysis is validated, and exemplary adaptation measures are derived. Figure 4 shows an overview of the individual steps of the proposed procedure.

The development of all results takes place in cooperation between researchers and representatives of the company by means of discussions, information exchange *via* e-mail, and through workshops. In total, a maximum of four half-day workshops can be expected, in addition to a preliminary discussion of up to 90 min duration and possible further short periods of time for

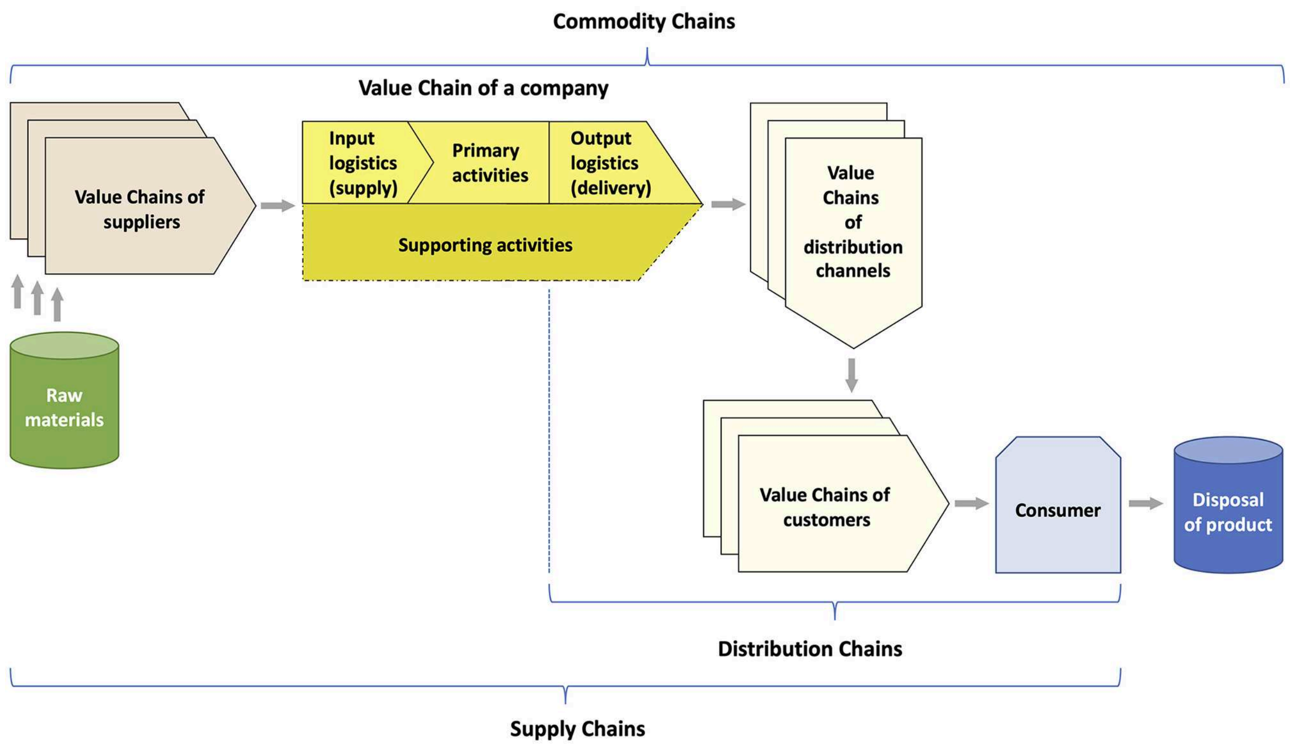

FIGURE 2
Ranges of and relations between commodity chains, supply chains, distribution chains, and value chains.

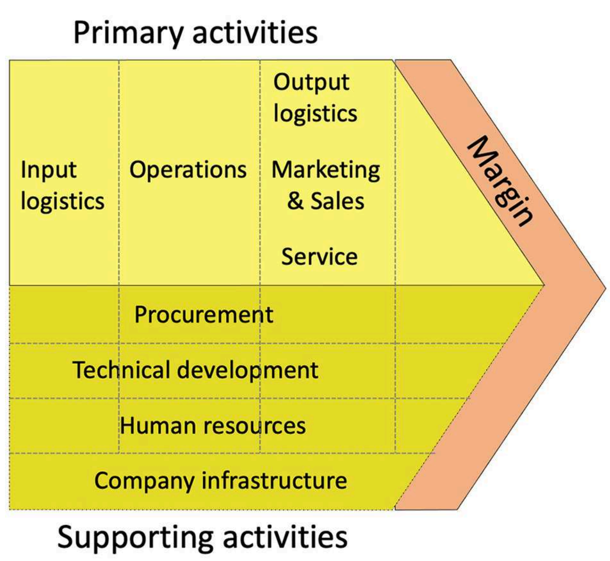

FIGURE 3
Value chain of a company [after (Porter, 1991)]; light yellow, upper half: primary company activities; dark yellow, lower half: supporting company activities; orange, leading chevron shape: company margin.

validation of the results. The participants from the company are ideally one or two main contact persons and, if necessary, experts on specific company areas (depending on the planned scope of the in-depth risk analysis). The steps of the process are briefly explained below.

Step 0: Determination of the objective and the available (personnel) resources

Together with the users, the goal of the risk analysis is specified in more detail: How detailed should the risk analysis be? Which company departments or persons should be involved? What information is available (organizational charts, process manuals, annual business reports, etc.)? What do confidentiality agreements look like? When should the next step be taken? The agreements are recorded in a results protocol.

Step 1: Elicitation of a company's value chain

If a documentation of a corporate value chain does not exist, it needs to be elicited. In our case study, researchers and stakeholders have performed this elicitation jointly. The level of detail can vary depending on the objectives and available time/personnel resources. At a minimum, the different company divisions involved in the value creation (like purchasing/procurement, sales, production, etc.) and their activities and core processes should be included. Preliminary information, e.g., organizational charts or descriptions of the structural and process organization, can be used for preparation. Areas of the value chain that are particularly interesting and/or affected by climate change can then be broken down in more detail, if necessary. The intermediate result of this step is the value chain of the company in diagram form (Figure 5). Afterwards, the terminology can be harmonized, and the presentation can be made more precise, which is then validated by the participants before the next step.

An initial catalog of questions on the following four topics is prepared for eliciting of the corporate value chain. Here, we provide the catalog used in our case study as an example.

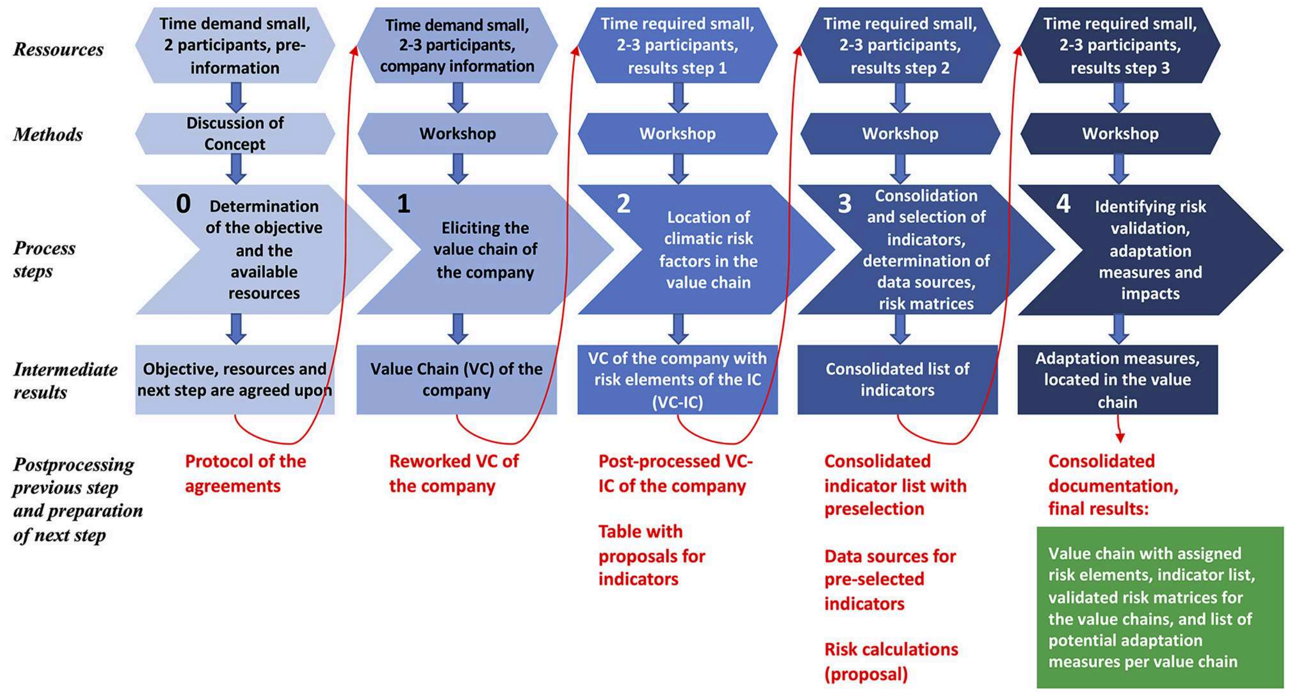

FIGURE 4
Procedures for the elicitation of a value chain, for pinpointing risk factors therein, for risk quantification and validation, and for the planning of adaptation measures.

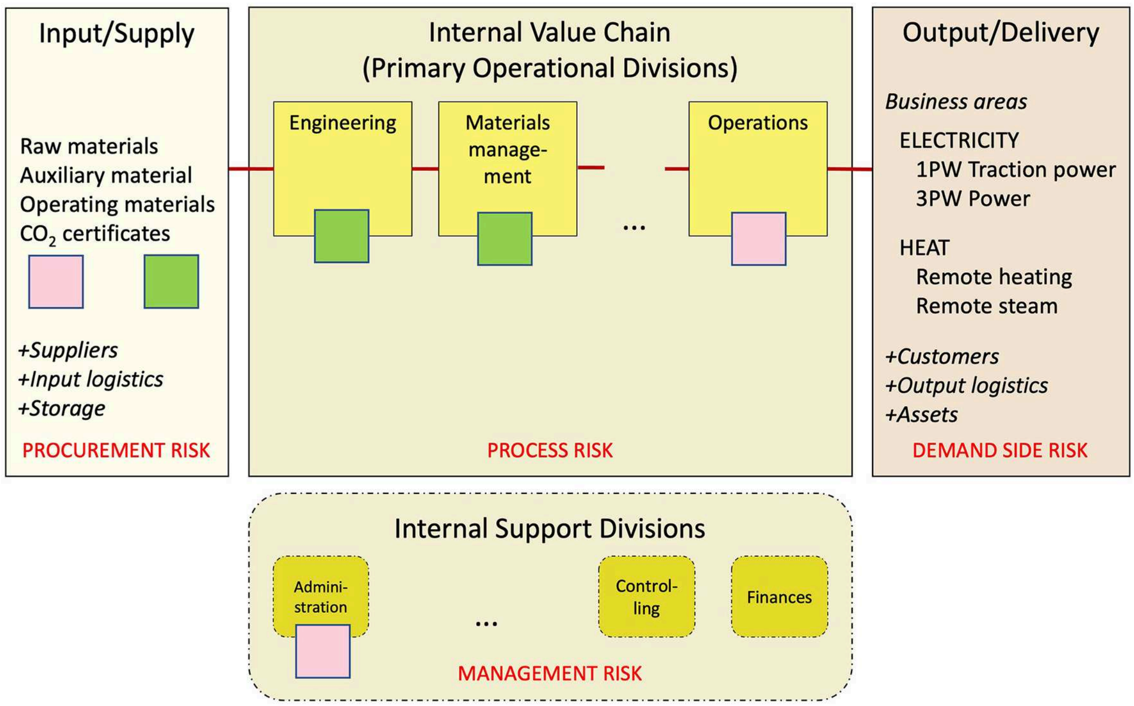

FIGURE 5
Scheme of the corporate value chain enriched with risk factors. For each group of units, activities, and processes, a group of associated risk factors is designated. Each such element of the value chain may have any number of assigned capacities (green squares) and sensitivities (pink squares). The full enriched value chain created in the case study is confidential.

- Organization, products, and customers of the company.
  - Definition of the most important products (output) and raw materials and supplies (input): Are our stated inputs and outputs correct, or is there a need for change?
  - Definition of business areas: What are the main business areas?
  - Who are the customers? Is the list complete?
  - How does the regulation of the power grids affect the business?
  - Who imports/exports the electricity?
- Value chains of the company (if already elicited).
  - Which business units are involved in the production of the different products and how? (per business unit/product)
  - Example question: "Which company areas are involved in the generation of traction current—from purchasing to generation?"
  - What is the process/sequence from purchasing to production? (per business unit/product).
- Core processes and value creation processes of the company.
  - Consideration of the most important processes per value creation step/company area: Please explain roughly what exactly happens in the value creation step.
  - Are there any relevant external factors that need to be considered for value creation?
  - If applicable, if time available: Identify key interrelationships between the main processes of the value-adding steps.
- Check for completeness.
  - Relation between process steps, externals factors, and maybe more.

The elicitation approach should lead from the organization to individual processes, roughly in the following order:

1) Building understanding of the business and the organization.
2) Identification of organizational units relevant for value creation and their sequence (per product).
3) Identification of process steps within organizational units and their sequence (per product).
4) Understanding of the company's resilience mechanisms (e.g., business continuity management and IT security).
5) Other interrelationships and relevant external business factors (e.g., market and market mechanisms).
6) Categorization according to core processes, support processes, and management processes.

Intended outcomes of the elicitation include:

- List/mapping of organizational units relevant for value creation and their interrelationships (per product).
- List/mapping of process steps within individual organizational units (per product).
- External factors relevant for the business
- Visualization of the value chain (see Figure 5).
- Subdivision into core processes, support processes, and management processes.

Step 2: Pinpointing the climatic risk factors in the value chain

Based on the post-processed value chain and the pre-defined risk to be investigated, the researchers and stakeholders jointly record the potential climate change-related impacts on individual areas and process steps of the value chain (e.g., delivery delays or failures, increased production costs, necessary changes in regular transport modes) as well as the relevant associated risk factors. The intermediate result of this step is the value chain with the relevant risk elements from the climate Impact Chain assigned to the business units, activities, and process steps (see Figure 5). If a climate Impact Chain already exists, its risk elements (hazards, sensitivities, capacities, and impacts) can be assigned to the value chain and, if necessary, further specified.

In our case study, the joint researcher and stakeholder team transferred relevant risk factor from the second regional Impact Chain ("drought and low water risk") to appropriate elements in the value chain. Subsequently, the stakeholders named additional company-specific risk factors that were also pinpointed to elements of the value chain. Figure 5 shows the graphical scheme of the enriched value chain. As before, harmonization and clarifications that still need to be validated can be made subsequently.

Step 3: Consolidation and selection of indicators, determination of data sources, assessing risk quantitatively

In this step, the risk is assessed and visualized along the value chain. If sufficient data is available, a quantitative risk assessment can be made; otherwise, a semi-quantitative risk assessment can be made using expert estimates. Even with good availability of company data, it is possible that indicator data cannot be provided in nominal form due to confidentiality. In such cases (partial), anonymization techniques can be applied, such as conversion to percentage values or reporting additional costs instead of total costs.

In our case study, the joint team proposed indicators for each linkage of risk element/process step/element of the value chain. The result is a table containing potential indicators per combination of risk area, element of the value chain (business unit), process step in that element, and risk factor (like impact, capacity, and sensitivity). For each potential indicator, its dimension and data availability are entered. Table 2 shows an excerpt of the table generated in our case study.

Step 4: Identification of potential adaptation measures and their impacts

Based on the calculated risk, a check is made for the most severely affected areas and process steps in the value chain to determine whether and, if so, which adaptation measures are required. To do this, it is first necessary to identify the resilience mechanisms already in place, which are components of business continuity management, or which result from external market mechanisms. Then, the effects of the adaptation measures are determined, both direct effects on the

TABLE 2 List of potential indicators for corporate climate risk (excerpt for risk factor "impact").

	Indicators for which data are available or estimates could be made					
Risk type	Element of the value chain	Process step	Impact	Potential indicator(s)	Dimension	Data availability
Procurement risk	Transport/Input	Transport (to ARA seaports)	Higher costs	Additional costs for inland water freight transport during low water periods	€	Derivable from low water surcharge (KWZ), gauge level history and transport quantities history
Procurement risk	Transport/Input	Inland transport	Reduction of payload per cargo ship	Freight quantities	Quantity per cargo ship	Correlates with number of cargo ships
Procurement risk	Transport/Input	Inland transport	Increased demand for cargo ships	Number of cargo ships	–	Derivable from number of cargo ships/gauge level, gauge level history and transport history

value chain (e.g., changes in process flow) and indirect effects (e.g., increased production costs).

4. Case study results

Using the process described in the previous section, three major results were produced that jointly present the research innovations achieved within our case study. These results are:

- A co-produced Impact Chain for the risk of "Negative impacts of extended periods of drought and low waters of the Rhine River on infrastructure, logistics and population in the metropolitan region of Mannheim" that employs an adapted visualization scheme compared to the original Vulnerability Sourcebook method;
- A corporate value chain for the Mannheim Large Powerplant, enriched with risk elements from the co-produced Impact Chain, allowing qualitative risk assessments of the value chain; and
- An Excel-based risk analysis tool to estimate risks of "Additional costs for inland water freight transport during low water periods."

These results are described in detail in the next sections.

4.1. Impact chain co-produced with stakeholders of the metropolitan region of Mannheim

The validated regional Impact Chain is shown in Figure 6. The layout of the resulting final Impact Chain is an adaptation of the original Impact Chain layout as introduced in the Vulnerability Sourcebook: As the stakeholders involved in the risk analysis work with distinct, but potentially related sets of exposed elements (e.g., harbor infrastructure, container ships, and electricity production), we grouped impacts, sensitivities, capacities, and exposed elements in the Impact Chain into different "impact fields", based on the fields of action of the German Adaptation Strategy (e.g., logistics, traffic infrastructure, industry & trade, energy industry, water balance and water management, ecology/hygiene, and tourism and leisure industry). These impact fields are included in the Impact Chain as gray, transparent, labeled rounded rectangles into which all other Impact Chain elements, except hazards, were placed. Impact fields can overlap, if they have impacts, sensitivities, capacities, or exposed elements in common, and they can also be nested, if it is necessary to distinguish between different sub-groups of impacts (e.g., changes to the ecosystem are defined as a sub-group of the impact field ecology/hygiene). In total, the Impact Chain contains 50 direct physical and intermediate impacts. For instance, a long duration of extreme heat could increase water temperature in the river (direct physical impact), leading to a sequence of intermediate impacts: increased temperature of cooling water taken from the river, impaired use of cooling water, cooling water shortage for thermal plant, service interruption, reduced turnover.

Clustering impacts, exposed elements, sensitivities, and capacities within impact fields allows to show interdependencies and potential cascading effects between businesses and impact fields. In addition, it allows to identify joint adaptation measures and measures of one stakeholder that support another stakeholder, which can in turn allow to identify adaptation measures early in a dependency chain that help to reduce cascading effects for following businesses. This latter approach allows to make adaptation efforts of different business partners transparent and allows to facilitate a joint discussion, e.g., on distributing adaptation costs fairly across the dependency chain.

The Impact Chain also contains a stack of adaptation measures—right side of Figure 6—that were mentioned during the workshops or during the validation process, and circular dark gray labels containing comments or hints to potential data sources. A legend is contained in the top row of Figure 6. Also included, but omitted here for space limitations, we provided IPCC definitions of the risk factors.

4.2. Quantitative risk assessment using combined impact chains and value chains of individual businesses

For performing a quantitative risk assessment based on results of the qualitative regional assessment, we collaborated

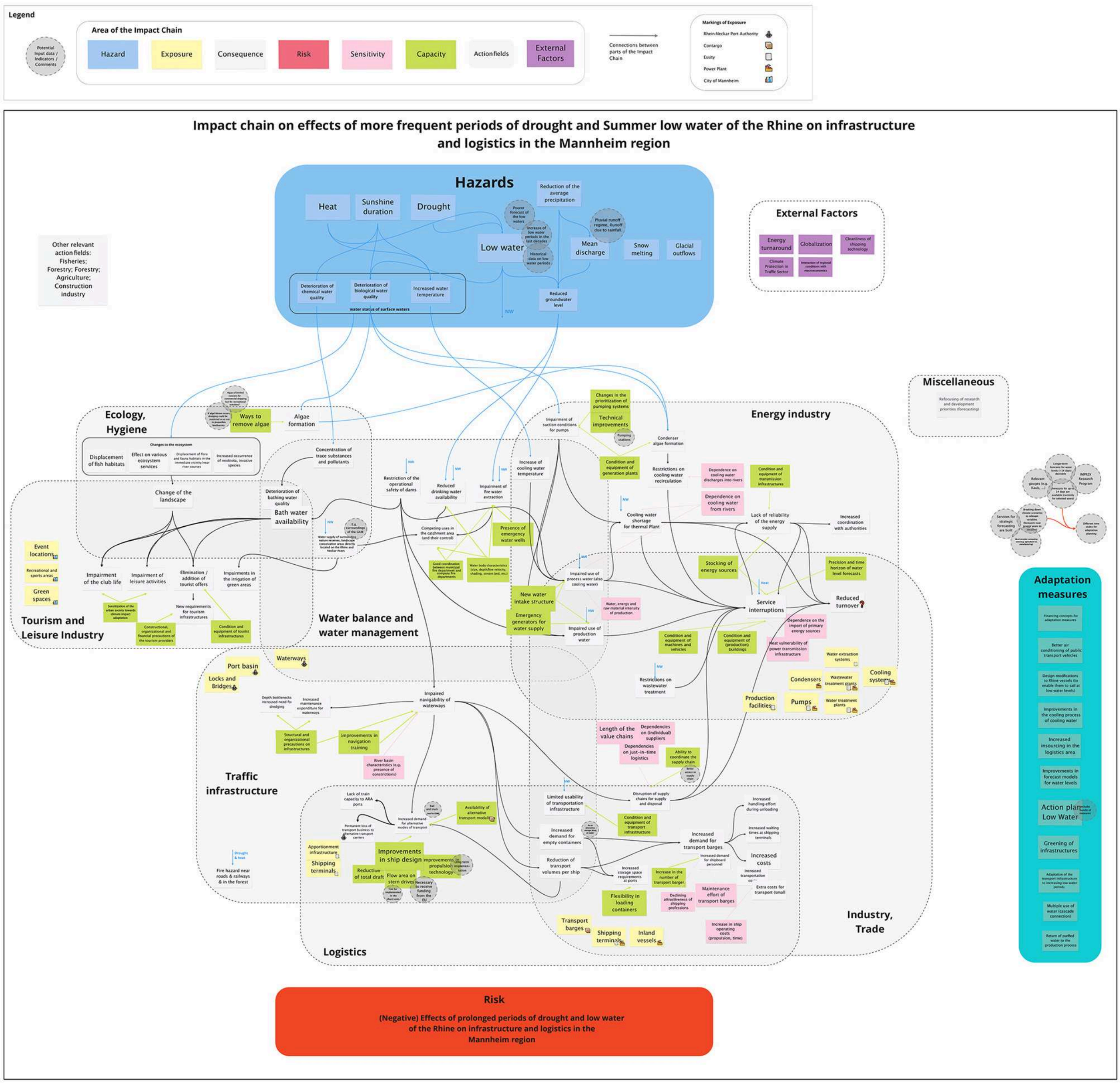

FIGURE 6
Impact Chain depicting the results of the qualitative assessment of the risk of "negative impacts of extended periods of drought and low waters of the Rhine River on infrastructure, logistics and population in the metropolitan region of Mannheim."

with the Mannheim Large Powerplant that operates several fossil-thermal units. We started with applying the method described in section "CRVA on corporate level using Value Chains." Here, we provide some additional information on the actual application of the method.

During step 1, we separated the value chain of the company into four sections: (1) input/supply (i.e., all units, activities, and process steps related to suppliers, input logistics, and inbound storage); (2) internal value chain (i.e., all units, activities, and process steps related to the internal value production); (3) internal support divisions (i.e., all supporting units, activities, and process steps that are relevant to enable the actual value production, but do not contribute directly to it); and (4) output/delivery (i.e., all units, activities, and process steps related to customers, output logistics, and assets). After this separation, the different business units, their relevant process steps, and the relations between the different business steps are identified (e.g., *via* organigrams or business process documentation). Lastly, the value chain sections, business units, and activities are visualized in diagrammatic form, similar to Impact Chains, with the input section either at the top or on the left, the internal value chain in the middle, the internal support division beside the internal value chain, and the output section at the bottom or on the right (see Figure 5).

Step 2: Once this value chain model was created, we pinpointed the risk factors—impacts, sensitivities, and capacities—from the regional Impact Chain within the corporate value chain model, by trying to place them beside the operational processes, which constitute the exposed elements of the combined

Impact/value chain. If risk factors cannot be related to individual process steps, it is also possible to locate them at the level of business units. The actual value chain diagram produced cannot be shown here for reasons of confidentiality. In the discussion part of this paper, we will point to the ethical dimension of assessing vulnerabilities of Critical Infrastructure. Also, we will explain why we believe that omitting the full risk-enhanced value chain does not impair the reproducibility of our approach.

Pinpointing Impact Chain elements within the value chain of a business allows to identify potential cascading effects that might otherwise be missed. In addition, this approach allows to locate potential adaptation measures within different business units or even process steps.

Step 3: For identifying indicators, the risk factors pinpointed in the validated combined Impact and value chain are transferred to tabular form. For each risk factor, the table specifies the risk type (as shown in Figure 5), the element of the value chain, and the (operational) process step. The potential indicator (or indicators) is (are) entered: designation or description, dimension (the indicator must be measurable), and known data availability. Table 2 shows an excerpt of the working table that was co-produced.

Due to resource limitations—explained in the Section "Discussion," we agreed with the stakeholders to perform an exemplary quantitative assessment using only one of the indicators. The stakeholders proposed to use the indicator "Additional costs for inland water freight transport during low water periods", abbreviated to "low water transportation surcharges." The next section describes in detail how we proceeded for concluding step 3 of the method.

4.3. Risk assessment tool for a power production company

We adopted a risk matrix approach to visualize the outcomes of the quantitative risk assessment. The method is standardized[10] and is employed for civil protection (BBK, 2011) and in many other areas. Using this method had the additional advantage of familiarity, since the Mannheim Large Powerplant also uses a risk matrix approach for other operational aspects. The risk matrix is a tabular representation of risk and relates the magnitude of impact or damage caused by a hazard to the likelihood or probability of the hazard's occurrence. The user then must decide which combinations of impact and likelihood, for instance, are acceptable, require staying alert, or require immediate action. Such decisions may be political ones, as in the case of civil protection, or based on business continuity or corporate risk management policies.

For our case study, we selected the low water transportation surcharge as an indicator for further assessment. The estimated additional transportation costs under a given scenario are categorized in six different impact levels, while the likelihood is based on the frequency of the water level at the gauging level at station Kaub ranging within a specific interval that is relevant for any of five different transport surcharge ranges. The combination of impact and likelihood (see Figure 7) then constitutes the basis for the stakeholders' risk classification.

Waterway transport surcharges grow exponentially with decreasing water levels. Certain water levels mark critical surcharge amounts: 220 cm (first significant rise), 150, 100, 50, and 40 cm (highest cost, several times as high as normally). These water level ($\boldsymbol{wl}$) values delimit surcharge relevant intervals $\boldsymbol{wli_2},\ldots,\boldsymbol{wli_6}$ (in list order):

$$\mathbf{150}\ \boldsymbol{cm} < \boldsymbol{wl} \leq \mathbf{220}\ \boldsymbol{cm}$$
$$\mathbf{100}\ \boldsymbol{cm} < \boldsymbol{wl} \leq \mathbf{150}\ \boldsymbol{cm}$$
$$\mathbf{50}\ \boldsymbol{cm} < \boldsymbol{wl} \leq \mathbf{100}\ \boldsymbol{cm}$$
$$\mathbf{40}\ \boldsymbol{cm} < \boldsymbol{wl} \leq \mathbf{50}\ \boldsymbol{cm}$$
$$\mathbf{0}\ \boldsymbol{cm} < \boldsymbol{wl} \leq \mathbf{40}\ \boldsymbol{cm}$$

For determining likelihoods, we used water level data from gauging station Kaub[11] for the 120-year spanning period 1900–2020. We first calculated the number of days per year in which the daily mean gauging level at Kaub falls within the surcharge relevant water level intervals. Based on these values, we then created a reference scenario by calculating the 120-year average number of days in each of the five intervals and then we calculated the fictive expected surcharge for an "average year" (based on current surcharge rates) against which historical or fictive low water scenarios can be compared.

To determine the impact classes, we calculated the average transportation amount of coal—in tons—using the monthly transportation values for 2017 and 2018 provided by Mannheim Large Powerplant as reference. For these years, we estimated the additional transportation costs—the surcharge—using the number of days the gauging levels at station Kaub fell within a specific surcharge interval, i.e.,

$\boldsymbol{I_j} = \boldsymbol{adtq} * \boldsymbol{dwl_j} * \boldsymbol{s_j}$, where:

$\boldsymbol{I_j}$ denotes the impact contribution of surcharge interval $\boldsymbol{j}$, $\boldsymbol{j} \in \{\mathbf{2},\ldots,\mathbf{6}\}$, i.e., the total annual transport surcharge in euros for water level interval $\boldsymbol{wli_j}, \boldsymbol{j} \in \{\mathbf{2},\ldots,\mathbf{6}\}$,
$\boldsymbol{adtq}$ denotes the average daily coal transport quantity in tons,
$\boldsymbol{dwl_j}$ denotes the number of days per year in which the water level at gauging station Kaub was in water level interval $\boldsymbol{wli_j}, \boldsymbol{j} \in \{\mathbf{2},\ldots,\mathbf{6}\}$, and
$\boldsymbol{s_j}$ denotes the surcharge costs per ton associated with water level interval $\boldsymbol{wli_j}, \boldsymbol{j} \in \{\mathbf{2},\ldots,\mathbf{6}\}$.

The total impact $\boldsymbol{I_1} = \sum_{j=2}^{6} \boldsymbol{I_j}$ sums up the total annual transport surcharge.

Based on these calculated values, we introduced an initial impact classification $\boldsymbol{C_k}$, $\boldsymbol{k} \in \{\mathbf{1},\ldots,\mathbf{6}\}$ using five empirically determined surcharge values, $\boldsymbol{Limit_1},\ldots,\boldsymbol{Limit_5}$. The impact $\boldsymbol{I_j}$, $\boldsymbol{j} \in \{\mathbf{1},\ldots,\mathbf{6}\}$ belongs to impact class $\boldsymbol{C_k}$ where:

$$\boldsymbol{k} = \mathbf{1}\ \textit{if}\ \mathbf{0} \leq \boldsymbol{I_j} \leq \boldsymbol{Limit_1}$$
$$\boldsymbol{k} \in \mathbf{2},\ldots,\mathbf{5}\ \textit{if}\ \boldsymbol{Limit_{(k-1)}} < \boldsymbol{I_j} \leq \boldsymbol{Limit_k}$$
$$\boldsymbol{k} = \mathbf{6}\ \textit{if}\ \boldsymbol{Limit_5} < \boldsymbol{I_j}$$

10 ISO 31010.

11 The water level data have been kindly provided by the German Federal Institute of Hydrology.

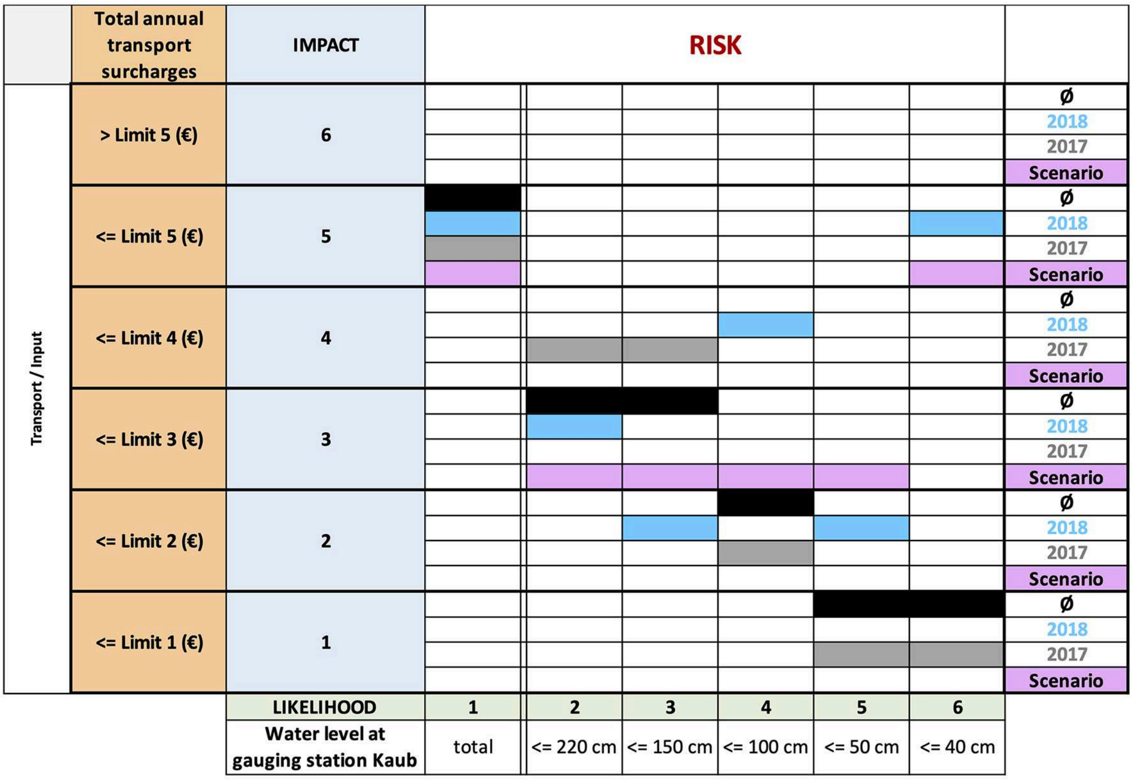

FIGURE 7
Risk matrix for transport surcharges per low water days in water level interval, i.e., likelihood based on frequency, and annual surcharges (impact). The colored matrix cells indicate the magnitude of the surcharge total per water level interval wl_{ij}, $j \in \{2, \ldots, 6\}$, ("likelihood" class) for each of the 4 years (historic average year ∅, 2017, 2018, and a fictive "Scenario" year). The additional column for "likelihood" class 1 is not related to a specific water level interval but indicates the total impacts for each of the four scenarios.

These five thresholds are determined by stakeholders' risk management. For completing a standard risk matrix, the stakeholders also must assign risk categories—typically three to five—to each of the 30 possible combinations of impact and likelihood. These risk categories may indicate the type of action that is required to compensate the surcharge costs, like switching to cheaper transport modalities or saving money in other business areas.

Since fluvial water levels are highly volatile and low water days do not follow regular patterns, we proposed using the risk matrix representation for creating a decision support tool that helps comparing impacts (transport surcharges) and frequencies of low water days for a few scenarios.

Using the impact and likelihood classification, we designed a matrix with the likelihood classes on the ***x*** axis and the impact classes on the ***y*** axis. At each intersection of a likelihood class with an impact class, this matrix contains four cells, each representing additional transportation costs:

1) for the reference scenario year calculated based on the 120-year averages,
2) for the historical values of 2017,
3) for the historical values of 2018, and
4) for a user-defined fictive scenario year. In addition, the matrix contains one column that calculates (and categorizes as impact) the sum of all additional transportation costs under a given scenario. The scheme of the resulting matrix is shown in Figure 7.

The resulting tool allows entering all relevant data: distribution of low water days in the cost-relevant intervals, transport surcharge per such interval, and annual volume of fuel shipped *via* inland water transport. The scenario allows assessing the consequences of more frequent and severe low water situations and may aid decision-making. That is, the stakeholder may now answer questions like:

- "How did last year compare to an average year in terms of distribution of low water days and resulting surcharges?"
- "How would a year with even more extreme low water levels than 2018 compare to 2018 and to the average year?"
- "What total transport surcharges could we expect for three extreme years in a row?"

The four examples displayed in Figure 7 show that for all four scenarios, the distributions and amounts of surcharge costs can be vastly different. Combined with improved water level forecast methods, the tool may support early preparedness for low water situations, optimizing transport modes and minimizing costs.

4.4. Narratives—providing additional information for the risk analysis

To combine the information from the Impact Chains, value chains, and risk analysis with relevant additional information, we produced an eight-page dossier "Evaluation of the Reports and

Analyses on Economic Damage Caused by Summer Low Water in the Rhine". This dossier gathers information on the investigated risk, its impacts, adaptation measures (implemented, on-going, and planned), and policies (political and industrial). It has been produced by research in the scoping phase, by gathering stakeholder information during the co-production workshops, and by parallel research updates. A good part of this information has been covered in the section "Case study background" and in the annex of this paper. Here, we focus on adaptation measures to mitigate negative impacts of low water periods of the Rhine River.

