Final Report

Case Studies Evaluation: The inclusion and contribution of UNCHAIN innovations to improve climate risk assessment for adaptation planning

Work Package 4 – Deliverable 4.1
Delivery date: 15/10/2022

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Project full title: *Unpacking climate impact chains - a new generation of climate change risk assessments*
Grant Agreement number: *776608*

Funding scheme: *H2020-SC5-2016-2017*

Project acronym: *UNCHAIN*

Project start date: *1st September 2019*
Duration: *36 months*

Title	**Date** 15/10/2022
Case Studies Evaluation: The inclusion and contribution of UNCHAIN Innovations to improving climate risk assessment for adaptation planning	
Project title *Unpacking climate impact chains. A new generation of action- and user-oriented climate change risk assessments (UNCHAIN)*	**Number of pages** 37
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Summary

This document contains the results of the evaluation of UNCHAIN case studies. It presents the information on how the five innovations of UNCHAIN project were included in 11 case studies conducted under different contexts in Europe. Using knowledge gaps identified in an initial literature review as the basis and adopting the analytical approach of the Theory of Change, the case innovations were analyzed based on input, activities, output and outcome in addition to context and assumptions. Furthermore, the report contains a synthesis of critical ways the five innovations contributed to improving the climate risk assessment using the Impact Chain method. This report will serve as input into subsequent analysis to advance the IC methodology and influence adaptation decisions and policy.

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1. Background

The UNCHAIN project seeks to improve the methodology for performing climate risk assessment to support the development of robust adaptation. It pursues this objective by building on the knowledge of the Impact Chain (IC) framework and introducing five main innovations, which include; the Societal transformation, uncertainties, co-production of knowledge, Socio-economic scenarios and societal exposure to climate change and transborder climate change impacts.

The UNCHAIN project utilized a case study approach to experiment with the innovations. This report presents the results of the analysis of all 11 case studies detailing the transformative aspects of the innovations. The evaluation aimed at *systematically assessing how the innovations have been included in the case studies, how they performed and to what extent they have contributed to improved risk assessment and better-informed decision-making and climate change adaptation*. Two levels of evaluation were performed iteratively. The first is a case-level evaluation that served as input for the second evaluation that is the cross-case evaluation.

The case studies were conducted from 2020 to 2022. Results of case-level evaluation were framed within the Theory of Change (ToC) framework; input, activities, and outputs in addition to the necessary context and assumptions governing the implementation activities and analysis. Each case study also reported on the performance of the innovations using the OECD evaluation criteria; relevance, coherence, effectiveness, efficiency, impact and sustainability. Appendix 1 shows an overview of the 11 case studies, their objectives, the countries in which they were conducted and the institutions involved in the case study.

This report presents the results of a comparative analysis and synthesis of the 11 case studies. It builds upon the summarized tables from case-level evaluation developed by researchers of each case study and subsequent information gathered via interviews.

The remaining sections of the report are structured as:

- Case studies approach and evaluation methodology (Chapter 2): This chapter focuses on the role of case studies in developing UNCHAIN Methodological framework.
- Conceptual and analytical framework for the evaluation (Chapter 3): This chapter presents the choices behind the analytical framework adopted for the evaluation.
- Main findings with respect to:
  - Overview of case studies and prioritized UNCHAIN innovations (chapter 4): This chapter presents an summary of which innovations and their sub-research questions were applied in each case study. It aimed at identifying and examining which innovations are relevant for which situation and why not.
  - How the innovations were included in case studies (chapter 5)
  - Performance of innovations in case studies (chapter 6)
  - How the innovation contributed to the improvement of risk assessment (chapter 7)

2.0 Case studies and UNCHAIN methodological development

The UNCHAIN project aimed at advancing the IC model and therefore requires a solid research design. Due to the methodological implication of UNCHAIN research, the case studies were designed to be reflexive, and the case study protocol, therefore, contained several specific choices and issues for consideration. This chapter describes the main methodological choices made and provides an overview of the guiding principles behind the case study development

to offer insight into the analyses. In this way, it is specified how the comparison of 11 case studies helped to answer the central research question of UNCHAIN Project.

Using a multi-method approach at different levels and scales, the case studies aimed at helping understand the local climate change adaptation process. The success of the case studies was based on the researchers' and stakeholders' criteria for planning and monitoring the impact of their respective project. Therefore the objectives of the case studies were:

(1) to develop with and for local stakeholders, testing changes and alterations of the current IC model for risk assessments

(2) to evaluate how the IC model creates a more resilient and climate robust society

(3) to offer practical examples and multiple ways in which climate change (impacts and policies) influence individual and collective adaptation measures across space (transnational climate impact exposure).

2.1 Case demarcation

As with embedded case studies that contain more than one sub-unit of analysis and integrate quantitative and qualitative methods into a single research study, the boundary of our case studies was quite porous, and therefore demarcating the cases was challenging. The UNCHAIN responded to this challenge primarily by including a set of the main research and sub-research questions for each innovation in the case study protocol. These questions provided a degree of boundary in which the case studies are implemented. In the case study protocol, cases were still offered room for open-end; researchers had the responsibility to define what is possible and not in their case. However, the case studies were designed to have distinct characteristics (local, mixed method, inclusive) to ensure better outcomes.

First, the case studies were designed to be local, in a way that they focus on local initiatives and engage local stakeholders who make real decisions on climate change adaptation in their community. We recognized that some local initiatives can be national or regional initiatives like those of Case 7: food production, Case 9: enterprises Case 10: city level risk, while in others it could be a small group of people in a specific local office like in the cases Case 8a: financial investments. Depending on the innovation at hand (in particular Transborder climate change impacts) the focus of some cases as mentioned earlier was transnational. Transborder in this sense means the local activity has a spillover effect with other actors and initiatives that are connected and shares similar identity across national borders. Climate change risk needs to be understood more in its cross border effects.

Second, the case studies differed in scope and therefore used mixed methods; combining quantitative modelling and qualitative methods such as document analysis, interviews, and workshop techniques. The case protocol encouraged the cases to use a mix of research techniques that can be combined or 'triangulated' into more balanced findings. The case research guidelines provide both descriptions of the research techniques and rough directives for the extent they should be deployed.

Third, the case studies were designed to be inclusive enough to involve all partners (including economists, climatologists, policymakers, etc.) in adopting a bottom-up approach in its implementation. UNCHAIN aims at being socially relevant research that empowers different actors in their respective roles in formulating climate adaptation action. And so it explicitly adopts a co-production of knowledge approach between researchers and stakeholders of the

initiatives. The commitment to knowledge co-production was shown in the development of working relations and joint discussion of findings with stakeholders to increase the internal validity and reliability of findings (Yin, 2003). Beyond the stakeholders, UNCHAIN explicitly encouraged the cases to invite relevant researchers to contribute to the research process, which forms a substantial part of selecting interesting themes to explore, and include in the research.

2.2 Comparative case study

Following the case protocol is the case study evaluation framework that contained the methodological choices for evaluating the case studies. Central to the evaluation is the comparative analysis of case studies with mix methods. The underlying motives behind the comparison of multiple cases using multiple methods are solidification of the results and learning from diverse contexts. An advantage of this method is that it ensures that what is compared across several cases is sufficiently identical to be analytically compared (Halkier, 2011, p792).

2.3 Limitations

It would have been desirable to obtain a detailed report from each case study for evaluation However with the project deadline approaching many of the cases had not had enough time to write a full case level project report. To ensure that all cases were evaluated a tool was developed with instructions and questions to collect input from all the case studies (See appendix 2). Additionally, interviews were conducted for clarification and to obtain more detailed information about the cases. In the end lots of information was collected both in term of quality and quantity to ensure a representative case study evaluation.

Further constraints resulted from the fact that primary cross-case evaluators were not involved in case-level evaluation and in the absence of detailed information regarding each case important case level information/knowledge was lost as a consequence, as will be seen below in some of the specific points evaluated.

Finally, the ratings of the performance of the innovations were based on a rubric that is subjective and qualitative. Results based on the informed perspectives of the researchers could be slightly skewed towards individual interest.

