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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;

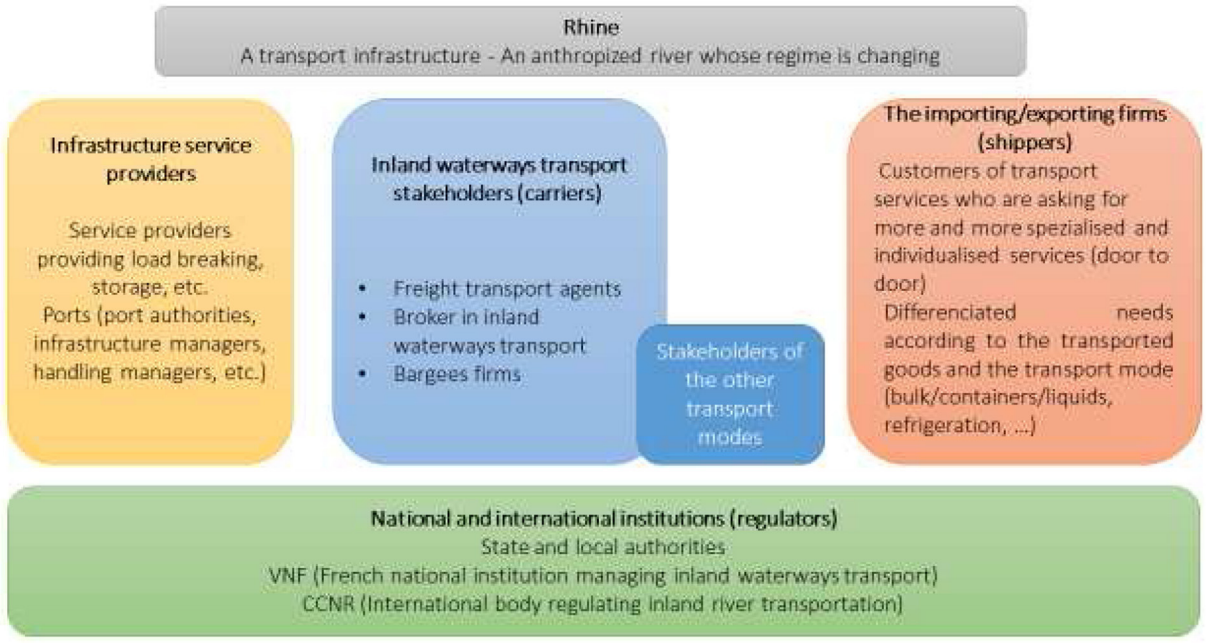

FIGURE 1
The different stakeholders involved in the process and impacted by low waters.

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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References

Abson, D. J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., et al. (2017). Leverage points for sustainability transformation. *Ambio* 46, 30–39. doi: 10.1007/s13280-016-0800-y

Anand, N., Gupta, A., and Appel, H. (2018). *The Promise of Infrastructure*. Durham: Duke University Press. doi: 10.1215/978147800 2031

Argyroudis, S. A., Mitoulis, S. A., Hofer, L., Zanini, M. A., Tubaldi, E., and Frangopol, D. M. (2020). Resilience assessment framework for critical infrastructure in a multi-hazard environment: case study on transport assets. *Sci. Total Environ.* 714, 136854. doi: 10.1016/j.scitotenv.2020. 136854

Averbeck, P., Rudolf, F., and Gobert, J. (2021). "Natürlich natürlich ?! Wie natürlich sollten die Wälder des Biosphäre Reservat Pfälzerwald-Nordvogesen in Zeiten des Klimawandels sein," in *Aurélie Choné et Philippe Hamman (dir.) Humanités environnementales en France et en Allemagne: Circulations et renouvellement des saviors* (Bern; Berlin; Frankfurt am Main; Oxford; New York, NY).