One of the points in the BMVI's action plan "Low Water Rhine" (BMVI, 2019) has recently been implemented, namely an improved forecast of low water levels. In July 2022, the Federal Institute of Hydrology (BfG) has deployed a 6-weeks forecast for several gauging stations to users—typically logistics companies and industries along the Rhine. Before July, the forecast was limited to 10 days. Another important action point, the *"off-loading optimization of the navigation channels on the Middle Rhine,"* will take until 2030 to be realized (BMVI, 2019). The plan involves several constructive measures for removing the depth bottlenecks. The goal is to increase the off-loading depth from 1.90 m to 2.10 m on a length of almost 50 km, 11 km downstream of the gauging station Kaub and 38 km upstream.

Implemented, on-going, and planned adaptation measures include also:

- Installing re-cooling systems for enabling the reuse of river water. It is by law prohibited to discharge industrial cooling water from power plants and production facilities into a river when the temperature of the river is equal to or higher than 25°C. Re-cooling systems cool down used and thus heated cooling water and enable to reuse it several times for cooling in a closed cycle, instead of discharging it after one use and extracting fresh river water. Without re-cooling systems, power plants and industrial plants might need to be shut down if the river temperature stays in the prohibitive temperature range for too long a time.
- Optimization of loading and unloading times at ports for accelerated dispatch of the higher number of cargo ships required for transporting the same total amount of payload in periods of low water levels.
- One company that extracts water from the Rhine River for industrial processes, for cooling, and for firefighting has constructed a new facility for uptake of river water from the Rhine that can cope with much lower water levels than the previous facility, and
- Conversion of cargo ships for improved navigability during periods of low river water levels. This includes lighter ship structures and modified propulsion for reducing the overall height of the ship.

5. Discussion

5.1. Methodological implications

The rising need for more resilient infrastructure systems has resulted in advances in risk analyses of supply chains and analyses of interdependencies in infrastructure systems from a Critical Infrastructure Protection and Resilience perspective. However, results from such analyses on the level of interconnected infrastructure systems have seldomly be broken down to the level of individual corporate value chains. We address this gap by introducing and combining four improvements to IC-based climate risk and vulnerability analyses.

First, we developed an adapted visualization method for Impact Chains, by introducing the concept of "impact fields" and clustering exposed elements, sensitivities, capacities, and impacts within these fields. We argue that this allows pinpointing which stakeholders need to deal with which impacts along the dependency chains and who might bear the brunt of the impacts (as well as their related economic losses). This in turn enables stakeholders to identify where mitigation measures might be most (cost) effective, by allowing to identify measures that can be implemented early on in the dependency chain to prevent or lessen the impact down the line. This approach also allows to identify sensitivities and capacities that influence individual or multiple impact fields, thus allowing to identify adaptation measures that affect multiple impact fields. We believe that this in turn can allow to identify the most efficient adaptation measures, i.e., measures that can have positive effects on multiple impact fields. In combination, locating exposed elements, sensitivities, capacities, and related adaptation measures within (overlapping) impact fields allows to identify which stakeholders need to take (or are already taking) action and where the (initial investment) costs of these actions (currently) lie, making the efforts (and investments) of individual stakeholders and their effects more transparent to all stakeholders of the infrastructure system.

Second, we based the regional climate risk assessment on national ICs and their fields of action. From a knowledge co-production perspective, not starting from scratch with the Impact Chain creation but using relevant parts of the more general national (German) climate Impact Chains had two effects: (1) co-production started with concrete examples, which avoided "re-inventing the wheel" and gave case study participants an easier start toward commencing the CRVA process, and (2) the resulting qualitative ICs are consistent with the national ICs. We believe that this can be an advantage for subsequent adaptation measures, as they can be related to national-level measures and potential funding options. The first effect is consistent with experiences of the authors from the Horizon 2020 project RESIN[12], in which municipal stakeholders often articulated the need for adaptable Impact Chain "blueprints" to make the method less time consuming and more accessible.

Third, we developed a method to locate risk components from regional Impact Chains within value chains of individual businesses. This allows to break down national/regional impacts of climate change toward individual business units and even single process steps, supporting more targeted adaptation measures within organizations and allowing to connect national/regional CRVA with business continuity practices. We believe that this approach leads to more consistency of climate risk assessments across governance levels.

Fourth, we developed a method for economic assessment of climate impacts that links individual (impact) indicators under different scenarios to economic losses, allowing to link the IC-based value chain CRVA approach to the Risk Matrix Approach, which is a standard and familiar way of visualizing risk in business continuity

12 https://resin-cities.eu/

practice. We argue that the presented approach is in principle generalizable for all kinds of impacts, provided there is sufficient data available or experts for providing value judgements.

Overall, the application of the methods involved the exploitation of qualitative (stakeholder knowledge) as well as quantitative information and data (publicly available resources). We did not explicitly address and report any potential uncertainties of these information and data used, though we are aware of sources of uncertainty. For instance, the calculation tool that we provided can be used in two ways: (1) analysis of historic data for assessing the influence of low water periods on transport costs and (2) assessing potential future scenarios. For case (1), the stakeholders may use the real costs; thus, the uncertainty in our model calculation—explained in the next paragraph—is not relevant for this application case. For case (2), stakeholders need to assume future developments of transport volumes, transport costs, duration of low water periods and water levels during those periods. The first two parameters are hypothetic and thus uncertainties would be present and could be derived from economic forecast, but we believe that this is not necessary for exploring future cost scenarios. The assumptions regarding low water periods may be aligned with regional climate models, and then the uncertainties of these models would apply.

One source of uncertainty originates from our specific use of the water level data. The data for the water level at the gauging station Kaub are validated values of the measured water level provided by the German Federal Institute of Hydrology. We used a set of daily mean water level values, derived by the data provider, to determine the number of days per calendar year in which the water level lies within one of the surcharge-determining intervals. By using this provided data, it may be possible that although the average water level value for a given day lies within a certain interval range, the real water level on that day may lie outside that interval for several hours. Given the approximate travel time of 3 days between the ARA seaports and Mannheim, we may assume that a possible shift of the water level to another surcharge interval for a couple of hours intra-day does not have a significant influence on the total surcharge for one such trip.

5.2. Limitations of the method, lessons learned, and need for additional research

The method presented in this paper has been successfully applied to create a regional Impact Chain with multiple stakeholders and to locate risk components from this Impact Chain down toward the value chain of one individual business. While both the Impact Chain approach and modeling value chains are well-established approaches that have been applied in numerous case studies, their combination—as described in this paper—is a novel approach that needs further validation by applying it to further businesses, ideally to businesses within the same region or within the same supply chain. The steps described in this paper (see section "The process of creating value chain CRVA") and the building blocks (Impact Chains and value chains) provided, should allow other researchers to conduct further case studies to validate the method. Although the specific value chain created within out case study cannot be disclosed, the scheme we describe can be applied to all businesses of the production sector. However, as every business has its individual organizational setup, the value chain model will have to be further adapted to fit the specific needs of the business. We believe that applying the method to additional business within the same supply chain would allow to identify how impacts and risks from the regional Impact Chain that are located up and downstream of an individual value chain propagate through the whole supply chain.

We were also not able to complete the fourth step of the process presented in Figure 4, due to resources limitations—partially resulting from the fact that the impacts of the Russian-Ukrainian war required the stakeholders needing to reorganize their fuel procurement and transport activities, leaving them no time to complete the planned fourth step. Consequently, while our approach enables calculating economic impacts of different low water scenarios, which would allow to include effects of different adaptation measures, we did not have the chance to test this hypothesis with specific adaptation measures identified with the case study stakeholders.

With this case study, we provided a proof of concept for a single business. For a clear validation of the generality of our proposed method it would be necessary to apply the method also to another type of business. We want to point out here that Porter's value chain model has been applied to numerous, different types of businesses over the last 40 years. This fact makes us confident that our proposed combination of using the Value Chain approach to model business system elements and then pinpointing climate risk elements onto these elements would also work for other businesses.

One thing that we learned in case studies across three different, related projects is that stakeholders are almost always short of personnel resources for climate change risk analysis and adaptation. This holds especially for small and medium sized enterprises and municipalities. Risk analysis, adaptation planning, and monitoring need to be scaled such that the stakeholders can manage it with their resources. Hence it is crucial to know for external experts and scientists who engage in such activities and for the participating stakeholders what the estimated resource demand of the methods presented in this paper—or alternative methods—actually is. We consider the experience values for the time demand of the activities that we provided here a valuable piece of empirical information.

5.3. Ethical dimension of assessing vulnerabilities and implications for reproducibility

Climate risk assessment includes the identification of sensitivities and vulnerabilities. When applied to Critical Infrastructure, identified vulnerabilities of certain system elements may point to a security risk. If a stakeholder decides to keep such an assessment result confidential, then we believe that it would be irresponsible and unethical to publish it. This is the reason why we have omitted the full risk-enhanced value chain diagram in the Results section.

Does this restriction impair the reproducibility of our method? We believe that it does not. The concept of Value Chains has been introduced almost 40 years ago. There is ample literature on Value Chain analysis, and guidance for eliciting Value Chain diagrams is available[13] and is not complicated to apply. The Value Chain elements need to be elicited and the workflow of processes between business

13 For instance, https://miro.com/blog/value-chain-diagram/.

units determined as described in this paper. This is already sufficient, determining the margin is not necessary here. Instead, risk elements are pinpointed to Value Chain elements. This is easy and requires just the stakeholder knowledge of their enterprise, common sense thinking, and facilitation of the process—as detailed in Figure 4—from the scientific-technical experts.

6. Conclusion

With the accelerating climate crisis and the rising interconnectedness of critical infrastructure systems, it becomes more relevant to move away from analyses for single infrastructure sectors toward the analysis of whole infrastructure systems and cross-sectoral dependencies. However, as the functioning of these interconnected infrastructure systems is dependent on a myriad of different stakeholders and actors from European to local level who need to cooperate to operate them, the need to increase the resilience of these systems of systems brings questions of shared responsibilities for implementation and financing of mitigation/adaptation measures to the fore to ensure their efficiency and effectiveness.

In this paper, we have presented a case study that tried to take a step toward closing these gaps by addressing shared implementation of adaptation measures using an integrative approach to CRVA. The first type of integration is the (vertical) uptake of results from CRVAs from higher governance levels on lower ones, the second type of integration is the (horizontal) multi-stakeholder, multi-sectoral regional CRVA. Our case study employed a novel approach for value chain climate risk and vulnerability analysis that combines a participatory, indicator-based method with a semi-quantitative risk matrix method that allows linking analyses from national to local scale and also supports economic assessment of climate change impacts for individual businesses. This approach has been successfully applied within a multi-stakeholder case study in the metropolitan region of Mannheim, where a part of the results have been and will be transferred into daily practice: (1) The Impact Chain developed with municipal stakeholders as a "test run" (IC 1) has been included in Mannheim's heat action plan; and (2) the developed risk assessment tool is currently being evaluated by the Mannheim Large Powerplant for inclusion in their business continuity management. The risk-enhanced value chain diagrams also offer opportunities for further coordinating risk analysis along supply chains or along value chains that span more than one business due to shared organization of work.

The workshops for creating the regional Impact Chain led to an exchange of information on implemented and on-going adaptation measures and to better awareness of the regional situation. Some stakeholders have expressed their wish to continue exchanges on regional adaptation beyond the duration of the case study.

We believe that our case study makes a significant contribution to better understanding of socio-economic impacts within and adaptation measures for interconnected infrastructure systems. However, further application of the proposed method in additional case studies is necessary to assure it is applicable for a broad range of infrastructure systems affected by different climatic hazards.

Moreover, our approach currently solely focuses on CRVA for preparing climate change adaptation. But for an infrastructure system to become truly resilient—and to avoid mal-adaptation/-mitigation—it would be advisable to also examine how to include climate change mitigation measures and effects within the approach. This would require additional research to extend the IC-based CRVA—and specifically the Impact Chain method—with a way to account for (positive or negative) mitigation effects of impacts and adaptation measures, an avenue that should be pursued further in future.

Our case study showed that IC-based CRVA can be meaningfully combined with other risk assessment practices that are common in businesses, namely value chains and risk matrices. This facilitates the integration of outcomes of IC-based CRVA in existing risk management and business continuity practices of organizations.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Data on gauging levels is available upon request at the German Federal Institute of Hydrology BfG (https://www.pegelonline.wsv.de/gast/start). Data related to business practices and economic impacts used for the risk assessment is not provided due to confidentiality reasons. Requests to access these datasets should be directed to DL, daniel.lueckerath@iais.fraunhofer.de.

Author contributions

DL contributed the idea of combining Impact Chains and Value Chains and co-designed the Impact Chain graphical template with KM. KM and DL jointly analyzed and post-processed the co-produced Impact Chains, indicator lists, the Value Chain diagrams, and jointly processed and aggregated the raw water level data. ER designed and implemented the risk matrix like tool for estimating the transport surcharges, performed most of the background and context research for the case study, and contributed the idea of building the Impact Chains for the case study on the national Impact Chains. All authors jointly prepared, conducted, documented, and evaluated the participative stakeholder co-production of knowledge in the described case study. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2023.1037117/full#supplementary-material

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Appendix

List of non-standard acronyms.

Acronym	Meaning
ARA	Amsterdam, Rotterdam, and Antwerp (seaports)
BBK	Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (German Federal Office for Civil Protection and Disaster Assistance)
BMDV (BMVI)	Bundesministerium für Digitales und Verkehr (German Federal Ministry for Digital and Transport; formerly BMVI)
BMUV (BMU)	Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection; formerly BMU)
CRVA	Climate Risk and Vulnerability Assessment
ERA-NET	European Research Area Network
IC	Impact Chain
IC-based CRVA	Impact Chain-based Climate Risk and Vulnerability Assessment
IPCC	Intergovernmental Panel on Climate Change
SC	Supply Chain
SCOR	Supply Chain Operations Reference
UFZ	Helmholtz-Zentrum für Umweltforschung (Helmholtz Center for Environmental Research)
VC	Value Chain

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Constructing a social vulnerability index for flooding: insights from a municipality in Sweden

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Floods disproportionately affect disadvantaged groups. Social vulnerability assessments are the first step in designing just and equitable flood risk reduction strategies. In Sweden, earlier social vulnerability indices apply top-down approaches. In this paper, we develop and apply a combined bottom-up and top-down approach to assess social vulnerability to flooding at a sub-municipal level in Sweden. We tested an indicator-based climate risk and vulnerability framework, more specifically the impact chain method suggested by the Vulnerability Sourcebook. We involved stakeholders using various participatory methods in three workshops, interviews, and informal exchanges to identify variables and indicators for social vulnerability. The Indicators were aggregated into a composite social vulnerability index using exploratory factor analysis. We thereafter mapped the social vulnerability index scores to uncover spatial injustices. We found that the proposed social vulnerability index captures municipal nuances better than national-level approaches. Our findings indicate an uneven spatial distribution of social vulnerability that mimics the overall patterns of income segregation found in the municipality. Many areas that score low in social vulnerability endure high exposure to floods. The social vulnerability index can support municipalities in designing just and equitable interventions toward flood risk reduction by serving as an input to policymaking, investment strategies, and civil protection.

KEYWORDS

Sweden, flooding, justice, social vulnerability, social vulnerability index, bottom-up assessment, stakeholder involvement, impact chain method

1. Introduction

Floods cause major human suffering, economic damages, and infrastructure disruptions (UNDRR, 2022). However, impacts vary across communities. Disadvantaged groups tend to experience disproportionate losses and distress (Wisner et al., 2004). Exposure and vulnerability are driven by deep-rooted societal injustices (Thomas et al., 2020). To address this challenge, the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2022), European Union (European Union, 2021) and United Nations (UNDRR, 2022) plead for just and equitable resilience to prevent vulnerable groups from being left behind.

Sweden endures growing social injustices and inequalities (Bertelsmann Stiftung, 2019) which is expected to entrench social vulnerabilities further and complicate efforts toward disaster risk reduction (Pettersson et al., 2021). Flood risk is gaining national recognition in Swedish policymaking, as in, for example, the National Floods Directive (2009), the National Strategy for Climate Change Adaptation (2018), and Planning and Building Act (2010). Most legislation, however, neglects the social dimension of flooding although the European Union Floods Directive (European Union, 2021) encourages member states to consider fairness and solidarity in their flood risk management.

In Sweden, civil contingency planning focuses on maintaining critical infrastructures and vital societal functions rather than empowering people (Eriksson et al., 2011). Although research on social vulnerability in Sweden is emerging (see for example Nieminen Kristofersson, 2007; Guldåker, 2009; Sparf, 2015; Orru et al., 2022), few decision-support tools and policy instruments exist for assessing disaster justice and social vulnerability (Pettersson et al., 2021). Social vulnerability assessments are the first step in designing just and equitable risk reduction strategies and strengthening resilience among the most vulnerable segments of the population (Chakraborty et al., 2019).

Social vulnerability indices have gained recognition as a powerful decision support tool among both policymakers and researchers (Rufat et al., 2015; Oulahen et al., 2019). These indices consist of several variables and indicators representing social vulnerability and can map its spatial and temporal dimension using census areal units (Cutter and Finch, 2008). Social vulnerability indices can bring to light the injustices that drive differentiated impacts across groups and draw attention to the unequal spatial distribution of vulnerability and exposure (Chakraborty et al., 2019).

In Sweden, social vulnerability indices are gaining increasing attention. The geographical resolution varies, and includes municipal census areal units, regional census areal units (RegSO-areas), and demographic census areal units (DeSO-areas). Karagiorgos et al. (2021) replicate an existing social vulnerability index developed for the United States for Sweden using municipal census areal units and DeSO-areas. Indicator selection for DeSO-areas was, however, limited due to insufficient data availability. Haas et al. (2021) develop an adapted version of the social vulnerability index based on a literature review to investigate the spatial distribution of social vulnerability to landslides, flooding, and wildfires at a national level. The study includes both municipal census areal units and RegSO-areas.

Most previous research employs a top-down approach using secondary statistical data and academic literature to derive indicators for social vulnerability (Benzie, 2014; Beccari, 2016; Parsons et al., 2016). In Sweden, all previous social vulnerability indices apply a top-down approach (Haas et al., 2021; Karagiorgos et al., 2021). There is an untapped potential made of local experiences and knowledge, which can ensure that conceptualizations of injustices and vulnerabilities are anchored in the social, economic, and political reality experienced by the local community. A bottom-up approach allows local communities to define who is vulnerable and why, and avoid reproducing misrepresentations of injustices formulated by outsiders (Velasco-Herrejon and Bauwens, 2020). More importantly, bottom-up approaches can reconceptualize what constitutes expert knowledge and open scientific and technocratic processes for non-academic stakeholders to participate (Daniels et al., 2020). Co-benefits might be generated from the participatory process such as strengthened social networks and mutual learning (Hansson and Polk, 2018; Cvitanovic et al., 2019; Bremer et al., 2021). It can capture the social amplification of risk, and serve as a bridge between technical experts and public risk perceptions (Kasperson et al., 1988). Moreover, a bottom-up approach can identify socially-just flood protection that accounts for local conditions and avoids maladaptation that triggers new injustices and vulnerabilities (Malloy and Ashcraft, 2020).

In this paper, we wish to further advance the current state of the art by presenting and applying a combined bottom-up and top-down social vulnerability assessment process with an emphasis on local injustices and thereby enable policymakers to design socially-just flood protection. To this end, we aim to design and test a social vulnerability index to floods at a sub-municipal level in Sweden. We combine a bottom-up stakeholder involvement and top-down statistical analysis to derive a social vulnerability index. We use the smallest census areal unit (DeSO-areas). This allows us to study social vulnerability in depth and context to form an understanding of how social vulnerability varies within the same municipality. We also map the social vulnerability index scores to uncover potential spatial injustices.

To meet these objectives, we run a pilot study in which we zoom into Halmstad Municipality. Halmstad Municipality makes an interesting case as it endures significant exposure to coastal and river flooding while also battling with substantial socioeconomic inequalities (National Board of Housing Building Planning, 2020), which allows us to study the interaction between exposure and societal inequality and its effects on social vulnerability. It allows us to explore whether disadvantaged and marginalized areas suffer from higher flood exposure or not.

The remainder of the paper is organized as follows: First, we delve into the concept of social vulnerability. Thereafter, the methodology is introduced. The following section presents the results starting with the variables determining social vulnerability, followed by an analysis of the spatial distribution of vulnerability to flooding. We thereafter discuss the implications for research and practice and juxtapose our findings with previous research. Finally, conclusions are provided.

2. Social vulnerability to natural hazards

2.1. Social vulnerability

The literature on vulnerability contains a wealth of definitions as a result of being a field that engages researchers from disparate disciplines such as development studies, disaster management, economics, geography, ecology, anthropology, and medicine to name a few (Vogel et al., 2007; Cutter et al., 2009; Armaș and Gavriș, 2013; Segnestam, 2014). Cutter (1996) finds 18 definitions of vulnerability that diverge in terms of their unit of analysis, epistemological traditions, and conceptualizations. Two archetypes, however, exist: *biophysical vulnerability* which assesses the likelihood and magnitude of a hazard, and *social vulnerability* which focus on people's capacity to cope with stresses (Brooks, 2003; Cutter and Finch, 2008).

We use the definition presented in the IPCC Fourth Assessment Report (AR4) (IPCC, 2007, p. 883): "the degree to which a system is susceptible, or unable to cope with adverse effect of climate change, including climate variability and extremes, vulnerability is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity".

TABLE 1 Factors and variables for assessing social vulnerability.

Factors	Variables
Demography	Population changes, age groups, gender
Wealth	Regional economic prosperity, household income, child poverty
Livelihood	Occupation type, skilled, and unskilled labor, retirement, unemployment, care responsibilities, location of livelihood
Knowledge and skills	Local knowledge, language proficiency, access to information, educational attainment, previous flood experience, beliefs
Health	Frail and physically limited individuals, people with mobility impairments
Housing	Tenure, insurance, building type, housing quality, overcrowding, household composition
Social capital	Participation in decision-making, networks, trust
Access	Access to critical infrastructures and vital societal functions, rural-urban divide, vehicle ownership

Thieken et al. (2007), Tapsell et al. (2010), Lindley et al. (2011), Vink et al. (2014), Welle et al. (2014), Garbutt et al. (2015), Kazmierczak et al. (2015), Koks et al. (2015), Sayers et al. (2018), and Fekete (2019).

It captures complex socio-ecological interactions, and allows us to structure the assessment around exposure, sensitivity (the degree which a system is affected), and adaptive capacity (ability to adjust). The latest IPCC definition of vulnerability omits exposure as a function of vulnerability. It overlooks exposure as a precondition and driver of vulnerability, hence neglecting socially differentiated exposure although it can generate an additional layer of injustice (Ishtiaque et al., 2022).

While hazards are shaped by timing, location, and meteorological context, variables like livelihoods, politics, finances, infrastructures, and culture shape their impact on people (Tapsell et al., 2010; Garbutt et al., 2015; Fekete, 2019). Social vulnerability is a pre-existing condition that stems from societal injustices, in which political and cultural structures put certain groups at disadvantage based on their individual characteristics, social standing, and human and financial resources (Bullard, 2008; Rahimi-Golkhandan et al., 2021; Drakes and Tate, 2022). Accordingly, social vulnerability tends to be attributed to a range of socioeconomic and demographic variables (see Table 1 for an overview).

Framing disasters as social phenomena that emerge from deep-rooted inequalities gives rise to claims for justice (Bankoff, 2018). Disaster studies using a social vulnerability lens show significant injustices in which disadvantaged and marginalized people are disproportionality affected in disasters (Wisner et al., 2004; Cutter and Finch, 2008; Segnestam, 2017). Accordingly, social vulnerability is about structural injustices rather than inadequate capacities and resources (Thomas et al., 2020). That is, social vulnerability links to distributional justice (fair distribution of costs and benefits) and procedural justice (fair decision-making processes and recognition of different forms of knowledge) (Lukasiewicz, 2020). A better understanding of social vulnerability can both uncover flood-disadvantaged people as well as the pre-existing forces that create or cement disaster injustices (Chakraborty et al., 2019).

2.2. Measuring social vulnerability

Many methods exist for assessing social vulnerability (see Birkmann et al., 2013 for an overview). As noted by Tate (2012, p. 326), "the social analog to the quantitative physical hazard model is the social vulnerability index". The social vulnerability index has been applied and adapted to numerous contexts and hazards (see for example de Loyola Hummell et al., 2016; Hagenlocher et al., 2016; Roder et al., 2017; Kirby et al., 2019; Tascón-González et al., 2020; El-Zein et al., 2021). Social vulnerability indices can represent socio-ecological complexity; monitor social vulnerability over time and space; pinpoint areas for intervention; and in the end ensure just flood risk management (Chakraborty et al., 2019).

Methodologically, the choice of indicators requires further attention. Indicators diverge across indices, due to diverging conceptualizations; contextual characteristics; intangible and immeasurable variables; and insufficient data availability (Garbutt et al., 2015). Social vulnerability indices are at times "black boxes" with little theoretical and empirical justification (Beccari, 2016). Approaching index construction from the bottom-up can overcome such challenges by involving stakeholders in a transparent and open dialogue in which underlying assumptions surface. It also ensures that the choice of indicators reflects the local context and its complexities (Daniels et al., 2020).

In Sweden, social vulnerability must be explored across analysis scales. So far, existing social vulnerability indices have municipalities as their areal units of analysis (Haas et al., 2021; Karagiorgos et al., 2021). The smallest census areal unit, DeSO-areas, is underutilized. Municipal areal units provide an insufficient spatial resolution as social vulnerability can vary significantly within the same municipality (Nelson et al., 2015). In practice, municipalities hold the primary responsibility for flood risk management and emergency services (Bynander and Becker, 2017). Methodologically, the risk for ecological fallacy increases as census aerial units grow, i.e., attributing the characteristics of a group to an individual. The population is more homogenous the smaller the census aerial units (Wood et al., 2010).

3. Methods

To develop a social vulnerability index, we applied an exploratory mix-method approach combining stakeholder engagement and statistical analysis. We structured the social vulnerability index around (i) factors describing a group of interdependent variables, (ii) variables describing a characteristic that determines social vulnerability, and (iii) indicators describing the metrics that measure the variables.

In this study, we followed the indicator-based climate risk and vulnerability assessment approach the "impact chain" method outlined in the Vulnerability Sourcebook (Fritzsche et al., 2014). The impact chain method draws on the definitions provided by the IPCC AR4, and breaks vulnerability into its components of exposure, sensitivity, and adaptive capacity. The impact chain illustrates the main cause-effect relationships behind climate change and its impacts on people: climate change exposure (e.g., heavy precipitation or meteorological drought) interacts with the system's sensitivity (e.g., population pressure or resource depletion) and adaptive capacity (e.g., financial resources or risk awareness) to produce potential impacts and vulnerabilities.

Operationally, the impact chain method combines stakeholder engagement and quantitative data analysis in an eight-step approach: scoping, developing impact chains, identifying and selecting indicators, data acquisition and management, normalizing, aggregating indicators, aggregating vulnerability components, and presenting the outcomes. We merged some steps since they overlapped (see Figure 1). The impact chain method encourages collaborative stakeholder engagement to strengthen the policy-science interface; ensure contextual relevance; build stakeholder ownership of outcomes and risk awareness; and improve research legitimacy and uptake (Menk et al., 2022). We involved stakeholders using various participatory methods in three workshops, interviews, and informal exchanges during the scoping phase, impact chain development, and validation process. Stakeholders were not involved in the statistical analysis, in which we instead departed from methods found in the academic literature.

3.1. Scoping

The scoping phase included several steps to further specify our aims and research questions and to inform the design of the case study and the participatory process. To gain a better understanding of the context, we first conducted a brief document study reviewing available documentation on climate risk and disaster risk reduction in Halmstad Municipality. Key documents included a flood risk and impact assessment, climate adaptation plan, risk and vulnerability assessment, climate change situation analysis, and spatial plan. It allowed us to tap into ongoing work in the municipality, and ensure relevance for policy and practice.

We thereafter reviewed the academic literature on social vulnerability indices to better understand the scientific debate and state of art. We performed a scoping study to collect variables used for assessing social vulnerability. It is worth noting that the review was not designed to be exhaustive, but to anchor our process in scientific research and gather input for the participatory process (for a meta-analysis of social vulnerability metrics see Rufat et al., 2015). At the time of research, there was no social vulnerability index for Sweden as Haas et al. (2021) and Karagiorgos et al. (2021) published their work in 2021 (after we conducted our initial search). We, therefore, broadened the search to include studies from similar contexts in Northwestern Europe. We identified literature by applying intuitive Boolean searches in Scopus, LubSearch, and Google Scholar. Keywords included "social vulnerability", "Europe", and "index". The search period was set to 2005–2020. In total, we reviewed 11 articles. Variables were noted and clustered into themes.

In close dialogue with our contact person in Halmstad Municipality, we invited 17 stakeholders to an online scoping workshop about capacity needs. Ten stakeholders participated representing different areas of work: climate adaptation, water engineering, social services, risk management, urban planning, and environmental protection. The workshop aimed to establish collaboration and partnership, discuss capacity needs, and scope the context. During the workshop, we co-explored current and future challenges and risks in the municipality. We thereby gained an initial understanding of relevant hazards, past impacts, capacities, and non-climatic drivers. We defined the scope of the social vulnerability assessment together as a group. The researchers then further refined the aims and research questions based on the stakeholder input in order to boost the relevance and usefulness of the research to the problem context.

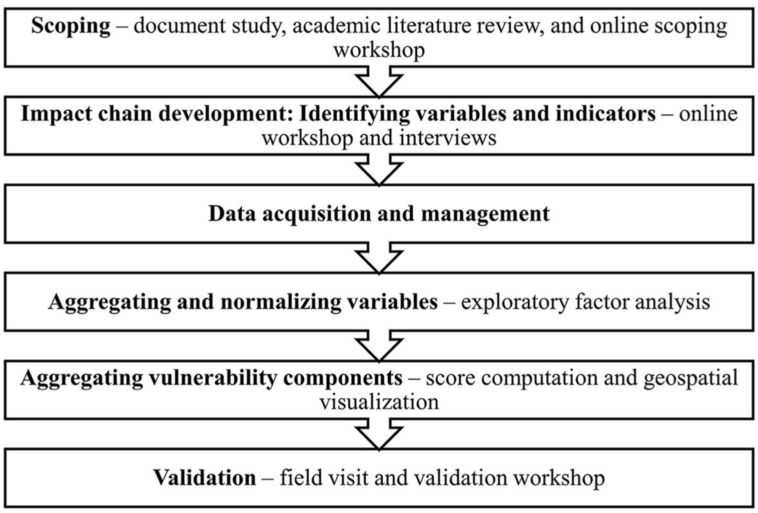

FIGURE 1
Methodology overview.

3.2. Impact chain development: identifying variables and indicators

We engaged stakeholders in a collaborative process to identify variables and indicators for social vulnerability in Halmstad Municipality. The Halmstad Municipality climate adaptation plan and stakeholder inputs from the workshop served as a point of departure in order to ensure context and location-specific relevance. It was an iterative feedback process that built on a close collaboration between the researchers and stakeholders, in which the list of variables and indicators was refined as the process moved along.

We invited 16 representatives from Halmstad Municipality to a second online workshop. In total, eight participants attended. The aim was to continue to co-explore drivers of social vulnerability. We used the digital tools Miro and MentiMeter to support the stakeholder dialogue. We asked the participants to brainstorm about what social groups might render vulnerable in the case of river flooding and coastal inundation in Halmstad Municipality. We divided the participants into smaller groups in which they discussed the political, social, economic, and institutional factors that determine sensitivity and adaptive capacity in Halmstad Municipality. The participants were brought back to the full group to share their main points from their discussions. We asked the participants to justify and elaborate their answers to challenge underlying assumptions.

After the workshop, the research team extracted an initial list of variables for social vulnerability. At this stage, we added variables found in the academic literature to identify gaps that the upcoming data collection had to address. This formed the basis for a survey consisting of 19 variables. The survey consisted of four-point Likert-scale questions. The survey delved into two questions: What social groups are vulnerable in the case of a disruptive event? What social groups might need assistance in the case of a disruptive event?

We shared the survey with the same group of stakeholders in online interviews. Five group interviews were conducted virtually, involving nine municipal representatives. The interviews aimed to further refine the list of variables for social vulnerability, and ensure its contextual relevance. Considering the online format, the survey served as a basis for discussion. Participants were first asked to individually fill out the survey and informed that the results would not be included in the formal analysis but support the full group discussion. We thereafter shared the results with the full group. It was followed by a discussion about the results in which the participants elaborated and justified their answers. No quantitative data were included for analysis. Instead, we extracted variables for social vulnerability from the interview notes and transcripts.

Findings were thereafter consolidated by the researchers into a list of contextually relevant variables for further analysis. We assigned quantitative indicators to the variables.

3.3. Data acquisition and management

Data was collected for the indicators from Statistics Sweden and the Delegation against Segregation (Delmos). Data was gathered for DeSO-areas that consist of 700-2700 inhabitants for 2018. From a total of 56 DeSO-areas in Halmstad Municipality, 41 with complete datasets were considered.

We then collected data for flood exposure. A coastal inundation map was generated for Halmstad Municipality using the results from the NEMO-Nordic model (Hordoir et al., 2018). A flooding map along the Nissan River was obtained from the Swedish Civil Contingencies Agency. Both maps corresponded to storms of a 100-year return period, with sea level rise and land uplift assumed for the year 2,100 under the RCP8.5 climate change scenario.

3.4. Aggregating and normalizing indicators

To mitigate the influence of overlapping variables when determining the social vulnerability index, exploratory factor analysis was conducted to group correlated indicators into a reduced number of factors (Cutter et al., 2003; Holand et al., 2011). Principal component analysis is another commonly applied method to aggregate variables to develop vulnerability indices (Haas et al., 2021; Karagiorgos et al., 2021). We preferred exploratory factor analysis over principal component analysis as it allowed us to interpret the patterns arising from the latent variables instead of only reducing the number of variables (Widaman, 1993). The data reduction was realized by investigating whether the collected indicators were linearly related to a smaller number of factors that account for a particular amount of variance in the observed data. The exploratory factor analysis was conducted in three steps: (i) testing of data adequacy, (ii) determination of the number of factors, and (iii) interpretation of factors.

The Kaiser-Meyer-Olkin Test was applied to the dataset to measure sample adequacy. The obtained score of 0.79 is considered adequate for sample sizes below 100 (Shrestha, 2021). We found the included indicators appropriate for exploratory factor analysis based on Barlett's Test of Sphericity. We carried out a scree-test to determine the appropriate number of factors. Eigenvalues were calculated as the ratio between common and specific variances associated with the extracted factors. Kaiser's Eigenvalue Criterion states that an eigenvalue >one is significant since the associated factor is explained more by the common variance than the specific variance (Shrestha, 2021). Extreme positive and negative loadings were considered as appropriate variables that explain the variability within each factor. We selected the orthogonal approach with the varimax rotation method over the oblique approach to perform factor rotation. It provided results that were easier to interpret and maximized the spread of loadings after extraction (Shrestha, 2021).

Each factor score was then comprised of a sum of indicators that increase or decrease vulnerability, representing either sensitivity or adaptive capacity. We normalized the data from zero to one using a minimum-maximum scaling technique.

To account for flood exposure, we added a factor representing the average distance to areas exposed to inundation. Exposure was not included in the exploratory factor analysis as it is possible to be exposed but not sensitive (IPCC, 2007). We calculated the distance from inundated areas due to extreme storm surges or river discharge by using the buffer tool in ArcMap 10.8. The distances were averaged within each demographic area. Averaging has the limitation that smaller demographic areas near inundation maps are more exposed than larger areas.

3.5. Aggregating vulnerability components

To find social vulnerability index values, individual factor scores were added together. In line with previous research (Tate, 2012), we adopted an equally weighted approach. We presented the standardized normal variables (Z-scores) to highlight the data variability relative to the mean value. We assumed that the results were normally distributed. Areas corresponding to one standard deviation above the mean were considered the most vulnerable.

We then presented the results in a geospatial format. We retrieved the latest GIS layer containing DeSO boundaries from February 2020 from Statistics Sweden (SCB, 2022a). Using Python's libraries GeoPandas and GeoViews, the Z-Score results for each demographic area were merged into their corresponding boundaries in the DeSO geodata and plotted as choropleth maps. Geographic visualizations were produced for the aggregated social vulnerability index values, as well as the individual factors.

3.6. Validation

In spring 2022, we conducted fieldwork in Halmstad Municipality to collect observations of the neighborhoods that scored high and low in the social vulnerability index. It put the findings into context, and helped us to justify the selection of variables and indicators.