3. Conceptual and analytical framework for the case evaluation

Case study research fundamentally provides a lens through which in-depth analysis of a particular context is obtained through an exploratory, iterative and inductive stance. The case study approach allows the examination of real-life situations, developing theory, evaluate programs and developing suitable interventions (Stjelja,2013; Yin, 2009; Baxter and Jack, 2008; Soy 1997). Yin (2003, p.3) highlights that case studies depend on multiple sources of evidence, where prior theoretical propositions guide data collection and analysis in a triangulating manner; a process where many methods are combined to ensure the validity of case study research (Johansson, 2003). According to Kohlbacher (2006), the definition of a case study should not be based on its research methods but on its purpose, thus case studies should be considered as a strategy rather than a method. Yin, (2003) identified three main approaches to case studies; explanatory, exploratory, and descriptive. *Explanatory* case studies are used to explain causal relationships between phenomena. This is done together with a discussion of alternative explanations that are consistent with the facts (Harder, 2010). The *exploratory* case study explores interventions without clear outcomes. They are often

used as an initial step for an explanatory case study approach due to their broad focus (Streb, 2010). *Descriptive* case studies describes intervention as it occurred. They are focused and thorough in their assessment (Tobin, 2010). Furthermore, Yin (2003) distinguishes between *single*- case studies and *multiple*-case studies.

The UNCHAIN project in its design adopts all three types of case studies approach and evaluation were performed at both case-level (*single*- case studies) and cross-case level *(multiple*-case studies). Either way, the case studies are used as *instruments* to improve the methodology of climate risk assessment and *collectively* provide a general understanding rather than *intrinsically* understanding the case themselves (Stake,1995). The analytic framework of the evaluation is framed around *theoretical propositions*, *case descriptions* and *rival explanations* using both quantitative and qualitative data (Yin, 2003, chaps. 4 and 5). Given these three strategies, we employed three techniques for the analysis; pattern matching, explanation building, and synthesis (Yin, 2003). The synthesis techniques are particularly relevant when individual case studies are independently conducted. With this technique, tables are created to collect data from each case according to the research questions and measured indicators to draw cross-case conclusions. The analytical framework, in general, helped treat the evidence impartially, generate persuasive logical conclusions, and eliminate alternative interpretations.

At the heart of the UNCHAIN case(s) evaluation is the Theory of Change (ToC) to analyse how and why the five innovations contributed to improving or otherwise the climate risk assessment methodology to support the development of adaptation options (figure 1). Drawing from the work of Weiss, (1995) and Connell & Kubisch (1998), we implement ToC in this evaluation as a systematic and collective study of linking activities, outcomes, and contexts of the UNCHAIN to determine how and why the innovations worked. ToC suggests that the first step toward evaluation is to determine its intended outcomes, the activities to be implemented toward those outcomes and the contextual factors that may affect the implementation of activities and their potential to bring about desired outcomes (Connell & Kubisch, 1998). For example, the goal of the fifth innovation for instance is to capture the transnational impacts of climate change and link mitigation and adaptation in climate risk assessments. One key activity is to access data to describe the system boundaries of each case, the contextual factor may be that the data policy environment in each case might not enable access to the required data. Ultimately, ToC helps strengthen the scientific case for attributing subsequent changes in the expected outcomes (from initial levels) to the activities performed. Results from evaluations using ToC approach generate useful new scientific knowledge to enrich the design of future climate risk assessment methods.

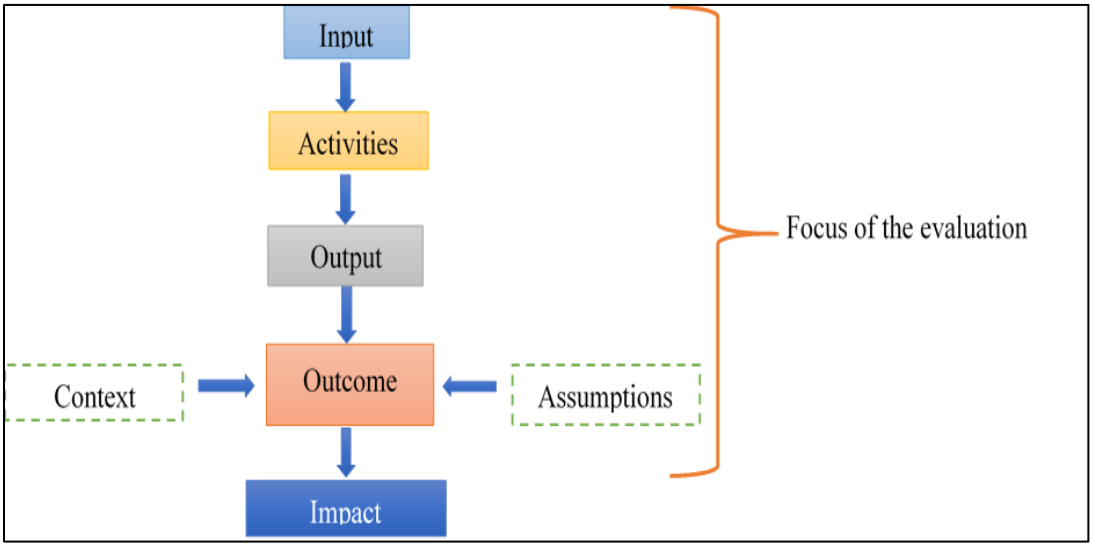

Figure 1: A guiding framework for the evaluation

The analysis also captured the overall performance of the innovations using the revised evaluation criteria developed by the Organisation for Economic Co-operation and Development (OECD); relevance, coherence, effectiveness, efficiency, impact and sustainability (Chianca, 2008). The criteria are explained as follows: *Relevance:* The extent to which the innovation responds to beneficiaries' needs, policies, and priorities, and continues to do so if circumstances change. *Coherence:* The compatibility of the innovations with other interventions in the country, sector, or institution. *Effectiveness:* The extent to which the objective of the innovations was achieved. *Efficiency:* The timely and cost-effective manner in which the innovations were delivered. *Impact:* The extent to which the innovations generate significant positive or negative effects. *Sustainability:* The extent to which the benefits of the innovations may continue. For each of the criteria, we assigned a rating of either poor, average, good, very good or excellent using a standardized rubric. Finally, it is worth noting that the ToC analysis did not cover impact of the case studies as this element takes time to be properly evaluated. However the OECD criteria included the impact in the analysis because captures the immediate differences the innovation make.

4. Case studies and prioritized UNCHAIN innovations.

Results synthesized from the case studies show that at least one of the innovations was experimented in one of the case studies. The most widely used innovation is the user-interface and stakeholder involvement and the Societal transformation while the two least used innovations were (1) Socio-economic scenarios and societal exposure to climate change and (2) Transboundary climate change impacts. All except cases 3 and 7 experimented with the innovation in addressing uncertainties. A synopsis of the innovations and research questions handled by each case study is presented in Table 1. Results of the interviews show that the choice and usage of innovations were driven by three key factors; first, the purpose of the case study itself which is largely informed by the problem under consideration and interest. Second, resources (data and finance) and time availability. Third, researchers' expertise to conduct certain kinds of analysis (mainly quantitative modeling) and inadequate technical know-how of stakeholders.

Table 1: A matrix demonstrating case studies and prioritized UNCHAIN innovations.

UNCHAIN Innovations and research Questions		Case 1: Tourism comfort	Case 2: critical infrastructure	Case 3: Inland water transport	Case 4: International supply chain	Case 5: Agricultural drought	Case 6: Multiple hazards	Case 7: food production	Case 8a: financial investment	Case 8b: Railway infrastructure	Case 9: enterprises	Case 10: city level risk	Case 11: agriculture risk
Societal transformation	How to identify the relevant system elements and their interrelations when doing impact chain analysis?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	How to better integrate quantitative, semi-quantitative, qualitative and narrative approaches?	✓	✓			✓		✓	✓				✓
	How to integrate into the impact chain framework knowledge from other approaches already existing in the literature on the normalization and aggregation phases and the definition of critical thresholds?	✓				✓			✓		✓	✓	
	How to address limitations in the availability of reliable data? (heterogeneity, spatial/temporal resolution, the mismatch between resolution)			✓		✓	✓		✓	✓			
	How to forward the impact chain approach from a 'linear' representation of risk components towards more system dynamics-oriented models?	✓	✓		✓	✓		✓			✓	✓	✓
Addressing uncertainties	How to better address uncertainties and confidence levels for each step in the impact chain assessment?		✓						✓	✓			✓
	How to overcome the problems of deep uncertainty about future climatic and socio-economic conditions, as well as the lack of data – even of	✓	✓			✓	✓						✓

	present conditions – when doing risk assessments?												
	How to address uncertainties related to the socioeconomic aspects involved in impact chain assessments?	✓	✓		✓		✓		✓	✓			
User-interface and stakeholder involvement	How do knowledge co-production in climate risk assessments inform decision-making and adaptation action?	✓		✓			✓		✓	✓			✓
	How was results from the climate risk assessment perceived by stakeholders and scientific knowledge providers?	✓				✓	✓		✓				✓
	What are the parameters of the knowledge co-production process that affect, positively or negatively, decision-making and adaptation action?	✓					✓		✓	✓			✓
	What are the benefits of adopting an integrated approach combining knowledge co-production and impact modelling?	✓			✓		✓		✓				✓
Socio-economic scenarios and societal exposure to climate change	How to include future vulnerability conditions based on socio-economic scenarios to better depict future critical conditions?	✓	✓		✓				✓	✓			✓
	How to gain a better understanding of socioeconomic consequences involved in climate change adaptation?	✓	✓		✓								✓
	How to combine the differences in scale between where statistical data is produced (within administrative borders at national, county or municipal levels) and where the impacts of climate change manifest itself		✓										✓