Bailey, R., and Wellesley, L. (2017). *Chokepoints and Vulnerabilities in Global Food Trade*. Chatham House. Available online at: https://www.chathamhouse.org/2017/06/chokepoints-and-vulnerabilities-global-food-trade (accessed October 5, 2021).

Berrang-Ford, L., Pearce, T., and Ford, J. D. (2015). Systematic review approaches for climate change adaptation research. *Reg. Environ. Change* 15, 755–769. doi: 10.1007/s10113-014-0708-7

Birkmann, J., Buckle, P., Jaeger, J., Pelling, M., Setiadi, N., Garschagen, M., et al. (2010). Extreme events and disasters: a window of opportunity for change? Analysis of organizational, institutional and political changes, formal and informal responses after mega-disasters. *Nat. Hazards* 55, 637–655. doi: 10.1007/s11069-008-9319-2

Blanck, J. (2016). Gouverner par le temps. Cadrages temporels du problème des déchets radioactifs et construction d'une irréversibilité technique. *Gouvernement et Action Publique* 5, 91–116. doi: 10.3917/gap.161.0091

BMDV (2022). *Bundesverkehrswegeplan 2030*. Bonn: BMDV. Available online at: https://www.bmvi.de/DE/Themen/Mobilitaet/Infrastrukturplanung-Investitionen/Bundesverkehrswegeplan-2030/bundesverkehrswegeplan-2030.html (accessed July 25, 2022).

Boltanski, L., and Thévenot, L. (2000). The reality of moral expectations: a sociology of situated judgement. *Philos. Expl.* 3, 208–231. doi: 10.1080/13869790008523332

Bremer, S., and Meisch, S. (2017). Co-production in climate change research: reviewing different perspectives. *WIREs Clim. Change* 8, e482. doi: 10.1002/wcc.482

Burch, S., Andrachuk, M., Carey, D., Frantzeskaki, N., Schroeder, H., Mischkowski, N., et al. (2016). Governing and accelerating transformative entrepreneurship: exploring the potential for small business innovation on urban sustainability transitions. *Curr. Opin. Environ. Sustain.* 22, 26–32. doi: 10.1016/j.cosust.2017.04.002

Burnham, M., Rasmussen, L. V., and Ma, Z. (2018). Climate change adaptation pathways: synergies, contradictions and tradeoffs across scales. *World Dev.* 108, 231–234. doi: 10.1016/j.worlddev.2018.04.014

Caris, A., Limbourg, S., Macharis, C., Van Lier, T., and Cools, M. (2014). Integration of Inland waterway transport in the intermodal supply chain: a taxonomy of research challenges. *J. Transp. Geogr.* 41, 126–136. doi: 10.1016/j.jtrangeo.2014.08.022

Cavallucci, D. (2018). *La TRIZ, une théorie de l'invention en support des activités de R et D: fondements et méthodes*. Techniques de l'Ingénieur. Available online at: https://www.techniques-ingenieur.fr/base-documentaire/innovation-th10/ingenierie-de-l-innovation-42833210/la-triz-une-theorie-de-l-invention-en-support-des-activites-de-r-et-d-fondements-et-methodes-ag5211/ (accessed November 24, 2022).

Chester, M. V., Underwood, B. S., and Samaras, C. (2020). Keeping infrastructure reliable under climate uncertainty. *Nat. Clim. Change* 10, 488–490. doi: 10.1038/s41558-020-0741-0

Commission internationale pour la protection du Rhin (2018). *Inventaire des conditions et des situations d'étiage sur le Rhin*. Groupe d'experts. Available online at: https://www.iksr.org/fileadmin/user_upload/DKDM/Dokumente/Fachberichte/FR/rp_Fr_0248.pdf

Coulibaly, A., Rudolf, F., Ory, M., Cavallucci, D., Bastian, L., and Gobert, J. (2022). "Open inventive design method (OIDM-Triz) approach for the modeling of complex systems and the resolution of multidisciplinary contradictions. Application to the exploration of innovative solutions to deal with the climate change impacts," in *Mathematical Modelling and Formalization of TRIZ: Trimming for Product Design*, ed C. Edward (Cham: Springer International Publishing).