Thereafter, an interactive validation workshop was held with seven representatives from Halmstad Municipality. The aim was to share the findings with the stakeholders and gather their feedback for further improvement. We first presented the selected variables, factors, and geospatial visualizations. This was followed by a discussion, in which the participants provided additional information for areas that scored high and low in the social vulnerability index. We then provided the participants with printed impact chains for them to elaborate on the findings and make changes as deemed appropriate.

In the workshop, the stakeholders commended the quality of the results and validated them. No changes were made to the selected variables and indicators. However, the factors were renamed based on stakeholder input. Moreover, the stakeholders provided additional input to the justification of variables and indicators based on their local expertise and experience. It anchored the findings in the local context and improved the accuracy and transparency of the information.

4. Results

In this section, we present the social vulnerability index and its application in Halmstad Municipality. The results section is structured around the impact chain method. We first present findings from the scoping phase, and provide a brief description of Halmstad Municipality. We proceed with introducing the results from the impact chain development process. Variables and indicators were interpreted and extracted from the stakeholder dialogues. Thereafter, the aggregation of indicators is presented followed by the aggregation of vulnerability components. The aggregation of indicators and vulnerability components is accompanied by a visual representation to showcase the spatial distribution of social vulnerability.

We integrate secondary data from the scoping phase throughout the results section. It allows for the empirical data to be presented in a wider societal context, and reduces the risk of individual biases interfering with the results.

4.1. Scoping: about Halmstad municipality

Halmstad Municipality is located in Halland county (see Figure 2) in the southwest of Sweden, with a population of around 105,000. Since 1970, the population has grown by 48% (SCB, 2022b) and it is expected to continue growing (Halmstad Municipality, 2022a). Most inhabitants reside in urban settlements. About half of the households are single-person households (SCB, 2022b). The municipality receives a large influx of tourists every summer, which results in a three fold population increase (Jouper et al., 2019).

In Halmstad Municipality, the average income is less than the Swedish average (SCB, 2022b). In total 14% of the population has a disposable income <60% of the national median. In line with national trends, foreign-born persons are three times more likely to have a disposable income <60% of the national median (Delmos, 2020a). The biggest employers in the municipality are the regional and municipal administration, the Swedish Armed Forces, Biltema Logistics, Halmstad University, and Martin & Servera Logistics (Halmstad Municipality, 2022a).

Its geographical location makes Halmstad Municipality prone to various natural hazards, including, but not limited to, storm surges, erosion, river flooding, heatwaves, droughts, and heavy precipitation (Jouper et al., 2019). As climate change unfolds, extreme weather events are expected to increase in frequency and magnitude (SMHI, 2014). The municipality is located in Laholmsbukten where there is a local effect triggering extreme water levels. Water levels are 50–100 centimeters higher in Halmstad compared to nearby coastal towns in the case of an extreme weather event (Johansson, 2018).

4.2. Impact chain development: variables and indicators for social vulnerability

From the stakeholder dialogues and interviews, we extracted ten variables for social vulnerability to flooding in Halmstad Municipality. The variables represent human and social capital, access to resources, and exposure. Some variables represent sensitivity (increase vulnerability), whereas others represent adaptive capacity (decrease vulnerability). We assigned one or more indicators for all variables (see Table 2 for an overview).

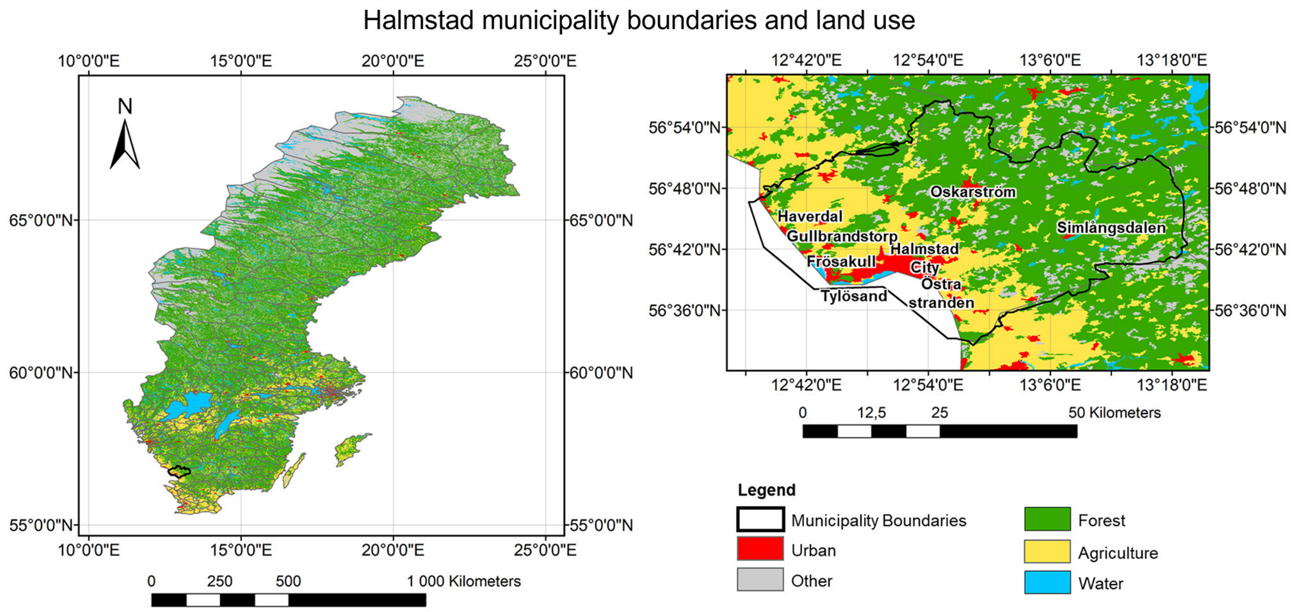

FIGURE 2
Halmstad municipality (Copernicus, 2018).

4.2.1. Age

Stakeholders highlighted the very young and very old as the vulnerable groups in case of flooding due to their dependency on others (e.g., evacuating without support from others), difficulty accessing information, and potential mobility constraints. Haas et al. (2021) suggest considering the percentage of people younger than 15 as an indicator for children when assessing social vulnerability in Sweden. Drawing from epidemiological research, the percentage of people aged 75+ serves as an indicator for the elderly as this age group is more likely to have various health conditions (Tapsell et al., 2002).

4.2.2. Language proficiency

From the stakeholder discussions we identified language as a variable for social vulnerability. It was, for example, argued that language barriers inhibit information access as witnessed during the COVID-19 pandemic. There is, however, no data on language proficiency in Sweden. In line with previous research (Fielding, 2012; Kazmierczak et al., 2015; Koks et al., 2015; Kirby et al., 2019), the percentage of foreign-born persons is used as a proxy indicator for language proficiency. Foreign-born persons may also lack an understanding of the Swedish crisis management system. It was noted during the stakeholder dialogue that foreign-born persons comprise a diverse group with different capacities and sensitivities depending on other intersecting variables such as housing, educational attainment, income, and time of residence in Sweden.

4.2.3. Illness and disability

In line with previous research (Vink et al., 2014; Welle et al., 2014), the stakeholder dialogues revealed that health conditions and impairments increase vulnerability. Some groups depend on others for safety including people with significant mobility impairments, developmental disabilities, intellectual disabilities, and healthcare service users.

We are using the number of sick leave days as an indicator of illness and disability. It indicates the number of people with reduced functional capacity due to illness or disability. It excludes people with minor illnesses or disabilities as they have the functional capacity to take personal responsibility for their safety. The indicator shows the number of days paid by social insurance in relation to the number of people with insurance aged 20–64. It includes paid days with sickness cash benefits, sickness compensation, activity compensation, and rehabilitation allowance (Delmos, 2022).

4.2.4. Educational attainment

Further, it was noted during the dialogues that adults with lower levels of educational attainment have less access to information. Low educational attainment correlates with low income (Cutter et al., 2003; Fekete, 2010; Welle et al., 2014). In line with previous research (Bremberg et al., 2015), two indicators are included: (i) the percentage of people who have completed primary education or less and (ii) the percentage of people who have an educational attainment of at least 2 years of university or similar.

4.2.5. Single parent households

In line with previous research (Garbutt et al., 2015; Sayers et al., 2018), it was noted during the participatory process that single parent households are a potentially vulnerable group. Extreme weather events impose increased demands on parents. Single

TABLE 2 Overview of variables and indicators for social vulnerability to flood hazards in Halmstad Municipality.

Variable	Indicator	Increase (+) or decrease (−) vulnerability
Age	Younger than 15 (%)	+
	Older than 74 (%)	+
Language proficiency	Foreign-born (%)	+
Health	The average number of sick leave days	+
Educational attainment	Highest educational attainment primary school or less (%)	+
	Highest educational attainment of at least 2 years at university or similar (%)	-
Single parent households	Single parent households (%)	+
Vehicle ownership	Number of vehicles	-
Housing	House owners (%)	+
	Average living space per person (m^2)	-
Income	Children 0–17 years living at home in families with a low-income standard (%)	+
	Disposable income per consumption unit (SEK)	-
	Households with income below 60% of the national median	+
	Households with income 200% over the national median	-
Unemployment	Unemployed longer than 6 months (%)	+
Exposure	Average distance to areas exposed to coastal or river flooding (km)	+

parents are less likely to share the responsibility with another adult in comparison to co-habiting parents. It increases the dependency on childcare services. The number of single parent households in an area serves as an indicator for this group.

4.2.6. Vehicle ownership

As suggested by previous research (Kazmierczak et al., 2015; Sayers et al., 2018), insights from the stakeholder dialogue suggested that owning a vehicle reduces social vulnerability as it can facilitate the evacuation of people and goods. We use the number of vehicles per capita in an area as an indicator.

4.2.7. Housing

House owners have greater responsibilities than apartment dwellers in the case of flooding. Apartment dwellers can rely on their housing association for proactive and reactive flood risk management. Costs and benefits are shared in a larger group compared to house owners, who have the legal responsibility for protecting their property against natural hazards. We used an indicator that includes the percentage of house owners in an area.

4.2.8. Income

In line with previous research (Holand et al., 2011; Rød et al., 2012; Breil et al., 2018; Fekete, 2019), income was identified as a critical variable for determining social vulnerability. Households below average income have less capacity to cope in the case of a crisis as they have fewer financial resources to invest in efforts toward flood risk management. To assess income, we included four indicators: (i) households with an income <60% of the national median, (ii) households with an income >200% of the national median, (iii) disposable income, and (iv) children living in households below the poverty threshold.

4.2.9. Unemployment

In line with previous research (Aroca-Jimenez et al., 2017; Breil et al., 2018; Nikkanen et al., 2021), insights from the stakeholder dialogue suggested that people in long-term unemployment are less likely to have the financial resources to cope in the event of a flood. To assess long-term unemployment, we included an indicator that considered those unemployed longer than 6 months [as defined by SCB (2020a)].

4.2.10. Exposure

Human exposure to flooding was highlighted as an important variable for social vulnerability. Flood exposure can translate to social and economic impacts. As mentioned earlier, we use the average distance to areas exposed to river floods and coastal inundation as an indicator.

4.2.11. Gender

When interpreting the empirical data, we found conflicting findings with regard to gender and its impact on social vulnerability to flooding. During the analysis, we decided to *exclude* gender as a variable for social vulnerability to flooding in Sweden. Gender might play an important role when assessing social vulnerability to other hazards. During the interviews, some stakeholders from Halmstad Municipality identified men and women as vulnerable in the event of a flood. However, these differentiated vulnerabilities were attributed to variables of vulnerabilities already included in our study: women have more caring responsibilities and lower incomes. In line with earlier research (Jonkman and Kelman, 2005; Doocy et al., 2013; Salvati et al., 2018), it was noted that men are overrepresented in flood-related causalities due to risk-taking behavior.

This is in line with the literature on social vulnerability in Nordic countries. Gender is an important determinant of vulnerability in some contexts (Fekete, 2010; Vink et al., 2014; Garbutt et al., 2015), whereas in other contexts it is not (Holand and Lujala, 2013; Drakes and Tate, 2022). Nordic countries rank among the most gender equal in the world. It reduces the role of gender in determining vulnerability (Holand et al., 2011). Variations within

TABLE 3 Factor analysis loadings.

Factor label	Indicator	Factor 1	Factor 2	Factor 3
Factor 1: House-owners with children	Households with income below 60% national median (%)	−0.63	0.59	−0.29
	Younger than 15 (%)	0.83	0.14	−0.33
	Single family houses (%)	0.93	−0.18	0.09
	The average number of vehicles per person	0.78	−0.05	0.21
	Percent of children living at home 0–17 years in families with a low-income standard (%)	−0.64	0.51	−0.11
Factor 2: People outside the labor force	The average number of sick leave days	−0.09	0.79	−0.14
	Foreign-born (%)	−0.53	0.66	−0.34
	Highest educational attainment primary school or less (%)	0.10	0.64	−0.13
	Unemployed longer than 6 months (%)	−0.51	0.60	−0.25
Factor 3: Elderly with accumulated wealth	Households with income 200% over the national median (%)	0.20	−0.44	0.66
	Older than 74 (%)	−0.09	−0.06	0.56
	Average living space per person (m^2)	0.53	−0.35	0.78

genders appear greater than variations across genders due to intersecting variables related to for example class, ethnicity, and physical and mental ability (Ajibade et al., 2013; Rufat et al., 2015).

4.3. Aggregation of indicators

We performed a scree test to generate a composite index from the selected variables and indicators. The scree plot identified three factors according to the Kaiser criterion for retaining factors. This amount was applied to generate a loading table for further analysis (see Table 3). The analysis reduces the indicators into three factors consisting of correlated indicators for sensitivity and adaptive capacity.

Table 3 shows the social vulnerability index and its factor labels, dominant variables, and factor loadings. The factors account for 70% of the cumulative variability. The first factor, which we named "House-owners with children", explains 32% of the dataset variability and is characterized by a high incidence of single-family houses, people below 15 years old, a higher number of vehicles per residence, and low presence of households with income below 60% national median. The second factor, which we called "People outside the labor force", explains 23% of the variance found in the dataset and is dominated by a large number of sick leave days, foreign-born people, highest educational attainment primary school or less, households with income below 60% national median, and unemployment. The third factor was labeled "Elderly with accumulated wealth", and represents 15% of the dataset variability. It consists of households with an income of >200% of the national median, people with larger living spaces, and people aged 75+.

The spatial distribution for each factor is illustrated in Figure 3. Blue indicates decreased vulnerability, red indicates increased vulnerability, and dark gray indicates missing data. Even though the adopted indicators characterize vulnerability, factor labels are considered neutral and describe major societal groups in the municipality. These groups could be more or less vulnerable depending on their specific indicators. Therefore, vulnerability results are interpreted according to their absolute numerical values, where positive values are more vulnerable and negative numbers are less vulnerable, for every factor label. The main characteristics of each factor and their vulnerability hotspots within municipality areas are described next.

4.3.1. First factor—House-owners with children

The first factor, "House-owners with children", scored high in rural areas and small towns. Only 30% of the population in Halmstad Municipality lives outside the city of Halmstad (Halmstad Municipality, 2022b). Most land is used for agriculture or forestry (Copernicus, 2018). Most households are located far from the commercial center. Most households reside in single family houses (Delmos, 2020b). Many residents own a vehicle (SCB, 2021a), due to the long distance to municipal services and employment opportunities.

4.3.2. Second factor—People outside the labor force

The second factor, "People outside the labor force", presented the highest level of vulnerability. In this factor, the eastern part of Halmstad scored high. Most neighborhoods were built during the 1965–1975 wave of great investment in housing (also known as the Million Housing Program) (National Board of Housing, 2022). At this point, most urban planning applied the SCAFT Guidelines 1968—principles for urban planning for road safety. To stimulate safety, residential areas were designed as low-traffic neighborhoods. This has implications for response efforts, as rescue services struggle to enter and exit the residential area (The Swedish Police Authority, 2015). Most inhabitants reside in rental apartments. Unemployment is twice the municipal average (Delmos, 2020c). Around half of the inhabitants have a low economic income (Delmos, 2020a). Foreign-born persons make up a majority of the population (SCB, 2021b).

Östra Stranden also scored high. Östra Stranden is characterized by tourism and summer houses. Few people have their permanent residence at Östra Stranden. In the low tourist season, summer houses are often sublet. Sublet agreements are often poor, attracting students and others struggling to find accommodation. Östra Stranden endures high exposure to coastal and fluvial floods. Risk and vulnerability assessments show that

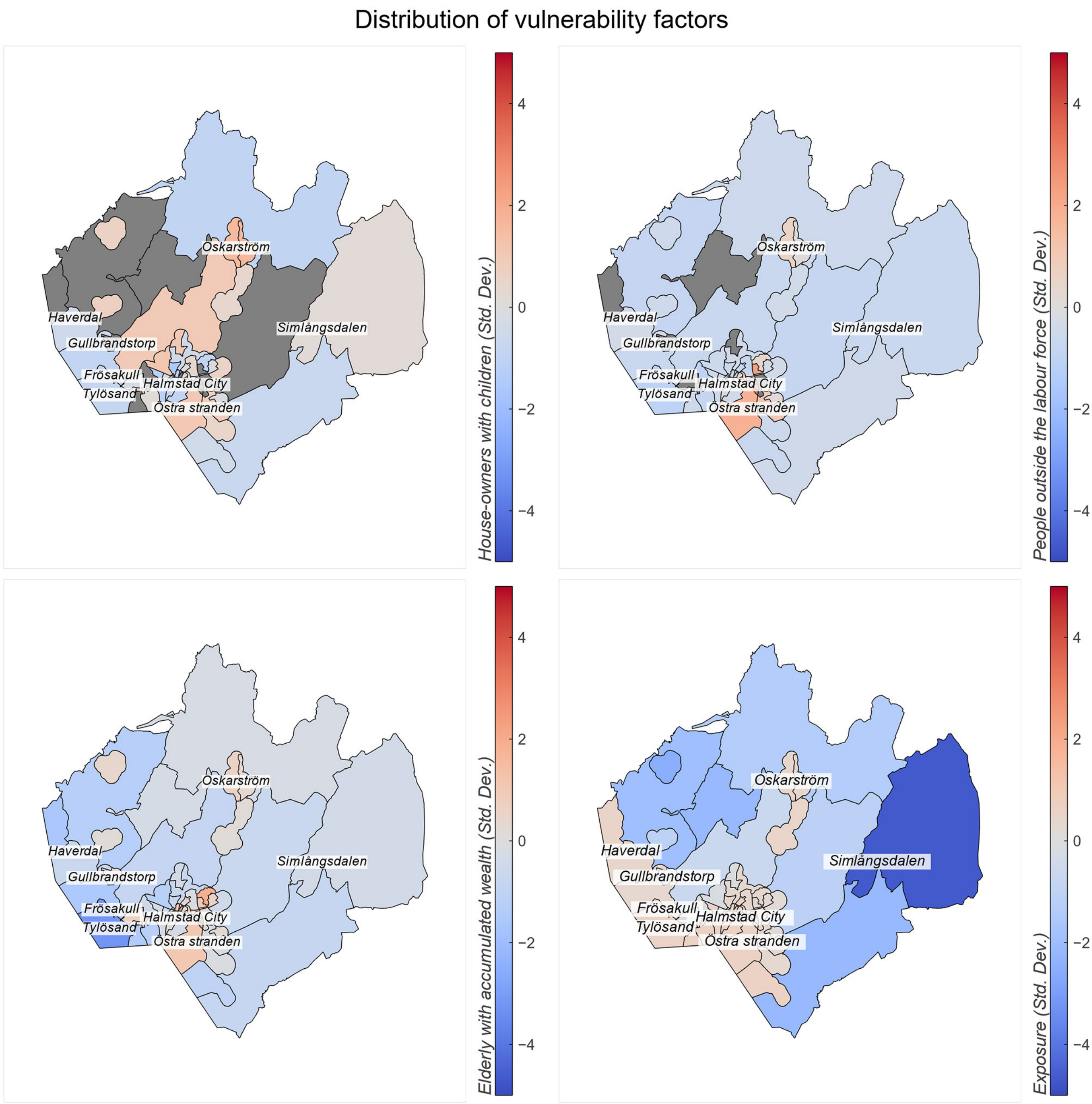

FIGURE 3
Separate factor relative vulnerability distributions in Halmstad Municipality.

flooding may cut off Östra Stranden from critical infrastructures and their services, which has serious implications for emergency services (Halmstad Municipality, 2022c).

Oskarström also scored high. With a population of 4,157 (SCB, 2020b), Oskarström is the second-largest locality in the municipality. Around 17% have an income <60% of the national median income (Delmos, 2020a). Most have completed upper-secondary education, whereas few have a post-secondary education from a university or similar (Delmos, 2020d). Most inhabitants are born in Sweden (SCB, 2021b).

4.3.3. Third factor—Elderly with accumulated wealth

The final factor, "Elderly with accumulated wealth", presented the lowest level of vulnerability. This factor is dominated by the western part of the municipality close to the coast. The coastal neighborhoods attract residents with an income above the national median (Delmos, 2020a). In the summer season, the population exponentially increases due to an influx of tourists (Halmstad Municipality, 2022c). Most reside in single-family houses (Delmos, 2020b).

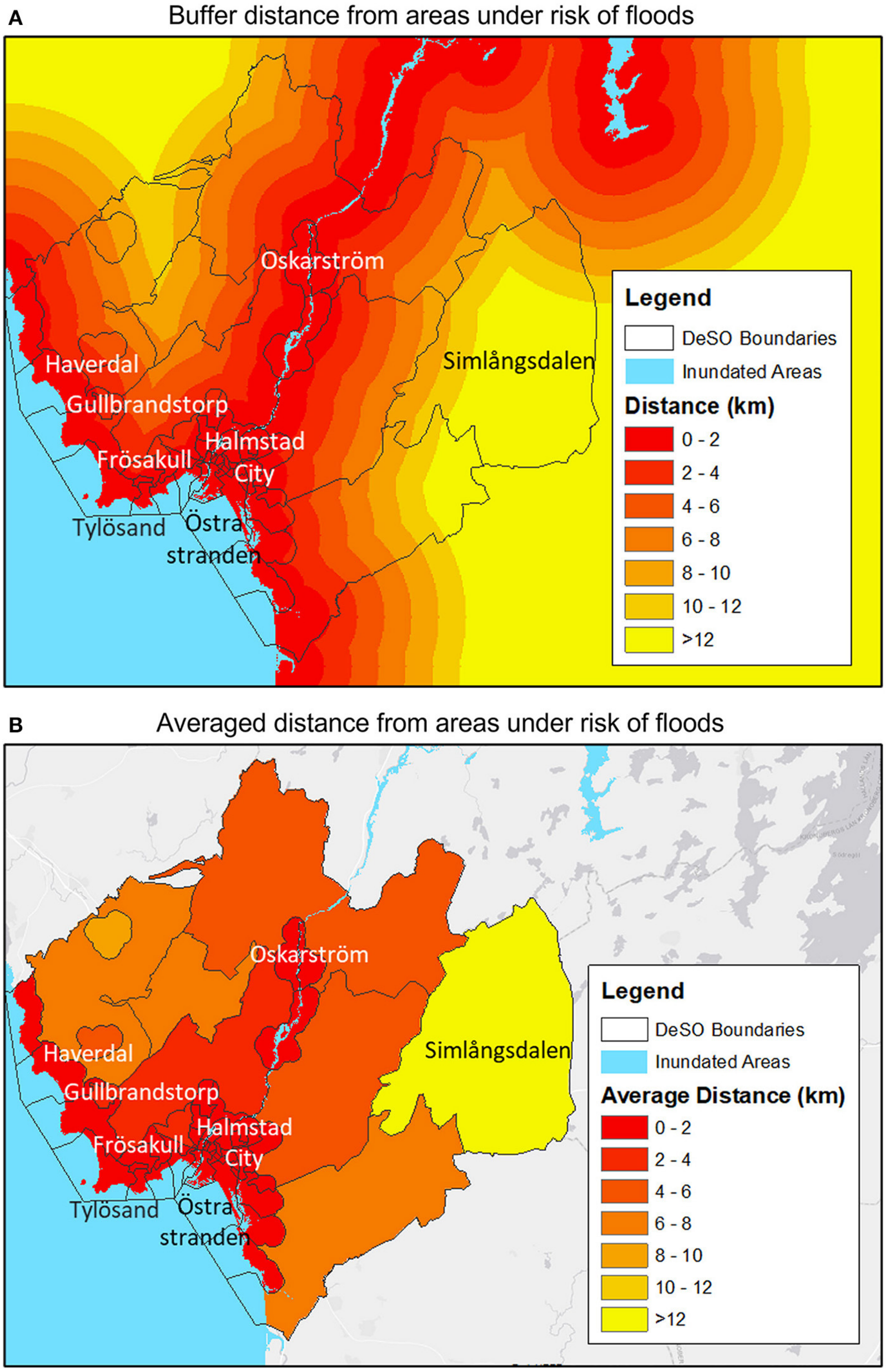

FIGURE 4
(A) Buffer distance to inundated areas. **(B)** Average distance to inundated areas.

4.3.4. Fourth factor—Exposure

As expected, we found that flood exposure within Halmstad Municipality was higher in areas near the coast and the Nissan River (Figures 4A, B). In general, the most populated neighborhoods are located in these risk areas and host major residential and commercial activities. Touristic beaches are subject to coastal inundation. Surrounding rural areas stand out as the least exposed to flooding.

4.4. Aggregation of vulnerability components

The aggregated social vulnerability index score is illustrated in Figure 5, visualizing the spatial distribution of social vulnerability in Halmstad Municipality. The Nissan River runs through Halmstad, dividing the city into two areas with clear socioeconomic differences. Citizens residing in the eastern neighborhoods have less

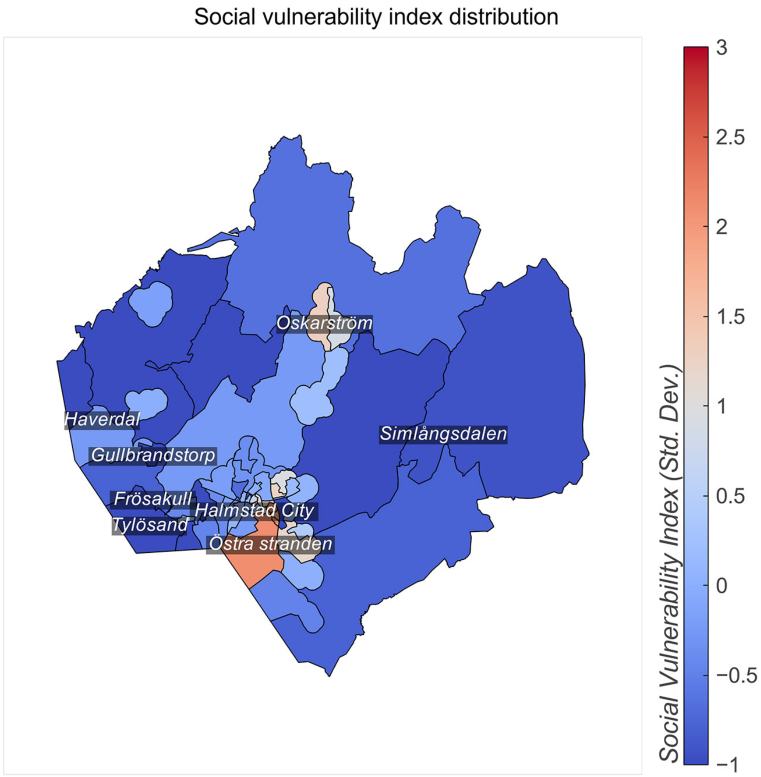

FIGURE 5
Social vulnerability index distribution in Halmstad Municipality.

education, income, and employment opportunities in comparison to those living in their western counterparts (Delmos, 2020e).

The results vary from −1.7 standard deviations to 2.1 standard deviations. Eleven DeSO-areas are considered the most vulnerable as they have standard deviations > +1. Neighborhoods with high levels of vulnerability have 21,910 inhabitants, and account for 22% of the total population.

5. Discussion

In this section, we discuss the findings and research process. First, we juxtapose the findings from developing and applying a social vulnerability index to floods at a sub-municipal level in Sweden against earlier social vulnerability and justice research. We pay special attention to the exposure and vulnerability paradox. Thereafter, we proceed with discussing the methodological contributions of combining bottom-up stakeholder involvement and top-down statistical analysis, ensuring fine-grained spatial data, and utilizing the impact chain method.

5.1. Mapping social vulnerability to uncover spatial injustices

In Sweden, the social dimension of flood risk remains understudied despite that growing socioeconomic inequality is expected to spur increases in social vulnerability. We address this gap by developing and applying a local social vulnerability index. In line with previous research (Roncancio and Nardocci, 2016; Sayers et al., 2018; Kim and Bostwick, 2020), the application of the social vulnerability index shows an uneven spatial distribution of social vulnerability that reflects the overall pattern of societal inequality and development. It uncovers injustices faced by the vulnerable segments of the population, and acknowledges the importance of considering the social dimension for flood risk management and climate adaptation to be effective, efficient, and equitable.

As stressed in the Vulnerability Sourcebook (Fritzsche et al., 2014), it is critical to involve stakeholders with local expertise and experience when assessing vulnerability. We identified variables and indicators for social vulnerability in close collaboration with stakeholders representing different departments in the municipal administration. The choice of variables and indicators for social vulnerability reflected the local context with respect to the vulnerability dimensions expressed by the stakeholders, but was also justified by earlier literature on social vulnerability to flooding in other countries in Northwestern Europe. Our findings show that social vulnerability depends on personal finances and resources, functional capacity, skills and knowledge, social capital, and housing. Some indicators stand in conflict to earlier top-down social vulnerability assessments. For example, both Haas et al. (2021) and Karagiorgos et al. (2021) include renters as an indicator of vulnerability. Little justification is provided other than references to academic literature, of which most studies were taking place in the United States before 2015 (Morrow, 1999; Cutter et al., 2003; Collins and Bolin, 2009; Gaither et al., 2011, 2015; Poudyal et al., 2012; Rufat et al., 2015; Wigtil et al., 2016; Davies et al., 2020). In this paper, we include house owners as an indicator of vulnerability as they have the legal obligation to protect their property (Planning and Building Act, 2010). House owners are alone bearing the financial burden in the case of a flood whereas renters or apartment dwellers can share the cost.

We found that many areas that score low in social vulnerability endure high exposure to floods, despite that the environmental justice literature asserts that marginalized and disadvantaged groups endure disproportionate flood exposure (Walker and Burningham, 2011; Fielding, 2012; Breil et al., 2018). In Sweden, people with a higher income, and therefore adaptive capacity, tends to settle near the waterfront despite the risk of river and coastal flooding (Delmos, 2020a). That is, there is little association between flood exposure and indicators of social vulnerability. Similar patterns are found in the United States (Chakraborty et al., 2014). That leads us to conclude that vulnerability is not the product of merely exposure, but also depends on sensitivity and adaptive capacity (Collins et al., 2018). Social vulnerability is a pre-existing condition influencing the human-hazard interaction rather than an outcome of a hazard event (Drakes and Tate, 2022). Social vulnerability exists irrespective of a hazard and illustrates societal injustices and inequities. Human exposure can bring societal inequalities to light, and trigger cascades beyond the inundated area itself. For example, flooding can reduce performance of infrastructures that may trigger cascading disruptions beyond the inundated area (Alexander and Pescaroli, 2019; Arrighi et al., 2020) ultimately exposing new groups to service and infrastructure disruptions.

5.2. Methodological contributions

This study makes a methodological contribution by assessing social vulnerability using a combined bottom-up and top-down approach that captures municipal nuances better than national-level assessments. We put a strong emphasis on stakeholder involvement to ensure that the choice of indicators for social vulnerability represented the political, institutional, economic, and social context experienced by the local community. Local stakeholders were engaged representing the municipality in an open and transparent scientific process with the ambition to prompt procedural justice. In theory, collaborative stakeholder engagement can bring about contextual relevance; yield intangible co-benefits such as strengthened social networks and trust, improved organizational capacity, and social learning; improve research legitimacy and uptake; and in the end bridge research and practice (Wall et al., 2017; Daniels et al., 2020; Menk et al., 2022). However, evaluations are recommended to investigate the participatory process and its impact on procedural justice and whether any intangible co-benefits emerge. We also suggest that future research engages disadvantaged groups when constructing social vulnerability indices and impact chains to prompt procedural justice for the most vulnerable segments of the population.

As noted in the section above, identifying social vulnerability indicators from the bottom-up produces different results compared to top-down approaches. It challenges previous top-down assessments building on academic literature, and highlights differences between countries and their vulnerability contexts. In line with previous research (Holand and Lujala, 2013), we argue that social vulnerability indices must be carefully modified and contextualized through close dialogue with local stakeholders before being replicated in a new context.

We argue that future social vulnerability indices must build on fine-grained spatial data in order to effectively inform policy and practice. In Sweden, municipalities have the primary responsibility for identifying, reducing, and addressing flood risk (Bynander and Becker, 2017; van Well et al., 2018). Local level assessments employing fine-grained spatial data produce findings in a more appropriate scale and resolution for municipalities, thus facilitating the process of transforming knowledge into policy and practice (Ernst et al., 2019; Daniels et al., 2020; André et al., 2021).

Besides its operational benefits, fine-grained spatial data also better locates the vulnerable segments of the population. We find significant differences in sensitivity and adaptive capacity across neighborhoods in Halmstad Municipality, whereas spatial variations in social vulnerability within the municipality remain by and large unnoticed in earlier top-down assessments (Haas et al., 2021; Karagiorgos et al., 2021). In line with previous research (Wood et al., 2010), we find that larger census areal units produce ecological fallacy i.e., attributing group characteristics to an individual. It can spur discrimination and injustices if assuming that individuals have certain characteristics or behaviors due to the group they belong to. It can produce an unjust and inefficient distribution of resources for flood risk management, ultimately entrenching vulnerabilities and inequalities.

However, using fine-grained spatial data also comes with challenges. We encountered limitations regarding the data input. The social vulnerability index builds on open access data to ensure procedural justice and transparency, as well as stimulate further refinement and application. Open access data is, however, limited for DeSO-areas. In addition, data on specific indicators were missing for some DeSO-areas. Census data only include registered citizens, hence excluding potential vulnerable groups such as tourists, undocumented migrants, and the homeless. Also, census data show where citizens have their residence not their actual location in the case of a disruptive event. The question also remains as to whether the suggested social vulnerability index can explain situations beyond Halmstad Municipality. Future research is needed to test the social vulnerability index across spatial scales and contribute to further refinement and validation, at the end supporting the implementation of socially-just flood risk management and climate adaptation.

To develop the social vulnerability index we followed the impact chain method outlined in the Vulnerability Sourcebook (Fritzsche et al., 2014). While the method identifies knowledge, technology, institutions, and the economy as drivers of vulnerability, it provides limited attention to disadvantaged and marginalized groups (Fritzsche et al., 2014). This study shows that it can support social vulnerability assessment processes by capturing the multidimensional, time-dependent, and situational factors that determine social vulnerability, and thus go beyond climatic and technical factors. The practical and standardized step-by-step approach thus appear to be applicable for various sectors and topics, geographical scales, and time horizons, and it can help stakeholders and researchers to disentangle social vulnerability and its complexities. The impact chain method can anchor the social vulnerability index in the local context, define measurable indicators, describe and visualize vulnerability pathways, and provide a sound knowledge base for disaster risk reduction and climate adaptation.

6. Conclusions

In this paper, we present a social vulnerability index for flooding in Sweden. We complement earlier research by assessing social vulnerability using a combined bottom-up and top-down approach with an emphasis on stakeholder involvement and local context. When mapping the social vulnerability index scores, we find pronounced injustices arising from the uneven distribution of social vulnerability across neighborhoods and groups. It highlights that flood risk assessments must go beyond climatic and technical parameters and consider people and their vulnerabilities, in order to design just risk reduction strategies and avoid reproducing inequalities.

The social vulnerability index can support Swedish flood risk management policy and practice, and prompt socially just-informed decision-making processes. Social vulnerability indices can guide decisions and investments in disaster risk reduction by identifying and locating vulnerable populations. It can shed light on distributional injustices, and spur actions toward just and equitable flood risk management in which no one is left behind. The social vulnerability index can also support monitoring and evaluation, and provide conclusions on whether policies and actions are effective–or not—in addressing the vulnerability of different social groups. It can help to avoid producing or reproducing injustices, and prevent other maladaptive outcomes such as gentrification and entrenched inequalities.