	(mostly independent of administrative borders)?												
	What are the criteria for selecting a set of indicators that yields a usable risk analysis and how to determine the impact of omitting relevant indicators for which data are not accessible?	✓	✓		✓				✓				✓
	How do we ensure that local/context-specific 'first experiences' with impact chain methodology and framework are fed back into the improvement of the framework?		✓		✓								
Transborder climate change impacts	What are the most important transborder climate change risk in the involved countries/cases?			✓	✓						✓		✓
	How can different levels of governance identify and then adapt to transborder climate change risks?										✓		✓
	Who (private/public actors, at different levels and within different sectors) are most accountable for managing different sub-categories of transborder climate change risks?			✓							✓		✓
	What are the most important factors that limit the capabilities of policymakers to address transborder climate change risks?										✓		✓

5. Inclusion of innovations in case studies

This section shows how each innovation was included in the case study. The results are structured based on input, activities, output, outcome (with assumptions and context), and outcome of each innovation.

5.1 Societal transformation

This innovation seeks to cover the possible need for long-term and large-scale efforts of societal transformation by answering the question *how to link knowledge co-production processes with societal change, and how to evaluate the success of doing so?*

5.1.1 Input

Depending on the case study, different resources were used as input to experiment with the impact chain method. All case studies tackled this research innovation using direct stakeholder information exchange, expert knowledge of relevant scientific literature, grey literature (including reports from public institutions, NGOs, and private businesses), and the National climate change impact and risk database. Only cases 2,3 and 8a analyzed the impact model using data from the National climate change impact and risk database. Case 2 utilized the 2021 Climate Impact and Risk Assessment for Germany (Kahlenborn et al 2021). Case 8a in the Netherlands used Dutch Climate Impact Atlas (www.klimaateffectatlas.nl/en/).

5.1.2 Activities

Different case studies performed different activities based on their set goals. The activities form the core part of the experimentation of the IC model. Some of these activities include interviews, workshops, stakeholder consultations (reference group meetings), desk studies, feedback sessions among researchers, online surveys, homogenization of the different sources of information, setting up a methodology to objectively quantify weights in the IC, development of a probabilistic framework, development of a categorization strategy, verbal description of impact chains elements and underlying factors. The activities also include the application of the macroeconomic models GINFORS and PANTA RHEI, scenario analysis based on three national SSPs. Case 3, for example, conducted 7 co-production workshops, 8 meetings, and 4 individual exchanges which helped in problem definition, stakeholder acquisition, preparing and conducting IC workshops, validation meetings, and individual risk assessment for an energy supplier. The stakeholder workshop in case 5 saw the presentation of qualitative and quantitative results using graphs and illustrations in Insightmaker (a software tool) dashboard showing analyzed spatial presentations of the drought-agriculture system in Austria. Approval of the IC model developed by stakeholders at the workshop signaled better results in capturing the risk system in a way that corresponds to their needs. Also, case 6 utilized workshops to identify indicators for GIS mapping and aggregated the statistics into an index. Case 8a also drew clear causal links between climate signals and impact/actual risk to the investigated asset by identifying the climate signals and impact at workshop and subsequently modelling these impacts.

5.1.3 Output

Several products were obtained from the input and activities for the IC innovation. These include finalized impact chain, a tool to estimate the interlinks and compute the final risk in a probabilistic framework. Also, several tree-structured graphs are defined from the key root issues of climate risk. A clear categorization for qualitative and narrative approaches that can be integrated with quantitative indicators, a method linking indicators to final risk, and an updated IC graphic that acknowledged the stakeholder feedback and validated IC. Case 2 for example identified relevant impacts on considered critical infrastructure (transport, energy, health) and interdependencies. It also obtained a description of impact chains and underlying

aspects in addition to the macroeconomic effects expressed in terms of economic indicators such as GDP, production, and employment. Case 3 obtained a mapping of individual risk factors to the value chain of energy supply represented in a diagram. Case 5 shows a graphic representation of the IC using the Insightmaker and bar charts displaying the characteristics of each region and an automated, standardized workflow for spatial data integration; a shiny dashboard programmed in R. A normalization strategy where all datasets were scaled to an 8-bit interval ranging from 0 - 255. This allows comparability in image analysis software. Case 6 developed a visualized impact chain together with a narrative outlining sectors of importance and social groups that are vulnerable to disruptions in critical infrastructure and vital societal functions, or might become vulnerable; vulnerability maps and social vulnerability index. Case 8a obtained a list of climate signals and a map of climate impact (flood, heat stress, and subsidence). Case 9 also developed a graphical representation of issues and solutions including a table with strengths and weaknesses (SWOT analysis), validated by all participants. Also, a common definition of key issues and associated problems is validated by stakeholders. We succeeded in integrating qualitative criteria into TRIZ without units because of the qualitative nature of the data. Case 11 produced a value chain and resource map with discussed adaptation options.

5.1.4 Context and assumptions
Context

Throughout the implementation of IC, certain context issues in one way or the other affected the results. *First*, a critical context issue is the subjectivity of the individuals involved in the case studies especially in establishing the categories and translating qualitative issues into numerical values. This largely resulted in differences in the content of information collected from stakeholders, as well as data obtained from interviews and focus groups. The quality of data is largely limited to the inputs from stakeholders. Stakeholders' availability, interests, resources, and previous knowledge and actions played an essential role in what information is provided and gathered for analysis. The willingness and involvement of certain stakeholders such as political authorities in the process and sharing data were difficult. Stakeholders that are already well-prepared for climate change were not interested in starting the discussions from scratch. *Second,* the case studies were guided by findings from existing interventions in each country and other relevant publications on the subject of study. Case 11 reports that the case studies fall within an ongoing local sector plan for agriculture and thus the case study was limited to stage 2 of the IC. *Third*, the number of participants in some of the workshops were few and this might result in the issues not being dealt with from multiple perspectives. *Fourth*, internal and skills issues of researchers were critical for the successful implementation of the IC innovation. The level of programming skills of some of the researchers and the available knowledge of the system was essential. For example case 5 reported that having its researchers with Geo-informatic background made it easy to work with spatial data and accompanying software that was relevant to the case. *Fifth,* the project was conducted during the covid-19 pandemic and therefore all meetings, interviews and workshops were adapted to online sessions. Case 6 reported the difficulties of such online meetings affecting in-depth discussions and analysis of the issues. This largely affected the level of co-production expected to be undertaken by the case studies. Case 9 on the other hand claimed that this led to much shorter than intended meetings and therefore only the researchers decided connections between the IC elements. *Sixth***,** additionally, other in-country situations affected the IC innovations. Case 9 for example reported that the 2018 low water crisis and Post Low water crisis impacted the case study implementation and outcome of the innovation and the fact that computation was done in-house / without any external factors influencing the process.

Assumptions

Several assumptions were made during IC implementation. *First*, it was assumed that the selected stakeholders were sufficient and diverse enough to fully help understand the relevant elements and interrelations of IC thus identifying the climate risk of the understudied sector. Further, the stakeholders were assumed to have enough knowledge of the system elements and their interrelations to validate IC results. Second, the interviews and workshops were well organized to extract the required information from stakeholders. Also, the case studies assumed that experts have a broad enough view and knowledge to help identify the indicators and provide information that is relevant for IC development. *Third,* it was assumed that the contributing factors leading to risk are interdependent and that it is useful to carve out and display these interdependencies. Also, it is useful to collect and analyze and afterward cluster spatial data into homogenous risk regions, and to present analysis results to the stakeholders. Fourth, several assumptions were made regarding the choice of tools for data analysis and result presentation. For example, in case 5, the Insightmaker software utilized was assumed to best fit the purpose although, in hindsight, the case team realized there would have been better tools and ways such as using an interactive dashboard for the presentation of the regional risk profiles. Also, some case studies assumed the state of the problem and needs of the stakeholders without any prior literature review and need assessment. The impact chain in some situations like case 6 was outlined based on the assumption that cascading effects from extreme weather events are causing disruptions in critical infrastructure and vital societal services that may have an impact on vulnerable groups in society, and may lead to emerging vulnerabilities. Therefore it was assumed that it is possible to capture social vulnerability using several indicators.

