



Measuring transformation concerning climate change and extreme events at the regional level: actor needs and spatial assessment in the Cologne district, Germany

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Abstract The article focuses explicitly on transformation and analyzes how it can be measured both quantitatively and qualitatively in a case study region in western Germany. It addresses blue, critical, and green infrastructures in a region that was affected by the 2021 floods in Europe. Together with regional actors, co-creative solutions for developing adaptation strategies and infrastructure planning will be developed. Using and combining different conceptual models and applying them to the project region as well as to human infrastructure highlights the different types of change and transformation. This also shows the complexity of such an overall assessment, which needs to include a lot of diverse actors and disciplines. The project's first results are overviews of national and cross-regional changes to infrastructures and administrative structures after the 2021 floods in Germany and at the district level. The interim results reveal that more needs and plans exist than real, measurable transformations and that certain transformations stem from planning long before the floods in 2021. Maps and land use potentials are presented that provide overviews of regional differences in flood, drought, and wildfire exposure and capacities for nature-based solutions. Both the conceptual

models developed in this study as well as the application examples could be useful for other researchers and administrative bodies to measure transformation to climate change and other stimuli.

Keywords Climate change · Extreme events · Adaption · Transformation · Infrastructure · Nature-based-solutions · System theory

Introduction

Relevance of the topic

Climate change is an urgent global and regional concern (ICLEI & ICLEI, 2018; IPCC, 2023). Extreme events, such as floods, droughts, or wildfires, increasingly affect local communities, raising awareness about the impact of climate change. At the international level, agendas and the Conferences of the Parties of the climate change negotiations try to push for global strategies that should invoke changes at the local level to mitigate and adapt better to climate change (United Nations, 2015a). Similar agendas include disaster risk reduction (United Nations, 2015b), urban and settlement planning (UN/HABITAT, 2017), sustainability (United Nations, 2015c), and humanitarian action (United Nations, 2016). Agenda alignment is currently demanded, as well as the operationalization of these agendas at the national, regional, and local levels to improve preparedness,

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better planning, and better action for more sustainable, resilient, risk-informed, and climate-proof action (Flood et al., 2030). This is also the case in the German Strategy for Strengthening Resilience to Disasters, which is the national context of this study (Die Bundesregierung, 2022).

However, implementation needs to catch up for many of these international programs. For example, the midterm reporting of the Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations, 2015b) shows success in many areas but also points out that several countries still need support with disaster risk reduction and preparedness, and that agendas need to be better aligned (International Science Council, 2023). The international climate change negotiations receive wide media attention, criticism, and skepticism. Activist groups expose the persisting gaps between knowing about climate change and acting. The same gap has been observed by scientists in disaster risk studies for several decades (White et al., 1945, 2001). Many nations have experienced various types of crises and disasters. The global perception of the COVID-19 pandemic, the Russian invasion of Ukraine, the Israeli–Palestinian conflict, and other wars and crises, as well as disasters caused by natural hazards, is raising awareness of multiple crises and is also triggering changes in research.

These multiple and overlapping crises result in current research no longer focusing on single hazards or crises, but on the overlaps, interrelations, and interconnectedness between them (UNU-EHS, 2021). This is reflected by trends within climate change, sustainability and disaster risk research on pathways (Field et al., 2014; IPCC, 2023; O'Neill et al., 2014; Turnheim et al., 2015), compounding events (Kruczkiewicz et al., 2021; Zscheischler et al., 2018), concurrent hazards (Lang et al., 2022; Pappadà et al., 2018; Quigley et al., 2020), systemic risk (Kreps & Quarantelli, 1998; Renn & Lucas, 2022; Sillmann et al., 2022), and multi-risk (Gallina et al., 2016; Garcia-Aristizabal et al., 2015; Greiving & Birkmann, 2006). This introduces a more comprehensive, all-hazard (Goss, 1996), whole-of-government (Christensen & Lægheid, 2007) and all-of-society approach (Matsuoka & Gonzales Rocha, 2020), which also acknowledges the non-linearity of the inter-relations and the multitude of the systems involved. Following a line in the science of system

theory, complexity theory, chaos theory, and complex adaptive systems, this is an important area of research. Especially in recent times, when increasing multiple crises are no longer hypothetical risks but lived experiences.