Our findings add to the body of research investigating social vulnerability. We make a significant contribution to Swedish flood risk management, by shedding light on the social dimension that constitutes flood risk. Above all, this can strengthen the justice and disaster risk reduction nexus and improve overall flood risk management.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

ME: conceptualization, methodology, validation, formal analysis, investigation, writing—original draft, writing—review, editing, and supervision. MV: methodology, formal analysis, writing—original draft, and writing—review and editing. KA: methodology, investigation, writing—original draft, writing—review and editing, project administration, and funding acquisition. ÅG and KB: writing—review and editing, project administration, and funding acquisition. LS: conceptualization, writing—review and editing, and funding acquisition. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Research advancements for impact chain based climate risk and vulnerability assessments

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As the climate crisis continues to worsen, there is an increasing demand for scientific evidence from Climate Risk and Vulnerability Assessments (CRVA). We present 12 methodological advancements to the Impact Chain-based CRVA (IC-based CRVA) framework, which combines participatory and data-driven approaches to identify and measure climate risks in complex socio-ecological systems. The advancements improve the framework along five axes, including the existing workflow, stakeholder engagement, uncertainty management, socio-economic scenario modeling, and transboundary climate risk examination. Eleven case studies were conducted and evaluated to produce these advancements. Our paper addresses two key research questions: (a) How can the IC-based CRVA framework be methodologically advanced to produce more accurate and insightful results? and (b) How effectively can the framework be applied in research and policy domains that it was not initially designed for? We propose methodological advancements to capture dynamics between risk factors, to resolve contradictory worldviews, and to maintain consistency between Impact Chains across policy scales. We suggest using scenario-planning techniques and integrating uncertainties via Probability Density Functions and Reverse Geometric Aggregation. Our research examines the applicability of IC-based CRVAs to address transboundary climate risks and integrating macro-economic models to reflect possible future socio-economic exposure. Our findings demonstrate that the modular structure of IC-based CRVA allows for the integration of various methodological advancements, and further advancements are possible to better assess complex climate risks and improve adaptation decision-making.

KEYWORDS

Climate Impact Chain, climate risk and vulnerability assessment, climate change, knowledge co-production, uncertainty management, transboundary climate risk, socioeconomic scenarios

1. Introduction

European policymakers face growing pressure to take action on climate change, such as following local climate actions plans recommended by the European Union (European Commission, 2021). However, effective climate change adaptation (hereafter adaptation) requires a scientific information-base of empirically grounded local, actionable knowledge concerning climate risks and adaptation options (Kirchhoff et al., 2013; Scherhaufer, 2014).

Assessing climate risks at the local level and providing actionable evidence remains a challenge, despite increasing sophistication of climate projections. The complexity and variability of factors that shape climate risks, which can lead to uncertain results complicate the assessment process (Viner et al., 2020; Aall and Groven, 2022). Furthermore, influence of factors such as policy decisions being driven by economics or views that seem to contradict with adaptation goals hinder the uptake of outcomes into action (Storbjörk, 2007; Klein and Juhola, 2014). As a result, the outcomes of such assessments are rarely utilized in decision-making processes (Larsen et al., 2012; Klein and Juhola, 2014).

The European Environmental Agency (EEA) has identified key lessons learned from conducting national and subnational CRVA and developing national adaptation plans (Füssel et al., 2018). The report highlights that while national CRVA provide general overviews and assist in setting thematic and regional priorities, targeted adaptation measures require subnational and local information. Additionally, the report, inter alia, underscores the need for common metrics to compare and identify priority areas, proactive stakeholder engagement, systematic assessment of uncertainties, exploration of non-climatic factors influencing exposure and vulnerability, and attention to cross-sectoral interactions and transboundary impacts (Füssel et al., 2018). Furthermore, CRVA frameworks should follow standardized procedures to produce comparable results across time and space while being adaptable to different contexts and policy scales (European Commission, 2019, 2020, 2021; ISO 14090, 2019; Bundesregierung, 2022).

This paper examines the Impact Chain-based CRVA (IC-based CRVA) framework as the departure point to address these challenges. Numerous guidelines and handbooks advise on CRVA (Daze et al., 2009; UNDP, 2010; Bharwani et al., 2013). However, the IC-based CRVA framework goes further by providing a standardized approach that covers various sectors and spatial levels, as well as time horizons. It offers step-by-step guidance for designing and implementing CRVA (Zebisch et al., 2021). As such, the framework holds promise for being advanced in a way to respond to the needs identified by the EEA. In here, we advance the framework by suggesting methodological advancements resulting from case studies conducted during the course of the "UNCHAIN - Unpacking Climate Change Impact Chains" project. By doing so, eventually the accuracy, insightfulness, and impact of CRVA outcomes may be improved. Furthermore, testing the method's potential for use in research and policy domains it was not originally designed for may ultimately upscale its potential and increase the uptake of assessment results into decision-making. Accordingly, our two research questions are:

(a) How can the IC-based CRVA framework be advanced methodologically to produce more accurate, insightful or impactful results?
(b) How effectively can the IC-based CRVA framework be applied in research and policy domains that it was not initially designed for?

The article is targeted toward practitioners and researchers who are considering implementing the IC-based CRVA framework, and second, to inform and enhance the upcoming 2023 update of the Vulnerability Sourcebook (VS) (Fritzsche et al., 2014).

2. The IC-based CRVA framework and the vulnerability sourcebook

The IC-based CRVA framework assesses climate-related risks through a combination of collaborative knowledge creation and quantitative data analysis to eventually identify specific adaptation measures. The framework is based on Impact Chains (Schneiderbauer et al., 2013) and explained in detail in the Vulnerability Sourcebook (Fritzsche et al., 2014) and the Risk Supplement to the Vulnerability Sourcebook (GIZ Eurac, 2017). These resources were developed for the German Agency for International Cooperation (GIZ) as an indicator-based approach to measure and compare vulnerability in different locations, originally for policymaking and national adaptation plan design in low-income countries (Zebisch et al., 2021).

The VS has been applied in national adaptation plans and scientific studies since 2014. As a result, is has been modified for specific contexts (Table 1) and incorporated into the ISO Standard for Adaptation to climate change (ISO 14090, 2019). Supplementary Table 1 provides a detailed overview of past applications. The term "IC-based CRVA" refers to the framework outlined in the VS, the Risk Supplement to the VS, and the other derivatives (GIZ, 2018; Rome et al., 2018).

The IC-based CRVA framework comprises eight modules, which are divided into four participatory and four operational ones (see Figure 1, left side). The participatory modules focus on knowledge co-production techniques and provide the backbone for the operational modules, which assess quantitative, indicator-based data and models[1] (Zebisch et al., 2021).

Collaborative efforts between researchers and the policy- and decision-making community are increasingly being used to integrate assessment outcomes into decision-making (Lövbrand and Stripple, 2011; Hoppe and Wesselink, 2014; Dannevig and Aall, 2015; Graham and Mitchell, 2016). These efforts are moving toward a more interactive approach, where researchers and practitioners work together to create actionable results, instead of just transferring knowledge from research to practice (Klein and Juhola, 2014; Runhaar et al., 2018; Palutikof et al., 2019; Norström et al., 2020). Such partnerships can enhance the perceived saliency, credibility, and legitimacy of outcomes, facilitate the inclusion

1 Trends point toward inclusion of stakeholder and expert knowledge in all assessment phases, rendering all modules essentially participatory (Zebisch et al., 2021). For readability and clarity reasons we, however, continue to distinguish between participatory and operational modules.

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TABLE 1 The vulnerability sourcebook, its derivations and respective uptake.

Resource	Purpose	Applications	Publications
Vulnerability sourcebook (Fritzsche et al., 2014)	Designed to support the development of NAPs for low-income countries	10	5
Risk supplement to the vulnerability sourcebook (GIZ Eurac, 2017)	Modifies the method to the new risk concept introduced in the IPCC AR5[a]	22	5
IVAVIA-Impact and Vulnerability Analysis of Vital Infrastructures and Built-Up Areas (Lückerath et al., 2018; Rome et al., 2018)	Optimized for cities and urban environments	10	5
Climate Risk Assessment for Ecosystem-based Adaptation (GIZ, 2018)	Systematically considers ecosystem-based solutions	3	-

[a]The conceptualization of risk follows the definitions given by the Intergovernmental Panel on Climate Change (IPCC). Prior to the IPCC AR5 (Field, 2014; Huq et al., 2014) assessments focused on vulnerability rather than climate risk. To acknowledge this recent conceptual shift, in this paper we refer to climate risk and vulnerability assessments. However, all case studies presented here follow the newer logic of a climate risk assessment, as suggested in IPCC AR5 and AR6 (IPCC, 2022a), that understands risk as a function of hazard, vulnerability and exposure factors.

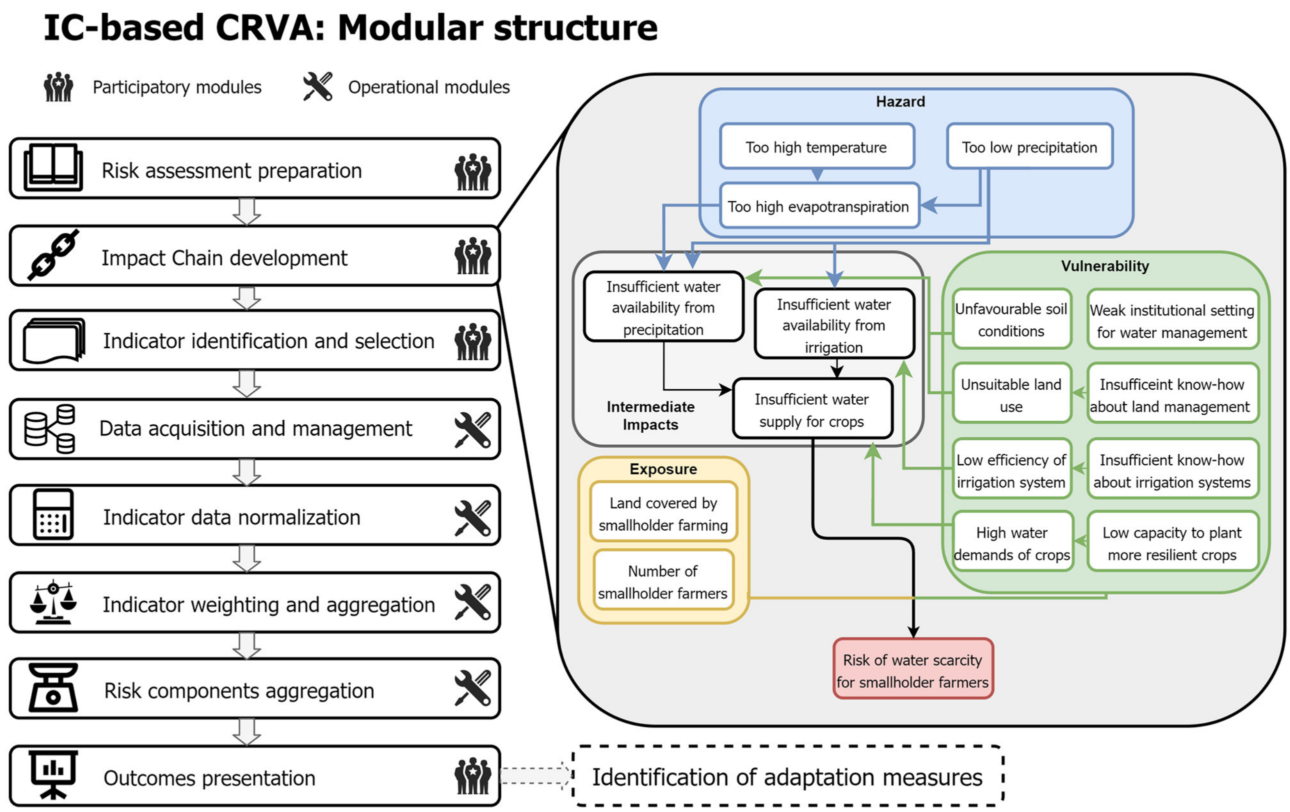

FIGURE 1
The IC-based CRVA modules of the Risk Supplement to the VS **(left)** and a simple Impact Chain **(right)**. The Impact Chain development module is the distinctive characteristic on which all other modules build.

of multiple knowledge systems, and foster mutual learning and problem ownership (Gusfield, 1989; Kabisch et al., 2014; Greiving et al., 2015; Kienberger et al., 2016; Hansson and Polk, 2018; Bremer et al., 2019; Cvitanovic et al., 2019; Kahlenborn et al., 2021).

The VS's participatory modules offer guidance on establishing communication between researchers and stakeholders, identifying information needs, developing Impact Chains collaboratively, selecting appropriate indicators, and presenting and validating outcomes through various means such as maps, risk matrices, tables, diagrams or narratives. The validation of the Impact Chains involves independent experts who were not involved in the co-production process. At the core of the participatory approach is the development of Impact Chains, which are conceptual diagrams illustrating the qualitative cause-effect structures that lead to climate change risks (see Figure 1, right side).

An Impact Chain organizes risk factors based on hazard, exposure, and vulnerability factors as defined in the IPCC AR5 (Field, 2014; Huq et al., 2014).[2] Figure 1 (right side) shows how

2 The original Vulnerability Sourcebook presented a different conceptualization. The goal of the Risk supplement was to align with the updated concepts found in the IPCC AR5 report (Field, 2014; Huq et al., 2014), which represents a shift from the concepts in the previous IPCC AR4 report (Parry et al., 2007). All case studies presented in the supplement adhere to the IPCC AR5 conceptual framework.

an Impact Chain focuses on specific hazard factors (such as high temperatures), and identifies exposure factors (such as smallholder farmers in a specific location), intermediate impacts on biophysical elements, and the final human-centered risk. Vulnerability factors, which can increase or decrease the risk, include non-climatic dimensions. Identifying the most influential vulnerability factors is critical for creating a meaningful, context-specific Impact Chain, and requires local knowledge and a deep understanding of driving forces involved (Fritzsche et al., 2014; Zebisch et al., 2021; Menk et al., 2022).

To back the Impact Chains with quantitative (spatial) data, the framework provides operational modules describing indicator-based assessments. Indicators are a useful tool for turning complex structures into something measurable and comparable across regions and over time (Vincent and Cull, 2014). They are effective in conveying messages and providing policy information, especially when used comparatively across a large number of regions. Once data is acquired to populate the indicators, they are normalized, weighted and aggregated into a composite risk indicator. Examples of a complete assessment workflow can be found in the annex of the VS (GIZ, 2014) i.e., applied to assess risk of water scarcity for smallholder farmers in Bolivia.

As part of the UNCHAIN project, we conducted eleven case studies that followed the IC-based CRVA framework with varying degrees of strictness. However, all of them incorporated "new" elements into the framework, which we refer to as "methodological advancements" in this paper. The method section details how we distilled the most noteworthy methodological advancements from the various case studies. In the results section, we explain each methodological advancement in the context in which it was applied. Then, we discuss the main findings, their implications and limitations and close with a conclusion.

3. Materials and methods

3.1. The UNCHAIN research pipeline and the case studies

To better incorporate the EEA-identified requirements into the IC-based CRVA framework, we advanced the framework across five "innovation areas." Some of these areas relate to existing modules in the framework, such as (1) elaborating the existing modules or (2) improving stakeholder engagement. Other areas are not yet reflected in the framework, such as (3) managing uncertainty and (4) modeling socio-economic scenarios. Finally, we explored the application of the framework in a new context by (5) examining transboundary climate risks through Impact Chains. As a methodological advancement we understand developing or refining a method, technique, or approach to improve research or problem solving (based on Bergh et al., 2022).

Our research pipeline (Figure 2) began with a literature-based State-of-the-Art analysis to identify research questions related to challenges and opportunities with regards to the innovation areas, which were then addressed through a common case study protocol. This protocol provided guidelines for preparing, conducting and evaluating the case studies, facilitating consistency and an overarching case evaluation. Case study protocols are particularly useful in research projects involving multiple researchers and data collection across multiple locations and time periods (such as UNCHAIN) (Yin, 1994; Pervan and Maimbo, 2005).

Besides their focus on varying innovation areas, the case studies differed in several other respects, their topical and geographical foci, spatial and administrative scales and disciplinary representation of researchers. The project partners selected the topics, scope, and stakeholder groups for the case studies individually based on contextual relevance and predicted climate risks. The research pipeline accounted for the alignment of individual characteristics with the objectives of the project. Some cases were planned before the project phase began, and stakeholder contacts were established at that time. Other case studies were planned and conducted during the project phase (2019–2022).

3.2. Validating advancements

As part of the research pipeline, we developed an evaluation framework and validation criteria based on the works of Zeil and Lang (2009) and d'Oleire Oltmanns et al. (2015). These criteria were applied to identify the most noteworthy methodological advancements from the case studies. The validation process involved an evidence-based self-evaluation approach. Additionally, nine of the eleven case studies are being published in peer-reviewed publications and thereby provide an independent validation step.[3] To determine whether a methodological advancement met the validation criteria, we assessed its relevance, applicability, comprehensibility, scientific validity, effectiveness, transferability and scalability. The criteria were not set with fixed thresholds due to the multifaceted nature of the cases.

We evaluated the criteria as follows:

- Relevance: Is the advancement relevant to the field, and does it address current research questions in the field of climate risk assessment? Does it provide useful and actionable information for decision-making?
- Applicability: Is the advancement generic and accessible to a wide range of users, regardless of their technical background?
- Comprehensibility: Is the advancement explained with sufficient detail for others to understand and replicate it?
- Scientific validity: Is the advancement built upon existing scientific knowledge and has it been peer-reviewed?
- Effectiveness: Can the advancement be implemented without primary data collection? Does it allow the integration of heterogeneous data? Was the implementation practical regarding timeframe and team size? Did it take into account stakeholder needs and perspectives and did it receive positive feedback?
- Transferability and scalability: Can the method be applied across a range of different contexts, locations, and scales?

3 Nine of the eleven cases are being published in the special issue "New Approaches to Local Climate Change Risk Analysis" in Frontiers in Climate.

FIGURE 2
The research pipeline developed for UNCHAIN.

3.3. Evaluating validation criteria

Following the case study phase, the leading researchers of each case study evaluated whether a methodological advancement met the relevant validation criteria based on their evidence. The main author (of this article) and each individual case study leading researcher then discussed the selection in an online interview. We chose to focus on one methodological aspect per case study to be able to explain its application in more detail in this article.[4] The case studies themselves might have encompassed many more methodological aspects. In the results section, we will focus on how the advancements were applied and the lessons learned, rather than presenting how they passed individual validation criteria. However, for the sake of scientific validity, we provide all relevant material on the validation procedure in Supplementary Table 2.

3.4. Limitations

While we established validation criteria as guidelines to steer the selection process, not all methodological advancements needed to meet all criteria, due to the multifaceted nature of the case studies. To some extent, the decision was left to the main researchers. A further limitation is that we did not seek feedback from stakeholders specifically on the validation process to avoid overburdening them, as their insights and feedback were already required before in the research pipeline.

4. Results

The methodological advancements will be presented according to the "innovation areas" they contribute to, in the following order: (1) elaborating the existing modules of the IC-based CRVA framework, (2) improving stakeholder engagement, (3) managing uncertainty, (4) modeling socio-economic scenarios, and (5) examining transboundary climate risks. We organized each case study section into three parts: the addressed challenge or opportunity, the methodological advancement, and a conclusion. Figure 3 gives an overview of the case studies.

4 Except for the Mannheim case, which is featured twice.

4.1. Elaborating the existing modules of the IC-based CRVA framework

4.1.1. The Mannheim case A: using national impact chains for efficient and consistent CRVA at the regional level

Related publication: (Lückerath et al., 2023).

4.1.1.1. Challenge/opportunity

The Mannheim case built on the national climate Impact Chains (IC) included in the German Adaptation Strategy (Umweltbundesamt, 2016, 2019), to avoid developing local Impact Chains from scratch. The German National Impact Chains have been co-produced by the experts who developed the VS, by stakeholders from German Federal Agencies and Ministries, and by domain experts. These national ICs characterize the possible climate impacts on a national level, clustered into 15 fields of action. The Impact Chains visualize components of climate risk as a diagram. This graphical representation includes (1) direct physical impacts of climate related hazards on exposed system elements, (2) the sensitivities of the exposed system elements, (3) the nature of the damage, and (4) impacts of damage to system elements on other system elements. Indirect impacts may propagate and thus form ICs and are not restricted to one field of action or one sector.

4.1.1.2. Methodological advancement

For assessing the specific risk of two hazards in the Mannheim case, only a subset of the national Impact Chains was needed. That is, we extracted the relevant subset of components from the national Impact Chains regarding the selected hazards, the sectors represented by the participating stakeholders, the related national fields of action, and all related sensitivities and relational information. The original layout of this true subset of the national Impact Chain has been optimized for result documentation and reference, but it is not ideal as a basis for further elaboration. In the next step, the layout of this subset was transferred into a suitable online collaboration tool and collaboratively enriched with regional risk factors (exposures, sensitivities, capacities, stressors, impacts). The resulting Impact Chain was subsequently improved and validated in several post-processing cycles.

4.1.1.3. Conclusion

Based on the stakeholders' oral feedback and completed questionnaires, we believe that this method was a successful and efficient way to conduct IC-based CRVA, mitigating the often-criticized time demand of the approach. Furthermore, the multi-stakeholder regional CRVA fostered information exchange and

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FIGURE 3
Case study locations and notable characteristics relevant to this article. The lower left icons indicate each case study's innovation area, while the lower right icon suggests the thematic focus.

awareness regarding climate risk and adaptation opportunities in this heterogeneous group.

The benefits of this approach included (a) a faster start and general time saving by starting with concrete examples, and (b) a resulting regional Impact Chain that is consistent with the national ICs (Umweltbundesamt, 2016) and does not "re-invent the wheel." We believe that the latter point could be an advantage for planning subsequent adaptation measures and for acquiring their funding, because national funding is indicated per national field of (climate) action. Therefore, building local climate risk analysis on national Impact Chains and structuring elements of risk (exposure, sensitivity, capacity, impact) per national field of action facilitates the identification of funding opportunities. The regional IC, in turn, can serve as a starting point and context for local CRVA. The approach of nested scales allows to establish consistent links between local, regional, and even national adaptation measures. However, while national Impact Chains were available for Germany, globally this availability is still an exception. In the future, standard Impact Chains for various sectors and systems could be the basis for local adaptations.

4.1.2. The Salzburg case: moving beyond static impact chains to dynamic causal loop diagrams

4.1.2.1. Challenge/opportunity

The current Impact Chain notation style has limitations in capturing the dynamic nature of climate risk, which is influenced by complex interrelationships between system factors spanning socio-economic, political, and environmental realms (Menk et al., 2022). Factors contributing to risk are summarized into a final risk score that does not feed back into the system, failing to account for the feedback loops that shape risk over time.

4.1.2.2. Methodological advancement

To address this limitation, the Salzburg case study employed a Causal Loop Diagram (CLD), which depicts causal flows within a system and allows for a more nuanced understanding of the dynamic interrelationships between risk factors (Figure 4). Using CLDs to map a risk system acknowledges the balancing or reinforcing effects of these factors, providing a more comprehensive view of the risk landscape. The study used a combination of stakeholder engagement, spatial data analysis, and literature review to create a CLD for drought risk, highlighting the role of water availability as a major driver of risk, and identifying the wider range of factors that influence agricultural success or failure.

4.1.2.3. Conclusion

The CLD-based approach was well-received by stakeholders, who appreciated the larger system understanding it provided and the identification of entry points for medium- and long-term planning. The study suggested that the use of CLDs can support the development of more effective and sustainable adaptation measures. However, the study also recognized that more extensive CLDs should be developed and presented as comprehensible sub-systems before being combined to create a bigger picture of the risk system.

4.1.3. The Paris case: moving beyond weighted arithmetic aggregation to reverse weighted geometric aggregation

4.1.3.1. Challenge/opportunity

Abstracting a complex Impact Chain into a simplified indicator requires careful attention to weighting and aggregation methods. To aggregate indicators into a composite indicator, the Vulnerability Sourcebook recommends weighted arithmetic aggregation. This method multiplies individual indicators by their weights, sums them, and then divides by the sum of their weights (Fritzsche et al., 2014). If individual indicators show extreme negative values, an alternative method, weighted geometric aggregation, may be used (as already suggested in the VS as a side-note). This method is popular in indicator construction and decision-making, as it is a prioritization tool in Analytic Hierarchy Process (Krejčí and Stoklasa, 2018) and other multi-criteria analyses. Weighted geometric aggregation limits substitutability between risk factory due to its bias toward low values. Notably, the Human Development Index has shifted from the arithmetic to the geometric method.

4.1.3.2. Methodological advancement

This methodological advancement to IC-based CRVA involved the use of *reverse* weighted geometric aggregation instead of the weighted arithmetic aggregation recommended by the VS. The reverse weighted geometric aggregation method assigns greater weight to particularly high-risk factors and avoids the risk of low-risk factors compensating for them in the final risk score, which can result in an underestimation of risk. In the Paris case study, risk scores resulting from arithmetic and reverse weighted geometric aggregations were compared. The results consistently showed that the scores produced by the reverse weighted geometric method were higher, particularly in cases where sub-indicators had relatively high dispersion among coefficients.

4.1.3.3. Conclusion

We argue that for most of the applications using the risk value obtained by IC-based CRVA it is more favorable to overestimate, than to underestimate, risk. Therefore, we suggest using reverse geometric aggregation, to shift the bias toward high values instead (Guillaumont, 2009). Given that the method accounts for the interdependencies of the system and produces higher scores, we believe that it is relevant to apply it. To ensure clarity and consistency, we recommend providing a more detailed explanation of the method in the next edition of the VS. Alternatively, the quadratic average method could be used to address this issue.

4.2. Improving stakeholder engagement

4.2.1. The Upper Rhine case: integrating TRIZ into IC-based CRVA for participatory identification of adaptation measures in contradictory situations

Related publication: (Coulibaly et al., 2022; Gobert and Rudolf, 2022).

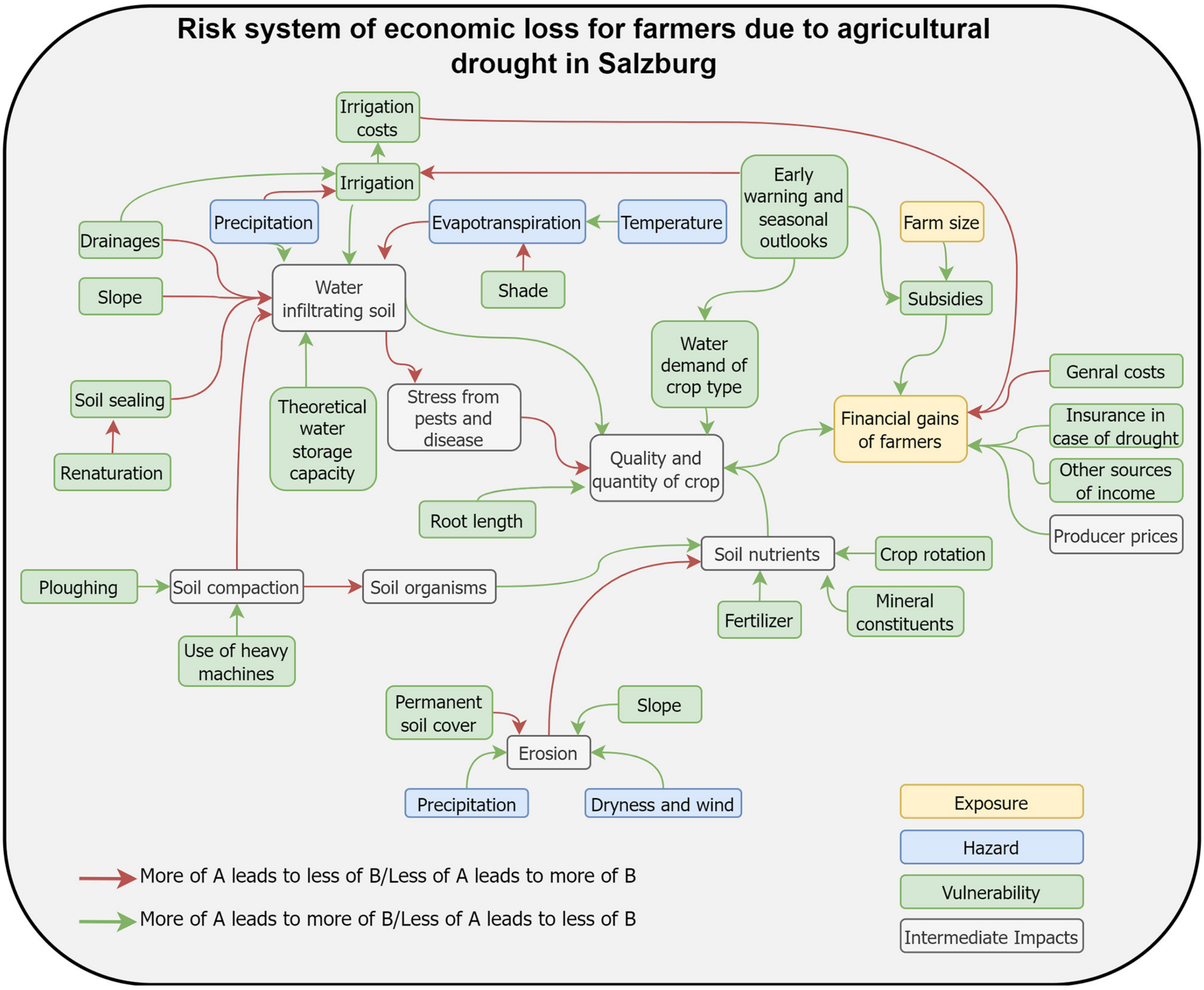

FIGURE 4
The impact chain in the style of a causal loop diagram. It has been developed based on a literature review, a stakeholder survey and workshop and has been approved in a second stakeholder workshop. The relationships are to be read as pairs of two.

4.2.1.1. Challenge/opportunity

Stakeholder knowledge and needs do not necessarily result in one Impact Chain that everyone can agree on, due to possibly diverging interests and opinions (Schneiderbauer et al., 2020).

4.2.1.2. Methodological advancement

The Upper Rhine case utilized TRIZ (Theory of Inventive Problem Solving) Inventive Design Method, which was originally developed in the engineering domain, and combined it with IC-based CRVA to address problems and find solutions in contradictory situations. The method involves breaking down a problem into its various components and is easily integrated with the IC-based CRVA framework. However, unlike Impact Chain development, this method is primarily focused on identifying solutions, particularly adaptation measures. The idea is to identify partial solutions for various parts of the problem. For instance, for a problem such as low waters inhibiting barges to transport regular volumes of freight, a partial solution, such as barges carrying less freight, could be identified. Partial solutions that are straightforwardly quantifiable are usually easy to resolve. However, this method also accounts for situations where different stakeholders hold differing "worldviews" about a problem and potential solutions. The method captures these worldviews in a special software, highlights contradictions, and then a consensus is sought in the next step.

4.2.1.3. Conclusion

Enriching IC-based CRVA with the TRIZ method improved participatory Impact Chain development and to identify and select indicators and adaptation measures. The approach involved a combination of workshops and individual interviews to account for the issue of individual stakeholders dominating discussions and influencing the general opinion. Working with the TRIZ software enabled a cross-breeding of qualitative and quantitative methods. This increased the perceived impartiality of the methods and results among stakeholders, which helps counteract the issue that simple qualitative methods are often considered insufficient or biased by stakeholders (Cheek et al., 2004).

However, the approach faced some challenges. Contradictory situations, especially on inherently subjective issues such as the level of social acceptability of a partial solution, were not always easy to solve. This difficulty resulted in a marginalization of qualitative problem dimensions, which are difficult to weight but are nonetheless essential to the identification of viable solutions. Additionally, the process was time-consuming and required deep involvement of the stakeholders, as well as a certain level of expertise to work with the TRIZ software. Nonetheless, the approach's combination of sociological and engineering expertise made it possible to convince stakeholders of the reliability and robustness of the results.

4.2.2. The Halmstad case: exploring social vulnerability through exploratory scenarios in the IC-based CRVA framework

Related publication: (Englund et al., 2023).

4.2.2.1. Challenge/opportunity

Climate change is expected to have significant impacts on social groups, with those with known vulnerabilities likely to be disproportionately affected and others becoming newly vulnerable. However, there is limited understanding of which groups will be affected and how, as well as the economic, social, and physical factors that drive their vulnerabilities. Social aspects of vulnerability are often difficult to measure and quantify (Hudson et al., 2019), and while the IC-based CRVA approach identifies knowledge, technology, institutions, and the economy as key drivers of vulnerability, it provides only a limited understanding of vulnerable groups, with generic representation of women and disadvantaged groups. To address this limitation, a method to assess social vulnerability was searched (see Birkmann, 2013 for an overview) that would engage stakeholders in a co-production process and align with the IC-based CRVA approach.

4.2.2.2. Methodological advancement

The Halmstad case explored flood hazards triggering cascades in the infrastructure system and their impacts on vulnerable groups in Halmstad Municipality, Sweden (Barquet et al., 2022). An exploratory scenario approach was adopted which is a form of storytelling that forecast how evets unfolds over time (Kok et al., 2007). A transdisciplinary process was designed in which key stakeholders from Halmstad Municipality were engaged using surveys, interviews, focus group discussions, and workshops (for further details see André et al., 2022; Englund et al., 2022). Exploratory scenarios helped to overcome issues related to data confidentiality as stakeholders could discuss a hypothetical scenario instead of sharing sensitive information on infrastructures and their services. It also allowed adding information on social aspects of risk, normally not considered when developing an IC-based CRVA. In an online workshop, scenarios with key stakeholders were co-developed to forecast cascading effects in flooding events and their impacts on people. The exploratory scenario and the Impact Chain were used as boundary objects to help stakeholders understand the social dimension of risk. Using digital tools Miro and MentiMeter, stakeholders identified possible infrastructure disruption and mapped social groups at risk in case of a disruption. Following the workshop, we conducted online interviews with the same stakeholders to refine scenarios and identify additional vulnerable groups.

4.2.2.3. Conclusion

Exploratory scenarios were found to be a valuable addition to the IC-based CRVA framework. While scenario planning is already widely used to support climate risk decision-making (Brown et al., 2016; Star et al., 2016; Flynn et al., 2018), in our case study, it helped overcome challenges associated with limited data availability and measuring intangible risks. It supported stakeholders in considering low-frequency but high-impact risks where historical data is scarce. The exploratory scenario also led to various co-benefits, such as increased awareness, simplified complexity, and possibly also improved decision-making support. In line with previous research, the boundary object improved the quality of discussion and data (Star and Griesemer, 1989). Our case study indicates that the IC-based CRVA framework is flexible and adaptable to suit diverse stakeholder needs and objectives.

4.2.3. The Mannheim case B: implementing value chain CRVA for mobilizing industrial stakeholders

Related publication: (Lückerath et al., 2023).

4.2.3.1. Challenge/opportunity

Although the available guidelines to IC-based CRVA emphasize the importance of including relevant local stakeholders in the assessment process, specific guidance for addressing specific groups of local stakeholders is rare. For mobilizing industrial stakeholders, it is essential to understand how they manage operational risk. Typically, this is an integral part of their business continuity management or enterprise risk management. We concluded that results of any CRVA conducted for a participating corporate stakeholders need to be integrable with their risk management approach. One way to achieve this is to pinpoint climate risk factors to business units, activities, and processes, since these are the places in which operational risk management procedures are anchored in. An established model for describing these business elements is the Value Chain (Porter, 1985). Porter divided a company's activities into primary and supporting activities. Value Chain diagrams describe these activities in graphical form (Figure 5). The further division of activities into units, areas, and interlocking processes that take place in these areas and across areas offers opportunities for analysis and optimization, including risk assessment. Since Business Continuity Management (BCM) is typically process- or unit-oriented, the mapping of climate risk factors (sensitivities, capacities) and intermediate impacts (knock-on effects from direct physical impacts) to Value Chain C elements is suited to inform BCM managers on climate specific risk.