Available online at: https://www.springerprofessional.de/open-inventive-design-method-oidm-triz-approach-for-the-modeling/23533046 (accessed November 22, 2022).

Curtis, F. (2009). Peak globalization: climate change, oil depletion and global trade. *Ecol. Econ.* 69, 427–434. doi: 10.1016/j.ecolecon.2009.08.020

Desquesnes, G., Nouasse, H., Lozenguez, G., Doniec, A., and Duviella, E. (2016). A global approach for investigating resilience in Inland navigation network dealing with climate change context. *Proc. Eng.* 154, 718–725. doi: 10.1016/j.proeng.2016.07.574

Durand, S., and Ferroudji, A. R. (2016). "Le principe de prévention à l'épreuve des cultures locales du risque d'inondation," in *Les villes à la croisée des stratégies globales et locales des enjeux climatiques*, ed F. Rudolf (Presses universitaires de Laval), 267–290. Available online at: https://hal.inrae.fr/hal-02605989

Fazey, I., Wise, R. M., Lyon, C., Câmpeanu, C., Moug, P., and Davies, T. E. (2016). Past and future adaptation pathways. *Clim. Dev.* 8, 26–44. doi: 10.1080/17565529.2014.989192

Fedele, G., Donatti, C. I., Harvey, C. A., Hannah, L., and Hole, D. G. (2019). Transformative adaptation to climate change for sustainable social-ecological systems. *Environ. Sci. Policy* 101, 116–125. doi: 10.1016/j.envsci.2019.07.001

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., and Rockström, J. (2010). Resilience thinking: integrating resilience, adaptability and transformability. *Ecol. Soc.* 15, 9. doi: 10.5751/ES-03610-150420

Gobert, J., and Brullot, S. (2017). La mobilisation du capital territorial pour le développement d'une logique d'Écologie industrielle et territoriale. *Revue d'Economie Regionale et Urbaine* 5, 881–904. doi: 10.3917/reru.175.0881

Gobert, J., Rudolf, F., Kudriavtsev, A., and Averbeck, P. (2017). L'adaptation des entreprises au changement climatique: questionnements théoriques et opérationnels. *Revue d'Allemagne et des Pays de Langue Allemande* 49, 491–504. doi: 10.4000/allemagne.606

Godard, O. (2010). Dossier ≪Adaptation aux changements climatiques≫: Cette ambiguë adaptation au changement climatique. *Nat. Sci. Soc.* 18, 287–297. doi: 10.1051/nss/2010036

Hadarits, M., Pittman, J., Corkal, D., Hill, H., Bruce, K., and Howard, A. (2017). The interplay between incremental, transitional, and transformational adaptation: a case study of Canadian agriculture. *Reg. Environ. Change* 17, 1515–1525. doi: 10.1007/s10113-017-1111-y

Harries, T. (2021). Understanding small business adaptation to natural hazards: a critical review. *Int. J. Disaster Risk Reduct.* 63, 102403. doi: 10.1016/j.ijdrr.2021.102403

Head, B. W. (2022). *Wicked Problems in Public Policy: Understanding and Responding to Complex Challenges*. Cham: Springer International Publishing. doi: 10.1007/978-3-030-94580-0

Heazle, M., Tangney, P., Burton, P., Howes, M., Grant-Smith, D., Reis, K., et al. (2013). Mainstreaming climate change adaptation: an incremental approach to disaster risk management in Australia. *Environ. Sci. Policy* 33, 162–170. doi: 10.1016/j.envsci.2013.05.009

High, C., Kelly, A., and Mair, J. (2012). *The Anthropology of Ignorance: An Ethnographic Approach*. New York, NY: Springer. doi: 10.1057/9781137033123