5.1.5 Outcome

Several results were obtained for the IC innovation. The impact chain for each case was well-defined and climate risk problems properly framed. The results of the risk assessment were translated into easy-to-understand information relevant to the stakeholders. The innovation allows the collection of a set of comparable indicators irrespective of origin and type and the development of an operational probabilistic framework for the IC risk assessment as in case 1. Also, the innovation offered a clearer picture of causal links between climate signals and impacts, comparable economic indicators; linking the IC method to macroeconomic modeling; providing the quantitative values for the qualitative strands of the IC as in case 2. The innovation also helped in adjusting the visualization of IC to national adaptation actions to support the better finding of adaptation measures, compatibility of national and local impact chains, combination of business value chains and ICs, and support for climate risk analysis along supply chains as seen in case 3. Results also show that stakeholders became more sensitive to risk dynamics after results were presented in a standardized automatized workflow for spatial data integration, maps and charts showing risk scores and profiles of different geographic regions and systems. The innovations as implemented in Case 6 help them understand the drivers of social vulnerability in a selected number of sectors, as well as what (types) of critical infrastructures, are perceived to be at the most risk. All of which will provide stakeholders with better knowledge about how to work with social vulnerability in local adaptation planning processes. The IC innovations help establish knowledge on the extent of climate impact which is translated into established preliminary ideas for potential adaptation solutions and pathways. The innovation also allows the identification of uncertainties about efficacy, time, efficiency, and social/environmental acceptance. IC enabled the identification and designing of adaptation pathways not just on a territorial basis, but more precisely for firms.

5.2 Addressing uncertainties involved in local decision

This innovation aims at developing and test a standardized analytical framework for addressing uncertainties involved in local decision-making on climate change adaptation. By so doing the innovation addressed the question of *how uncertainties and confidence levels are better addressed to overcome the problems of deep uncertainty for each step in the IC assessments?*

5.2.1 Input

The cases utilized background knowledge from stakeholders, experts' judgment, and literature review as qualitative data sources. Inputs from quantitative sources such as highly detailed economic modeling that rests on macroeconomic theory (national model PANTA RHEI as in case 2; multi-national model GINFORS as in case 4), SSP scenarios (O'Neill et al., 2014; O'Neill et al. 2017) and national scenarios, modelled climate data for RCPs up until 2100 were also employed. These inputs encompass strong inclusion of a social science discipline. Additionally, quantitative data on climate, environmental and socio-economic were used. Also case 1 used using mathematical techniques such as Monte-Carlo method to develop probability density functions to account for uncertainties.

5.2.2 Activities

The implementation of the innovation includes several activities that were relevant to the experimentation. Scenario-based approaches and workshops were to address data unavailability. Development of a methodology that allows the comparison of final risks with other existing risks. Strategies were developed to link indicators to the final risk and analyze existing significant gaps. Also, a probabilistic framework was developed to analyze uncertainties as in case 1. Case 2 for example applied macroeconomic model PANTA RHEI, scenario analysis; calculate the economic effects of climate-related impacts on infrastructure in the context of different societal developments according to the SSPs and the economic effects of adaptation up to 2050. Further case 2 aligned three national SSP-Parametrisations to incorporate key assumptions from Germany's latest Climate Impact and Risk Assessment (Kahlenborn et al. 2021). Local experts were consulted and their knowledge, insight, and data on uncertainties were gathered and integrated with available quantitative data for analysis. Subsequently, data normalization, harmonization, aggregation, and resampling were conducted in addition to structuring the IC elements in the style of a Causal Loop Diagram and performing one risk assessment per RCP. Some case studies such as cases 7 and 8a and 8b, and 9 embarked on co-production efforts using workshops to dialogue with stakeholders to address the uncertainty issues and their possible implications in addition to how to address them. Cases 9 and 10 for example co-designed with the stakeholders a new theoretical framework to address the uncertainties of the existing IC model. Also, a system dynamic framework was developed to collect and present data during the workshops and meetings.

In this case, data gathered from stakeholders were handled in a very qualitative and in some cases substantiated with relevant literature. These datasets had to be done qualitatively, as it is probably close to impossible to approach this challenge with a traditional statistical analysis (Aall and Groven, 2022).

5.2.3 Output

The resulting output of this innovation includes a method linking indicators to the final risk and accommodating uncertainties in different steps of the IC. Case study 1 developed and applied a general formalism that allows integrating uncertainties into IC. The formalism are in two forms; suitable computer codes (e.g., in Python or MATLAB) and web-based UNTIC tool (untic.pythonanywhere.com) which can be used without much technical expertise. The formalism replaces scalar quantities, such as weights and indicator values, by probability density functions (PDF). The PDFs are propagated through the whole impact chain and cumulate in a final risk PDF. Also, a comprehensive set of annual macroeconomic time series

projecting future developments in individual sectors (intermediate demand, output & prices, individual components of value added) as well as for individual actors (private households, public sectors: final consumption expenditures, firms: investment activities) and the overall economy were determined as in case 2 and case 4. Additionally, the economic effects of climate-related impacts on infrastructure (transport, energy, health) in the context of societal developments (according to SSPs) and the economic effects of adaptation were also determined. A graphic representing the risk system in a manner as used in System Dynamics research in addition to two risk assessments based on two RCPs, for two time slices (mid of century/end of the century) was obtained from using this innovation. Case 10 for example produced a new dynamical conceptual IC with 2 different types of IC one for Senegal and one for the city of Paris. Asystem dynamic model was developed by case 11 and presented in a report to Klepp municipality.

5.2.4 Context and assumptions

Context

The innovation was conducted within the context of the original SSP parametrizations published by IIASA as in case 2. Analyses of climate impacts, climate risks, and climate adaptation were conducted at the national level. The willingness of stakeholders to provide private data was critical. Not all data were readily available from stakeholders e.g. data related to security or business practices were difficult to obtain. The technical background of the research teams limited the use of quantitative approaches. Case study 11 reported that the innovation has to be conducted qualitatively because it's probably close to impossible to approach this challenge in traditional statistical analysis. Also, there exist limited available knowledge of the dynamic relationships between the risk factors. Data obtained from external sources as in case 5 from the Austrian meteorological office were already modelled and aggregated.

Assumptions

Several assumptions underpin the implementation of uncertainty innovation in the case studies. It was assumed that the stakeholders had a broader view on climate risk which was accurate enough to inform the assessment. Also, the assumption that uncertainties can be identified using surveys and databases was key for this innovation. Furthermore, the combination of "hard" data and expert judgments was seen as an essential approach to obtaining a wholistic understanding of uncertainty. Other specific assumptions include the strategies adopted was the most straight-forward one to make datasets with different value ranges comparable, the aggregated/resampled/normalized data would still be valid to represent the risk factors at hand, all system elements could be integrated into the same system representation and that simple colours and illustrations would be enough to represent their relationship (red arrow - balancing relationship vs. green arrow - reinforcing relationship as in case 5), and finally, the modelled climate data would adequately represent the possible future climate conditions.

5.2.5 Outcome

A consistent framework for uncertainty treatment in the impact chain risk assessment was developed. Also, a method to compare different risks, allowing the identification of missing indicators and quantification of uncertainties was developed (as in case 1). Also, a consistent quantification of a range of possible macroeconomic outcomes for selected climate change impacts (concerning energy, transport and health related impacts) and different adaptation measures under altered socioeconomic scenario assumptions were produced as in Case 2. The impact chain method was linked to macroeconomic modelling, providing the quantitative values for the qualitative strands of the impact chains. This allowed the discovery of new effects and further intermediate impacts that have not yet been encountered in the qualitative development of the impact chains. In some cases (such as case 5) a comparable stack of data

sets was generated in addition to harmonized/integrated data; an automated programming workflow for data harmonization/integration.

5.3 User-interface and stakeholder involvement

To refine a structured method of co-production of knowledge and integrate this into impact modelling, we pose the question of *how to in different ways improve and at the same time critically reflect on stakeholder involvement and their roles in the IC process, and what are the critical factors concerning how knowledge co-production processes can lead to changes in actual adaptation action?*

5.3.1 Input

Background information about the IC method, existing case study documents, expert opinions and stakeholder dialogue and consultations and published articles and documents on co-production in climate change were primary sources of information for conducting this innovation. Stakeholders interests and sectoral expertise were used for the parametrization of macroeconomic ex-ante assessments in case 4 for example. Necessary to include users for deciding system boundaries / scoping stage, selecting relevant nodes / links, and providing date / sources of data / data needs / knowledge gaps about the identified nodes/links. Other cases solicit input from knowledge providers, county governors, regional municipalities, public / private businesses/NGOs, local/regional levels, departments in local authority, state government, and from sectoral advisory service providers

5.3.2 Activities

Workshops, interviews, focus group discussions, online meetings, and phone calls were among the central activities performed. For all the case studies that implemented this innovation, stakeholders were engaged to different degrees throughout the project. Together with the stakeholders, the key climate risk problems were identified, assessed, and discussed. The usefulness of the results and IC method were also discussed with stakeholders. In case 6 for example stakeholder workshop was used to explore results and a survey to follow-up on how results were perceived. Researchers' observations and reflections on the knowledge co-production process were done for this innovation.