But here, too, there is a knowledge-to-action gap for many reasons (Albris et al., 2020; Gaillard & Mercer, 2012; Rufat & Fekete, 2019; Weichselgartner & Pigeon, 2015). Despite knowing about climate change and extreme events, the complexity and the dimensions of risks overwhelm preparedness, especially at the local and regional levels. International agendas often need to be translated into local languages and are less known locally.

Based on this background the topic of transformation has gained ground in fields of climate change adaptation pathways research, at least in climate research and in a conceptual understanding (IPCC, 2023). Empirical studies and methods for measuring transformation are rather unclear, however, fragmented or lacking so far (Fekete et al., 2022). They are fragmented since the methods either employ traditional land use change detection using spatial assessments, or statistical planning data or else (Egidi et al., 2023; Reidsma et al., 2023; Rogatka et al., 2021). And the spatial focus often is either on rural or urban transformation (Reidsma et al., 2023; Salihoğlu et al., 2021).

This all results in the research and policy gap this study aims to address. Since many international and strategic documents exist, the connection gap to local actions seems wide. The analysis of where and how the transfer from knowledge to action occurs is stuck. To address this, a conceptual and transferable model of methods and criteria of analysis will be developed as part of the project.

Since this topic is complex and broad, the study has to narrow it down. Therefore, the focus is on a case study of a district and its municipalities in western Germany, that was affected by the 2021 floods in Europe. It also narrows down the overall topic on the thematic area of infrastructure. Furthermore, floods, droughts, and wildfires are focused on as drivers of disasters and spurring changes in the area. These natural hazards and infrastructure were focalized since they represent crosscutting topics that can help better align different perspectives necessary for such complex topics.

Problem area and description

The metropolis of Cologne characterizes the administrative district of Cologne in western Germany with a population of over 1 million, several large cities with populations ranging from 100,000 to 500,000 thousand, such as Bonn and Aachen, and numerous smaller communities that form a densely populated urban–rural continuum. Situated between Cologne, Aachen, and Bonn is the Rhenish mining area, the largest lignite mining area in Europe, which will, however, be shut down by 2030. The district area has been repeatedly affected by floods, while droughts and wildfires have been increasingly experienced in the last decade, which have seen record temperature highs (Waldbrände, 2022). The floods in 1993 and 1995 in Cologne city (Engel, 1993) have led to several structural and nonstructural changes and can be analyzed to which extent these changes resemble a transformation. For example, Cologne established a flood warning and competence center after the floods. Large investments have been made to improve the city utilities such as water and sewage, including mobile flood protection systems and many more. A citizen NGO has

also been created based on the lessons learned from failed warnings and integration.

In this local setting and based upon years of cooperation with administrative bodies, NGOs, networks, and enterprises, a research project was created to work jointly on the challenges of floods, phasing out of mining, and other ongoing transformations in the region. The project Co-Site uses a co-creation approach to foster climate change adaptation and hazard mitigation on a local scale. The TH Köln—University of Applied Sciences invites actors in the region to co-design demands and actions for a more customized transfer of ideas, knowledge, and practices in the district of Cologne. Several scientists and experts from different areas of blue, critical, and green infrastructure, risk communication, innovation management, science communication, and IT work together with co-designers at the university. The university's vision, mission, and transfer strategy (Köln, 2017) to shape social innovations are behind the overall idea of the project (Fig. 1, top line). Within the overall societal context of adaptation to climate change and coping with natural hazards, a thematic leverage topic of infrastructure as a cross-cutting theme is selected (Fig. 1 point 1.). It supports