4.2.3.2. Methodological advancement

For implementing the Value Chain CRVA for a single business as the last phase of the Mannheim case study, we built upon a previously developed Impact Chain. We started by validating

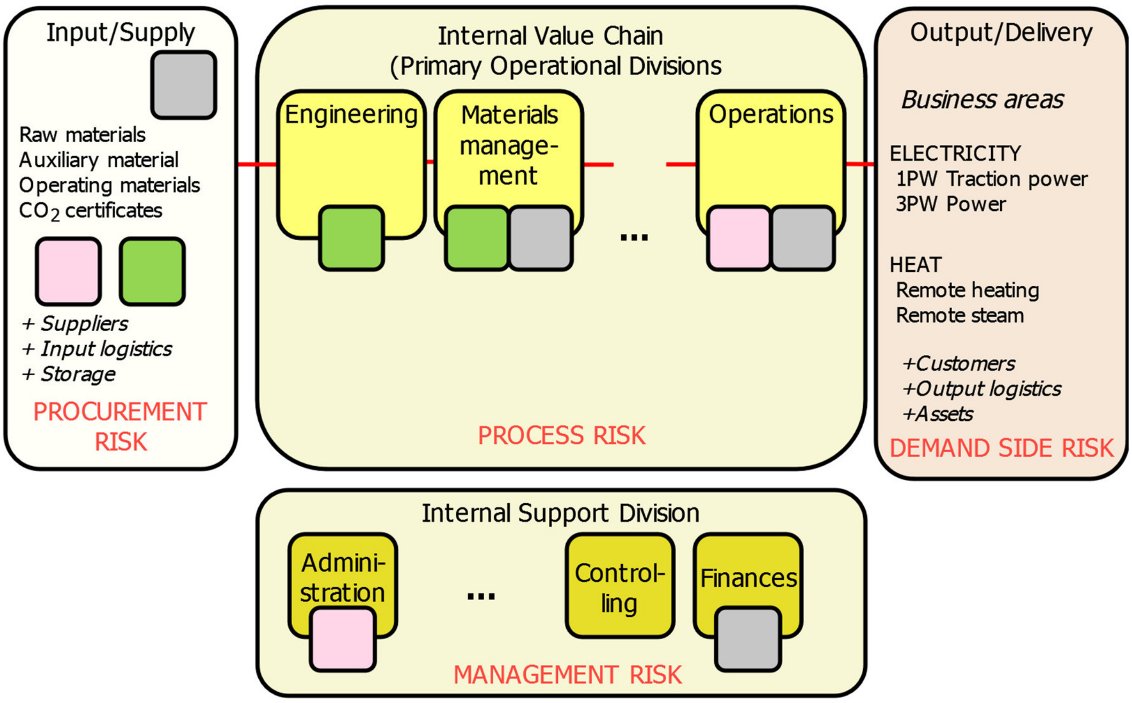

FIGURE 5
An energy producer's Value Chain, incorporating risk factors and intermediate impacts from an Impact Chain. Each unit, activity, or process is assigned a corresponding group of risk factors. Additionally, each element may have assigned capacities (green squares), sensitivities (pink squares), and intermediate impacts (gray squares). The complete enriched Value Chain is confidential. Adapted from Melo-Aguilar et al. (2022).

the relevant climate risk *factors* for the corporate stakeholder, the Mannheim Large Powerplant, ruling out factors that were only relevant for other participating stakeholders. We continued with eliciting the company's Value Chain, then pinpointing the remaining climate risk factors to the Value Chain elements and identifying suitable measurable indicators for each factor. Furthermore, we conducted a quantitative risk assessment focused on the economic effect of low waters of the Rhine River on costs of transporting freight, i.e., coal, via inland waterway.

4.2.3.3. Conclusion

We investigated just one indicator due to resource limitations. However, we produced a tangible, actionable decision support for one element of climate risk, which the stakeholders appreciated. Users of this approach should be aware that businesses may keep certain information and data private. In our case, we worked with disclosed surcharges instead of undisclosed total costs. Bringing these results into the Value Chain of businesses reduces entry barriers for the implementation of adaptation measures, as one could incentivize organizations to invest in climate change adaptation by bringing the topic into regular business continuity practice.

4.2.4. The Netherlands case: an IC-based CRVA on the asset level for financial risk portfolios

Related publication: (Attoh et al., 2022).

4.2.4.1. Challenge/opportunity

Climate change risks have become increasingly important for (large) financial investments in the real estate sector. Yet, meaningfully integrating climate risk information into investment portfolios remains difficult. To address this, the Netherlands case explored potential climate risks affecting two real estate assets in Utrecht and Rotterdam using IC-based CRVA. The case study aimed to assess and find effective ways to secure assets against flood risks by combining knowledge co-production and scientific information to support financial decisions.

4.2.4.2. Methodological advancement

To engage industry stakeholders and gather data for a climate risk assessment, the case utilized semi-structured interviews and a workshop. Real estate and finance companies, as well as consultancy companies, were involved as stakeholders and end-users of the final risk assessment. The knowledge co-production process was central to the assessment, and the aim was to advance the IC-based CRVA's user interface. The case study relied on open-access data collection and interactive maps showing current and future flood risks in the Netherlands for hazard and exposure data. However, data at the asset scale were not readily available in open-access databases, so close working partnerships with stakeholders from real estate companies were needed to obtain this data.

4.2.4.3. Conclusion

Feedback analysis of the process showed that knowledge co-production was well appreciated and the dialogue and interaction helped refine the companies' needs. Some information requested by the companies were impossible to meet with available climate knowledge, but through continuous engagement enabled by co-production, these expectations were addressed after explanations were given. However, knowledge co-production presents key challenges such as the subjectivity of some data collected that could impact the quality of the results. The process was laborious with a series of back and forth with stakeholders including workshops, interviews, meetings and phone calls. As a result, applying the IC-based CRVA framework became complex and time consuming.

4.3. Managing uncertainties

4.3.1. The Balearic Islands case: addressing uncertainty in IC-based CRVA using probability density functions

Related publication: (Agulles et al., 2022; Melo-Aguilar et al., 2022).

4.3.1.1. Challenge/opportunity

Uncertainties in data and the selection of weighting and aggregation processes make it difficult to confidently turn results into adaptation action. Incorporating qualitative indicators and knowledge gaps can also be challenging and may jeopardize the validity of the assessment. Even with extensive stakeholder and expert involvement, our understanding of the factors which influence climate risk remains imperfect (Booysen, 2002; Gall, 2015; Gawith et al., 2016). Thus, there is a need to account for uncertainty in the development of Impact Chains, that remains unaddressed by the current methodological framework which relies heavily on data that may not be available. Some initiatives include uncertainties management strategies in CRVA, such as the probabilistic impact risk model software CLIMADA (Aznar-Siguan and Bresch, 2019) *or CAPRA* (Cardona et al., 2012). However, although they are valuable tools that provide a way to consider uncertainty measures in different risk components, they are restricted to specific software that requires some level of expertise, thus, limiting its usability.

4.3.1.2. Methodological advancement

The Balearic Islands case developed a general formalism for integrating uncertainties into IC-based CRVA. The formalism uses probability density functions (PDFs) instead of scalar quantities for weights and indicator values. PDFs are propagated through the entire Impact Chain using a Monte-Carlo approach, resulting in a final risk PDF (Figure 6; Melo-Aguilar et al., 2022). The PDFs can be defined freely, but a Gaussian function is a common choice, where the amplitude of the PDF is determined by the assigned uncertainty. In the Balearic Islands case, indicator-related uncertainties were estimated from data (e.g., spread of climate projections for future temperatures) or the standard deviation of time series, while weight-associated uncertainties were established through an Analytical Hierarchy Process survey with stakeholders (Melo-Aguilar et al., 2022). The formalism can be implemented by developing the suitable computer codes (e.g., in Python or MATLAB) or using the UNTIC tool (untic.pythonanywhere.com) which can be used without much technical expertise.

4.3.1.3. Conclusion

Our proposed methodological advancement is robust and flexible, allowing to be integrated with different aggregation methods (for example the reverse geometric aggregation as applied in the Paris case) and a wide range of situations. It offers a new perspective on Impact Chains for integrating factors even when knowledge of their severity and role is limited. This allows to include all relevant factors and indicators without requiring data availability. This methodological advancement is valuable as current IC-based CRVA heavily relies on data, and when no data is available, indicators tend to be discarded (Kienberger et al., 2016), leading to biased results. Future work should focus on developing strategies to validate risk analysis, producing robust information that is as independent from subjective choices as possible. Calibrating the IC operationalization by computing the risk for past situations and comparing it to real-world impacts would increase the validity of the results.

4.4. Modeling socioeconomic scenarios

4.4.1. Challenge/opportunity

In IC-based CRVA, cause-effect relationships are often only analyzed qualitatively and not converted into numerical simulation models (Menk et al., 2022) due to the time and resource intensive process of numerical parameterization. Thus, to perform a more comprehensive quantitative assessment of climate risks, mitigation and adaptation strategies, it appears cost-effective to use existing simulation models. The IPCC relies on Biophysical climate models and Integrated Assessment Models (IAMs) to project future emission pathways and climate scenarios. However, traditional IAMs may not account for cross-sectoral interdependencies in detail. For detailed analyses of the socio-economic impacts of energy and climate policy scenarios, macro-economic simulation models are generally utilized (Pollitt and Mercure, 2018).[5] Among the few assessments of transboundary macro-economic climate risks conducted to date, trade in agricultural commodities received relative frequent attention. However, these assessments often do not model future socio-economic developments, which will substantially affect exposure and vulnerability levels. As a result, there is a need for further advancements in this area to better account for the role of socio-economic factors in transboundary climate risks risk assessments.

In UNCHAIN, two case studies used macro-econometric models to assess the effects of climate change on different sectors and under different socio-economic scenarios. However, the cases differed in scope and modeling approach. One focuses on the impacts of transboundary climate risks in Germany [it is therefore also a contribution to the last innovation area "Examining transboundary climate risks" (TCR)], while the other focused

5 Macroeconomic simulation models may be basically categorized into Computable General Equilibrium models and Macro-econometric models. For further methodological annotations in this regard and an introduction to policy-relevant differences between both modelling approaches we refer to (Scrieciu et al., 2013).

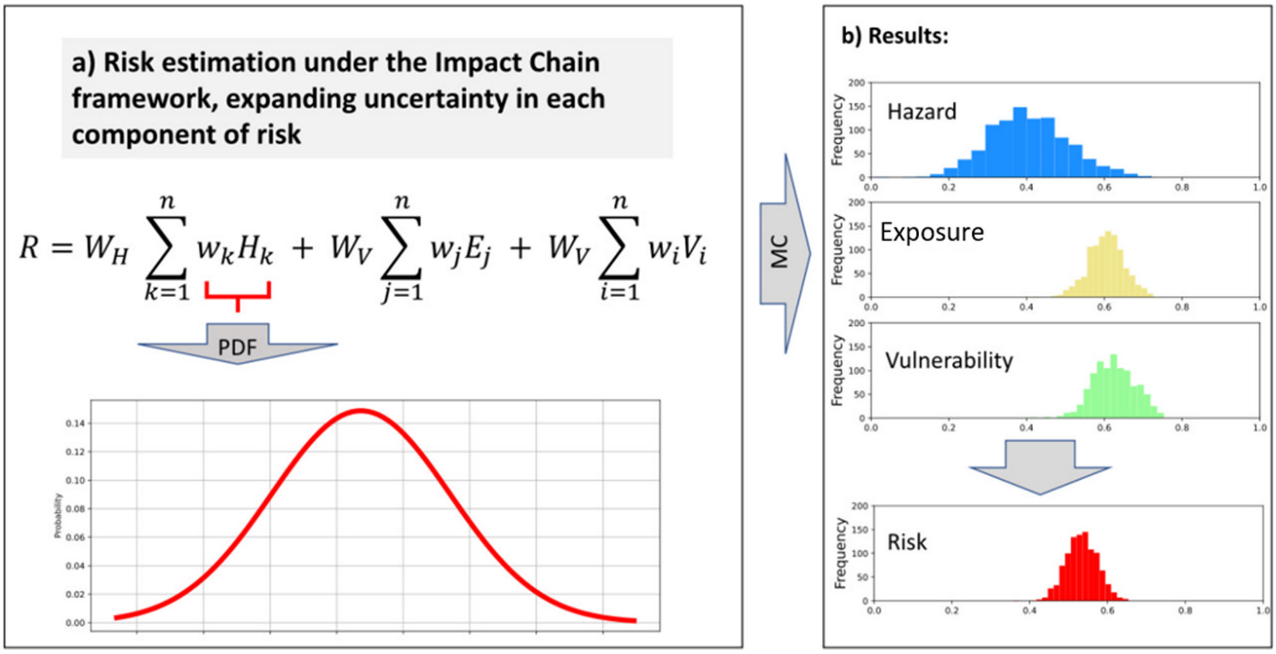

FIGURE 6
Schematic of the proposed methodology for integrating uncertainties into IC-based CRVA. **(A)** Risk aggregation formula. **(B)** Results of uncertainty expanding in each component of risk. Adapted from Melo-Aguilar et al. (2022).

on the monetary costs of climate impacts on specific sectors in Germany.

4.4.2. The Germany cases (transboundary and national): dynamic modeling of cross-sectoral (socio-) economic interlinkages

4.4.2.1. Methodological advancement (transboundary)

The transboundary Germany case uses a global multi-regional input-output model (MRIO), called GINFORS-E (GWS, 2022a) to assess the impacts of transboundary climate risks on agricultural commodity markets. The model combines detailed agricultural information with integrated MRIO-based modeling of global economic developments, mapping the multinational interplay of demand, trade, and production for 20 crop commodities and eight livestock products.

4.4.2.2. Conclusion (transboundary)

The case study demonstrates that using a global and regional economic modeling approach can provide a dynamic assessment of the indirect economic impacts of climate change, including trans-regional impacts, and is thus valuable for evaluating TCRs in agriculture commodities. However, there is still room for further development of MRIO models to fully utilize the available information and involve stakeholders at all stages of the participatory Impact Chain development process. In the UNCHAIN project, this potential was not fully realized, highlighting the need for continued research in this area. The main advantage of this approach is its ability to project self-contained and consistent multi-national socio-economic developments over time, allowing for the assessment of the impacts of climate risks on trade and production in different regions.

4.4.2.3. Methodological advancement (national)

In contrast, the national Germany case assesses the future monetary costs of domestic climate impacts in Germany under different socio-economic scenarios (a trend scenario, a sustainable scenario, and a dynamic scenario), by applying the national macro-econometric model PANA RHEI (GWS, 2022b). The model simulates the impacts of climate change on transportation, health care, and electricity sectors and the effects of possible adaptation measures. The results are presented using socio-economic indicators such as the gross domestic product, employment, or production, making them comparable so that they function as decision supporting information.

4.4.2.4. Conclusion (national)

The main methodological challenges arose from quantifying effects of adaptation measures. Additionally, since the direct macroeconomic effects of climate impacts depend on many factors, it remains challenging to quantify the resulting monetary costs, especially for medium to long-term projections. As a result, more research is needed to strengthen the evidence base for individual effects of future adaptation measures on increasing resilience and avoiding direct economic. So far, no quantified national reference values have been established for (socio-) economic scenario analyses at the sector level. The more detailed representations of economic developments in macroeconomic models compared to most IAMs can be used to derive corresponding projections. Hence, it would be promising to obtain further detailed macroeconomic assessment results through complementary modeling studies of climate impacts, adaptation costs, and benefits for focal sectors in a joint project.

4.4.2.5. Overall conclusion

From a methodological perspective, both applications highlight similar challenges. Furthermore, as the estimated macroeconomic costs of climate impacts and adaptation measures vary significantly across individual socioeconomic scenarios, the case studies illustrate the need for dynamic risk assessments. Compared to earlier approaches that projected future adaptation actions and implied adaptation costs by applying traditional IAMs (see, for example, Agrawala et al., 2011), this approach differs methodologically in that it does not rely on any optimization assumptions. This implies that the modeling approach is not rooted in a highly abstract theoretical framework (like the "Ramsey optimal growth framework" applied by both models compared by Agrawala et al., 2011) as it does not intend to deduce any normative conclusions about "optimal" mitigation and adaptation measures. Instead, a positive analytical approach is followed by this approach as well as the by the MRIO Model GINFORS-E featured for transboundary climate risk assessments: Both models project the future evolution of inter-sectoral economic impact relationships from historical empirical observations under alternative socio-economic scenarios. Given these pathways projections, researchers as well as involved stakeholders can then examine in detail how different direct climate impacts and adaptation measures in individual sectors and/or world regions affect other sectors, and/or world regions economically.

4.5. Examining transboundary climate risks

4.5.1. Addressing transboundary climate risks in Norway

4.5.1.1. Challenge/opportunity

Impacts of climate change are not confined or experienced only at a national and local level. According to the Intergovernmental Panel on Climate Changes' (IPCC) Sixth Assessment Report (AR6) Working Group III it is a problem that affects all parts of economy and society and requires actions across sectors and scales (13-16f; IPCC, 2022b). As in most European countries, Norwegian municipalities have largely been given responsibility for climate adaptation and focus so far has been mostly on adaptation to local climatic changes. However, a recent trend is shifting transboundary risks into focus, asking how Norway may be impacted by climate impacts elsewhere on the planet through trade, finance, people (tourism, health, and migration) and through biophysical processes. Therefore, it is important to have information about the patterns and magnitudes of climate risks in and between different regions and sectors, and methodological frameworks for the assessment of climate-related interactions between economic sectors and world regions have been promoted recently.[6] Currently, most assessments of transboundary climate risks are conducted at the global or regional (cross-country), and to sometimes at the national level. However, there is a lack of information about how these risks affect the sub-national level of governance (Harris et al., 2022).

In UNCHAIN, two case studies addressed transboundary risks for Norway through stakeholder integration in participatory workshops.

4.5.2. The Klepp case: challenges and opportunities at the sub-national level

4.5.2.1. Methodological advancement

The IC-based CRVA approach was employed to identify transboundary climate risks that are pertinent to food production in Norway, through consultation with key stakeholders in Klepp Municipality. By breaking down the climate risks into nodes and links, this method seemed to be well-suited for analyzing TCRs.

4.5.2.2. Conclusion

The IC-based CRVA framework was useful for communicating the concept of transboundary climate risks to local stakeholders, showing the differences, similarities, and possible interactions between traditional "local" risks and new "transboundary" risks. However, producing numerical indicators and indexes was too complicated and time-consuming for the case's scope, making it challenging to produce actionable knowledge for addressing transboundary risks at the local governance level. Focus from practitioners on TCRs is correlated to specific governance measures (i.e., requirements), a focus often lacking as policy mostly has focused on carbon footprint and "local" climate risks and the strengthening of resilience and adaptive capacity to such.

Practitioners tended to focus on local climate risks and building resilience and adaptive capacity to those risks, rather than on transboundary risks. However, it is important to link work and analyses on local and transboundary risks to avoid potential conflicts and unintended consequences. Local climate risks may be reduced at the expense of increasing transboundary risks, which was presented to local stakeholders. They responded that other means of adapting to local climate risks need to be investigated, which is also discussed in a recent report from the Environmental Protection Agency of Norway on climate change and food security (Bardalen et al., 2022).

4.5.3. The Nordland case: transboundary climate risks and the need for improved risk assessment and governance - insights from a salmon farming industry workshop

4.5.3.1. Methodological advancement

A workshop was arranged to identify risks associated with salmon farming, and to develop Impact Chains that would span the inputs, production and markets involved. The participants were farmers who belonged to an industry cluster and who were responsible for addressing environmental issues in their respective companies. None of the companies had a specific climate change risk assessment plan developed yet. The identified risks ranged from environmental degradation, such as the potential collapse of

6 See, for example, the IPCC AR6 Working Group III's recognition of current global Multi-Region Input-Output models (Owen, 2017; Wiedmann and Lenzen, 2018) as a major area of advance since AR5 in terms of the availability of valid data and consistent methods for global footprint calculation approaches.

soy production in Brazil, to geopolitical concerns that may or may not be triggered by climate change, and from increases in freight prices to a collapse in local salmon markets.

4.5.3.2. Conclusion

During the workshop the participants discussed and acknowledged the complexity and multiplicity of issues related to risk identification, and they recognized the need for clear risk ownership as the basis for decision-making and for tailoring measures to strengthen adaptability. The participants also recognized that timing is crucial when investing in improved adaptive capacity, as premature investments could create new risks. Therefore, there is a clear need for assessing the identified risk(s) and establishing risk ownership and regulatory guidance. These discussions highlighted the potential for improving risk assessment practices within individual producer organizations.

The application of an IC-based CRVA was found to be useful in discussing these complex issues. This approach facilitated a high level of co-production and allowed for a focus on the interconnections between different risks, across scales, geographical boundaries, and sectors. The overall experience suggests that a mixed-methods approach with knowledge co-production, literature analysis, media analysis, and assessment of industry strategies on environmental issues, is the most effective. The workshop revealed a certain sensitivity and awareness of the interconnectedness of climate change challenges across borders, which is often overlooked in more nationally-focused climate policy discussions. However, when it comes to identifying actionable steps, the industry stakeholders tended to focus on areas that are already prioritized, such as specific policy measures, obligations, and challenges. This underscores the importance of governance risk ownership in shaping decision-making, as confirmed by these co-production and workshop settings.

5. Discussion

We have addressed the needs and research gaps identified by the EEA regarding CRVA in five key innovation areas with methods to improve the existing IC-based CRVA framework, proactive stakeholder involvement, systematic assessments of uncertainty, and exploration of non-climatic factors that influence exposure and vulnerability. Additionally, we emphasized the importance of paying attention to cross-sectoral interactions and transboundary impacts.

5.1. Innovation area "elaborating the IC-based CRVA framework"

This innovation area is unique in the sense that it encompasses multiple methodological advancements that did not fit into any other category and that it closely aligns with the original IC-based CRVA framework. While these methods are not entirely groundbreaking, they serve as valuable additions to the original framework. Combining the framework with methodological additions is something which is already suggested in the Vulnerability Sourcebook.

We identified three key messages from this innovation area:

- Incorporating feedback loops via Causal Loop Diagrams (Salzburg case) better accounts for the dynamic and interwoven nature of climate risk. CLDs enable identification of feedback loops in a wider risk driver system, allowing for a shift in focus to important factors and cascading effects, and identifying mid- to long-term adaptation measures. However, CLDs require a better understanding of the system, or else uncertainties may be exacerbated.
- Using national Impact Chains to develop local Impact Chains (Mannheim case) can ensure consistency between different scales and save time in developing Impact Chains. Optimizing Impact Chain development leaves more resources to discuss and identify entry points for adaptation measures.
- Different aggregation methods can modify the sensitivity of aggregated indicators to extreme values (Paris case).

5.2. Innovation area "improving stakeholder engagement"

Improving stakeholder engagement is a promising approach for the IC-based CRVA framework, but it can be time and resource intensive. This approach offers co-benefits beyond the co-production of knowledge, including increased awareness and perceived saliency of results, as demonstrated in other studies (André et al., forthcoming; Bremer et al., 2019; Cvitanovic et al., 2019).

The MCI-TRIZ Inventive Design Method provides a structured approach for problem definition and consensus-oriented identification of adaptation measures (Upper Rhine case). By modeling differences and commonalities of viewpoints of participating stakeholders, this method helps to "objectify" problem- and solution definition.

In the Halmstad case, restructuring the risk-oriented Impact Chains can help identify social vulnerabilities and trends in climate change impacts. This enables awareness raising for future social inequalities and identifying consensus-based adaptation measures. The method helps understand which social groups already are or will be bearing the brunt of climate change impacts and which groups might be able to shoulder a larger share of adaptation measures.

IC-based CRVA is readily applicable in the Mannheim and Netherland cases. IC-based CRVA can be integrated with business Value Chains, and by assessing future climate risks for real estate assets, the IC-based CRVA workflow can inform financial investment portfolios.

5.3. Innovation area "managing uncertainty"

Our findings suggest that incorporating a probabilistic framework, such as probability density functions (PDFs), can account for missing or uncertain information in IC-based CRVAs (Balearic Islands case). Moreover, macro-econometric models can address uncertainties in future socio-economic impacts. While the proposed PDF formalism is compatible with various indicator aggregation approaches, we note that results from different aggregation methods (e.g., arithmetic, geometric, or reversed geometric) can differ significantly, as demonstrated in the Paris case. Therefore, it is crucial to test the sensitivity of the chosen methods, and the UNTIC web-tool offers a straightforward way to conduct sensitivity analysis. However, while Agulles et al. (2022) and Melo-Aguilar et al. (2022) have proposed retroanalyses to partially validate results, validation in IC-based CRVA remains underexplored. Developing more advanced validation strategies, even in the absence of comprehensive knowledge and data, could increase the general credibility of IC-based CRVAs and should be further explored.

5.4. Innovation area "modeling socio-economic scenarios"

An important enhancement for IC-based CRVA is to estimate the future monetary costs of climate impacts under different socioeconomic scenarios using macro-econometric models such as PANTA RHEI (national Germany case) and GINFORS-E (transboundary Germany case). These models provide a more detailed analysis of socioeconomic impacts and developments, which can result in better quantitative assessments of uncertainty for decision-making. Such simulation models are already widely used in ex-ante assessments of policy measures and strategies.

It is worth noting that traditional IC-quantification approaches can involve uncertain and somewhat arbitrary indicator selection, weighting, and aggregation procedures, even with extensive stakeholder and expert involvement. Therefore, relying on established modeling approaches for ex-ante assessments of future exposure levels and relevant economic drivers is a logical choice. To further refine these models, detailed inputs for focal sectors can be derived from complementary biophysical modeling studies on climate impacts and adaptation measures, and co-production approaches can be integrated into the proposed probabilistic framework to enhance the accuracy of the model's results.

5.5. Innovation area "examining transboundary climate risks"

We found that while it is conceptually easy to integrate transboundary climate risk into IC-based CRVAs, assessing this type of risk in practice poses significant challenges (as observed in both Norway cases). Although incorporating transboundary risk in IC-based CRVAs can raise awareness of risk origins and impacts, we encountered difficulties in assessing such risks due to unresolved issues of risk ownership and limited access to remote data. Addressing these challenges requires further research and international collaboration.

In terms of using IC-based CRVAs to assess transboundary risks, we found that while the approach can stimulate awareness and prompt discussions about risk ownership, the operational modules can be complex due to the intricate interplay of risk factors. However, the transboundary Germany case showed that existing dynamic macro-econometric MRIO models can be applied to assess transboundary risks related to trade in agricultural products. These models offer a promising starting point for integrating insights into the multi-national economic feedback effects that are critical to understanding transboundary risks.

5.6. Implications

Although the methodological advancements presented in this study were applied in separate cases, we believe that they are generalizable and applicable in other contexts. To account for this, we developed validation criteria to ensure that our findings contribute to the development of standardized CRVA frameworks that produce comparable results across different contexts and policy scales, while remaining adaptable to changing circumstances. We have shown that our contributions are relevant for policymakers, practitioners, and other stakeholders involved in developing adaptation plans. By improving policy decisions and supporting sustainable development, our study can help to assess risks for companies, as required by the European Union taxonomy (European Union, 2021). Overall, our work provides practical guidance and insights for a wide range of stakeholders involved in climate risk assessment and management. With standardized and validated CRVA frameworks, we can facilitate better decision-making and help build resilience to climate change impacts.

5.7. Limitations

One limitation of our study is that the cases were not initially designed to align perfectly with each other, as the research team consisted of individuals from diverse backgrounds who needed time to develop a shared language and collaborate effectively. Coordinating a large project with many researchers from different domains takes significant time and effort, which should be budgeted for accordingly. In retrospect, we suggest planning future case studies with greater harmonization and a clearer plan for validating the best methodological advancements in a scientific and objective manner. Although we took measures to address this issue by establishing a research pipeline and developing validation criteria at the beginning of the project phase, we ultimately had to rely on some subjective judgment.

Furthermore, although the methodological advancements worked well in their respective case studies, there may be additional advancements that were not explored in UNCHAIN. Finally, because the innovations were tested in separate case studies, a joint application of the advancements should be tested and validated in future research.

6. Conclusion

Overall, the methodological advancements discussed here have made significant contributions to the field of CRVA. All eleven cases revealed at least one key advancement based on validation criteria and practical experiences gained during the studies. Our state-of-the-art analysis has also helped us identify and partially address various challenges and opportunities, which will enable the provision of tangible methodological advice in the forthcoming new edition of the Vulnerability Sourcebook and for practitioners in the field.

Although not all modules were implemented in all case studies due to resource constraints or lack of data, the modular structure of the framework allowed for barrier-free testing and integration of methodological advancements from different scientific disciplines. In the future, IC-based CRVA could be seen as a toolbox of methods and techniques that can be chosen according to the intended purpose, rather than a rigid workflow to be applied from start to finish. While the core method remains stable, there may be variations in specific recommendations for certain stakeholder groups, as well as variations in how it can be integrated with other risk management methods or specialized decision support tools.

It is worth noting that while the discussed methodological innovations have been effective in the cases they were applied in, there may be additional advancements that have yet to be explored. For example, the methods were tested in separate case studies, so a joint application of the advancements would need to be tested and validated. Furthermore, while IC-based CRVAs can be applied in different contexts, they must be adapted to take into account the different levels of competence and relevant solutions needed for each specific case.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization: LP, ER, CA, and ÅG. Data curation: LP. Investigation: LP, JG, FR, DL, KM, ER, CA, ÅG, KA, ME, BD, MB, KR, AC, EA, MM, SR, GJ, SK, MA, and CM-A. Methodology and supervision: SK, ÅG, ER, and CA. Funding acquisition: CA, GJ, SK, and MM. Project coordination: CA, AC, and SK. Visualization: LP, ER, and ÅG. Writing–original draft: LP, JG, FR, DL, KM, ER, CA, ÅG, KA, ME, BD, MB, KR, AC, EA, MM, GJ, MA, and CM-A. Writing–review and editing: LP, JG, FR, DL, KM, ER, CA, ÅG, KA, ME, BD, MB, KR, AC, EA, MM, SR, GJ, MA, SK, and MZ. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2023.1095631/full#supplementary-material

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Improving stakeholder engagement in climate change risk assessments: insights from six co-production initiatives in Europe

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It is increasingly recognized that effective climate risk assessments benefit from well-crafted processes of knowledge co-production involving key stakeholders and scientists. To support the co-production of actionable knowledge on climate change, a careful design and planning process is often called for to ensure that relevant perspectives are integrated and to promote shared understandings and joint ownership of the research process. In this article, we aim to further refine methods for co-producing climate services to support risk-informed decision-support and adaptation action. By drawing on insights and lessons learned from participatory processes in six case studies in Northern and Central Europe, we seek to better understand how associated challenges and opportunities arising in co-production processes play out in different case-specific contexts. All cases have applied a standardized framework for climate vulnerability and risk assessment, the *impact chain* method. The analysis builds on multiple methods including a survey among case study researchers and stakeholders, interviews with researchers, as well as a project workshop to develop collective insights and synthesize results. The results illustrate case studies' different approaches to stakeholder involvement as well as the outputs, outcomes, and impacts resulting from the risk assessments. Examples include early indications of mutual learning and improved understanding of climate risks, impacts and vulnerability, and local and regional decision contexts, as well as actual uptake in planning and decision contexts. Other outcomes concern scientific progress and contribution to methodological innovations. Overall, our study offers insights into the value of adopting good practices in knowledge co-production in impact chain-based climate risk assessments, with wider lessons for the climate services domain. While collaborations and interactions have contributed to a number of benefits some practical challenges remain for achieving effective co-production processes in the context of climate change and adaptation. To overcome these challenges, we propose a carefully designed but flexible and iterative participatory approach that enables joint learning; reassessment of stakeholder needs and capacities; and co-produced, actionable climate services with the potential to catalyze climate action.

KEYWORDS

impact chains, climate risk assessment, climate services, Europe, climate change adaptation, stakeholder engagement, knowledge co-production, transdisciplinary

1. Introduction

While climate adaptation efforts are rolling out across the globe, so far most actions toward adaptation prompt research and planning rather than solutions and implementation (European Commission, 2021). Despite considerable scientific advancements, conventional research falls short in supporting adaptation processes as it rarely offers usable and actionable information for societal actors and is thus not effective in terms of achieving impact on policy and practice (Klein and Juhola, 2014; Bremer and Meisch, 2017; Palutikof et al., 2019). To address this challenge, a growing number of scientists and policymakers call for the re-conceptualization of the role of experts, practitioners, and citizens in the production and use of scientific knowledge, recognizing that different types of knowledge are considered necessary to come together in transdisciplinary processes (European Commission and Directorate-General for Research and Innovation, 2009).

This apparent shift from conventional, science-driven, top-down models to transdisciplinary approaches (Klein et al., 2001) is gaining popularity in the climate services domain (Brasseur and Gallardo, 2016; Vaughan et al., 2018; Vincent et al., 2018; Bremer et al., 2019; Daniels et al., 2020). Climate services are concerned with the development, delivery and use of climate-related knowledge that support long-term planning and decision-making for climate adaptation. They include a wide array of products and services, such as climate change scenarios and projections, climate impact indicators, vulnerability studies, climate risk assessments, socio-economic indicators, general guidance, and tailored user support and training (Máñez et al., 2014).

There are increasing calls for refocusing the climate services lens toward a truly collaborative, process-oriented, and user-driven approach that enables the use of integrated climate information (decision-relevant climate and non-climate information) and thereby increase its usability and uptake (Daniels et al., 2020). This means moving away from supply-driven, one-directional delivery of climate information from providers (e.g., climatologists, meteorologists) to users (e.g., decision-makers, city planners, and extension officers) (Brasseur and Gallardo, 2016; Daniels et al., 2020; Nyadzi et al., 2022).

In recent years, new collaborative and process-oriented climate service frameworks have been introduced (Vincent et al., 2018; Carter et al., 2019; Daniels et al., 2020) to support the design and implementation of transdisciplinary processes spanning across the science and society interface and thereby translating climate information into actionable, climate-resilient decision-making. This is important if we are to bring about fundamental, long-term societal benefits (such as shared understanding, trust-building, expanded networks and partnerships, engagement, ownership, and enhanced individual and institutional capacities) in the face of climate risks (Beier et al., 2017; Vincent et al., 2018; Gerger Swartling et al., 2019; Daniels et al., 2020). This mode of transdisciplinary knowledge generation we hereafter refer to as knowledge co-production, defined as research processes that transcends the divide between academia and society by involving multiple knowledge perspectives (Norström et al., 2020). While these terms are often used interchangeably, we see co-production as a key feature of transdisciplinary research (cf., Polk, 2015; Wibeck et al., 2022).

In this paper, we aim to further refine methods for co-producing climate services to support risk-informed decision-support and adaptation action. By drawing on insights from six case studies of climate risk assessments (one type of climate services) in Northern and Central Europe, we seek to better understand how the associated challenges and opportunities arising in co-production processes play out in different contexts and how lessons learned can help bring further clarity to what methods work when, where, and how (Lang et al., 2012; Harvey et al., 2019; Norström et al., 2020). Hence, we purposively go beyond the aspirational and methodological dimensions of co-production that have dominated the recent sustainability debate and literature (Lemos et al., 2018; Turnhout et al., 2020), to advance our understanding of the practice of applying a co-production approach in regional and local climate risk assessment initiatives.

Common for all selected cases of knowledge co-production processes is their application of a standardized framework for climate vulnerability and risk assessment, the *impact chain method*, outlined in the Vulnerability Sourcebook (Fritzsche et al., 2014; Zebisch et al., 2021) and its supplements (Zebisch et al., 2017). We qualitatively analyse the processes (including contextual factors) and their effects (outputs, outcomes, and impacts) that emerge from the cases and put them in the context of good practice in co-production of climate services.

In the following section we outline the key concepts of the paper, continuing with a description of the method applied. We then present a synthesis of the results based on the analysis of the six case studies, a discussion of the main findings as well as conclusions with focus on how co-production processes can be improved with wider lessons also for good practice climate services.

2. Co-produced climate services in the context of impact chain-based climate risk assessments

2.1. The impact chain method

In this paper, we define climate risk assessments as one type of climate service that can improve risk-informed decision-support and adaptation action (e.g., Máñez et al., 2014). The impact chain method is widely used in climate risk assessments and documented as a useful tool to develop climate information, communicate climate risk and complex cause-effect relationships, and identify and monitor adaptation options (Zebisch et al., 2021; Petutschnig et al., 2023).

With a starting point in the IPCC (2014) definition of the concept of risk, impact chains are based on a combination of top-down and bottom-up participatory approaches, applicable to local to national scales and different settings. The structure of the impact chain represents the main cause-effect chain: a hazard (e.g., a heavy rain event) may lead to a sequence of intermediate impacts (e.g., erosion upstream that contributes to flooding downstream), which in interaction with the vulnerability (e.g., widespread poverty) of exposed elements of the social-ecological system (e.g., a medium-sized city next to a river) finally lead to a risk or multiple risks.

Following the Vulnerability Sourcebook (Fritzsche et al., 2014), the impact chain method consists of eight modules and subsequent steps (Table 1). A key component is the participation of stakeholders with diverse knowledge as well as context- and location-specific information (Menk et al., 2022). Participatory methods are advocated in all steps, to validate the results and ensure ownership and sustainability. However, stakeholder engagement varies across stages: the first three and the last of these modules are highly participative, while the remaining four modules require operational quantification. This does not, however, exclude stakeholders from being part of the more operational modules. For example, participatory weighting methods are common in climate risk and vulnerability assessments (Haque et al., 2012; Barquet and Cumiskey, 2018).

A review of the impact chain method shows that stakeholder involvement in climate risk assessments is typically challenging, as it is both time and resource intensive and there is a fine balance to consider diverging interests and different opinions (Menk et al., 2022). However, the review also identifies potential benefits such as increased legitimacy of results; increased self-awareness of climate vulnerability and risk; and enhanced opportunities to validate results and verify adaptation measures (Menk et al., 2022). Yet, like any other participatory process, there are also challenges related to mobilizing enough capacity, resources, and expertise (Page and Dilling, 2019; Norström et al., 2020; Grainger et al., 2021).