Hoang, L. P., Biesbroek, R., Tri, V. P. D., Kummu, M., van Vliet, M. T., Leemans, R., et al. (2018). Managing flood risks in the mekong delta: how to address emerging challenges under climate change and socioeconomic developments. *Ambio* 47, 635–649. doi: 10.1007/s13280-017-1009-4

IPCC (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University. Available online at: https://report.ipcc.ch/ar6/wg2/IPCC_AR6_WGII_FullReport.pdf

Joly, P. B. (2015). "Le régime des promesses technoscientifique," in *Sciences et Technologies Émergentes: Pourquoi tant de Promesses?* Hermann: Editeurs des Sciences et des Arts. Available online at: https://hal.archives-ouvertes.fr/hal-01282561 (accessed June 6, 2022).

Jonkeren, O., Rietveld, P., van Ommeren, J., and Te Linde, A. (2014). Climate change and economic consequences for Inland waterway transport in Europe. *Reg. Environ. Change* 14, 953–965. doi: 10.1007/s10113-013-0441-7

Jonsson, A. C., and Lundgren, L. (2015). Vulnerability and adaptation to heat in cities: perspectives and perceptions of local adaptation decision-makers in Sweden. *Local Environ.* 20, 442–458. doi: 10.1080/13549839.2014.896326

Joyce, P. (2003). *The Rule of Freedom: Liberalism and the Modern City*. Brooklyn, NY: Verso Books.

Kates, R. W., Travis, W. R., and Wilbanks, T. J. (2012). Transformational adaptation when incremental adaptations to climate change are insufficient. *Proc. Natl. Acad. Sci.* 109, 7156–7161. doi: 10.1073/pnas.1115521109

Kingdon, J. W. (2003). *Agendas, Alternatives, and Public Policies, 2nd Edn*. New York, NY: Longman.

Klein, B., and Meissner, D. (2016). *Vulnerability of Inland Waterway Transport and Waterway Management on Hydro-meteorological Extremes. Rapport, EU-Horizon2020 IMPREX, Deliverable 9.1*. Available online at: https://www.researchgate.net/profile/Bastian-Klein/publication/311455497_IMPREX_D91_Vulnerability_of_Inland_Waterway_Transport_and_Waterway_Management_on_Hydro-meteorological_Extremes/links/5847d0dd08aeda69682491f1/IMPREX-D91-Vulnerability-of-Inland-Waterway-Transport-and-Waterway-Management-on-Hydro-meteorological-Extremes.pdf

Klitkou, A., Bolwig, S., Hansen, T., and Wessberg, N. (2015). The role of lock-in mechanisms in transition processes: the case of energy for road transport. *Environ. Innov. Soc. Trans.* 16, 22–37. doi: 10.1016/j.eist.2015.07.005

Latour, B. (1997). *Nous N'avons Jamais Été Modernes: Essai D'anthropologie Symétrique, Nouv. éd*. Paris: la Découverte.

Lejeune, C. (2015). *Manuel D'analyse Qualitative: Analyser Sans Compter ni Classer*. Antwerp: De Boeck.

Lemieux, C. (2018). *La Sociologie Pragmatique*. Paris: La Découverte. doi: 10.3917/dec.lemie.2018.01

Linnenluecke, M. K., Griffiths, A., and Winn, M. (2012). Extreme weather events and the critical importance of anticipatory adaptation and organizational resilience in responding to impacts. *Bus. Strat. Environ.* 21, 17–32. doi: 10.1002/bse.708

Luhmann, N. (1994). *Soziale Systeme*. Frankfurt am Main: Suhrkamp.