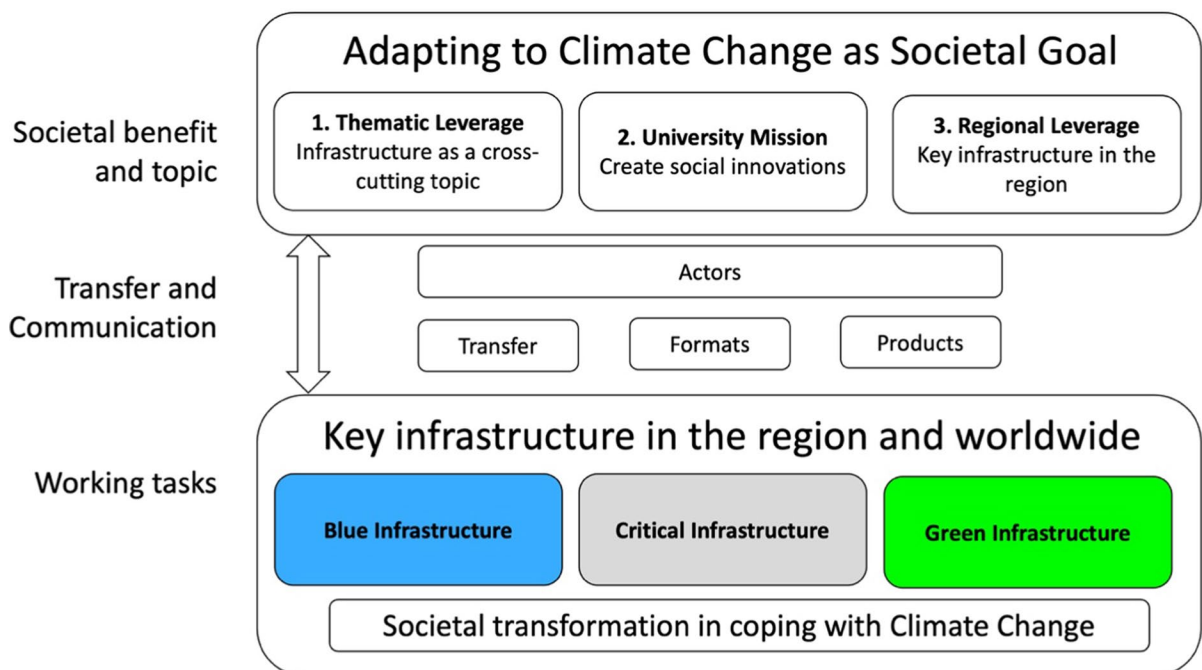


Fig. 1 Conceptual chart of the goals and tasks of the Co-Site project

the vision and mission of the university, in this case, adaptation to climate change and hazard mitigation, by conducting it in the region and selecting key infrastructure for the district of Cologne (Fig. 1 points 2. and 3.). This is done by working in the thematic areas of blue infrastructure, such as water bodies and rivers; critical infrastructure, such as energy, water, or information; and green infrastructure, such as protection forests (Fig. 1 bottom line). Blue and green infrastructures are understood here as specific approaches under the umbrella concept of nature-based solutions (Nehren et al., 2023).

Connecting these infrastructure types to shape social innovations by engaging in transfer and communication activities involves multiple actors, transfer modes (Gibbons et al., 1994; Heuchemer & Meinhardt, 2023; Köln, 2017), formats, and outcomes (Fig. 1 center). Selected examples will be described and analyzed in this study. The overall idea of the project is to co-create needs and actions, i.e., it will be nourished by inputs from the local actors throughout the process. Therefore, at the start of the project, the topics and analyses that will be addressed and analyzed are still to be determined. This study represents only the starting points of the first activities identified jointly by the actors in the first year. However, taking stock of the situation in the project's first year is important to analyze ongoing processes towards transformations later. Analysis and comparison of transfer achieved and transformations in the area to be measured will be needed until the project has progressed or ended in 2027.

Conceptual model

To analyze transformation, generic concepts must be derived and developed. These concepts serve as guidelines and blueprints to analyze and inform different processes in the project and are, therefore, systematically described in the following section.

Scientific procedures to categorize

The study draws upon traditional scientific procedures to classify or categorize. This includes the development of categories and components common in biology by creating classification schemes and relations between families and groups. There is also recourse

to stratigraphy that has been developed in geology to introduce temporal dynamics and hierarchical orders of explanatory layers. The study also draws upon system theory and its differentiation of phenomena to be observed by elements, their interrelations, and boundaries (Chorley & Kennedy, 1971). Hierarchy theory that puts the system of observation into relation to higher and lower layers of interrelated systems is also employed (Allen et al., 1982).