2.2. Key elements of good practice in co-production of climate services

Co-production is one of the key factors that contribute to successful climate services, commonly defined as "(perceived) usability" (Boon et al., 2022) and found to support adaptation and climate action (e.g., Lemos and Morehouse, 2005). Co-production and inclusive planning processes that span diverse areas of expertise can help build trust and capacities; develop a common understanding; promote learning, commitment, local ownership; and create networks and partnerships. These are all essential components of science-informed decision making for adaptation (Jönsson and Gerger Swartling, 2014; Rodela and Gerger Swartling, 2019; Daniels et al., 2020; André et al., 2021). While user-producer interactions are essential, they require careful consideration to the design and implementation to generate desired results (Boon et al., 2022).

Frameworks for good practice in co-production exist, which can serve as a guide to overcoming challenges and maximizing benefits. Here, we look at process-centric frameworks developed to support co-produced climate services, notably Vincent et al. (2018), Carter et al. (2019), and Daniels et al. (2020). While these frameworks emphasize different aspects of the co-production process, they have in common a focus on the users and the role of the process to facilitate the development of relevant and applicable climate services, while building resilience and stakeholders' long-term capacities to address climate risks and adapt.

First, the authors recommend to co-explore and consider *stakeholder needs* and the *decision-making context* both in the design of the process and the outputs produced. Stakeholder engagement is situating research and analysis within a broader planning or decision-making process (Beier et al., 2017). To ensure a decision-driven process (Vincent et al., 2018), relevant (adaptation) issues and stakeholder information needs have to be co-explored early on in the process (Daniels et al., 2020). It is also key to understand where and how the climate service and its outputs will be used as well as the wider context for stakeholder's ability to participate (e.g., Carter et al., 2019). In a similar vein, the *timing and delivery* of information must be aligned with the decision-making context to ensure knowledge uptake with consideration to stakeholders' preferred formats and means of communication (Carter et al., 2019).

The way knowledge co-production is conceptualized and implemented, including its aims and terminologies, affects what effects emerge from such processes (Fazey et al., 2014). Considering the lack of conceptual coherence as regards knowledge co-production aims, definitions and practices (Lang et al., 2012; Bremer and Meisch, 2017; Bremer et al., 2019; Chambers et al., 2021), part of the assessment of stakeholder needs is also to *bring to the surface the aims of the process* with the ambition to "ensure value-added for all involved" (Carter et al., 2019).

Moreover, the authors identifies the importance of having a *flexible, iterative, and learning-based approach* (cf. Boon et al., 2022). Flexibility is needed as it is not possible to fully map out the co-production process at the start, and monitoring and learning may be required to refine the product and process as a result of continuous knowledge exchange (Vincent et al., 2018). Focus and learning objectives should be established in the initial phase of the process to facilitate monitoring, evaluation, and learning (MEL) (Daniels et al., 2020).

As regards stakeholder involvement, Carter et al. (2019) emphasize the need to *embrace diversity*, *respect differences*,

TABLE 1 The impact chain method as outlined in the Vulnerability Sourcebook (Fritzsche et al., 2014; Zebisch et al., 2017, 2021).

Approach	Module	Focus
Highly participative including active participation from stakeholders	1. Preparing the risk assessment	Co-assessment of the initial situation, definition of objectives, topic, and scope.
	2. Developing impact chains	Co-explore impacts and outline cause-and-effect relationships.
	3. Identifying and selecting indicators	Joint identification and selection of indicators to quantify risk factors.
Highly operational and data-driven quantification of indicators and risks	4. Data acquisition and management	Acquire, review, and prepare data and link it to chosen indicators.
	5. Normalizing/threshold definition	Transfer and interpretation of data.
	6. Weighting and aggregating indicators	Assign weights and aggregate to risk components.
	7. Aggregating risk components	Aggregate risk components into a composite risk indicator.
Highly participative including active participation from stakeholders	8. Presenting risk assessment outcomes	Summarize and present findings.

and ensure inclusivity. It is acknowledged that expertise central to climate-informed assessments and decision-making processes comes not only from science but also from on-the-ground politics and practice. The most effective decisions thus emerge from incorporating diverse perspectives and disciplines (Daniels et al., 2020). Such well-designed, collaborative, knowledge integration processes bring together insights from people with experience in government, private sector, civil society, and climate science and support the true sharing of power and of knowledge (Daniels et al., 2020).

Further, it is recommended to build *human capacity* (cf. Palomo et al., 2016) and establish *trustful relationships* (cf. Culwick et al., 2019). Without trust, Carter et al. (2019) point to the risk that the outputs produced remain underutilized. It can also inhibit future engagements. However, enabling and sustaining trustful relationships and science-stakeholder interactions require both time and resources to achieve sustainability outcomes. Research shows that the costs of pursuing co-production are potentially high in terms of time, money, facilitation expertise, and individual commitment on the part of participants, compared to more conventional modes of knowledge production (Lemos et al., 2018). This highlights the importance of carefully designed processes (cf. Boon et al., 2022) where *skilled facilitators* are central to mediating between experts and stakeholders as well as ensuring that the process is transparent and fair (e.g., Carter et al., 2019; Daniels et al., 2020).

3. Material and methods

This research builds on work undertaken within the UNCHAIN[1] project which aimed to improve climate change risk assessment methods in general, and the impact chain method in particular. While the project had five sub-goals defined corresponding to specific research and methodological innovation areas (see further details in Petutschnig et al., 2023), this paper addresses specifically the innovation on the co-production of knowledge. The five research innovations in UNCHAIN were tested through 11 case studies in seven countries across Europe, selected to challenge and further develop the impact chain method and related research and innovations areas. The case study research approach enabled in-depth analysis of different contexts, obtained through an exploratory, iterative and inductive stance (Yin, 2009; Stjelja, 2013).

Our study focuses on six of the 11 case studies that have applied stakeholder engagement methods and co-production techniques in the concerned local/regional climate risk assessments (Table 2). The cases represented a diverse set of climate risks, sectors, and European countries: multiple hydrometeorological hazards (3), transboundary climate risks (TCR) (5, 6), critical infrastructure (1, 4), and agriculture (2) (Figure 1). They were designed and implemented independently by case study researchers under the guidance of a common case study protocol developed to support the knowledge co-production process as well as the proposed modules and steps outlined in the Vulnerability Sourcebook (Fritzsche et al., 2014). To extract challenges and opportunities for future climate risk assessments, we synthesized different experiences of applying the impact chain method and its participatory elements. Given the many differences, we avoid making a cross-case comparison. Even though the case studies did not relate to all the impact chain modules and steps as outlined in Table 1, they all implemented the first two modules that required active participation from stakeholders.

To examine how the case studies included knowledge co-production and the effects of these processes, an evaluation framework with qualitative indicators was developed. The framework used synthesized knowledge gaps found in the literature (Leander et al., 2020) as a baseline to construct both general and specific research questions and related indicators. These were validated against a review of 25 peer-reviewed articles suggesting co-production evaluation practices (Englund et al., 2022).

Noting the difficulties of attributing research impact to a specific intervention (Belcher and Palenberg, 2018; Reed et al., 2021) we adopted a so called "system perspective" approach focussing on capturing different factors that contributed to the results (Belcher and Palenberg, 2018).

1 https://www.vestforsk.no/en/project/unpacking-climate-impact-chains-new-generation-action-and-user-oriented-climate-change-risk

TABLE 2 Case study overview.

ID	Climate risk context	Years	Location	Impact chain modules	No. of participants	Stakeholder types
1.	Economic effects of adapting critical infrastructure (seaport and inland water transport)	2020–2022	Germany, Mannheim region	All	20	Municipal authorities, first responders, local businesses, federal research institutes, and academia
2.	Agricultural drought in the light of climate change	2020–2021	Austria, Province of Salzburg	All	10	Governmental institutions (national, provincial, and regional), farmer associations, farmers, insurance representatives, and academia.
3.	Social vulnerability to multiple hydrometeorological hazards and cascading effects	2021–2022	Sweden, Halmstad Municipality	All	10	Municipal authorities
4.	Climate change impacts on financial investment portfolios and on railway infrastructure	2020–2022	The Netherlands	All	15	Transport providers, port authorities, producers of goods transported on the Rhine, real estate asset managers, regulatory authorities
5.	Improving knowledge and management of TCR at the city level	2020–2022	France, Paris	1–6, 8	20	Municipal authorities, academia, and non-governmental organizations
6.	Regional knowledge base for local and TCR analysis: the case of agriculture	2021–2022	Norway, Rogaland County and Klepp Municipality	1–2	26	Municipal authorities, farmers, agrarian associations (local and regional), regional government, an agricultural cooperative, and politicians

To this end, we found the Wall et al. (2017) framework for evaluating co-produced climate science particularly useful, acknowledging multiple components—including internal, external and process related factors—of relevance. This framework also corresponds to key factors identified in the wider literature on evaluating co-production processes (Englund et al., 2022). In brief, we applied three overarching categories centered on: (1) the knowledge co-production process, (2) co-production effects, and (3) contextual factors (Table 3).

Indicators related to the *process* focused on assessing both input- and process-specific components including stakeholders' and researchers' preconditions and capacities to participate effectively, as well as the nature of interaction and knowledge exchange. To assess the *effects*, we focussed on indicators capturing different types of *outputs* (e.g., peer reviewed articles or technical reports), *outcomes* and *impacts*. Following Wall et al. (2017, p. 100) we defined outcomes as the "tangible and more conceptual results" of both the outputs produced and from the process itself. In line with Wiek et al. (2014), outcomes are generated during project life cycle whereas impacts refer to more long-term effects (see also e.g., Belcher and Palenberg, 2018). Impact related indicators thus aim to capture aspects such as how results were used to inform adaptation action or decision-making (Wall et al., 2017). Lastly, *contextual factors* refer to factors outside the process which may be important for understanding whether and how the results are being used or not. This could for example relate to political will and access to financial resources (Wall et al., 2017).

The different knowledge co-production processes were analyzed through a collaborative and iterative approach involving contributors of each case study (see Chambers et al., 2021). To collect insights from the cases a combination of methods was applied; surveys, interviews, and a workshop complemented with relevant case study documentation and research observations and reflections (Table 4). The three lead authors of the paper led the work whereas the co-authors and case study researchers contributed with results and empirical knowledge from their respective case studies and validated emergent findings (c.f., Chambers et al., 2021).

Guided by the evaluation framework, a survey was developed for case study researchers consisting of 32 quantitative and qualitative questions covering both basic information about the case study and the knowledge co-production process, effects, and context (see Supplementary material). The survey was completed by the case study research teams, one per case study. Complementary unstructured interviews were then conducted with one or several individuals in each case study for more in-depth insights and contextual information. In total ten researchers participated in the interviews.

We also collected stakeholder inputs to capture perceptions of the process and the results, and for validation of results. To this end, a protocol with questions was developed and adapted to the specific case studies including a selection of key questions related to the outputs, outcomes, and impacts. Responses were collected through interviews or surveys with key stakeholders in five of the case studies. Case studies 1 and 3 received responses from three stakeholders, case study 6 engaged six stakeholders

FIGURE 1
The geographical location of case studies.

whereas case study 2 gathered input from one stakeholder. Case study 4 conducted a feedback analysis with four representatives of three real estate companies that were involved in the study (see Attoh et al., 2022 for details). For case study 5 we relied on stakeholder feedback and contributions with 15 interviews of experts completed during the production stage, and a validation workshop with the Paris stakeholders for sharing and discussing the case study results. All in all, in the analysis we focused on process-related aspects, building primarily on researcher experiences and insights from designing and facilitating the co-production processes.

The results from the interviews and surveys were analyzed using an inductive approach based on the evaluation framework and suggested indicators. We developed codes as the analysis progressed, distilling themes and commonalities as they emerged and then organized the codes according to the categories outlined in the evaluation framework—process, effects, and context. We synthesized each code separately by clustering data into classes that consisted of similar objects. A workshop was held with case study researchers and co-authors to collectively discuss and synthesize results from the evaluation. The results were analyzed in terms of good practice co-produced climate services with a focus on user-driven and process-centric frameworks and principles (Vincent et al., 2018; Carter et al., 2019; Daniels et al., 2020).

4. Results

In this section, we present results from the analysis of the co-production processes in the six climate risk assessment initiatives. We begin with outlining process-related aspects and then proceed with describing the various effects (outputs, outcomes, and impacts) identified. Throughout, we relate to external and contextual factors that were found to be important to both the processes and the results.

TABLE 3 Framework for analysis (building on Wall et al., 2017).

Category	Factor	Definition	Examples of results emerging from the deductive and inductive coding
The knowledge co-production process	Input	Financial and human resources put into the process	• Identification and selection of stakeholders • Pre-existing working relationships and local champions • Stakeholder engagement aims and rationales • Skill set of the research team and stakeholders
	Process	Actions and activities	• Number of meetings/exchanges • Co-production activities • Points at which stakeholders participated
Co-production effects	Outputs	Tangible products	• Peer reviewed articles • Technical reports • Decision support tools • Project communication
	Outcomes	Tangible and intangible results from the outputs and process generated during the project life cycle	• New research questions and initiatives • Plans for future collaboration • Mutual learning among stakeholders and researchers • Increased awareness of climate risks, decision-making context, and role of others • Outputs perceived as relevant or usable • Scientific progress • Trust building
	Impacts	Long-terms effects emerging after the project life cycle	• Results used in climate adaptation decision-making and action • Results make it to the government agenda
Contextual factors	Context	External conditions that affect the process and its results	• Catalyzing events

TABLE 4 Outline of the evaluation process undertaken by the case study research team.

Activity	Timing	Aim
Survey to researchers	April-May-22	Gather information on the knowledge co-production process in each case
Interviews with researchers	May-22	Complement survey and follow-up for more in-depth insights and context
Survey and/or interviews with stakeholders	April-June-22	Validation of results
Workshop with researchers/case study contributors	May 2022–22	Validation of results, synthesis, and joint reflection of findings and recommendations

4.1. Process and nature of stakeholder engagement

4.1.1. Identification and selection of stakeholders

In each case, the knowledge co-production process was conducted within two-years, and engaged on average 17 participants from academia, national agencies, municipalities, civil society, private enterprises, and politicians (Table 2). Stakeholders were mainly identified through existing networks and research teams' previous relationships with stakeholders in respective case study location. We found that local champions were key in the process of setting up the case studies. With support from these local contacts additional stakeholders were identified and invited for participation if relevant in the climate risk context being investigated. The climate risk context was key in the process of identifying stakeholders, yet it turned out to be challenging in some case studies. Case study 1 noted for example, that the case study topic limited the number of interested stakeholders hence they slightly modified the geographical scope of the research. Case study 4 differed as stakeholders were predetermined as they requested the climate risk assessment of researchers.

4.1.2. Problem definition and expectations

Four of the six case studies were initiated by researchers. The problem definitions related to case study contexts were in many cases already formulated when seeking project funding. Most of the cases, however, refined and adapted the problem definition based on stakeholder priorities and needs (Table 5). In Sweden (3) this was done by inviting them to a workshop to discuss and gather feedback on the aim and scope of the case study, allowing the problem definition to represent inputs from both researchers and stakeholders. Yet a difference between expectations remained in some of the case studies. For example, there were occasions when stakeholders expected to identify adaptation measures whereas the case study was designed to test the impact chain method (case study 2). In the Netherlands (4) expectations from stakeholders exceeded what was possible to achieve in terms of scientific deliveries due to data availability and state of the art. The researchers carefully explained why some expectations remained unmet to address the mismatch in expectations. In the end, this clarification improved acceptance and ownership of the process.

In the analysis we found three overall aims underpinning the six case studies: informing decision-making; methodological development or improvement of the impact chain method;

TABLE 5 Nature of knowledge co-production processes in case studies.

ID	Objectives	Underlying aim	Problem definition	Continuity	Co-production activities
1.	Assess impacts of more frequent periods of drought and summer low water of the Rhine for industries, services, and logistics companies represented by potential infrastructure service reduction.	Methodological development	Compromise—defined by researchers but adapted to stakeholder needs	Stakeholders involved where appropriate	7 co-production workshops 8 other meetings, 4 individual exchanges
2.	Improve the spatial understanding and awareness of frequent agricultural droughts that increase the financial stress of farmers in Salzburg.	Methodological development	Together with stakeholders	The same stakeholder group was invited to both workshops, however, only a few attended the second workshop	1 survey 2 workshops
3.	Assess the spatial distribution of social vulnerability to flood risk in Halmstad Municipality.	Methodological development, Exploring a specific research topic and Decision-support	Compromise—defined by researchers but adapted to stakeholder needs	The stakeholder group remained the same	3 workshops 7 group interviews 1 field visit Individual exchanges
4.	1. Identify and assess climate risks and their impact on real estate portfolios at different spatial and timescales. 2. Determine the extent to which rail systems are exposed to heat and storms at different timescales.	Decision-support and Methodological development	Formulated by stakeholders	The stakeholder group remained the same	2 workshops 10 interviews Individual exchanges
5.	Understand the impacts of climate change on migration flows and adaptation pathways at the city level.	Decision support and Methodological development	Compromise—defined by researchers but adapted to stakeholder needs	Stakeholders involved when necessary	10 interviews 1 workshop 2 meetings
6.	Explore local climate risk and transboundary climate risk (TCR) for the agricultural sector.	Exploring a specific research topic and Methodological development	Compromise—defined by researchers but adapted to stakeholder needs	The stakeholder group remained the same	2 meetings 2 workshops 2 interviews

and exploring a specific research topic and contributing to scientific progress (Table 5). The first aim was characterized by extensive stakeholder engagement and communication where stakeholders could provide input to the framing of the case study. In contrast, the two latter themes engaged stakeholders to improve research findings rather than designing knowledge fit for informing decision-making.

4.1.3. Co-production activities

Depending on the specific aim, the participatory processes were purposefully structured differently. Most cases applied an iterative participatory process in which the climate risk assessment was validated and refined based on stakeholder input. The cases employed different approaches to co-production including online and in-person workshops, group interviews, individual exchanges, and field visits (Table 5). Individual exchanges entailed informal meetings with researchers and stakeholders to prepare for the climate risk and vulnerability assessment and build rapport.

Some cases involved their stakeholders on an *ad-hoc* basis where different stakeholders attended workshops at different points in time depending on their expertise. Others facilitated a continuous dialogue where the same stakeholders were engaged throughout the process. For example, case study 4 involved stakeholders for collaboration in all parts of the process. For the railway sector, there was one in-person workshop and 15 interviews, and for the financial sector, there were two workshops and five interviews conducted. In addition, several phone calls were made between the researchers and stakeholders throughout the process. Stakeholders provided data and shared detailed insights on the challenge itself, helping the researchers to better understand the problem.

Case study 1 followed the steps outlined in the Vulnerability Sourcebook, but through an iterative refinement process. They did not involve the same stakeholders in all workshops, but the group changed depending on workshop purpose. Some stakeholders were involved in several workshops whereas some were only involved in one. Two workshops were conducted to construct the impact chain, the process then continued with further refinements. In the words of the research team:

> *After the impact chain workshops, we introduced the relations between the identified elements in the impact chain. We made some suggestions on how these impacts could be related, which we shared with the stakeholders and made a detailed list of all the changes that were made. We received feedback and then we adapted the impact chain accordingly. Three times the impact chain was circulated back and forth. It was a continuous discussion. We ended up with results that were feasible for both us and stakeholders.*

Case study 3 combined a mix of workshops and group interviews. The first workshop was held online and aimed at introducing the project and to further define case study objectives. This was done through an open discussion with the stakeholders on risks and current challenges to the locality. Stakeholders were then invited to a second online workshop in which they brainstormed around what social groups might render vulnerable in the case of flooding. Based on results from the first and second workshop the research team developed an impact chain outlining social vulnerability to flooding. The third stakeholder iteration was structured as group interviews where a list of possible vulnerable groups was used for more in-depth discussions of drivers of vulnerability. Stakeholders were then invited to a validation workshop in person in which they provided feedback on the final impact chain.

Case study 2 took a somewhat different approach. Most information was collected from stakeholders prior to the workshops to instead focus the discussions on drivers of risks and adaptation measures. As described by the research team:

> *The first workshop was at the beginning of the case study. It was an online workshop presenting the project and then looking at the impact chain and drivers, as well as adaptation measures the different stakeholders were undertaking. We shared a survey with the participants prior to the workshop asking: In your opinion what is amplifying drought impacts? What are the drivers? What can we do about it? We collected this information before the workshop so we could show it to them to support the discussion. We did not make an impact chain during the workshop, we only discussed drivers and adaptation measures.*

This was also the situation in case study 5. The researchers conducted online interviews with selected key stakeholders to gather input and identify indicators to present in the impact chain. Stakeholders then provided data and validated the impact chain during a workshop. The actual development of the impact chain was done in-house without any involvement of stakeholders. Toward the end of the process, a workshop to identify adaptation measures was held together with city of Paris stakeholders.

Case study 6, on the other hand, facilitated several interactions with local stakeholders. During the initial phase of the process, the research team had two initial meetings with the municipal administration and local politicians to explain the project and to set the scene. They then had smaller meetings with the project leaders from the local and regional municipalities to discuss how to structure the workshops:

> *Before the first workshop, we gathered a small group for an online meeting to prepare them as group leaders and enable them to take charge of working with the impact chain method. The first workshop was on local climate risks, using the impact chain method. Stakeholders contributed with real content to the analysis and decided what was essential to include. Before the second workshop, we developed a flow chart which we sent out to the participants for evaluation beforehand.*

Since most case studies started in 2020, the co-production processes were adapted to the specific restrictions imposed in response to the COVID-19 pandemic. All case studies, therefore, used virtual forms of interactions, of which most used digital participatory platforms and online visualization tools such as Miro, Mural, or Mentimeter to support the process. As these online platforms enable user-generated content, they allowed participants to co-create perspectives and jointly develop impact chains and identify risk factors. In the Swedish case study (3), stakeholders were engaged using Mentimeter to co-design the research scope and objectives. Mentimeter allowed the stakeholders to suggest and vote for important risks for the municipality to consider, while disseminating results in real-time to support group discussions.

4.1.4. Capacity to engage

We identified several factors related to both stakeholders' and researchers' capacities and resources to engage effectively in the co-production processes. All researchers had prior experience with stakeholder engagement and four case studies had researchers with experience in using the impact chain method. Stakeholders, on the other hand, varied in terms of their previous experiences, knowledge, and skills regarding the adaptation challenges being addressed. Some were unfamiliar with scientific terminology to define and discuss climate risks and struggled to differentiate between exposure, vulnerability, and risk (case studies 2 and 4). The cases working with TCR (case study 5 and 6) required a high level of abstract thinking, which stakeholders found difficult. Similarly, researchers involved in the Swedish case study (3) noted that stakeholders sometimes found it difficult to think beyond their day-to-day field of work to also include social groups and their vulnerabilities.

As noted by all case study leaders, knowledge co-production is time- and resource-intensive and the time allocated to stakeholder engagement varied across cases. Many stakeholders had other tasks and duties to fulfill which limited their time availability for the study. Researchers also reported limited resources and consequently time to engage effectively with stakeholders. Here, we noticed the importance of unforeseen, external factors outside the system, such as the COVID-19 pandemic and the 2022 Russian invasion of Ukraine that imposed additional challenges as some stakeholders were unable to continue to participate. For example, in Germany (1) some stakeholders were prevented from participating as they were occupied with responding to the disruptions triggered by the pandemic, and later managing the energy crisis resulting from the invasion. In France (5), stakeholders needed to prioritize the flow of migration from Ukraine.

While most found the online meetings useful for example as they required less time investment on the part of participating stakeholders, there were also occasions when communication was hindered by poor internet connection (case study 5) or digital literacy (case study 1) which inhibited active participation and knowledge exchange.

4.2. Co-production effects

The assessment of case studies took place in 2022 meaning that there was only limited time for outcomes and impacts to emerge by the time of writing of this article. Another challenge is the apparent difficulty of attributing outcomes to particular activities (VanderMolen et al., 2020) which was not a central focus in our analysis. Despite these constraints, we identified a variety of effects emerging from the six co-production processes (Table 6).

TABLE 6 Overview case study results in the form of output, outcome and impacts.

ID	Output	Outcome	Impact
1	Project report, minutes, slides, impact chains, and Excel tool	Scientific progress, Future collaboration, New research questions, Mutual learning, Changed understanding, Trust-building	Supported ongoing climate and policy initiatives Findings implemented in practice
2	Impact chain graphic, project documentation, data, and interactive dashboard	Scientific progress, Future collaboration, New research questions, Changed understanding, Actionable knowledge, New knowledge, Mutual learning	Supported ongoing climate and policy initiatives
3	Discussion brief, maps, academic article, and impact chain	Scientific progress, Future collaboration, New research questions, Trust-building, New knowledge, Mutual learning, Actionable knowledge, Improved relationships, Changed understanding	Supported ongoing climate and policy initiatives
4	Visual maps and reports	Scientific progress, Future collaboration, New research questions, Change in perceptions, Mutual learning, Actionable knowledge, New knowledge, Improved relationships, Changed understanding	Supported ongoing climate and policy initiatives Findings implemented in practice
5	Project report, slides, impact chains (2), minutes	Scientific progress, Future collaboration, New research questions, New knowledge, Mutual learning, Actionable knowledge, Improved relationships, Changed understanding	Supported ongoing climate and policy initiatives Findings implemented in practice Agenda setting
6	Reports and impact chains (flow chart)	Scientific progress, Future collaboration, New research questions, The understanding of the roles of others	Supported ongoing climate and policy initiatives Findings implemented in practice Agenda setting

4.2.1. Outputs and communication

The survey showed that all case studies generated a diverse set of tangible outputs including excel tools, project reports, and journal articles (Table 6). Visual representations of the results included impact chains, interactive dashboards, and maps such as risk and vulnerability hotspot maps. Case studies 2–4 presented the findings in a final validation workshop, whereas the remaining case studies communicated their outputs via email. Most outputs were posted online for a wider audience. Some cases described how they adapted the outputs to stakeholder needs, for example by avoiding scientific jargon, using the local language, and keeping the written content brief. However, few case studies indicated that they had involved stakeholders in planning the communication of results as well as feedback. Researchers involved in case study 5 further noted that stakeholders shared the results internally which is a sign of the perceived relevance of the findings for a wider group of stakeholders.

4.2.2. Outcomes

Looking more specifically at the outcomes, we observe from the survey that *scientific progress* was the most common, especially regarding improvements in the impact chain method. Methodological innovations included modeling dynamic interactions, assessing transboundary risk, and developing feedback loops and casual relationships. Also, related to research advancements, all case studies developed plans for *future collaboration* and identified *new research questions* and initiatives. Future collaboration was foreseen, both among the researchers themselves, as well as with the involved stakeholders.

The second most reported outcome was a *change in perceptions* and *increased awareness* among stakeholders who experienced an improved understanding of climate change impacts and the significance of adaptation and risk assessments. In the Netherlands (4), stakeholders gained a better theoretical understanding of key concepts such as climate risks and uncertainty. In the Swedish case study (3), stakeholders increasingly considered the social dimension of flood risk in addition to its physical and climatic parameters. Similarly, stakeholders in the Norwegian case study (6) improved their awareness and understanding of TCRs. Three case studies also indicated *mutual learning* as an outcome, where the impact chains seem to have served as a boundary object supporting this to happen. Stakeholders learned about the research topics, whereas the researchers developed an understanding of the decision-making context. In Germany (1), mutual learning evolved through an iterative process in which the impact chain was circulated and adapted three times to integrate knowledge from stakeholders. Similar results were also found in Austria (2), where the co-development of the impact chain helped to reduce complexity while fostering creativity which improved stakeholder and researcher understanding of the topic of agricultural drought.

From the survey results, we also noted that the exchanges between researchers and different stakeholders increased *the understanding of the roles of others*. For example, representatives from the agricultural and industry sector in Norway (6) enjoyed learning about others' perspectives. However, according to the survey results, *trust-building* seems to have occurred in two case studies only (case studies 1 and 3). It appears that the restrictions implemented in response to the COVID-19 pandemic prevented trust from emerging in the other four case studies. This is likely because there were fewer opportunities for informal exchange which had negative implications for the quality of interaction and trust-building. For example, in Sweden (3) trust-building was facilitated by continuous interactions and a final face-to-face workshop that brought stakeholders and researchers together which improved the dialogue and collaboration. At the same time, all case studies had initiated plans for future collaboration, which is a clear sign of good relationships and possibly also mutual trust. Also, the fact that most cases relied on previous relationships when initiating the case studies indicates that case studies were characterized by high levels of trust from the very beginning.

4.2.3. Early signs of impact and the role of external factors

While we cannot see any clear impacts (as too early in the process), all case studies indicated that they *supported ongoing climate and policy initiatives.* For example, parallel to the research, case studies provided input to policies under development including climate adaptation strategies, heat action plan, agricultural plan, climate vulnerability study, flood protection plan, investment decisions, and municipal plan. Ongoing policy development was perceived to increase the relevance of the case studies. They also provided an entry point for results to be integrated into policymaking, facilitating the process of informing adaptation planning and decision-making. For example, the German (1) and Austrian (2) case studies supported policies and action plans drafted as a response to the 2018 heatwave. Thereupon, the heatwave in 2018 served as a window of opportunity for researching extreme heat and water scarcity. Based on researchers reports, their stakeholders perceived the topic as relevant already before the UNCHAIN project started.

More concrete examples of actual impact include the stakeholder engagement process in the city of Paris (5) that paved the way for the local government's decision to incorporate the TCR dimension in the municipal policy agenda and in their systems for assessing risk. Similar results appeared in the Norwegian case study (6) where reports provided by the project have been incorporated into two main municipal plans. These two examples further point to the importance of *contextual factors* where *external events* appeared to affect the uptake of knowledge. Researchers noticed that TCR appeared to gain importance on the public agenda, starting to make its way into planning and decision-making. Hence, the timing of the case studies coincided with increased attention paid to these issues. In addition, the 2022 energy crisis and the Russian invasion of Ukraine further highlighted the importance of considering TCRs, increasing the perceived relevance of the case studies (5 and 6) addressing such topics.

5. Discussion

In this section, we discuss challenges and opportunities arising from the studied co-production processes and how they played out in different case-specific risk assessment contexts, with the ambition to improve the usability of the impact chain method and climate services in Europe and beyond.

Overall, the analysis shows that the six case studies across Northern and Central Europe relate to elements of good practice co-production (see section 2.2) in different ways and that the impact chain method supported this process. To a varying degree and through a diverse set of approaches and formats, the participatory processes enabled the *co-exploration of stakeholder needs and adaptation pathways* in the respective localities. However, as case studies were informed by the overarching aim of methodological development, the seeming knowledge fit for decision-making was not the primary objective. Moreover, case studies *built human capacity* and *trustful relationships*, and *involved skilled facilitators*.

While this study did not go into depth with the question of *how* case studies *embraced diversity,* we note that different types of stakeholders were involved (academia, national agencies, municipalities, civil society, private enterprises, and politicians), and that they in most cases were identified and invited to participate in close dialogue with local contact persons. In addition, how case studies *respected differences* and *ensured inclusivity* has not been captured in the analysis. Researchers reported however that they used different methods and techniques to engage with stakeholders including online tools. Obviously, the online format might have benefited some stakeholders whereas other might have disadvantaged.

The COVID-19 crisis further illustrates the importance of both the external environment and how it shapes the co-production process, and the need for *flexible approaches* that are sensitive to contextual factors. However, here we see a challenge to both consider project-specific demands and limitations which makes it difficult to embrace a truly collaborative and stakeholder-driven approach. Moreover, aspects related to *communication, timing, and delivery* of results were not in focus in any of the case studies even though we found examples of how outputs were adapted to stakeholder needs.

Based on the analysis of the results we identify three domains to foster more collaborative and user-driven processes that support the acceleration of adaptation action and resilience: formulating joint learning objectives and expected outcomes; communicating and presenting results; and supporting iterative learning.

5.1. Formulating joint learning objectives and expected outcomes

Being "research-output-oriented" in nature, the empirical cases reported in this study were largely driven by what Chambers et al. (2021) frame as "Mode 1: Researching solutions". This has further implications for the type of outcomes and outputs that can realistically be expected. For example, we found that case studies that explicitly aimed to further develop the impact chain method generated an improved understanding of the topics and concepts in focus among stakeholders. Although the results seemed policy relevant in terms of informing ongoing planning processes, the extent to which involved stakeholders applied the results in adaptation planning remains unclear at the time of writing this article even though we see early signs of impact.

These research-focused approaches appear as one obvious explanation why stakeholders were only partly involved in defining the problems and risks. Following Carter et al. (2019) case studies operated along the spectrum of consultative and immersive co-production approaches. In some cases that were more on the consultative side of the spectrum, research objectives were defined by the researchers during the proposal development stage and hence without any involvement of stakeholders. In most cases, however, the problem definition was the product of a compromise between researchers' initial problem formulation and stakeholder feedback regarding their needs and expectations from the collaborative process. If the goal is to generate actionable knowledge and stakeholder empowerment, then the role of stakeholders and their inputs need to be more prominently featured throughout the process.

Consequently, in line with previous research (Reed et al., 2018), we argue that it is critical to engage stakeholders early on to ensure that their perspectives and needs are considered throughout the process. Inclusive priority setting and equal power sharing are generally aspired to in genuinely participatory processes. Studies show that power imbalances may be a challenge as elite actors are often able to shape these processes to serve their own interests (Parkinson, 2012). In co-production initiatives, power inequalities may be further compounded by the strong authority attributed to scientific expertise in relation to other knowledge systems (Turnhout et al., 2020). Thus, the sheer involvement of stakeholders throughout the process is not sufficient to address power dynamics. This challenge is not specific to the impact chain method but applies to any process that seeks to integrate different knowledge bases and expertise. In co-production processes it appears critical to facilitate, manage and co-ordinate the complex web of psychological, social, cultural and institutional interactions that are in play, and apply a constant critical reflective practice and dialogue to foster more equal relational co-production and co-design processes (Farr, 2018). This approach aligns with that of Daniels et al. (2020) who propose a framework for designing transdisciplinary knowledge integration processes based on co-exploration and co-production processes using a wide array of knowledge. Such a collaborative learning approach provides a structure for understanding decision needs; guiding actors in designing and delivering an effective transdisciplinary knowledge integration process; and, enhancing capacities (both individual and institutional), working relationships and networks necessary for longer-term change and action. Applied in the context of UNCHAIN, such a truly collaborative approach can assist in clarifying both stakeholders' and researchers' expectations of the process and identifying the knowledge and capacity gaps in relation to adaptation, while also mitigating power imbalances.

In this context, we note that the impact chain method (Fritzsche et al., 2014) provides good support and structure, especially through the first module and the scoping phase of the risk assessment. We, however, suggest incorporating a Theory of Change (ToC) to describe and illustrate how and why change is expected to occur and its impact, as well as who might be affected (van Es et al., 2015). A ToC engages stakeholders and researchers in a collaborative backward-mapping process, bridging potential contrasting values, epistemological beliefs, and diverging expectations. Stakeholders and researchers first co-explore desired long-term objectives, followed by designing a pathway of change that outlines intermediate learning objectives, activities and outputs, and assumptions (Fazey et al., 2014; van Es et al., 2015). The ToC fits well in the initial module of the impact chain method, scoping, as it allows stakeholders and researchers to co-explore issues and context in depth and formulate joint learning objectives and expected outcomes. Thereafter, the ToC can be used to monitor and evaluate the co-production process and encourage reflection and learning as new insights emerge (Englund et al., 2022).

5.2. Communication and presentation of results

One of the rationales for co-producing climate services is to increase the usability and uptake of results (e.g., Chiputwa et al., 2020; Boon et al., 2022). The process, if implemented effectively, can lead to science made more accessible to decision-makers and an increase in the perceived saliency, credibility and legitimacy of research outcomes (Cvitanovic et al., 2019). Making science more usable is, however, not only about the content and quality but also how the results are presented and communicated (Lemos and Morehouse, 2005; Vincent et al., 2018; André et al., 2021).

In our analysis, we found that few, if any, had involved stakeholders in the communication of results, for example by discussing preferred forms and format, resolution of data, and scale (e.g., spatial and/or temporal) and the timing of deliverables. Timing is, for example, important to consider in relation to case study planning and decision contexts (Carter et al., 2019). The outputs produced were mostly in the form of written reports and presentations, shared via email, and hence little scope for discussion and feedback. It thus appears that, while stakeholders had been actively engaged in previous steps of the process, they seem to have been more passively involved in the final impact chain module.

The current impact chain method provides little guidance on how results should be communicated to stakeholders. We therefore see a need to discuss this early in the process and clearly involve stakeholders in the communication as well as their preferences for how they want to receive the results (e.g., formats, scale, timing etc.). Previous research (e.g., Vincent et al., 2018) emphasize that, in order to be effective to users, scientific information needs to be communicated in a format and language that is relevant and understandable to them. However, there is often not one single type of user, which is why different formats might be preferred to ensure that the information is accessible and actionable to all relevant stakeholders. To guide the process, we suggest that relevant (tangible) outputs and desired outcomes are identified early on, ideally in the scoping phase of the process when co-exploring stakeholder needs. This could also be further connected with an assessment of stakeholder capacity building needs.