Meah, N. (2019). Climate uncertainty and policy making—what do policy makers want to know? *Reg. Environ. Change* 19, 1611–1621. doi: 10.1007/s10113-019-01492-w

Nogueira, L. A., Bjørkan, M., and Dale, B. (2021). Conducting research in a post-normal paradigm: practical guidance for applying co-production of knowledge. *Front. Environ. Sci.* 9, 337. doi: 10.3389/fenvs.2021.699397

O'Brien, K. (2012). Global environmental change II: From adaptation to deliberate transformation. *Prog. Hum. Geogr.* 36, 667–676. doi: 10.1177/0309132511425767

Park, S. E., Marshall, N. A., Jakku, E., Dowd, A. M., Howden, S. M., Mendham, E., et al. (1995). "Impact of climate change on the discharge of the River Rhine," in *Studies in Environmental Science, Climate Change Research*, eds S. Zwerver, R. S. A. R. van Rompaey, M. T. J. Kok, and M. M. Berk (Amsterdam: Elsevier), 911–918. Available online at: https://www.sciencedirect.com/science/article/pii/S0166111606801159 (accessed March 4, 2022).

Park, S. E., Marshall, N. A., Jakku, E., Dowd, A. M., Howden, S. M., Mendham, E., et al. (2012). Informing adaptation responses to climate change through theories of transformation. *Glob. Environ. Change* 22, 115–126. doi: 10.1016/j.gloenvcha.2011.10.003

Pelling, M. (2011). "Resilience and transformation," in *Climate Change and the Crisis of Capitalism: A Chance to Reclaim Self, Society and Nature* (New York, NY: Routledge), 51–65.

Petersson, J. (2021). Blurring the shoreline: de- and re-infrastructuring and the changing colors of European flood policy. *Environ. Plan. E Nat. Space* 4, 623–644. doi: 10.1177/2514848620921858

Petitimbert, R., Bouleau, G., and Guimont, C. (2022). (Re)politicization of climate change mitigating projects: environmental forms and motives of the seine Nord Europe canal. *Eur. J. Fut. Res.* 10, 7. doi: 10.1186/s40309-022-00195-6

PIANC (2020). *Climate Change Adaptation Planning for Ports and Inland Waterways: EnviCom WG Report N° 178*. Brussels: PIANC. Available online at: https://www.pianc.org/publications/envicom/wg178 (accessed November 22, 2022).

Pierson, P. (2000). Increasing returns, path dependence, and the study of politics. *Am. Polit. Sci. Rev.* 94, 251–267. doi: 10.2307/2586011

Pigeon, P. (2015). Risque digue: une justification à la relecture systémique et géopolitique des risques environnementaux. *L'Espace Politique Revue en Ligne de Géographie Politique et de Géopolitique* 24, 3256. doi: 10.4000/espacepolitique.3256

Puupponen, A., Kortetmäki, T., Paloviita, A., and Järvelä, M. (2015). Social acceptance of climate change adaptation in farms and food enterprises: a case study in Finland. *Int. J. Sociol. Agric. Food* 22, 105–123. doi: 10.48416/ijsaf.v22i2.131

Rip, A., and Kemp, R. (1998). "Technological change," in *Human Choice and Climate Change: Vol. II, Resources and Technology*, eds S. Rayner, and L. Malone (Ohio: Battelle Press), 327–399. Available online at: https://research.utwente.nl/en/publications/technological-change (accessed June 25, 2022).

Roelich, K., and Litman-Roventa, N. (2020). Public perceptions of networked infrastructure. *Local Environ.* 25, 872–890. doi: 10.1080/13549839.2020.1845131

Rudolf, F. (2007). Von einer Krisen- zur Risikosoziologie in Frankreich: Ein Beitrag zur Katastrophenforschung. *Hist. Soc. Res. Historische Sozialforschung* 32, 115–130. doi: 10.12759/hsr.32.2007.3.115-130

Rudolf, F. (2008). "Les glissements de sens de l'écologie dans ses associations avec la ville: écologie urbaine, ville écologique et ville durable," in *Penser le développement durable urbain: regards croisés, L'Harmattan*, ed P. Hamman (Pari), 47–68.