Another important area of scientific categorization is dynamics and changes. Changes are commonly analyzed in physics, where changes in vectors, for example, are important fields in mathematics. Linear versus logarithmic developments are used to describe system behavior and growth in economics or evolution in biology. Resilience is employed due to its high relevance in climate change, disaster risk, and sustainability research (Cannon & Müller-Mahn, 2010; Folke et al., 2010; Gallopín, 2006; Gunderson & Holling, 2002; Holling, 1973). It is especially important since it provides an additional or counter-example to evolution and linear developments. Certain scientific theoretical descriptions of changes, such as pathways, are also important to mention since they have an important role in climate change programs (Field et al., 2014).

There are also several important conceptual areas where theoretical or conceptual frameworks have tried to combine multiple components or dimensions of systems. Definitions of complex adaptive and social-ecological systems are especially relevant for this study (Gell-Mann, 1994; Lewin, 1992; Waldrop, 1992). In this area, criteria are used for complex systems characterized by nonlinear behavior, emergent properties, and other characteristics that are very suitable to describe climate change and disaster risks. Along this line of research, conceptual frameworks for sustainability and resilience, as well as disaster risks, have been developed (Birkmann & Birkmann, 2013; Khazai et al., 2015). These frameworks capture interrelations of systems, including triggering events or hazard events that impact different dimensions of society, including social, economic, institutional, and environmental systems. Derived from pressure and release models (Blaikie et al., 1994; Wisner et al., 2004), these include feedback loops and interventions. Some of these models also combine physical and natural science aspects, such as natural and human resources, with social science aspects, such as

distribution conflicts, ideological conflicts, epistemological gaps, and coordination gaps (Frei & Gaupp, 1978). Based on this background, the following considerations for the study are derived.

System composition

To identify the needs and actions of the actors, it is first necessary to understand the composition of the actors and the relationships between them. Therefore, actor mapping and network analysis are used. Hierarchy theory models are useful to structure the power, communication, and coordination relations within actor groups, such as public administration and the private sector or science. It is also useful for family structures but less so for individuals. Within the actor mapping, analyzing the communication channels, relations, and power structures between the administrative bodies is important. Using the hierarchy model helps better differentiate what is commonly only perceived as the administration or 'the decision makers'. Vaguely appointing public administration bodies as "decision-makers" per se by scientists is a common misconception in disaster risk studies. For example, the mayor of a municipality has different representative functions and relations to higher bodies, such as the county or the district, than its staff. However, the senior administration level is the one having thematic knowledge and responsibilities as well. The staff reporting to them have real thematic knowledge in very specific areas and need to be more connected with external administration.

System change types

To 'measure' the transformation, the system must be characterized first before and then again after a certain time. Measuring is to be understood as both quantifiable and non-quantifiable documentation of change. We use 'change' as a neutral denominator that still has to be scientifically analyzed whether it represents 'transformation' as a "fundamental change" (IPCC, 2019). The definition of transformation from the IPCC is adopted to measure transformation (IPCC, 2019, 2023). It includes the notion that a fundamental or regime change should occur. Since this is unclear, Fig. 2 indicates several aspects and categories for change to indicate categories for later analysis or measurement of change. Relating to the

components of system theory, a change can occur in the number, composition, and type of elements, their relations, all system's boundaries, and their subsystems. Another dimension of change is the composition of the subsystems, their location, and their number. A third type of change is related to a change of context. This especially includes relations between the system and observation with other external systems, but it also includes changes in the environment and, therefore, the interrelations of anything outside of the system of observation.