5.3. Iterative learning

Our findings indicate that the impact chain method can support an iterative feedback process. Most case studies invited stakeholders to validate and refine the climate risk assessment. We found, however, that stakeholders were sometimes involved on an *ad hoc* basis. Moreover, we observe challenges when stakeholder needs must be reconsidered. As highlighted by some case studies, external events can trigger changes in project plans or even objectives. Other case studies experienced a mismatch in expectations. This highlights the need for an iterative and flexible approach to allow for the reflection and processing of information as new knowledge emerges throughout the process. To this end, we suggest integrating a mechanism for practices to adapt as new information emerges. One promising approach is to draw from certain principles of interaction that mediate the consequences of practices that suppress uncertainty to gain or maintain control, and instead aim for more adaptive management (Armitage et al., 2011; Bremer and Meisch, 2017; Arora, 2019).

Further, co-production processes are rarely evaluated (Lemos et al., 2018), yet a growing body of research suggests that monitoring and evaluation can support iterative learning and adaptive management in complex endeavors (Patton, 2010; van Tulder and Keen, 2018; Englund et al., 2022; Visman et al., 2022). A monitoring framework allows stakeholders and researchers to reflect whether learning outcomes are achieved and adjust the implementation process accordingly, hence stimulating a continuous real-time feedback loop that connects evaluation findings and decision-making. To ensure contextual relevance, the co-production process must adapt as new information or needs emerge. An iterative approach can thus support the impact chain method in learning and feedback by monitoring the progress, refining the climate risk assessment, and adapting to new circumstances.

While the impact chain method is a standardized approach for conducting climate risk assessments, the absence of iterative learning and flexibility has less to do with the method *per se* but rather a potential discrepancy in research project design and funding agency requirements. The development of climate services—in this study in the form of climate risk assessments—therefore needs to increasingly emphasize capacity building and long-term climate resilience beyond the scope of a specific project. In line with Vincent et al. (2018) and Daniels et al. (2020) we observe that iterative learning and adaptive management require a process-centric approach when co-producing climate risk assessments. This approach is underpinned by sustained engagement and interaction that allow for iterative learning and co-benefits to emerge, for example related to networks, empowerment, and trust.

6. Conclusions

This article has presented findings on the practice of knowledge co-production which represents one of six research innovations of the impact chain method investigated in the UNCHAIN project. The study is based on a qualitative analysis of six European climate risk assessment initiatives that collectively testify to the potential benefits of combining good practice knowledge co-production beyond what is currently practiced in impact chain studies, and the potential barriers to undertaking such co-production approach in a real-world context. While the structured and stepwise approach of the impact chain method proved beneficial to the knowledge co-production process *per se*, in reality there was a predominantly expert-driven approach to stakeholder-informed climate risk assessments, where stakeholder perspectives and needs remained somewhat hidden or (at least partially) untapped.

At the same time, we have observed that the collaborations and interactions have contributed to a number of benefits on the part of participating researchers and stakeholders. These include awareness raising and mutual learning where stakeholders, on the one hand, have gained understanding of climate risks, impacts and vulnerabilities, whereas researchers have deepened their knowledge about local and regional decision-making contexts and the need for tailor-made climate risk assessments. Plans for future collaboration also indicate that case studies have been successful in establishing good relationships to further build on, which may ultimately foster deeper researcher-stakeholder interactions in the longer term. Some case studies reported scientific progress and methodological innovations emerging from the co-production approach to climate risk assessments. Importantly, although the climate risk assessment processes are relatively recent results have to some extent proven to inform and contribute to ongoing adaptation policy and planning processes.

However, challenges remain as to how to adopt and integrate a flexible and iterative approach to co-production, where stakeholder needs and capacities are reassessed during the process, especially to account for external events and circumstances. Altogether these lessons demonstrate the complexity involved in co-production processes that aim to support actionable climate services. In this paper, we argue that these challenges can be overcome through due attention to joint iterative learning facilitated through co-developing a Theory of Change (ToC) and by introducing monitoring, evaluation and learning (MEL) frameworks to support a flexible approach while providing an opportunity for joint discussion and feedback.

In line with Lemos et al. (2018), we see co-production as a mechanism to enhance the uptake of scientific knowledge informing adaptation planning and decision-making, yet it cannot be an end-goal in itself. To move beyond awareness raising to adaptation action, which is called for by the EU Adaptation Strategy (European Commission, 2021), co-production processes need to be carefully designed and facilitated as well as further reflected upon (cf. Bremer and Meisch, 2017). As one first step we propose future research to assess the value of applying more flexible, iterative and reflexive participatory approaches that foster long-term capacity building. This capacity enhancement is required both within academia to engage effectively with stakeholders, and in practice to equip stakeholders with actionable climate services.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KA: conceptualization, methodology, validation, formal analysis, investigation, writing—original draft, writing—review

and editing, project administration, and funding acquisition. ÅG: conceptualization, methodology, validation, investigation, writing—original draft, writing—review and editing, supervision, project administration, and funding acquisition. ME: conceptualization, methodology, validation, formal analysis, investigation, writing—original draft, and writing—review and editing. LP: validation, investigation, visualization, writing—original draft, and writing—review and editing. EA: methodology, validation, investigation, writing—original draft, and writing—review and editing. KM: validation, investigation, writing—original draft, and writing—review and editing. DL and TB: validation, investigation, and writing—review and editing. AC: validation, investigation, writing—original draft, writing—review and editing, and funding acquisition. MH: writing—original draft and writing—review and editing. MB: investigation and writing—review and editing. ER: validation, investigation, writing—review and editing, supervision, and funding acquisition. All authors contributed to the article and approved the submitted version.

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Conflict of interest

AC and MB are employed by Ramboll France SAS.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Think global—act local: the challenge of producing actionable knowledge on transboundary climate risks at the sub-national level of governance

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A growing number of countries are putting transboundary climate risks on their national adaptation policy agenda. The designation of subnational governments as key actors in climate change adaptation policy appears to be appropriate when the risks associated with climate change are defined as "local." In this study we have investigated whether local authorities can plausibly play an equally central role when it comes to transboundary climate risks. Three cases have been studied: Paris in France and the topic of migration and integration, Klepp in Norway and the topic of agriculture and livestock production, and the river harbors in the Upper Rhine region of France and the topic of freight transportation and river regulation. Even if the sub-national actors involved in the three cases showed strong interest in analyzing and addressing transboundary climate risks, it remains an open question whether such authorities can and should play an equally central role in addressing transboundary climate risks as they do in the case of local climate risks. On the other hand, assigning responsibility for managing transboundary climate risks exclusively to national authorities may increase the risk of conflicts between measures to reduce local climate risks (frequently developed and implemented by sub-national authorities) and transboundary climate risks. The authors of this paper therefore advocate a strong partnership between the different levels of governance, and between public and private-sector stakeholders, in adaptation to transboundary climate risk. It is therefore crucial that national governments explicitly account for transboundary climate risks in their national adaptation agendas and, as part of their process in determining "ownership" of such risks, decide on the role sub-national authorities should play. This choice will also affect the role of local authorities in managing local climate risks due to the interlinkages between them.

KEYWORDS

climate impact chain, climate risk and vulnerability assessment, climate change, transboundary climate risk, local climate action

1. Introduction

Climate change risks are currently and primarily assessed from a territorial approach. Using the Intergovernmental Panel on Climate Change (IPCC) framework for analyzing climate risk (Reisinger et al., 2020), a territorial approach means that the assessment of hazards, exposure and vulnerability is limited to the same geographical area. However, we live in an interconnected world where the impacts of climate change are not confined by geographical borders—they can cross countries and continents, cascade across sectors, and disrupt and destabilize global systems. The transboundary nature of climate risk is increasingly acknowledged in adaptation settings, such as the 2021 EU Adaptation Strategy (EU, 2021) which repeatedly cites the importance of considering cascading impacts, but rarely is "ownership" of these risks explicitly assigned (Harris et al., 2022).

The designation of subnational governments as key actors in climate change adaptation policy appears to be appropriate when the risks associated with climate change are assessed from a "local" territorial approach and thus considering the diverse and context-specific responses that effective adaptation requires (Agder, 2001). However, in the case of transboundary climate risk, we are called to assess "to what extent there is a fit or mismatch between the problem scale and the governance scale" (Termeer and Dewulf, 2014). The interconnected nature of global systems, and transmission of climate risk through flows of trade, finance, natural resources, and movements of people, means that local actors are not always equipped with the global outlooks, information and mandates they would need to successfully adapt to these types of climate risk.

Still, recent studies in Norway, addressing representatives of subnational authorities, indicate that concern for this "new" type of "global" risk compared to the conventional "local" and territorially defined climate risk is increasing. In a survey sent out by the Norwegian Association of Local and Regional Authorities to all Norwegian municipalities, the share reporting that they expect to be "strongly" or "very strongly" affected by transboundary climate risks, explained as "climate change taking place in other parts of the world," increased from 15% in 2017 to 40% in 2021. The 2021 study ranked transboundary climate risks as number 3 of 7 predefined climate threats, and the category of climate threats with by far the largest percentage increase from 2017 to 2021 (Selseng et al., 2021). No similar studies are found from other countries (Selseng et al., 2021).

Given that local actors and jurisdictions in most countries are charged with the mandate to implement adaptation, and have an emerging awareness and understanding of the transboundary nature of climate risk, to what extent is it feasible for them to manage adaptation also to the transboundary climate risks they face? In this article we explore the management of transboundary climate risks at the sub-national level of governance, unlike the many other studies that have used the nation state as a reference point (Benzie et al., 2016; Hedlund et al., 2018; Benzie and Persson, 2019). Drawing on insights from three cases studies on attempts at local adaptation to transboundary climate risk (Norway, France, and Germany), we address the following research question: What are the problems and prospects for sub-national authorities to address transboundary climate risks?

2. What do we know about transboundary risks and how to address them?

Climate risks are usually viewed through a local lens, as the ways in which climate change impacts generate risk for a particular community or ecosystem depend on local conditions and societal characteristics (for example, whether a place is heavily settled or rural; the main sources of livelihoods; levels of wealth; the strength of local institutions and so forth). It is perhaps not surprising, therefore, that adaptation has traditionally been delegated to the local or national level to plan and implement. However, that leaves an important gap: how to handle climate risks that result from climate impacts in other jurisdictions. In this article, we call those transboundary climate risks. However, several other terms are also used in the academic and policy literature, such as transnational, cross-border, cascading, indirect and systemic, among others (Benzie et al., 2016).

Transboundary climate risks are risks that are being transmitted through various pathways from their physical point of origin (e.g., a drought or a flood) to one or more recipient regions. Carter et al. (2021) identifies seven pathways for the cross-border transmission of climate risks:

- Trade—the import and export of goods and services, as well as transport and processing sites.
- Finance—the flow of capital and other assets, such as foreign investment and remittances.
- People—tourism, pastoralism, migration or forced displacement.
- Psychological (also referred to as the "cognitive filter")—the perception and communication of climate risks and opportunities, especially as delivered by the media.
- Geopolitical—impacts on international relations, resource access, and foreign policy strategies of nations.
- Biophysical—shared ecosystems and resources, such as mountain ranges and river basins.
- Infrastructure—transport and telecommunications links.

One of the first national-level policy reports to specifically address transboundary climate risks was published in the United Kingdom in 2011 (Harris et al., 2022). Since then, transboundary risks have been mentioned in many national climate assessments, including of Canada, China, Finland, Germany, Kenya, Nauru, the Netherlands, Norway, Sweden, Switzerland, and the United States (Benzie and Persson, 2019). Some National Adaptation Plans and Nationally Determined Contributions (NDCs) have also referenced specific transboundary climate risks to particular sectors (Harris et al., 2022): indeed, the United States government has discussed a particular type of transboundary climate risks—international climate risks in the context of national security—since the 1980s (White House, 1987).

By their very definition, transboundary climate risks involve two or more jurisdictions: a country that experiences the initial climate hazard and a country (or more than one country) that experiences the resulting risk (Carter et al., 2021). Sub-national actors—such as local authorities, municipalities, and other forms of devolved governments—are rarely equipped with the mandates or capabilities to fully manage risks that arise from outside their jurisdictions (Young and Jones, 2016; Harris et al., 2022). While it may be within their remits to mitigate or manage the resulting risk—creating food banks, for example, to diminish the effect of reduced availability of a critical food import because of a climate impact—they are unlikely to be able to directly influence either the "source" of the risk or factors along the chain(s) of impact, through the design of a new trade agreement, for example. This leaves them to act in a short-term "responsive" capacity rather than a long-term "preventative" capacity.

International relations are normally the domain of central governments at the national level (choreographed by finance, foreign policy or trade ministries for example), or regulated by international organizations, norms, and laws. This is certainly the case in the public sector, but it also applies to the private and social sectors with regards to capabilities and mandates at different scales This points to a mismatch of scale when assigning ownership (implicitly or explicitly) of transboundary climate risks to the sub-national level of governance. It is not only a question of mandate or authority. The relationships local actors tend to hold arguably do not often extend across an administrative border (to influence those who might be better positioned to pay for the risk, manage the risk, and are ultimately accountable for the risk) and they are less likely to be able to leverage others to act in these capacities (Young and Jones, 2016; Harris et al., 2022). There is also the question of administrative capacity to successfully implement measures to coordinate and manage the risk. Local actors tend to have more limited resources than national or international entities, and a more constrained operating environment within which to work. They are, essentially, small actors in a big world. This makes it harder for them to gain access to information, harder to mobilize resources (both financial and technical) to manage risks of a complex and dynamic nature, harder to hold enough sway to oversee the large-scale reforms that may be needed to prevent such risks from occurring, and harder to build in the redundancy and flexibility needed to cope with and respond to such risks when they do. Both their spheres of interest and influence are limited.

Still, sub-national actors can play an important role in setting an agenda in public debate and applying pressure on national and international entities to act. Such bottom-up or indirect actions from sub-national authorities are well-known in climate change mitigation. Front-runner municipalities, as well as national and international representatives of sub-national governments, have played an important role in advocating for ambitious GHG mitigation goals and the introduction of more effective national policy measures to support sub-national GHG-mitigation efforts (Aall et al., 2007).

Already in the first IPCC special report dealing with climate change adaptation, from 2012, the question of transformative strategies for adaptation is raised. The report presents the idea that some strategies for managing climate risks involve mere adjustments of current activities, whereas others require "transformative changes": "the altering of fundamental attributes of a system (including value systems; regulatory, legislative, or bureaucratic regimes; financial institutions; and technological or biological systems)" (IPCC, 2012, p. 4). This should be compared to the definition of incremental adaptation (op. cit.), as "the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities."

The most recent IPCC contribution, the working group II report of the sixth assessment report (AR6) on impacts, adaptation, and vulnerability states that "in human systems, adaptation can be anticipatory or reactive, as well as incremental and/or transformational" (IPCC, 2022, p. 5). In the same report, the concept of transformation is linked to the concept of adaptation limits and the differentiation between hard and soft adaptation limits. While the notion of hard limits applies to a situation in which a system cannot be secured from intolerable risks through adaptive actions, soft limits imply that no concrete adaptation actions are currently available, but (radical) options may exist and (if so) need to be rapidly developed and implemented. Such alternatives will often be of a transformative as opposed to incremental nature (Dow et al., 2013). This insight is formulated in following way in the summary for policymakers: "Transitioning from incremental to transformational adaptation can help overcome soft adaptation limits" (IPCC, 2022, p. 27).

In this light, the limited capabilities of sub-national actors—under current conditions—to act effectively to mitigate or manage transboundary climate risks could be seen not as an absolute barrier but as a conditional "soft" limit or barrier. Therefore, overcoming such a barrier could arguably be achieved by transitioning from incremental to transformational adaptation.

3. Theoretical and analytical framework: what works where?

Climate change adaptation governance has aimed to be truly multi-level since and as a result of the adoption of the Paris Agreement on Climate Change in 2015 (Gonzales-Iwanciw et al., 2020). The Paris Agreement includes normative principles for the governance of adaptation, underpinning the necessity of both local and national environmental policy development to be under the strong influence of international agreements and policy instruments—a situation that has gained increasing momentum in the last couple of decades (Bulkeley, 2001; Andonova et al., 2009; Amundsen et al., 2010). The integration of adaptation into government (and governance) across levels and scales is considered critical to long-term climate resilience (Bulkeley, 2013). A crucial question then, in addressing various forms of climate risk, is what role is best suited to what level of governance, thus helping us to gain "an understanding of adaptation processes [that] allow interventions and planned adaptations at the most appropriate scales" (Agder, 2001, p. 1).

To guide our study, we have been inspired by an analytical framework used to evaluate a state-initiated major reform of local environmental policy in Norway (Naustadslid, 1994). The framework is related to the notion of governance levels and the idea that the characteristics of an environmental problem should determine which level of governance is most appropriate in dealing with the problem in question. The framework distinguishes between "concentrated" and "dispersed" environmental problems alongside two dimensions—"origin"

TABLE 1 A typology of environmental problems (adapted from Naustadslid, 1994).

		Cause	
		Concentrated	Dispersed
Impact	Concentrated	(1) Local problem, e.g., local pollution from a local factory	(2) Global-local problem, e.g., acid rain originating from several sources abroad causing fish death in Norwegian salmon rivers
	Dispersed	(3) Local-global, e.g., radioactive fallout from the Chernobyl nuclear power plant affecting large parts of Europe	(4) Global problem, e.g., the "climate problem" with a multitude of small and large emission sources causing global warming

and "manifestation"—of environmental problems. Based on this framework, Naustadslid (1994) formulated a hypothesis that local governments will primarily relate to environmental problems that can be characterized as of "concentrated" origin and manifestation—the true "local" environmental problems—unlike those that are "diffuse" in both origin and manifestation—the true "global" environmental problems. According to Naustadslid, the assessment of local environmental policy reform in Norway corroborated this hypothesis. Naustadslid (1994, p. 22) points out that "local governance bodies in the first place hardly can function as activators in the work with more superior, global environment problems... the municipalities give priority to issues which lead to visible local gains." Naustdalslid further comments that "if one wants the municipalities to give priority to global environmental issues, there is a need for national coordination of local environmental policy." He claims that "[such] an environmental-political U-turn presupposes changes in people's values and priorities" (Naustadslid, 1994, p. 25).

Aall (2012) has adapted Naustdalslid's framework of environmental problems to a climate context and points out that conventional climate change adaptation, addressing "local" climate risks, has more in common with the category "local" than "global" environmental problem, whereas the mitigation-focused climate policy clearly falls under the latter category. This division of the climate problem is reflected—in line with Naustdalslid's model—by the fact that adaptation is largely left to subnational actors, while mitigation is to a greater extent under the purview of national and international governance actors.

Applying the framework presented in Table 1 to the "new" form of climate risks—transboundary risks—we can identify three varieties of such risks:

- Category 2 "Global-local": for example, when various kinds of climate events in various countries affect import flows of climate-sensitive goods and services to one country, typically with a high degree of open economy.
- Category 3 "Local-global": for example, when climate events in one country lead to the emigration of climate refugees to different countries.
- Category 4 "global-global": for example, when climate hazards reduce the production of food in many countries at the same time and thus leads to a global increase in food prices and a subsequent reduction in global food security.

In-depth case studies of frontrunners indicate that municipalities *can* give priority to other forms of environmental problems than distinctly local ones *if* local actors are able to transform the "global" problem into a "local" one (Aall, 2000; Corell, 2003; Kates et al., 2003). The extensive activities under the Local Agenda 21 policy initiative through the 1990s illustrates this point (Lafferty and Eckerberg, 1998; Lafferty, 2001). To achieve this, there is a need to develop appropriate concepts and metaphors which bring out the connection between the local and the global (Hägerstrand, 1991) as well as addressing the challenges noted earlier regarding interest and influence, mandate, and capability. Given that these conditions are present, local authorities can be more capable than national authorities in the task of translating a global issue into a local context—thereby making the problem at stake comprehensible and relevant for policy action (Aall, 2000).

A tool which can prove useful in translating "from global to local" which has also gained increasing interest in climate research is the creation and use of boundary objects and the identification or creation of "boundary organizations." The latter is defined by Dannevig et al. (2019) as an organization that can straddle the two domains of science and policy due to its dual duty to both. Boundary organizations, with sufficient legitimacy, may create bridges between stakeholders that are not used to working together and facilitate the transfer of different kinds of knowledge (Callon et al., 2001; Gustafsson and Lidskog, 2017). They may also increase the usability of climate knowledge for adaptation action across a wider range of users (Kirchhoff et al., 2014).

Boundary organizations can make use of and will often focus on developing specific boundary objects. According to Leigh (2010), a boundary object is information which can be presented in various formats (maps, figures etc.), used in various ways, by various actors for the purpose of creating collaborative work across scales. Using boundary objects can lead to institutional conflicts as well as innovations (Zietsma and Lawrence, 2010). Thus, following Spee and Jarzabkowski (2009), referred to by Willems and Giezen (2022), boundary objects can be utilized as artifacts to either change, maintain, or disrupt institutions.

Francxo-Torres et al. (2020) point at the important role boundary objects can play in sustainability transitions. They illustrate this point by analyzing the Copenhagen municipality's transition to more sustainable stormwater management between 2007 and 2019, which was strongly affected by the most intense local cloudburst ever recorded on 2 July 2011. In this case, it was the mere work on climate change adaptation that served as a boundary object. The authors summarize three ways in which the actors used boundary objects (op.cit.): (1) to articulate a specific challenge (e.g., a climate risk), (2) to mobilize the necessary resources to address the challenge in question (e.g., an adaptation measure), and (3) to build cooperation across actors with conflicting interests. In this example, the boundary object utilized is a conceptual artifact.

An important enabling factor for new challenges to become a salient policy issue is the formation of boundary objects and boundary organizations. This has proven important for the case of climate change adaptation (Dannevig et al., 2019), although so far (mostly, if not only) in the context of "local" climate risks. In this study, we look at the utilization of the Impact Chain framework as a boundary object and how effective it may be in relation to transboundary, and not just local, climate risk; and if so, what role it can play in putting transboundary climate risk on the local policy agenda. See Harris et al. (2022) for a justification of the use of the impact chain framework in the context of a transboundary climate risk assessment (including its innovative focus on risk drivers and the "cause–effect relationships" that define them, the emphasis on a systems-first approach, the opportunities it provides to distill "entry points" for adaptation responses that strengthen resilience at multiple points in a system, and its participatory and flexible process).

4. Applied method: what have we looked for?

The study consists of three cases: Paris in France, Klepp in Norway, and the river harbors in the Upper Rhine region of France (see Table 2). The cases cover three different risk pathways, and a large variety of policy sectors, actors, and instruments. The great variation in the characteristics of the selected cases illustrates what characterizes transboundary risk: this is a policy topic with very large differences in how the risk materializes, which drivers create the risk, and which actors are affected; that is, significantly more complex than is normal for many of the conventional forms of local climate risks. Our aim in selecting these particular cases has not been to cover all varieties of transboundary climate risks, but to illustrate the magnitude of variation.

All cases were based on the Impact Chain framework for structuring the work of analyzing climate risks. This framework consists of seven stages of action: (1) scoping, (2) developing impact chains, (3) identifying and selecting indicators, (4) data acquisition and management, (5) normalizing indicators, (6) weighting, and (7) aggregating indicators and components (Hagenlocher et al., 2018). The first three are by nature highly participative, whereas the latter five are highly operational (Fritzsche et al., 2014). For a detailed presentation and discussion of the seven stages, see Petutschnig et al. (2023) in this special collection. When applying this framework to the three cases, we used an adapted version of the protocol developed by Harris et al. (2022) for assessing transboundary climate risk in case-study research.

The process starts with scoping and classification, to define and characterize the system of concern, identify the key actors and relationships between them, and select one or more transboundary climate risks as the unit of analysis based on their significance. In this study, the three cases were selected and/or initiated by the research team based on their potential to depict transboundary climate risks at the outset and they were therefore classified as "transboundary climate risk centric," with the potential to advance the state of knowledge accordingly.

The next three stages are risk assessment, risk ownership and evaluation, which are interlinked with several feedback loops. This study used two different assessment approaches. The Paris case study performed a full technical risk assessment by following all steps in the original impact chain methodology, including both qualitative and quantitative evaluation of exposed or vulnerable system components. The Klepp and Upper Rhine case studies used qualitative approaches and thus performed a reduced version of the original impact chain methodology. They did detect important links and nodes of the impact chain but did not have enough data or well-known nodes and links established to go in depth with a full technical risk assessment to select indicators and quantify the factors leading to risk.

The risk ownership stage explores answers to three questions posed by Young et al. (2015): Who pays for the risk, who manages (is responsible for) the risk, and who is accountable for the risk? Each question was applied to all governance scales and administrative levels in the case studies. However, the questions were rephrased in the Paris case study to better suit the political and sensitive matter at hand, i.e., climate migration. There the focus was set on who can act and who should take more action.

The next stage according to Harris et al. (2022) should be to select suitable adaptation options (the best options evolving through evaluation of the risk and knowledge of who can manage the risk). In the final stage, presentation and iteration, several meetings and workshops were held in each case to involve and inform the stakeholders in the findings and to invite actors of concern in the process to iterate the results and increase uptake in policy and practice. Due to time constraints in the UNCHAIN project, none of the three case studies was able to fully cover the last two stages—but indications were collected of where local processes were heading in terms of deciding on adaptation measures.

In all three cases, stakeholder groups were involved in formulating the research questions, in addition to improving their knowledge and understanding of the issue, through deliberate co-production (Nilsson et al., 2017). To ensure real and equal influence in addition to ownership of the results, the capacity-building process was tailored to each stakeholder group.

The three case studies have followed the protocol from Harris et al. (2022) to a varying degree, depending on the stakeholders' maturity of knowledge concerning transboundary climate risk. Some stakeholders were introduced to the concept during the case study, while others had been managing such risks for a long time—without necessarily labeling them as "transboundary climate risks."

Data to describe the implementation and outcome of the case studies was collected in the following ways:

- Participant observation by researchers (who were also involved as advisers and facilitators in the case studies) during workshops with local stakeholders.
- Analysis of relevant background material describing the policy context in which the case studies took place, such as planning programmes or other policy documents.
- Analysis of specific outputs from the case studies that could qualify as conceptual or material boundary objects.
- Post-intervention interviews with involved local stakeholders.

In the sections below, we present the individual cases using a similar chapter division: "framing," "process," "output," "outcome," and "barriers and enabling factors." For more detailed information about the cases, see a full list of individual case descriptions on the UNCHAIN website (www.unchain.no).

TABLE 2 Cases for analyzing transboundary climate risks.

Case characteristics	The City of Paris, France	The rural municipality of Klepp, Norway	The Upper Rhine region, France
Risk pathway	People	Trade	Biophysical and trade
Policy sector	Migration and integration	Agriculture and livestock production	Freight transportation and river regulation
Main actors involved	Municipality (climate division, delegation for resilience strategy, social action center)	Local authority, county, local agricultural organizations	Central Commission for the Navigation of the Rhine, the French navigation authority, local authorities (ports management)
Policy instruments	Climate change adaptation plan, climate change adaptation strategy, resilience strategy	Municipality master plan, municipal agriculture plan	International and EU rules for transportation on Rhine, European regulations on infrastructure investments, funds in new infrastructures, co-operation and communication tools
Case process	Connected to a follow-up of the city climate plan on climate vulnerabilities	Connected to ongoing processes of updating the municipal master plan, and developing a new municipal agriculture plan	Initiated by the researchers taking part in the UNCHAIN project

5. Climate migration, City of Paris, France

5.1. Framing

As a participant in the global "100 Resilient Cities" initiative initiated by The Rockefeller Foundation in 2013, Paris adopted a resilience strategy of which climate change is one of six predefined dimensions. The Resilience strategy resolutely supports inclusion at local (neighborhood scales) and encourages building citizen networks. Taken together, these strategies provide a strong foundation for better urban resilience toward climate change.

Parallel to this initiative, the City of Paris in 2012 carried out the first territorial diagnosis of climate change vulnerability, highlighting major environmental and socioeconomic risks and opportunities. At the time, climate migration was already identified as a potential transboundary climate risk the city may have to deal with in future decades. In 2015, the City of Paris implemented its first climate change adaptation strategy. The document clearly stated anticipation of climate migration as a strategic goal. The underlying objectives were twofold: prepare a welcoming living environment for newcomers, and foster cooperation both within Paris and toward other foreign territories affected by climate change. The strategy also mandated further investigation into potential climate migration flows toward the city. In the context of its new climate plan (made mandatory in 2016), which deals with both mitigation and adaptation, the city council requested in 2020 an update of its territorial climate vulnerability assessment (Cauchy et al., 2021). This comprised a standalone study focused on climate migration (Arvis and Baret, 2021).

The latter study explores the links between climate change and the international and domestic migration patterns involving Paris. It highlights that despite the progress of thematic research on climate migrations, providing quantified estimates of future migration flows toward a specific destination such as Paris remains out of reach. A logical follow-up action to this study was to keep improving the knowledge of climate migrations through case studies in Africa or Asia using empirical approaches. The City Office in charge of climate matters thus acceded to the request for an UNCHAIN case study entailing progress on climate migration knowledge and adaptation responses at the city level. The case study focuses on transboundary migration triggered by environmental and climate factors between Senegal and the City of Paris. This specific case is justified by the important colonial and diasporic links between Senegal and France.

5.2. Process

From the onset, the City Office in charge of climate matters had the formal responsibility to keep informed of the research tasks and to involve relevant stakeholders, especially when assessing adaptive capacities at the municipality level. They were also responsible for the practical aspects of organizing the workshop to the study involved stakeholders all along the impact chain from Senegal to France. Thus, remote meetings were held with stakeholders to inform about impact chain development and indicator selection. For the "sender" impact chain, Senegalese stakeholders included academics, civil servants from the Ministry of Agriculture, and researchers from Consultative Group for International Agricultural Research (CGIAR). For the "receiver" impact chain, stakeholders interviewed included academics and civil servants working for the City of Paris (adaptation division, delegation to the resilience strategy, and social action center).

In the final stage, a workshop was held under the supervision of the city of Paris to share the results of impact chain development and explore adaptation options. Because of the political sensitive nature of the issue, only the portion of the risk and adaptation responses that are "owned" by Paris were explicitly considered in the workshop. During the workshop, stakeholder mapping was evaluated, and several adaptation options were discussed in terms of their feasibility and efficiency.

5.3. Output

The case work led to the development of two correlated impact chains (cf. Figure 1). The first impact chain ("risk sender") models the components of the decision to migrate

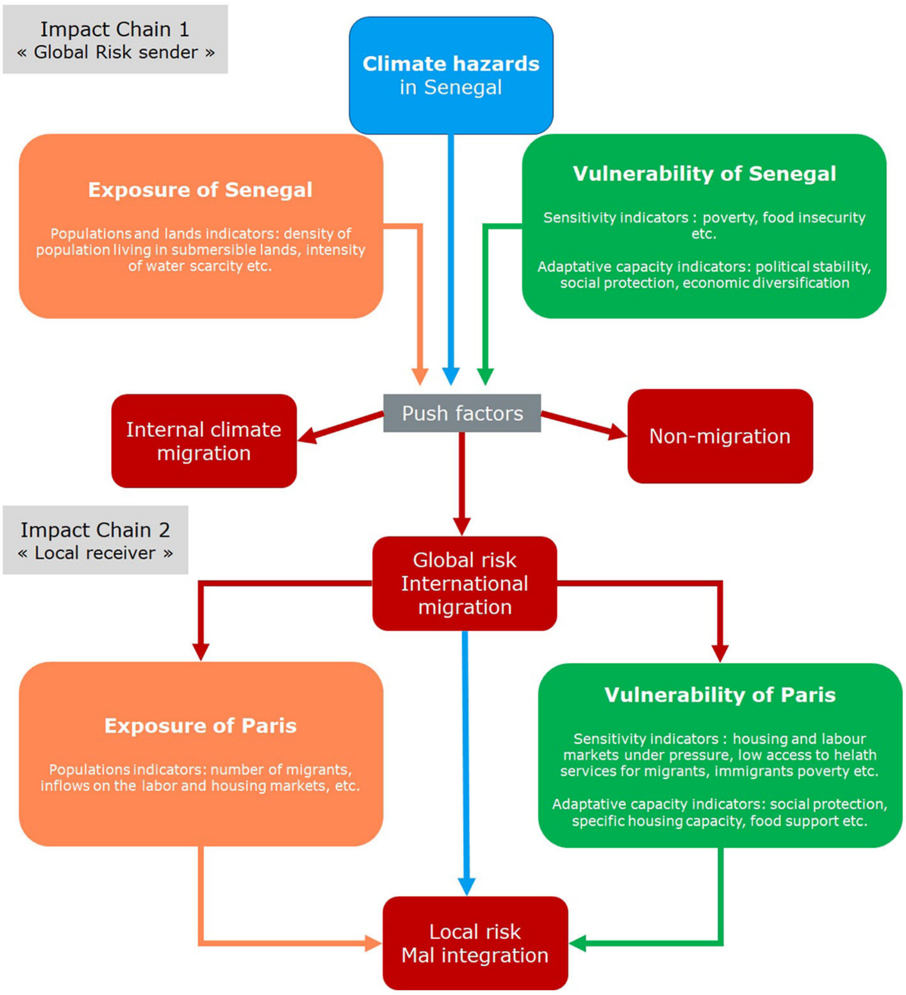

FIGURE 1
Impact chains related to the topic of climate migration for the case of Paris.

for rural Senegalese, accounting for hazard occurrence as well as the exposure and vulnerability. The outcome of the individual arbitrage is migration (internal or international), or immobility (willing or trapped). The second impact chain ("risk receiver") considers the integration process for international migrants, accounting for the exposure and vulnerability of Paris in multiple dimensions (economic, social, cultural, linguistic, residential).

The aggregation and weighting of the indicators for the first "sender" impact chain results in a *global risk score*. This score is used as the input for the *hazard* component in the second "receiver" impact chain, which does not directly reference any climate hazards. Risk scores were computed for three different representative concentration pathways (RCP) scenarios (RCP2.6, RCP 4.5, and RCP8.5). These risk scores are heavily influenced by the choice of methodology for aggregation and weighting, so their value has no significance in absolute terms. We instead interpret them in terms of their evolution over time or between climate change scenarios. The *global risk score* for the Senegal "sender" impact chain shows a logical increase from RCP2.6 to RCP8.5. For the Paris "receiver" impact chain, the variation of the risk score is low owing to the stability of the exposure and vulnerability components.

5.4. Outcomes

Defining *risk ownership* of the migrant risk is subjective and ideologically charged. On the "sender" side, the conundrum is the following: deterioration of economic conditions in the country of origin can be interpreted as a failure to adapt by the authorities, yet the root cause of climate change lies with developed countries. On the "receiver" side, the responsibility for welcoming and integrating migrants' inflows might be attributed to authorities of the host country (as it would be for "regular" asylum). However, the question could be asked about the potential sustaining role of the "sender," or the involvement, either voluntary or incentivized, of already settled diaspora from the same origin. Faced with the impossibility to clearly determine responsibility, several stakeholders favored a capacity-based approach, replacing the question "who is liable?" with "who has the means to act?" In the following, only *adaptation options* intervening at the *local* level that emerged during the case-process and during the final workshop are presented.

In the case of migration flows, there are several facets to the adaptation mechanism. On one hand, migration is considered an individual adaptation pathway for those leaving the country of origin. Better collective adaptation in the country of origin may lead to fewer out-migrations. For the host country, adaptation to migration flows requires multiple layers of action.

Paris is solely responsible, both as a municipality and as a department, for some sectors that are key for integration such as welfare allocation, social action, cultural and local services, public spaces, etc. For housing, responsibility is shared between national programmes, which own social housing units and oversees regulations, and the city, which owns and builds social housing and allocates housing allowances.

There are shortcomings in the current organizational scheme: the so-called "Refugee coordination platform," meant to coordinate action between municipal departments and other actors (state or non-state), was canceled following the last municipal elections and replaced by an information meeting. Coordination between different entities is shifting and often lacking, even more so as much of the Partnerships are important to implementing effective actions for migrant integration.

"Integration" is multi-dimensional and refers to migrants being able to access housing, employment, having access to social services, to education or vocational training, and health services. Two key areas are housing and employment.

Housing is a key condition of both migrants' wellbeing and their social integration. This is one of the biggest challenges in the Paris area, in which the housing market is already strained and the cost of housing high. Several types of housing allowances are afforded by the City and accessible to migrants: funds and emergency housing sites operationally managed by non-profits. Yet availability and cost of housing remains a major problem. More radical solutions include temporary seizing of private vacant housing. For short-term lodgings, suggestions include partnerships with Airbnb or the traditional hotel sector or citizen participation.