Rudolf, F. (2015). La territorialisation des changements climatiques: les entreprises à l'épreuve de la montée en compétences collectives. *Pollut. Atmos.* 225, 2268–3798. doi: 10.4000/vertigo.11825

Rudolf, F. (2016). *Les Villes à la Croisée des Stratégies Globales et Locales Des Enjeux Climatiques*. Quebec: Presses Universitaires de Laval. Available online at: https://www.pulaval.com/livres/les-villes-a-la-croisee-des-strategies-globales-et-locales-des-enjeux-climatiques (accessed August 10, 2022).

Rudolf, F., Gobert, J., and Averbeck, P. (2019). "Adaptation to climate change as a challenge for sustainability management in the forestry and timber sector," in *Sustainability Research in the Upper Rhine Region: Concepts and Case Studies* (Quebec: Presses Universitaires de Strasbourg). Available online at: https://hal-enpc.archives-ouvertes.fr/hal-02382954

Schneiderbauer, S., Pedoth, L., Zhang, D., and Zebisch, M. (2013). Assessing adaptive capacity within regional climate change vulnerability studies—an alpine example. *Nat. Hazards* 67, 1059–1073. doi: 10.1007/s11069-011-9919-0

Schweighofer, J. (2014). The impact of extreme weather and climate change on inland waterway transport. *Nat. Hazards* 72, 23–40. doi: 10.1007/s11069-012-0541-6

Settele, J. R., Scholes, R., and Betts, R. (2014). "Terrestrial and inland water systems," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press), 89.

Shughrue, C., Werner, B. T., and Seto, K. C. (2020). Global spread of local cyclone damages through urban trade networks. *Nat. Sustain.* 3, 606–613. doi: 10.1038/s41893-020-0523-8

Simoens, M. C., Fuenfschilling, L., and Leipold, S. (2022). Discursive dynamics and lock-ins in socio-technical systems: an overview and a way forward. *Sustain. Sci.* 2022, 1–13. doi: 10.1007/s11625-022-01110-5

Smit, B., and Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Glob. Environ. Change* 16, 282–292. doi: 10.1016/j.gloenvcha.2006.03.008

Stamos, I., Mitsakis, E., and Grau, J. M. S. (2015). Roadmaps for adaptation measures of transportation to climate change. *Trans. Res. Record.* 2532, 1–12.

Sys, C., Van de Voorde, E., Vanelslander, T., and van Hassel, E. (2020). Pathways for a sustainable future Inland water transport: a case study for the European Inland navigation sector. *Case Stud. Transp. Policy* 8, 686–699. doi: 10.1016/j.cstp.2020.07.013

Thirel, G., Perrin, C., Drogue, G., Gerlinger, K., Krummen, J., and Wagner, J.-P. (2015). "Future evolution of river discharge for the french rhine basin in a context of climate change – an updated evaluation based on the ar5 ipcc climate simulations," in *Water Tensions in Europe and in the Mediterranean: water crisis by 2050?* (Marne la Vallée). Available online at: https://hal.inrae.fr/hal-02601883/document

Thornton, T. F., and Manasfi, N. (2010). Adaptation–genuine and spurious: demystifying adaptation processes in relation to climate change. *Environ. Soc.* 1, 132–155. doi: 10.3167/ares.2010.010107

Wesselink, A., Warner, J., Syed, M. A., Chan, F., Tran, D. D., Huq, H., et al. (2015). Trends in flood risk management in deltas around the world: are we going "soft"? *Int. J. Water Govern.* 4, 25–46. doi: 10.7564/15-IJWG90

Winz, I., Trowsdale, S., and Brierley, G. (2014). Understanding barrier interactions to support the implementation of sustainable urban water management. *Urban Water J.* 11, 497–505. doi: 10.1080/1573062X.2013.832777

Zebisch, M., Schneiderbauer, S., Fritzsche, K., Bubeck, P., Kienberger, S., Kahlenborn, W., et al. (2021). The vulnerability sourcebook and climate impact chains: a standardised framework for a climate vulnerability and risk assessment. *Int. J. Clim. Change Strat. Manag.* 13, 35–59. doi: 10.1108/IJCCSM-07-2019-0042