5.3.3 Output

A great measure of the good feeling of understanding between researchers and participants was observed. Great level of involvement and commitment of different actors from academia and industry. Parametrization of a global multi-region model (GINFORS) with input from stakeholders. Assessment/summary of stakeholder perceptions of results according to knowledge quality criteria: credibility, saliency, legitimacy, and usability. Cases 8a and 8b obtained an analyzed list of the level of satisfaction with the risk assessment process. Mapped co-production process with positive and negative impacts on decision making.

5.3.4 Context and assumptions

Context

The knowledge co-production process is affected by several factors, related to both the process itself and methods adopted, who's involved, etc., but also by contextual and external factors that stakeholders and researchers cannot control. Also, results were assessed based on multiple criteria and stakeholders may perceive results differently.

Assumptions

The assumptions were that stakeholders had a good understanding of whether or not the results of the IC model are interesting and that they would influence the adaptation decision. Also, it was assumed that working systematically with stakeholders through the research

process leads to more relevant results that can inform the decision-making process and adaptation planning. Additionally, the co-production approach was assumed to be key to developing system boundaries and finding the key vulnerable nodes and links.

5.3.5 Outcome

The innovations provided better insight into end-users perspectives about IC methodology, processes used, and the holistic perspective on dynamic risks and results. Also a refined structured method of co-production of knowledge was produced. The innovation also resulted in an established understanding of the benefits of climate risk assessment, and what works and what does not work for knowledge integration/co-production. The process also resulted in follow-up projects and agenda setting. For example, in case 11 an idea for a follow-up project called the Transadapt project emerged from the co-production engagement. This project aimed to further explore how transboundary climate risk is linked to the food system in Norway.

5.4 Socio-economic scenarios and societal exposure to climate change

To develop and test an applicable framework for analyzing how societal change can affect local climate change vulnerabilities, we explore answers to the question of *how to include future vulnerability conditions based on socio-economic scenarios and better understand the socioeconomic consequences involved in climate change adaptation, and what are the most relevant economic indicators to include in IC assessments?*

5.4.1 Input

The central input for this innovation is the application of the SSP scenarios (O'Neill et al., 2014; O'Neill et al. 2017) and national socio economic scenarios. The macroeconomic assessment was in case 2 was based on highly detailed economic impact modelling (national model PANTA RHEI). Other information gathered from desktop research and exchanges with research groups & ongoing projects and case studies, and stakeholders. Case 7 for example used sustainability indicators for the growth in salmon production. Other case studies did not use formal scenarios but spent much time explaining the reasoning for using the IPCC matrix and analyzing vulnerabilities (as in case 11). Other relevant national documents on climate impact and risk assessment information was used.

5.4.2 Activities

Relevant socio economic indicators for IC were identified in case 2. Individual model calibrations (guided by external information retrieved from desktop research) for individual impact simulations were also performed. Application of the macroeconomic model such as PANTA RHEI and International Supply Chains based on a global multi-region model (GINFORS) were done in case 2 and case 4. Also, three national SSP-Parameterizations were aligned to incorporate key assumptions from Germany's latest Climate Impact and Risk Assessment (Lutz et al., 2019). The assessment of climate change impacts and adaptation is based on a national economic model (PANTA RHEI). A differentiated analysis of transboundary climate change risk is for example conducted in case study 4 where the simulated economic scenario was assigned to key reference values from global SSP-Parametrizations. Workshops and meetings were also organized to dialogue with relevant stakeholders introducing and explaining the logic of relevant concepts such as the risk framework and in particular the importance of analyzing social vulnerabilities, not merely climate hazards.

5.4.3 Output

The analysis of this innovation resulted in maps of climate risk under different socio-economic scenarios. A comprehensive set of annual macroeconomic time series projecting future

developments in individual sectors (intermediate demand, output & prices, individual components of value added) as well as for individual actors (private households, public sectors: final consumption expenditures, firms: investment activities) and the overall economy was obtained. The macroeconomic model PANTA RHEI used in case 2 and GINFORS in case 4 for example features (inter alia) a full integration of official macroeconomic accounting frameworks and the respective official statistics for Germany. For each of the chosen sub-themes (e.g. vegetable production, meat production) in Case 11, a listed 5-10 social vulnerability categories arise from the workshop discussions.

5.4.4 Context and assumptions

Context

The innovation was implemented bearing in mind the uncertainty of the future socio-economic scenarios and the lack of data and information on different indicators. The analysis was based on original SSP parametrizations published by IIASA. The assessment was aligned with national policy needs and ongoing national climate impact and vulnerability assessment activities. Also, the analysis was confined to the data and information available and stakeholders interests and sectoral expertise.

Assumptions

An important assumption made while implementing this innovation was that, despite the uncertainty of the future socio-economic scenarios and the lack of information on different indicators, the results are still useful in providing information that is actionable in developing adaptation actions. Case 11 for example did not question the general societal development trends, such as population growth, economic development, etc.

5.4.5 Outcome

The innovation resulted in a consistent quantification of a range of possible macroeconomic outcomes for selected climate change impacts (concerning energy, transport and health-related impacts) and different adaptation measures under altered socioeconomic scenario assumptions as in case 2. Inclusion of the analysis in the formal agriculture plan as in case study 11.

5.5 Transborder climate change impacts

To include the trans-border impacts of climate change and to link mitigation and adaptation in climate risk and vulnerability assessments. We answer the question *what are the most important trans-border impacts of climate change (TBCRs), how to best articulate and frame TCBRs, and how can different levels of governance as well as affected actors identify and then adapt to TCBRs?*

5.5.1 Input

The assessment of climate change impacts and adaptation is based on a national economic model (PANTA RHEI), a differentiated analysis of transboundary climate change risk, International Supply Chains based on a global multi-region model (GINFORS) and a global multi region macroeconomic simulation model as in the case study 4. National reports, stakeholders' expertise, and published articles were utilized for this innovation. Also, stakeholder expertise and published articles were also used. Case 3 for example used publications related to waterway management, publications of inland water transport associations, information from national climate adaptation guidance and policy documents and studies on comparisons of climate change impact on different transport modalities. Additionally, the macroeconomic model outputs and national development maps were used. Case 11, for example, uses national reports from the environment agency and the Norwegian

government to point out that transborder climate risk is an important issue, and points at agriculture as one of the most relevant areas to further investigate.

5.5.2 Activities

Workshops, stakeholder interviews, and meetings were central to implementing this innovation. Case 4 performed an Economic Assessment of supply chain risks from a sectoral perspective.

5.5.3 Output

A report on transborder climate risks used by governments as a knowledge base for making a local plan as in agriculture for klepp municipality in case 11. Relevant knowledge on supply chain operations and actors was collected (Case 3). Knowledge of key international and national actors and how they interconnect was identified. In case 3 for example, the following setting was identified: Owners of the power supply company determine the power demand, depending on the market situation; the power supply company manages local fuel logistics; the daughter company in logistics manages inland transport ship fleet; there are several different contracted international suppliers of fuel.

5.5.4 Context and assumptions

Context

The use of economic models and their challenges to assess climate change impacts and adaptation. External factors such as imported overseas fuel for power plants via the sea harbour of Rotterdam and inland water transport via Rhine river and internal factors such as fuel demand depending on power demand, agile logistics management plays a critical role in the analysis of this innovation mentioned by Case 3. Stakeholder's interests, sectoral expertise and commitment form an essential part of the context issues. The Rhine is an international natural and economic infrastructure that offered context to the study on the transnational effect of climate change. Other context issues include; low water phenomenon which has a consequence on different countries, on the supply chains in different sectors, and more particularly waterway transport, and multi-level governance (international and local authorities).

Assumptions

The assessment of climate change impacts and adaptation is based on a national economic model (PANTA RHEI), a differentiated analysis of transboundary climate change risk and its assumptions. Also, assumptions on International Supply Chains based on a global multi-region model (GINFORS)

5.5.5 Outcome

Knowledge on transborder aspects for the investigated stakeholder (power supply company) was generated. Knowledge of the business and operations of the power supply company which is required to perform a suitable risk assessment was also generated. A list of common / different solutions identified from one country to another. Deeper understanding of diverse National and local potential Adaptation Pathways. The inclusion of transboundary risks in the local plans as in the agriculture plan in Case 11.