Employment is a pre-requisite to having a stable income, improving access to accommodations, and fully integrating migrants in the host society by allowing interactions with natives. Solutions at City level include financial support to non-profit organizations promoting migrant employment. The city has also developed networks with the private sector to encourage employment of migrants and professional training. This private sector is particularly active, with independent NGOs, as well as caritative organizations working for integration through (self-)employment. Skill matching initiatives were mentioned to both improve migrant employment and meet employer needs in the region. Another pathway for action is to reform administrative constraints for working while awaiting judgement on residence permits, or speed up the administrative procedure, to limit the loss of human capital and self-confidence (Ukrayinchuk and Havrylchyk, 2020).

5.5. Barriers and enabling factors

In methodological terms, enabling factors include relying on co-production processes for the full duration of the impact chain (from Senegal to Paris), involving a wide range of stakeholders (institutions, researchers) who displayed strong commitment. Yet, the timing of the study, coinciding both with the COVID-19 pandemic, French presidential elections, and the Ukrainian refugee crisis, limited the amount of involvement from authorities.

Barriers to deploying the impact chain framework are significant, starting with its complex and data-intensive nature. The method incorporates some major assumptions, such as the transition between the two impact chains. The "receiver" impact chain does not use a climate hazard but a cascading anthropological hazard (migration), which implies that the risk induced by emigration from Senegal toward any destination is anything but precisely predictable in a context of climate change. Indeed, even if the choice of destination is influenced by some factors yet well identified (distance, network, former colonial link...), climatic factors bring different results on emigration rates (Beine and Parsons, 2015). The second impact chain does not focus on Senegalese immigrants, but on global migrant inflow. Finally, impact chain outputs are intricate. The global risk score obtained from aggregating indicators has no intrinsic value. It is only significant when interpreting the variation over time and through several scenarios.

6. Import of soy in husbandry production, Klepp municipality, Norway

6.1. Framing

Klepp municipality is a rural and a medium-sized municipality in a Norwegian context, with around 20,000 inhabitants. The municipality has an area of 115 km^2 and agriculture takes up 67% of this. Klepp is situated in the south-west part of Norway in one of the most productive agricultural regions of Norway. The main production is gras for local animal fodder, followed by corn, vegetables, potatoes, and vegetable production in greenhouses. The area has a wide range of animal husbandry: dairy cows, beef cattle, sheep, pigs, and poultry.

Prior to the UNCAIN project, Klepp municipality had started the process to revise both the agriculture plan and the municipal master plan. Rogaland county invited Klepp municipality into the UNCHAIN project based on a previous project in which the impact chain framework had been used to analyse climate risks at the county level (Jansen et al., 2019). The Klepp case had a twofold research question: (1) How can regional governments best help municipalities in analyzing climate risk; and (2) how can a municipality analyse transboundary climate risks? The case was limited to husbandry production. To support the needs of the local planning process, we included the task of assisting Klepp municipality to also address conventional local climate risks in connection with making the local agriculture plan.

6.2. Process

The case project was built around the municipality's progress plan and milestones for their planning processes. The municipality was responsible for the practical aspects of organizing meetings and workshops and selected and invited local actors to be involved. The county municipality acted as coordinator for the project, and together with the county governor guided the municipality in its work with analyzing climate risk and reflecting on options for climate change adaptation, while the researchers acted as advisors and facilitators on how to analyse climate risks.

Two information meetings were held prior to the actual risk assessment process: One with key-representatives of the administration in the municipality together with representatives of the county municipality and the county governor, and one with the municipal council. The main activities in the risk analysis process were two workshops with stakeholders from the local and regional municipality (administration and elected representatives), the county governor, and representatives from the agriculture sector. The later included representatives from regional and local agrarian organization, Norwegian agricultural advisory service, the dairy company Tine, Horticultural association—department Rogaland, and the Norwegian agricultural cooperative.

In the first workshop the stakeholders worked in groups to map out local hazards, vulnerability, exposure, and analyse local climate risks for the agriculture production, and to start discussing possible adaptation measures. One group started preliminary work on transboundary climate risks where they discussed possible risks linked to imported commodities.

The second workshop was committed to transboundary climate risks. Prior to the workshop a flow chart depicting the supply chain of resources going into the local farm from an international level was developed by the researchers in collaboration with the stakeholder representatives that discussed transboundary climate risks during the first workshop by means of direct contact through telephone and email. The flow chart was used as an instrument to single out which "nodes" and "links" may be exposed to climate risks and which import commodities to prioritize for further analysis.

Subsequently, interviews were conducted after the second workshop to follow up key stakeholders from the municipality, regional government, and the regional agrarian association on how they perceive local risk vs. transboundary climate risks and if they used the results.

6.3. Output

The concrete output of the case was two separate reports written by the researchers, one about the conventional local climate risks (Holm and Aall, 2021) and one about the transboundary climate risks (Holm, 2021). The core knowledge that came out of the latter was a flow chart developed with stakeholders depicting the flow of input factors for husbandry production (cf. Figure 2). The flow chart was presented as an indicator for climate risks, informing the stakeholders of which elements in the value chain that might be affected by climate hazards, and then let this be a basis for discussing at the workshop possible consequences regarding transboundary climate risks and subsequent needs and options for adapting to such risks. Based on the information that emerged in the flowchart, most attention was paid to risks linked to the heavy dependence on imported soybeans to produce concentrated feed.

During the workshop and the subsequent interviews of some of the key actors, options for adaptation strategies were discussed covering the whole scale from reactive, protective, preventive, to transformative strategies. Food security through national storage facilities was discussed as a reactive adaptation strategy. Then the overall preparedness and capacity to withstand a food crisis (e.g., disruption in supply chains) is enhanced. When it comes to securing the import of soybeans the Norwegian government has not undertaken a responsibility. However, they have a responsibility through the agricultural settlement that Norway should be more self-sufficient.

A protective measure could be to spread imports of soybeans from more countries than Brazil and Canada, which currently covers all imports. In the event, this could mean that Norway would have to give up its environmental protection motivated policy of only using non-GMO (genetically modified organisms) soybeans to produce concentrated feed.

Adaptation options, situated more toward the preventive and to some extent transformative end of the scale, were also mentioned. One would be to increase or switch to Norwegian-produced protein source to produce concentrated feed. Another option would be converting to organic farming to replace some of the imported (soybean-based concentrated feed) with local grazeland) means of production. The option of switching from livestock production to other forms of agricultural production (e.g., vegetables) was also mentioned.

The workshops, meetings, interviews, and communication in general happened digitally during the Covid pandemic. Even though digital meetings and digital tools can create good workshops, the ability to sit together, create connections, discuss, and draw conclusions was lost. Working with such a broad set of stakeholders their knowledge and experience with digital meetings and tools varies greatly and always create interruptions during workshops and discussions.

6.4. Outcomes

The project was carried out as part of two ongoing and independent of the UNCHAIN project local planning processes: (primarily) an agriculture plan and (to some extent) the municipal master plan. Both plans were submitted for consultation after the project was finished, but draft versions of the planning documents give indications of possible outcomes.

A first level indicator of a possible outcome related to is the fact that the first report that came out of the project—on the local

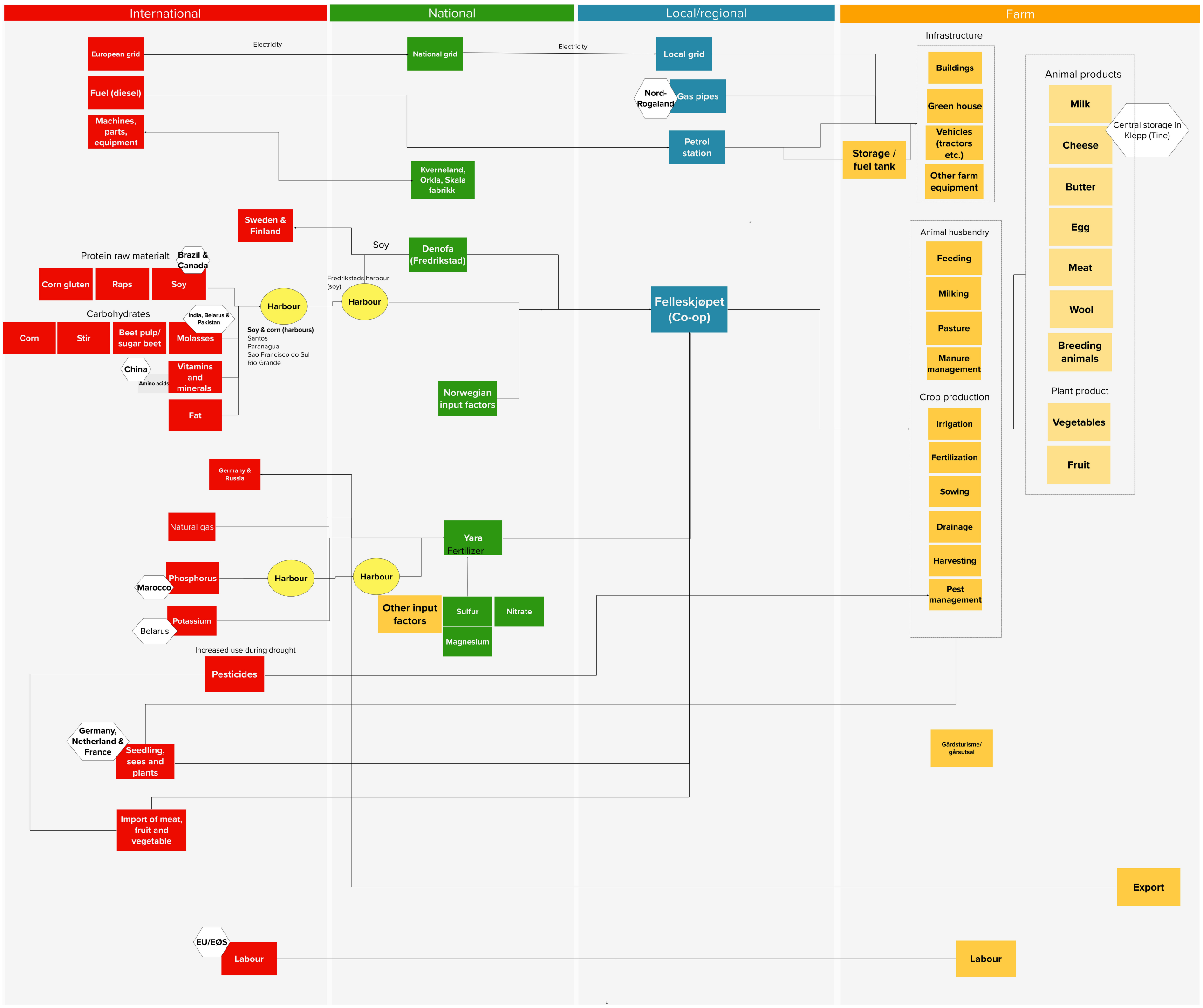

FIGURE 2
A flow chart of input factors for livestock production in Klepp municipality in Norway developed in dialog with and used to discuss among local stakeholders the transboundary climate risks and adaptation options.

climate risks (Holm and Aall, 2021)—is linked up in the draft web-version of both the *agriculture* plan[1] and the municipal master plan.[2]

In the municipal master plan, climate risk is thoroughly discussed in chapter 10 "Long-term land-use and transport development."[3] The UNCHAIN-project is referred to, and a combined summary from the two workshops—on local climate risks and transboundary climate risks—is presented (cf. Table 3).

6.5. Barriers and enabling factors

The flow chart presented in Figure 3 was acknowledged by the non-researchers involved in the workshops as a good tool for creating an understanding of what local as well as transboundary climate risk can entail and form the knowledge basis to develop ways of how to relate to the various forms of climate risk.

Working with a broad set of stakeholders across the public sector and the agriculture sector helped to identify important nodes and links through the supply chain. Furthermore, this also helped to identify key stakeholders that already had more knowledge about the threats and vulnerabilities to specific imported goods (e.g., soybeans) and could drive the discussion and development

1 https://pub.framsikt.net/plan/klepp/plan-afe5d8e8-10a1-43d6-a0c0-18cbdc9727aa/#/generic/summary/62f81e85-1686-4f1a-bc2d-85b410f72f44 (in Norwegian).

2 https://pub.framsikt.net/plan/klepp/plan-20956848-7c9e-4d7b-ab71-3ebcc6cf4683/#/generic/summary/2771bbbd-f536-4f2b-beeb-25dcc5708e72 (in Norwegian).

3 https://pub.framsikt.net/plan/klepp/plan-20956848-7c9e-4d7b-ab71-3ebcc6cf4683/#/generic/summary/7b052c17-6670-426b-998b-80249759c65a (in Norwegian).

TABLE 3 A summary of the workshops on local and transboundary climate risks presented in the draft version of the municipal master plan of Klepp municipality.

Hazard	Vulnerability
• Increase temperature • Longer growing season • Change in temperature (on-off winter/spring frost, periods with thawing and freezing) • Precipitation: increased frequency and intensity (extreme precipitation) • Floods (flooding due to rain) -> increased runoff (emergence of cyanobacteria) • Extreme weather events/storm wind • Storm surge + rise in sea level • "Locked" weather systems	• Politics—agriculture policies (increased demand to area used to spread fertilizer), climate policies (demands for electrification) and public health policies (change in dietary habits) • Import of goods (the import of soy might decline and lead to increase in prices • Dismantling of topsoil and marshlands • Shorter harvesting season • Emerging animal diseases (ticks, pests, and fungi) • Storage capacity for fertilizer • Knowledge (lack of or wrong knowledge) • Recruitment to the agriculture sector • Poor drainage systems • Spatial planning and development that may lead to water going astray • Infrastructure (transportation, roads, supply of energy and security of supply) • Road construction and division of land
Exposure	**Risk**
• Food security: crop failure • Arable area (soils and soil productivity) • Logistics: more difficult to drive in the field • Infrastructure: damage on buildings, power grid and transportation network • Area: more prone to erosion, damage on pasture which can change the length of the grazing season, the mowing and number of mows is changed due to climate change • Animal welfare: more illnesses, pests, and invasive species • Water course: erosion, draft • The soy imports to fodder • The trading markets • Peatlands • Culture landscape	• Loss of jobs—financial vulnerabilities that cause an increase in costs and psychological stress • Crop failure/loss of arable land (reduced food security, soil compaction that damage the soil structure and crop production) • The systematic use of pesticides may increase • Deterioration of ecosystem and ecosystem services • Floods, erosion, stormwater, changed water flow • Biodiversity loss • Disruption in the transport network • Reduced fodder production • Sand dunes disappear • A constant high-water level • Overgrowth

of the impact chain map further. By including the project into the processes of renewing the agriculture plan and the municipal master plan it became easier for the municipality to incorporate the outcome of the risk analysis into conventional policy making process, thereby increasing the chances of making adaptation to transboundary climate risks a salient issue on the policy agenda in line with that of conventional "local" climate risks.

At the same time, both the researchers and the users recognized that better tools and access to more relevant data is needed to develop effective policy measures.

But an even more important barrier is the absence of transboundary climate risks on the national climate change adaptation agenda, and thus the necessary clarifications of how the responsibility for addressing this type of risk is to be distributed between public and private policy actors, and in the next round the distribution of responsibility between the different geographical levels of policy actors. Such clarifications must be made specifically for different policy sectors; in this case within the agricultural sector—a challenge that was highlighted by the actors who participated in the second workshop.

7. River transportation, Upper Rhine region, France

7.1. Framing

The Rhine is evolving toward a rain-fed river (Parmet et al., 1994). The winter discharge increases, which can have consequences for safety, and summer discharge decreases with consequences for shipping, industry, agriculture, and ecology. In 2018, the Rhine transport sector experienced an unprecedented low-water crisis, during which large cargo vessels were no longer able to navigate on certain sections of the river. This led to a major disruption in the inland waterway transport. The severity of this crisis, which was the result of several months of drought, reinforced by heat waves and low rainfall over the same period, caused an upheaval in the inland navigation sector.

The transboundary aspect is the result from the biophysical dimension of the river as it crosses several countries but also from trade and political dimensions. The Rhine has an international status, which was decided 200 years ago driven by trade considerations. Environmental issues won consideration in the 1970's and got to a peak with the Sandoz chemical spill in 1986, a major environmental disaster caused by a fire and its subsequent extinguishing at Sandoz agrochemical storehouse located in Basel-Landschaft, Switzerland, which released toxic agrochemicals into the Rhine river. The international restoration plan is an example of multilevel agentively illustrating the willingness to respond in a successful way to a major environmental crisis. The question is whether such willingness can be repeated in this new type of transboundary crisis when the problem is caused by global climate change, not a specific local critical event.

7.2. Process

Taking advantage of the relationships established through a previous project addressing the Upper Rhine sensitivity to climate change (the project Clim'Ability financed by the Interreg V program from 2016 to 2022), the research team was able to establish a co-operation with the port authorities of the Upper Rhine region. This process has been enriched by the so-called "Inventive Design Method" (Cavallucci, 2018; Coulibaly et al., 2022), which is a participatory engineering approach to innovative solutions for problematic situations or industrial deadlocks. The understanding of the vulnerability of the firms and the territories to low waters has thus benefited from a methodological mix: semi-directive interviews with key stakeholders (transport providers, importers/exporters using inland waterway transport) concerned by low waters, and the implementation of the inventive design method to stimulate a cooperative understanding of the collective vulnerability to the risk.

7.3. Output

Different variables have been integrated to define an impact chain (Figure 3) which considers the cascading effects (Vinke et al., 2021) and the possible multiple effects of low waters on shippers, firms, and ports to make goods circulate.

Some of the other significant outputs were a collective decision about the issue that federates people, who are usually in economic competition; a collective map of partial solutions provided to resolve this common issue; and a map providing the distribution of knowledge and ignorance.

The crossing of data from individual interviews and collective situations made it possible to identify areas of ignorance among the stakeholders, as well as implicit collective norms.

From the above-mentioned material, different adaptation strategies have been proposed, discussed, and weighted through. We distinguish three main strategies: reactive adaptation, transformative infrastructural adaptation, and radical system transformation. Each strategy is based on specific technical, organizational, institutional modalities and a certain degree of knowledge and know-how: that is why we firstly display the possible strategies and secondly the organizational and technical solutions which may be mobilized by the different strategies (Gobert and Rudolf, 2023).

The *reactive* adaptation strategy corresponds to an immediate response to the crisis. This adaptive answer is limited to technical and organizational reactions (like short-time work, decreasing of the volumes transported). Stakeholders may attempt during the crisis period to shift to another transport, but flexibility needs to be prepared through social skills (network, confidence, etc.) to overlap the constraints due to the crisis (lack of drivers, increase of the demand, etc.). Agreements between transport firms must be structured during the crisis.

The *transformative infrastructural* adaptation is the kind of solution which convinced most of the stakeholders involved, i.e., strategies to increase the water level and overcome low water levels. Examples are using the Lake Constance as a water reservoir, creating of new water storage areas, and deepening of the channel at Kaub and Maxau. strengthen the vision that business as usual. This adaptation pathway, which is not even supported by robust scientific studies, improves the existing situation, makes more efficient the inland waterway transport and the associated logistics for all stakeholders (except the Rhine, as these solutions are considered as impactful). It reveals the path dependency regardless of impacts on the Rhine ecosystem as well as the weakness of the players. These infrastructural solutions are a means to redistribute the responsibility between stakeholders and to discharge individuals from a too heavy financial and organizational changes.

The *radical system* transformation takes into consideration that value and supply chains must be modified for more circularized flows and an integration of climate risk related uncertainties. This variety of the adaptation discourse was promoted especially by environmental representatives or authorities regulating the Rhine waterway.

7.4. Outcomes

The process as well as the outcome legitimates the harbor's authorities to pursue their work to gather the strengths of different stakeholders and to mobilize about the low water issue. They adopted different tools (information, lobbying and stakeholders gathering). They have started to edit a Newsletter, which was distributed at first in an inner circle. While they received positive feedback from different authorities, they decided to distribute widely. They enlarged the process of reflexion to the harbors of the Upper Rhine Region. The collective building is then in process. The harbors authorities are going to apply for a follow-up research project in the Interreg Program VI.

The harbor authority and Voies Navigables de France (the authority managing navigation on French rivers played the role of policy entrepreneurs and boundary organization between the stakeholders involved in the goods transport, the researchers, and the national as well as sub-national authorities in charge of the inland waterway transport management. They occupy a position of mediators between different scales. For example, they must be able to alert, relay, mobilize and influence other levels to ensure local ownership and satisfy their constituents. This is evident in the case of work on the infrastructure that cannot be undertaken by them. For that, they must push this issue on the agenda of other authorities and scales so that the low-water issue could be considered and tackled. On the other hand, the fact that the "hard" option (i.e., the transformative infrastructural adaptation strategy—prevails to a very large extent also suggests that local players, including port authorities, may be reluctant to assume some responsibilities.

Their way of asserting themselves as owners of the risk is expressed by commissioning scientific studies on parallel research, infrastructures or equipment which could decrease the pressure on the Rhine River. This openness has undoubtedly benefited from the approach taken by the researchers of the Interreg V projects, relayed by the UNCHAIN project, as evidenced by their current involvement in an Interreg VI research project carried out by seven Rhine ports.

7.5. Barriers and enabling factors

Transport modes have followed historical and sectoral logics. While it may seem logical to respond to the crises affecting shipping with intermodal responses, the reality of the transport modes does not easily allow this. Shipping has its own characteristics and advantages according to the goods transported and the transport modes (in bulk/container). Other transport modes also follow their own logics, constraints, and inertia. First and foremost, transferring all containers on roads or rail is impossible because of the considered volumes and the types of goods. Alternatives to shipping products on the Rhine River are expensive for shippers. It also appeared complicated to change the transport mode if the transport providers impacted by the crisis did not have previous contracts with rail or road transport companies. Moreover, some resources may have been lacking. Legislation may hinder the transfer as well as technical and organizational reasons. For example, the rail paths are considered as not sufficient and overloaded to assure the transferability. The lack of skilled truck drivers is a European issue, which reveals itself particularly symptomatic when a crisis breaks. That is why reacting to this crisis requires collective agility and deeper and longer work between stakeholders: firms which must transport goods or resources, carriers, port authorities.

Building trust between stakeholders is a very significant resource. For this purpose, it is particularly strategic to enlist individuals, who are recognized and have the legitimacy to gather stakeholders (social and symbolic capital). The role was mainly played by the Strasbourg port authority, which have attempted to recruit participants and to find ways so that the collective process could be prolonged. However, obtaining a collective involvement until the end of the process requires time and human resource for private companies. The involvement stays very partial and dependent on the co-organizer.

The transboundary character of risks involved in situations of low- (or high) water of the Rhine does not seem to ease to development and implementation of effective adaptation measures. Indeed, although the local stakeholders involved can try to attract the attention of national and international authorities to deal with the subject of low and high waters, inland waterway transport is above all dependent on the global trade system. The limited institutional capacity to influence in a positive way the resilience of the Upper Rhine River transport capabilities appears to put further pressure on an infrastructure system already overburdened by a global market.

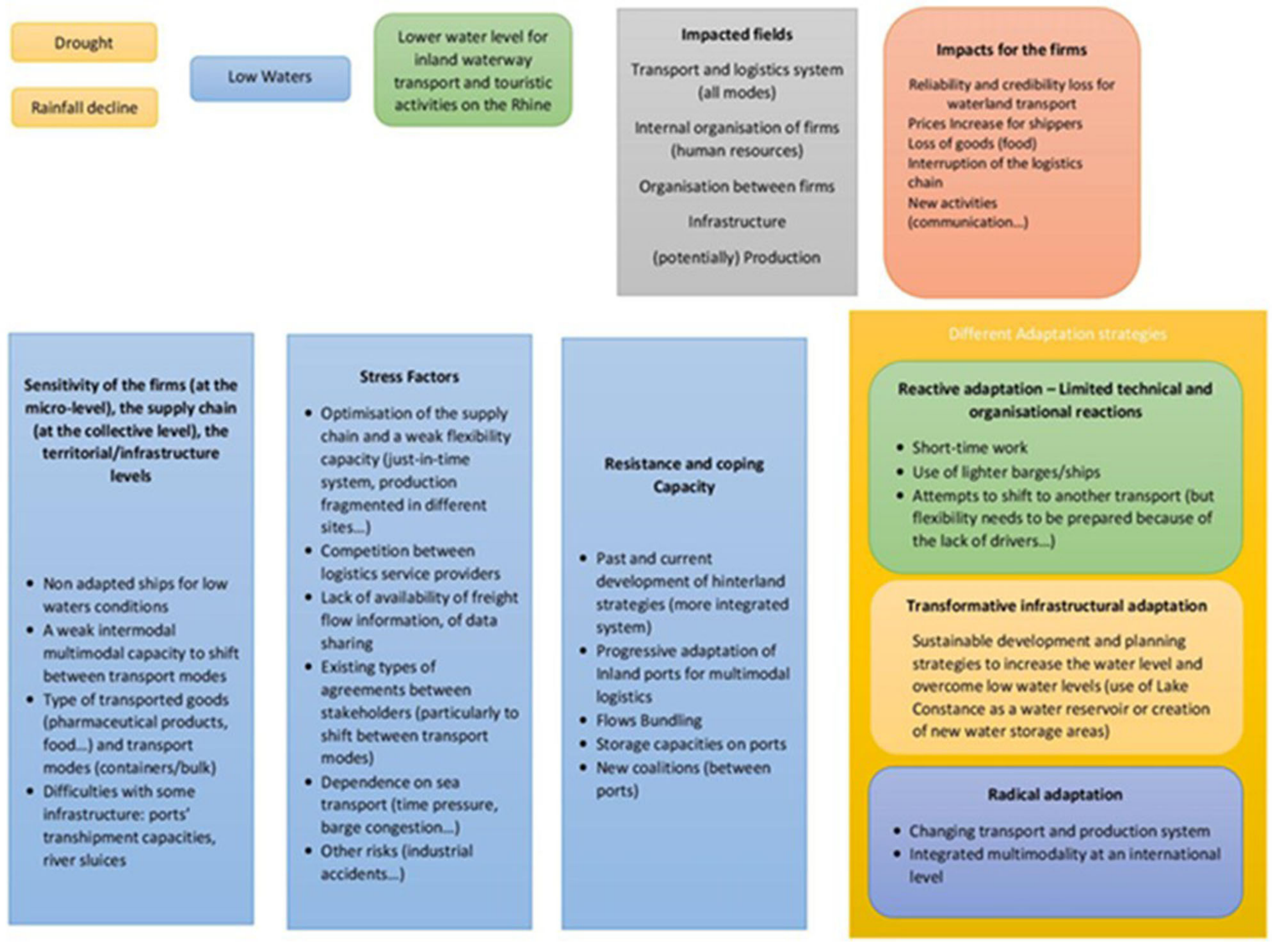

FIGURE 3
Impact chain produced to define with stakeholders the different issues raised by low water from the local level until the international supply chain.

8. Discussion: problems and prospects of putting a new global environmental problem on the local policy agenda

The cases presented above illustrate both problems and prospects for how transboundary climate risks—characterized by different variations of being a global or non-local environmental problem—can be translated into a local setting and put on a local policy agenda.

As stated by among others, Hägerstrand (1991), a crucial prerequisite for local actors—like local authorities—to address genuinely global environmental problems, like transboundary climate risks, is the ability to successfully translate the "global" into a meaningful local context. This implies understanding how complex interactions between cascading impacts at a global level—both those catalyzed by climate change and those generated by other crises and global dynamics—drive the creation or amplification of risks as well as opportunities at a local level. An increase in the number of immigrants (cf. the Paris case), an increase in the price of imported fodder in livestock production (cf. the Klepp case), and the threat of disruption to the import and export of goods (cf. the Upper Rhine case) are all very concrete translations of an externally created challenge (impacts of climate change located outside the area of investigation) that can trigger both negative impacts and positive opportunities in a local context.

The flowcharts derived from application of the impact chain framework (cf. Figures 2, 3) has proven useful for local actors as an illustration of how impacts that originate beyond the jurisdiction of a locality may create local risks which may require at least some level of response from local authorities. Thus, the impact chain framework appears to have the potential to become a boundary object for putting transboundary climate risks on the local policy agenda (notwithstanding the finding that the full instrumental version, which was initially developed for the purpose of analyzing conventional forms of local climate risk, cannot be applied in every case). Flow charts—such as the one produced in the Klepp case—clearly show both the extent and complexity of connections between the local and the global, and at the same time provides a basis for reflecting on the extent and type of climate risk that local livestock production faces, in addition to conventional local risks from physical climate impacts.

The logic underpinning the impact chain framework, of systemising and diversifying climate impacts into "links" and "nodes," makes it a relevant instrument for illustrating and assessing the complexity of transboundary climate risks. At the same time, precisely because the impact chain framework is so flexible, one risks falling into the trap of adding too much complexity to the analysis, which can make it difficult for policymakers and the layman user to relate meaningfully to the analysis. Thus, given that the impact chain framework was originally developed for analyzing local climate risks, alternations are needed to make it a more tangible and usable framework for also addressing transboundary climate risks.

The three cases illustrate clearly that local stakeholders can be made aware of the concrete and local challenges that transboundary climate risks can create, and that such risks should and must be addressed. They also demonstrate that due to the complexity of analyzing transboundary climate risks, applying techniques of knowledge co-production is an important prerequisite for creating actionable knowledge emerging from a risk analysis. Still, the cases also demonstrated several well-known barriers for conducting a robust analysis and producing actionable knowledge, such as lack of accessible and relevant data, lack of local competence, and lack of administrative capacity. The term "well-known" reflects that these are barriers relating to institutional and social conditions which we find mentioned frequently in the general literature on climate change adaptation (Amundsen et al., 2010; Biesbroek et al., 2013; Eisenack et al., 2014).

When facing the challenges involved in addressing transboundary climate risks, policy actors in the three local cases discussed various options for adaptation strategies, ranging from the more instrumental and technical reactive and protective measures, toward preventive and even transformative measures. The need or proposal for more transformative actions was particularly clear in the Klepp case, where actors also discussed a total restructuring of agricultural policy (toward organic farming) as one possible response, in addition to more traditional measures such as replacing imported soy with Norwegian-grown protein sources for use in concentrate. A possible consequence of transboundary climate risks increasingly being considered within the risk and vulnerability assessments that inform adaptation plans and strategies could therefore be that adaptation becomes more transformative over time. Even when infrastructural solutions that enable the delegation of responsibility to others are preferred, as in the Upper Rhine example, stakeholders recognized the need for a more balanced management configuration, where technical and infrastructural measures are combined with organizational and governance resolutions (Hoang et al., 2018). The organizational solutions are essentially based on inter- and multi-modality. The principle is: when the water level no longer allows inland waterway traffic, the transport provider switches to another mode of transport. This requires a transformative act, while considering a shared solution in the absence of reactivity from the national and international level.

TABLE 4 How addressing transboundary climate risks can help to unify the adaptation and mitigation part of climate policy.

		Cause	
		Concentrated	Dispersed
Impact	Concentrated	Adaptation to conventional "local" climate risks	Adaptation to transboundary climate risks
	Dispersed		Mitigation of greenhouse gas emissions

The three cases illustrated several challenges and barriers for adapting to the local risks catalyzed by transboundary climate impacts. The main barrier concerns access to data regarding the localized risk. This became especially problematic when assessing the "source" of the risk, cf. the Paris case, where data in Senegal were not easy to collect, but can apply to any context of transboundary climate risk (given the source is, by definition, beyond the recipient's jurisdiction). As demonstrated in the Klepp case, it is difficult to establish to what extent the challenges faced by farmers in Klepp, in relation to transboundary climate risks, differ to those facing all Norwegian livestock farmers. This breaks the logic of conventional local climate risk assessments, which aim to bring out local variation in the components that create the local climate risk—i.e., local hazards, local vulnerabilities, and local exposures.

One of the most exciting and innovative opportunities that presents itself as a result of local authorities engagement in the topic of transboundary climate risks is that it can contribute breaking down the cleavage between the adaptation and mitigation parts of climate policy (Table 4). A dichotomy between mitigation and adaptation was already well established by the early 1990s when the United Nations Framework Convention on Climate Change (UNFCCC) was established, giving adaptation a subordinate role in relationship to mitigation (Schipper, 2006). One aspect of this dichotomy is that the adaptation part of climate policy is often framed as a local environmental problem—a climate risk that manifests itself locally and therefore must be handled locally—while the mitigation part is more frequently framed as a global environmental problem that requires international targets and agreement. An institutional repercussion of this distinction is that adaptation is often handled by civil defense-related institutions, with a mandate to protect business-as-usual, while mitigation in most cases is dealt with by institutions with a mandate to enact at least some changes to business-as-usual (Groven et al., 2012).

Therefore, under current conditions—with few initiatives at the national level to seriously address transboundary climate risks—the most important contribution from local authorities to the better management of such risks might be to formulate requests for political initiatives at the national level (e.g., requests to change national agriculture policies in the Klepp case) and the supranational level (e.g., the participation of the city of Paris in the Mayor Migration Council). Such requests and initiatives may point toward adaptation measures that are more transformative than incremental in nature.

9. Conclusion: some critical factors for successfully addressing transboundary climate risks

A growing number of countries are in the process of considering transboundary climate risks in their national adaptation policy agenda (Beringer et al., 2022). However, even if the sub-national actors involved in the three cases showed strong interest in analyzing and addressing transboundary climate risks, it remains an open question whether such authorities can and should play an equally central role in addressing transboundary climate risks as do in the case of local climate risks.

Assigning responsibility for managing transboundary climate risks exclusively to national authorities may increase the risk of conflicts between measures to reduce local climate risks (frequently developed and implemented by sub-national authorities) and transboundary climate risks.

On the other hand, assigning responsibility for managing transboundary climate risks to sub-national authorities (to the same extent currently as for local climate risks) may lead to a situation that far too little is done, since transboundary climate risks must also involve national and supranational governance and international cooperation, particularly on issues like migration and trade.

The authors of this paper therefore advocate a strong partnership between the different levels of governance, and between public and private-sector stakeholders, in adaptation to transboundary climate risk; a partnership that will have to be closer and more mutually binding than that already established in most countries to adapt to local climate risks. It is therefore crucial that national governments explicitly account for transboundary climate risks in their national adaptation agendas, and as part of their process in determining "ownership" of such risks, decide on the role sub-national authorities should play. This choice will also affect the role of local authorities in managing local climate risks due to the interlinkages between them. Depending on the role sub-national governments are assigned, national governments need to finance the development of tools that sub-national governments can use to analyse transboundary climate risks akin to those developed to analyse conventional local climate risks (cf. the type of tools provided by the many climate service centers).

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: www.unchain.no.

Author contributions

Conceptualization: CA, KH, and FL. Data curation: CA and MJ. Investigation: TH, AC, FR, MJ, JG, BA, and MB. Methodology: CA, AC, MJ, and KH. Funding acquisition: CA. Project coordination: CA, AC, and MJ. Supervision: CA and KH. Visualization: CA, TH, JG, and AC. Writing—original draft: CA, TH, AC, FR, KH, MJ, JG, FL, BA, and MB. Writing—review and editing: CA, TH, AC, FR, KH, JG, FL, BA, and MB. All authors contributed to the article and approved the submitted version.

Conflict of interest

AC, BA, and MB were employed by Ramboll France SAS.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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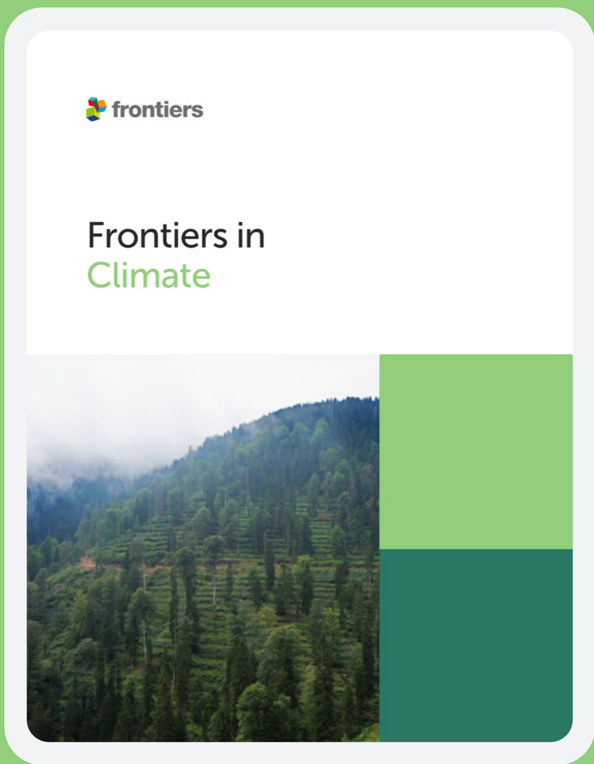

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