Zebisch, M., Schneiderbauer, S., Fritzsche, K., Bubeck, P., Kienberger, S., Kahlenborn, W., et al. (2022). "Climate impact chains—a conceptual modelling approach for climate risk assessment in the context of adaptation planning," in *Climate Adaptation Modelling*, ed C. Kondrup, et al. Cham: Springer International Publishing, 217–224. doi: 10.1007/978-3-030-86211-4_25

Zheng, Y., and Kim, A. M. (2017). Rethinking business-as-usual: mackenzie river freight transport in the context of climate change impacts in northern Canada. *Transp. Res. D Transp. Environ.* 53, 276–289. doi: 10.1016/j.trd.2017.04.023

Zhou, J. H., Zhu, Y. M., He, L., and Mu, B. X. (2022). Recognizing and coordinating multidimensional dynamic stakeholder value conflicts for sustainability-oriented construction land reduction projects in Shanghai, China: an integrated SA-SNA-TRIZ approach. *J. Clean. Prod.* 348, 131343. doi: 10.1016/j.jclepro.2022.131343

Appendix

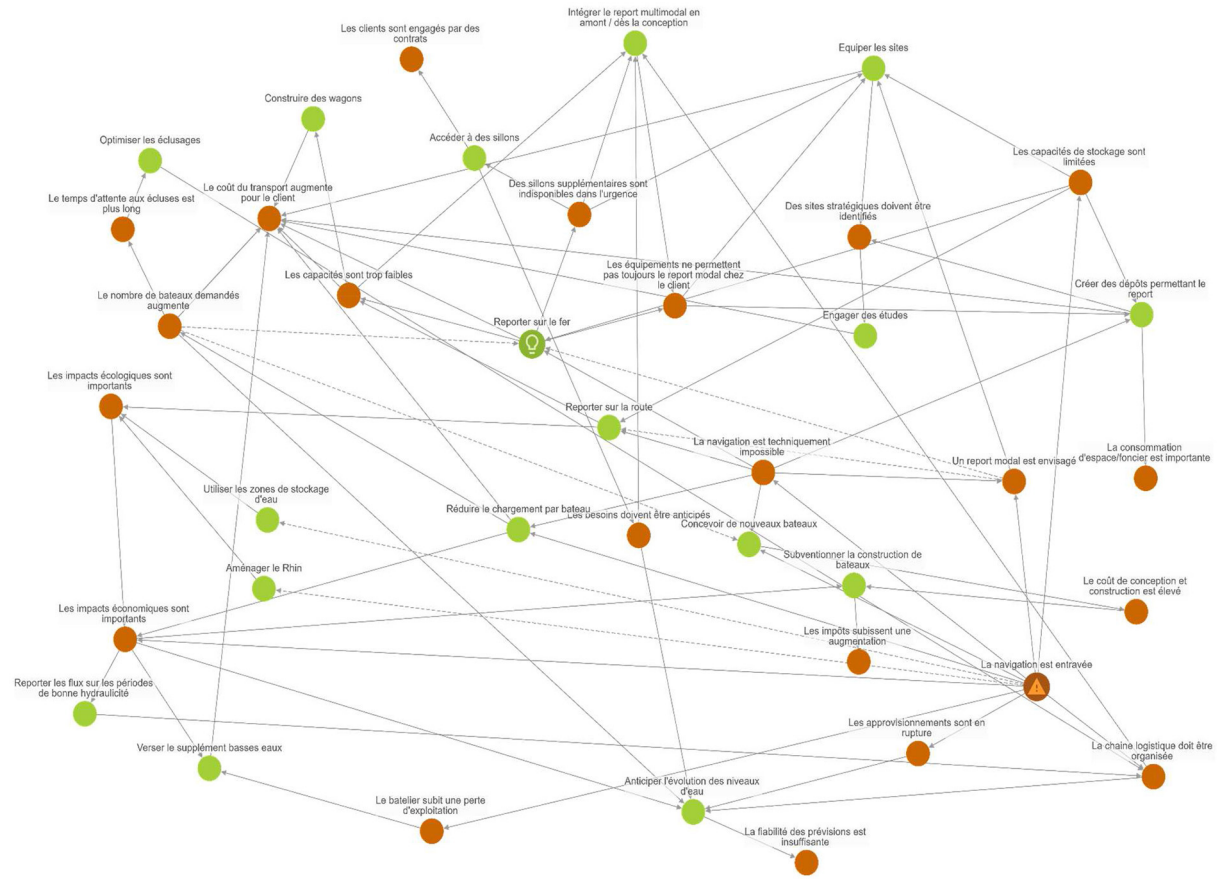

FIGURE A1
Problems graph worked by the group of in bulk carriers, storage providers and firms (TRIZ extraction).

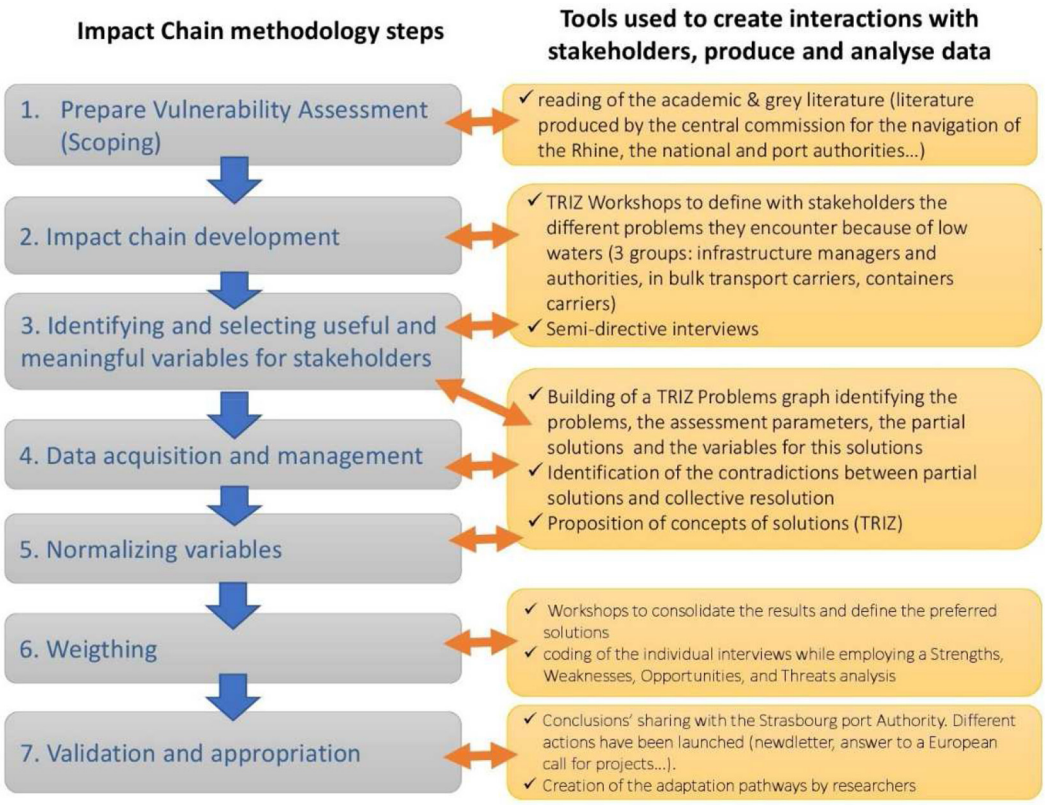

FIGURE A2
Methodology: Impact chain methodology in combination with TRIZ and semi-directive interviews.