6. Performance of innovations in case studies

An overview of the performance ratings of the innovations at a glance is shown in figure 2 and Table 1(details in appendix 3). To better understand the performance of the innovations at the case level, a rating system was established for the evaluation. The resultant rating reflects

the evaluation team's informed judgment, based on qualitatively or quantitatively captured indicators and data collected during the case implementation. The case study methodologies allowed ratings for non-quantifiable indicators with qualitative assessments through a review of data and analysis of the interviews conducted during the case implementation. The criteria for these assessments were established using a regular Likert scale rating of 1- 5 (poor to excellent) with detail explanations of each scale in a rubric accompanying the reporting tool (see appendix 4). This rating system was established by the lead evaluation researchers and is based on a qualitative standard scale. Therefore, results are to be considered an indicative evaluation of compliance with the project document in terms of the performance of implemented activities and the quality of achieved results.

Findings show that overall all the innovations showed a good performance except the transboundary effect which showed an average performance. Socio-economic scenarios were slightly lower in rating than the rest in absolute value. However, specifically, with regards to relevance, transboundary effect innovation performed excellently in terms of responding to the needs of the beneficiaries, policies and national priorities, Impact change, uncertainty and user interface were very good while socio-economic scenarios was good. In terms of how well the innovations were compactible with other interventions, all the innovations showed a very good coherence except socio-economic scenarios that was good. The user interface was however slightly higher in absolute values than impact chain and uncertainty.

The user interface and stakeholder involvement innovation was highest with a very good rate for effectiveness and all other innovations were good at helping the case studies achieve their objectives, thus effectiveness. With regards to efficiency, user interface and transboundary effect innovations were average at being delivered in a timely and cost-effective manner while the other three innovations were good. All the innovations made a good amount of difference at the case study level except transboundary effect innovation which was poor at making a difference. The user interface and stakeholder involvement innovation was rated the highest for sustainability with a very good remark, followed by impact change, uncertainty and socio-economic scenario rated good and transboundary effect rated average

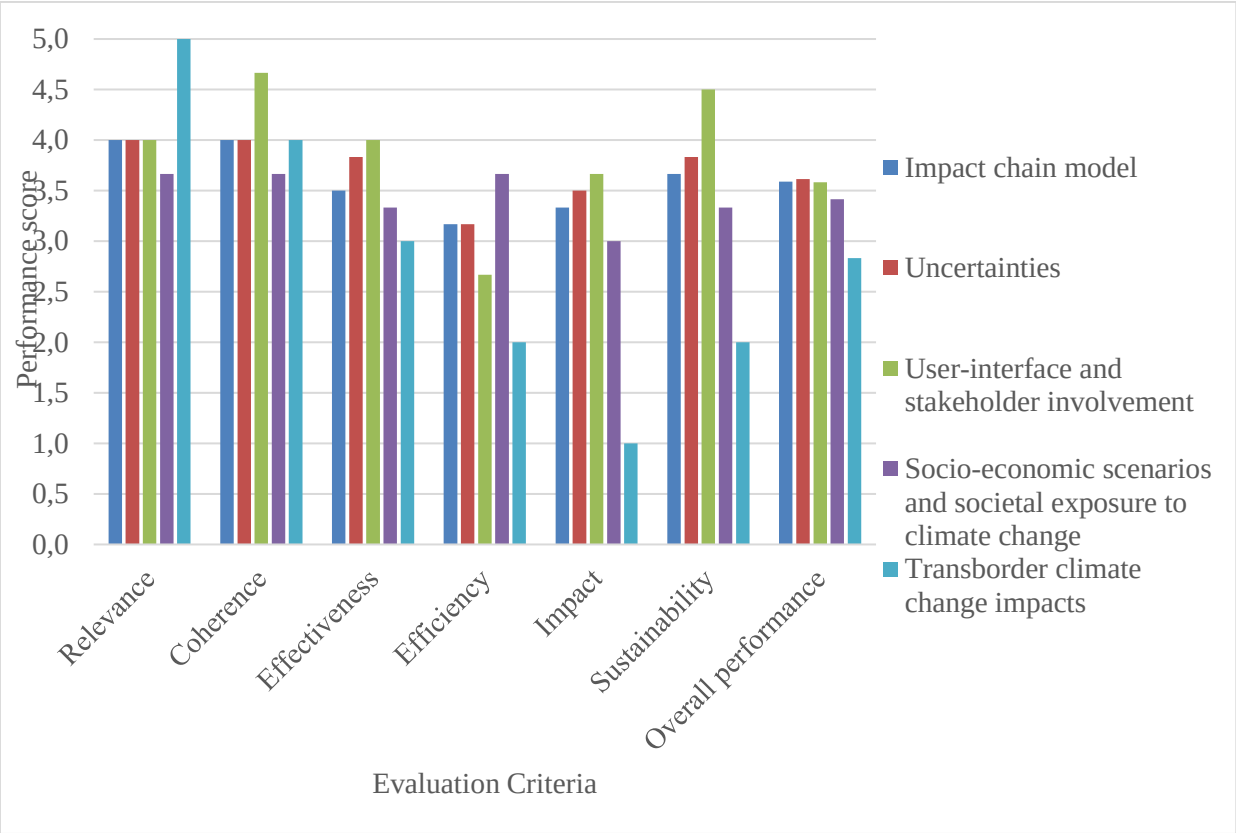

Figure 2: Performance of innovations

Table 1: An overview of the evaluation of innovation (Categories: poor=0-1;average+>1-2; good=>2-3; very good = >3-4; excellent =>4-5). All *bolden* ratings are ≥.5 of their category.

Performance/ Innovations	Societal transformation	Uncertainties	User-interface and stakeholder involvement	Socio-economic scenarios and societal exposure to climate change	Transborder climate change impacts
Relevance (Did the innovation respond to beneficiaries' needs, policies, and priorities?)	Very good	Very good	Very good	**Good**	Excellent
Coherence (How well is the innovation compactible with other interventions?)	Very good	Very good	**Very good**	**Good**	Very good

Effectiveness (Did the innovation achieve its objectives?)	**Good**	**Good**	Very good	Good	Good
Efficiency (Was the innovation delivered in a timely and cost effective manner?)	Good	Good	**Average**	**Good**	Average
Impact(Did the innovation make a difference?)	Good	**Good**	**Good**	Good	Poor
Sustainability (will the benefits of the innovations last?)	**Good**	**Good**	**Very good**	Good	Average
Overall performance	**Good**	**Good**	**Good**	Good	**Average**

7. Contribution of innovations to the improvement of risk assessment

Here, we reflect on how the implementations of the innovations addressed the knowledge gaps and prepositions identified in the initial international review. Initial literature review shows the need to improve the impact chain (IC) in two main ways; the successful design of participatory workshops, and the improvement of data analysis including methods and models. The Unchain project was therefore structured to address these issues and contribute to further improvement of the existing IC approach in several ways.

First, different approaches were developed and used to integrate quantitative, semi-quantitative, and qualitative data and to quantify uncertainties within the IC process (i.e. innovation 1 and 2). To have a better understanding of the impacts of heat and low rainfall resulting in unprecedented low-water crisis on the Rhine transport sector, case 9 of the UNCHAIN project introduced an Inventive Design Method called the Theory of Inventive Problem Solving (TRIZ). The method allows the collection of qualitative participatory data from stakeholders which were coded into semi-quantitative forms and then integrated with the impact chain modelling module of the vulnerability sourcebook(VS). The process offered the opportunity to combine the expertise of social scientists with engineers. Further, it allowed the generation of more convincing robust and reliable results. Also, in an attempt to address uncertainty in each step of the risk assessment, case 1 proposed and utilized a probability density functions (PDF) method to combine qualitative and quantitative indicators into the IC to assess the risk of loss of tourism attractiveness in the Balearic islands. The methodology helped to quantify three different types of uncertainty to improve confidence in the outcome of risk assessments; (i) uncertainty with existing datasets which affects the certainty of indicators (ii) the subjectivity and its potential bias in determining the relative importance of each element of the impact chain through participatory approaches, which increase uncertainty in final risk assessment and (iii) uncertainty in excluding key indicators and elements of the IC. The proposed PDF framework is based on the premise that all components of the IC, be it indicators or weights are not handled as a single value, but as a probability density function and therefore provides a full representation of all the possible values of a quantity and their probability of occurrence. The methodology has been consolidated into a

simple user-friendly web-based tool called UNTIC tool which can be accessed at untic.pythonanywhere.com. Furthermore, different methodical steps related to data aggregation have been used to handle the inefficiencies of an existing method. Case 10 applied a reverse geometric aggregation instead of the weighted arithmetic aggregation already used in the IC to analyze the migration of people from Senegal to Paris in France. The case study found that the arithmetic method favors low values and therefore normally underestimates risk. Given that it is better to overestimate risk than otherwise, they suggest the use of the reverse geometric aggregation method as it is more bias towards high values.

Second, the need to refine the process and role of knowledge co-production in climate change risk assessments to better inform decision-making and adaptation action has become necessary considering its value in ensuring sustainable development outcomes. The UNCHAIN project therefore designed and conducted the case studies to ensure a great level of stakeholder engagement (i.e. innovation 3). Almost all case studies operationalized this innovation. Results from the stakeholder interactions are mostly qualitative information on vulnerability and exposure but were semi-quantified in some cases and integrated with quantitative data mostly on the hazard to estimate climate risk. Using primarily interviews, focus group discussions and workshops differing perspectives were collected from different actors and better understandings of the problem definition, communication, and legitimacy of the climate information were obtained. However, the process as observed in all case studies was time-consuming and resource-intensive due to the efforts required to ensure that all relevant stakeholders are represented and able to participate. This evaluation did not capture the impact level of the UNCHAIN project, however the results of the outcome provided indications of the role of knowledge coproduction in informing adaptation decision-making. For instance, case 9 presents tangible indications of the benefit of co-production in addressing uncertainties to the financial sector. In this case, co-production helped address uncertainties in three main ways; characterizing, estimating, and communicating uncertainties. Participants and researchers identified potential uncertainties and agreed upon acceptable levels of these uncertainties. Thus, the result of the climate risk assessment served as input for reporting on physical climate risk to regulating bodies. Lastly, we learned that jointly developing impact chains was an effective way to develop capacities to include climate risk in investment decision making. Financial institutions already can incorporate other forms of risk into their decision making, yet there is a need to improve the capacity to understand the mechanism of climate risk and their uncertainties, as this could create a dilemma for investment decision making. Also in case 6 and through co-production, the flexibility of the impact chain was tested as it was adapted to analyze the multidimensional, time-dependent, and situational factors that shape social vulnerabilities. Together with stakeholders local knowledge and sectorial expertise were used to co-develop scenarios to determine cascading effects of disrupted water supply and anticipated vulnerable social groups in Sweden. Thus information from co-developed scenarios may be used to create awareness among stakeholders and supports adaptation decision-making. Additionally, through co-production, UNCHAIN has demonstrated transparency regarding stakeholder involvement, roles and outcome, and the effectiveness of linking knowledge co-production processes with societal change under different contextual factors as shown in the case studies.

Third, in an attempt to contribute to a better understanding of socioeconomic consequences involved in climate change adaptation and improvement of the application and representation of numerical simulation models in the IC, the UNCHAIN advanced the inclusion of future vulnerability conditions based on socio-economic scenarios into the IC (i.e. innovation 4). Case study 2 utilized the macro-econometric model PANTA RHEI to evaluate climate impacts on future monetary costs of transportation, health care and electricity sectors under selected socioeconomic scenarios The analysis was based on three SSP scenarios (SSP1, SSP2, SSP5) and a comprehensive set of annual macroeconomic time series projecting future developments

in individual sectors (intermediate demand, output & prices, individual components of value added) as well as for individual actors (private households, public sectors: final consumption expenditures, firms: investment activities) and the overall economy.

Fourth, several factors including knowledge, skill, and capacity gaps preclude the effort of policy to manage effectively transborder climate change risks. A limiting factor transnational climate risk is the lack of clarity about who is responsible for managing such risk. Therefore the UNCHAIN project aimed at exploring ways to incentivize stakeholder groups at different levels of governance (especially the lowest levels) to develop policy instruments that direct and provide concreate actions to manage transnational climate risk and build resilience (i.e. innovation 5). Till now IC has been used to only evaluate local risk. Using Norwegian municipalities as case study, case 11 examined transnational risks related to the production and transportation of soy from Brazil to be used in livestock production in Klepp municipality, Norway. Results show that IC remains valuable and useful in understanding and communicating transboundary climate risk to local stakeholders, proving the flexibility of the IC approach. Due to the complexity of the issues, the case adopted a more qualitative approach to handling indicators. It was suggested that linking actions of local and transboundary climate risk will help address tensions likely to emerge when implementing adaptation efforts in the livestock production industry. Also, looking at sustainable salmon farming, case 7 found that none of the participating stakeholders has a climate risk assessment plan. Additionally, several transborder climate change risks were identified and effective ways to include them in risk assessment were discussed. The identified risks include the potential collapse in soy production in Brazil due to environmental degradation, geopolitical concerns issues due to radical increases in freight prices, to a collapse in local salmon markets. Risk ownership was identified as the major reason for the ineffective management of these risks. Ultimately, the IC approach to studying transboundary climate risk proved relevant as it enables co-production of knowledge on salient issues and refined relationships between different threats, across scales and levels especially as the salmon industry does not recognize climate change as the most pressing threat to their activities.

In conclusion, the IC method proved to be flexible and useful under different context and space as explained above. All the case studies were successful at reaching their case objective using the IC methodology. Furthermore, the innovations introduced by UNCHAIN also contributed significantly to improving the outcome of the risk assessment in each case study.

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Appendices

Appendix 1: Case study description and design

Case Studies	Objective	Country	Institutions Involved
Case 1: Potential risk of loss of tourism comfort and destination attractiveness due to climate change	To investigate how the reduction of beach availability and increased temperatures will have an impact on the attractiveness of the Balearic Islands as a tourist destination.	Spain	Spanish Institute of Oceanography (CN-IEO/CSIC)
Case 2: Economic effects of adapting critical infrastructure	Analyze the economic impacts of climate change and adaptation in the context of different societal developments according to the SSPs on particular critical infrastructures Improving the impact chain method by providing quantitative values for the qualitative strands of the impact chains through the linkage with macroeconomic modelling.	Germany	Gesellschaft für Wirtschaftliche Strukturforschung (GWS - Institute of Economic Structures Research)
Case 3: Economic effects of adapting critical infrastructure (seaport and inland water transport)	Application objective: To investigate environmental and economic effects of repeated long periods of heat, drought and of low water of the river Rhine;	Germany	Fraunhofer IAIS; Mannheim municipal departments (Climate Office, Economic and Structural Development, Urban Development, Public Health Office, Professional Firefighters); state-owned Rhine-Neckar

	Research and innovation objective: to improve the core impact chain-based risk analysis method		Port Authority; logistics company; energy producing company; sanitary paper production company; German Federal Institute of Hydrology
Case 4: Improving climate change impact assessments of open economies by beyond state-of-the-art economic modelling approaches.	To assess the impacts of foreign climate change effects via multi-national supply chains on the German economy by dynamic simulation studies with the simulation models GINFORS and PANTA RHEI.	Germany, cross-boarder	Gesellschaft für Wirtschaftliche Strukturforschung (GWS - Institute of Economic Structures Research)
Case 5: Agricultural drought in the light of Climate Change	To integrate two components of the project: the revision and adaptation of the impact chain methodology as well as decision-making processes and adaptation policies and reflect on existing adaptation policy frameworks on how such drought events are managed on local (farm level) to national scale	Austria	University Salzburg (PLUS)
Case 6: Adapting to multiple water hazards in Sweden	Assess the spatial distribution of social vulnerability to disruptions in critical infrastructure due to multiple	Sweden	SEI; Swedish Meteorological and Hydrological Institute (SMHI); Halmstad Municipality

	hydrometeorological extreme events in the Swedish municipality of Halmstad.		
Case 7: Securing sustainable food production in Northern Norway under the auspices of climatic changes	To understand how the culturally embedded notion of resilience and adaptive capacity enables (or un-ables) industry actors when facing the cumulative impacts of global climatic changes and the policies expected to arise when seeking to adapt to them.	Norway	Nordland Research Institute (NRI)
Case 8a: Climate change impacts on financial investment portfolios	To determine the various climate risk associated with real estate assets and how to include climate risk information into (large) financial investment decision	Netherlands	Wageningen University; Climate Adaptation Services Syntrus Achmea Real Estate & Finance; Vesteda, MVGM International Advisory
Case 8b: Climate change impacts on railway infrastructure	To determine how the rail infrastructure and operations are exposed to climate risk at different timescales.	Netherlands	Wageningen University; Climate Adaptation Services; ProRail
Case 9: Sensibilities and vulnerabilities of small and medium enterprises in the Upper Rhine Region	To identify the sensibilities and vulnerabilities to climatic changes of small and medium enterprises at	Germany	The Port of Strasbourg (Port Autonome de Strasbourg - PAS); Waterways of France (Voies Navigables de France - VNF)

	the Upper Rhine and how this might affect productivity.		
Case 10: Improving knowledge and management of transboundary climate risks at city level; the example of Paris	To develop a new type of Impact Chain that can help the city integrate these indirect risks into their operational risk management system and long-term adaptation and resiliency strategies."	France	Ramboll; City of Paris
Case 11: Regional knowledge base for local and transborder climate risk analysis: the case of agriculture (Norway)	To determine how regional governments can best help municipalities in analysing climate risk and how can municipalities analyse transboundary climate risks.	Norway	Western Norway Research Institute; Rogaland fylkeskommune; Rogaland county; and Klepp municipality

Appendix 2: Tool for collecting case level information

Research Innovations / Research objectives	Sub-research questions	Input	Activities	Output (what products were obtained from the activities?)	Context	Assumptions	outcome (What results did we achieve?
Societal transformation and uncertainties	How to identify the relevant system elements and their interrelations when doing impact chain analysis?						
	How to better integrate quantitative, semi-quantitative, qualitative and narrative approaches?						
	How to integrate into the impact chain framework knowledge from other approaches already existing in the literature on the normalization and aggregation phases and the definition of critical thresholds?						
	How to address limitations in the availability of reliable data? (heterogeneity, spatial/temporal resolution, the mismatch between resolution)						
	How to forward the impact chain approach from a 'linear' representation of risk components towards more system dynamics-oriented models?						
	How to better address uncertainties and confidence levels for each step in the impact chain assessment?						
	How to overcome the problems of deep uncertainty about future climatic and socio-economic conditions, as well as the lack of data – even of present conditions – when doing risk assessments?						
	.How to address uncertainties related to the socioeconomic aspects involved in impact chain assessments?						
User-interface	How do knowledge co-production in climate risk assessments inform decision-making and adaptation action?						

and stakeholder involvement	How was results from the climate risk assessment perceived by stakeholders and scientific knowledge providers?						
	What are the parameters of the knowledge co-production process that affect, positively or negatively, decision-making and adaptation action? What are the benefits of adopting an integrated approach combining knowledge co-production and impact modelling?						
Socio-economic scenarios and societal exposure to climate change	How to include future vulnerability conditions based on socio-economic scenarios to better depict future critical conditions?						
	How to gain a better understanding of socioeconomic consequences involved in climate change adaptation?						
	.How to combine the differences in scale between where statistical data is produced (within administrative borders at national, county or municipal levels) and where the impacts of climate change manifest itself (mostly independent of administrative borders)?						
	What are the criteria for selecting a set of indicators that yields a usable risk analysis and how to determine the impact of omitting relevant indicators for which data are not accessible?						
	How do we ensure that local/context-specific 'first experiences' with impact chain methodology and framework are fed back into the improvement of the framework?						
Transborder climate change impacts	What are the most important transborder climate change risk in the involved countries/cases?						
	How can different levels of governance identify and then adapt to transborder climate change risks?						
	Who (private/public actors, at different levels and within different sectors) are most accountable for managing different sub-categories of transborder climate change risks?						
	What are the most important factors that limit the capabilities of policymakers to address transborder climate change risks?						

Appendix 3: Performance of innovations

Performance/ Innovations	Societal transformation	Uncertainties:	User-interface and stakeholder involvement	Socio-economic scenarios and societal exposure to climate change	Transborder climate change impacts
Relevance	4.0	4.0	4.0	3.7	5.0
Coherence	4.0	4.0	4.7	3.7	4.0
Effectiveness	3.5	3.8	4.0	3.3	3.0
Efficiency	3.2	3.2	2.7	3.7	2.0
Impact	3.3	3.5	3.7	3.0	1.0
Sustainability	3.7	3.8	4.5	3.3	2.0
Overall performance	3.6	3.6	3.6	3.4	2.8

NB: Performance of the innovation (for each criterion indicate whether 1-poor, 2-average, 3-good, 4-very good and 5-excellent and explain your ranking). See rubric explanations on ranking

Appendix 4: Rubric for evaluation criteria

TOC Criteria	poor(1)	average(2)	good(3)	very good(4)	excellent(5)	Score
Relevance: Did innovation respond to beneficiaries needs, policies, and priorities?	The innovation was not sensitive at all to the needs of beneficiaries but discussed at the start of the project.	The innovation was sensitive to at least one of the needs of beneficiaries. The innovation was discussed at the start of the project formulation but remained rather abstract throughout project life and did not seem to lead the implementation	Some needs of the beneficiary in the context of the innovation was addressed. The innovation was discussed at the start of the project formulation, considering that the goals of the project are sensitive to the economic, environmental, equity, social, political economy, and capacity conditions in which it takes place, though it was not always clearly considered during the implementation	The innovation was sensitive to almost all needs of beneficiaries. The innovation was clearly considered in project formulation and discussed at the start of the work, considering that the goals of the project are sensitive to the economic, environmental, equity, social, political economy, and capacity conditions in which it takes place. The analysis was sometimes performed in this context.	The innovation was sensitive to all needs of beneficiaries. Very clear formulation and implementation of innovation at the start and throughout the life of the project, the goals of the project sensitive to the economic, environmental, equity, social, political economy environmental, equity, social, political economy, and capacity conditions in which it takes place. The analysis was always performed in this context.	1.00
coherence: How well is the innovation compactible	No aspect of the innovation was considered in project implementation,	To some extent how other interventions support or undermine the innovation, and vice versa was discussed but	Some aspect of the innovation was considered at the project formulation and implementation. Analysis and interpretation of how	The innovation is clearly considered in project formulation and implementation. Analysis and interpretation of how other interventions support or undermine the	Critical reflection and analysis and interpretation of how other interventions support or undermine the innovation, and vice versa was thoroughly performed to capture both internal (interventions	1.00

with other interventions?	though part of the initial project goal	handled in a theoretical manner.	other interventions support or undermine the innovation, and vice versa is partial and there is no clear link to the conclusions	innovation and vice versa are mostly properly done although the link to further work and conclusions is not always traceable.	performed by same institutions)and external (other actors' interventions) coherence linked to conclusions and further work seemingly in line with this	
effectiveness: Did the innovation achieve its objectives?	Is not able to achieve the expected objectives of the innovations. Results were not at all related to the original aim of the innovation	Is able to achieve at least one of the specific objectives related to the innovation. But unable to analyse any differential results across groups.	Is able to achieve some of the specific objectives related to the innovation. But provide partial differentiation of results across groups	Is able to achieve almost all of the specific objectives related to the innovation and provided clear differentiation of results across groups with no account of the relative importance of the objectives or results.	Is able to achieve all of the specific objectives related to the innovation and provided very clear differentiation of results across groups taking into account the relative importance of the objectives or results.	1.00
efficiency: Was the innovation delivered in a timely and cost effective manner?	The innovation was complex in implementation, resource intensive compared to feasible alternatives in the context and delivery was way outside the required timeframe	The innovation was difficult to implement and resource intensive compared to feasible alternatives in the context but barley met the timeframe allocated to it.	The innovation was easy to implement, almost within the required timeframe but resource intensive compared to feasible alternatives in the context	The innovation was easy to implement, and falls within the expected timeframe but is resource intensive compared to feasible alternatives in the context	The innovation was easy to implement, falls within the expected timeframe and require less resources compared to feasible alternatives in the context	1.00
Impact: what differences did the innovation make?	The innovation generated insignificant positive or negative effects.	The innovation generated at least one significant positive or negative effect. No direct or indirect secondary and potential consequences was observed.	The innovation generates few significant positive or negative effects. Not all the identified effects had direct and indirect secondary and potential consequences of the innovation was observed yet not	Some significant positive or negative effects of the innovation was produced. Almost all the effects identified had direct and indirect secondary and potential consequences of the innovation and were transformative in nature.	Some significant positive or negative effects of the innovation was produced. All the identified effects had direct and indirect secondary and potential consequences observed were transformative in nature.	1.00

			transformative by nature.			
sustainability: will the benefits of the innovation last?	The innovation offers benefits, all of which are largely temporal and may not continue.	The innovation offers benefits, but only one is likely to continue depending on several conditions such as the financial, economic, social, environmental, and institutional capacities of the systems.	Few of the derived benefits from the innovation are likely to continue, subject to several conditionalities.	some of the derived benefits from the innovation will continue, with few conditionalities.	The majority (or all) of the benefits from the innovation will continue, irrespective of the conditionality.	1.00
Average score of the innovation performance						1.00