Hazard types

For this study, it is also important to characterize and classify hazards and other processes and triggers of change. There are different terms used for this. In the context of disasters, the terms risk, hazard, or threat are used to characterize external triggers or events that impact society or the environment. Concerning climate risks, there is often a separation between sudden and creeping changes, for example, thunderstorms and flash floods that occur rather suddenly, compared to droughts that take longer periods and are rather characterized as a process and less as an event (IPCC, 2023). Based on six influencing variables (transboundedness, fatalities, readability, camouflage, cascade effects, responsibility, and information quality) (Kalbassi & Kauf, 2017), a crisis or hazard can be characterized, and a development can be shown. Another way to categorize hazards relates to how much they have been experienced or are generally known. Derived from military language, this has become known within the context of war and weapons of mass destruction as known knowns, known unknowns, and unknown unknowns. Changes do not only have to be driven by negative impacts, hazards, or threats. They are also positive incentives for change driven by triggering factors such as interventions or innovations.

Dynamic change types

In addition to static descriptions, it is also important to capture the dynamics of change and categorize them. Typical types of dynamics in scientific descriptions are linear or logarithmic developments. Another type is the undulating or oscillating behaviors of systems. When these frequencies and magnitude

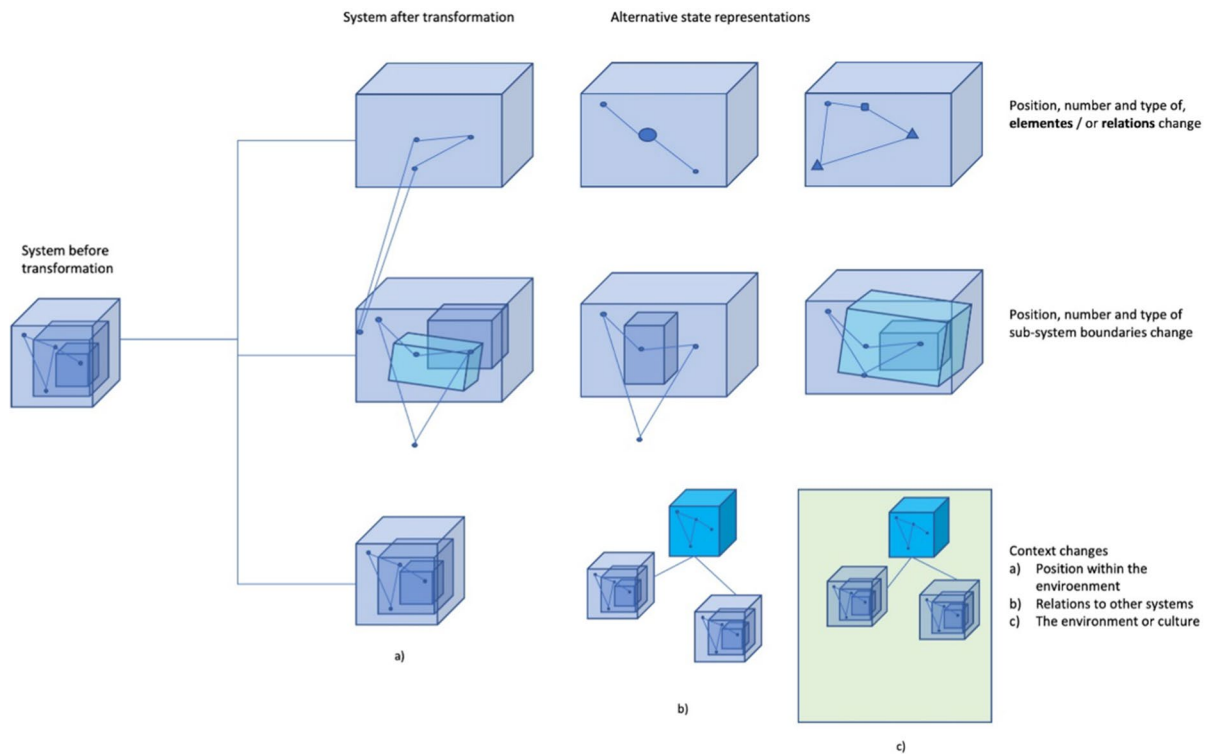


Fig. 2 Types of change within system elements, relations, boundaries, and environment

exceed normal behavior, they are also characterized as extreme changes. An alternative model inspired by resilient studies is fluctuation or different nonlinear change types that do not follow simple stability regimes but include bifurcation or complex instabilities (Gell-Mann, 1994).

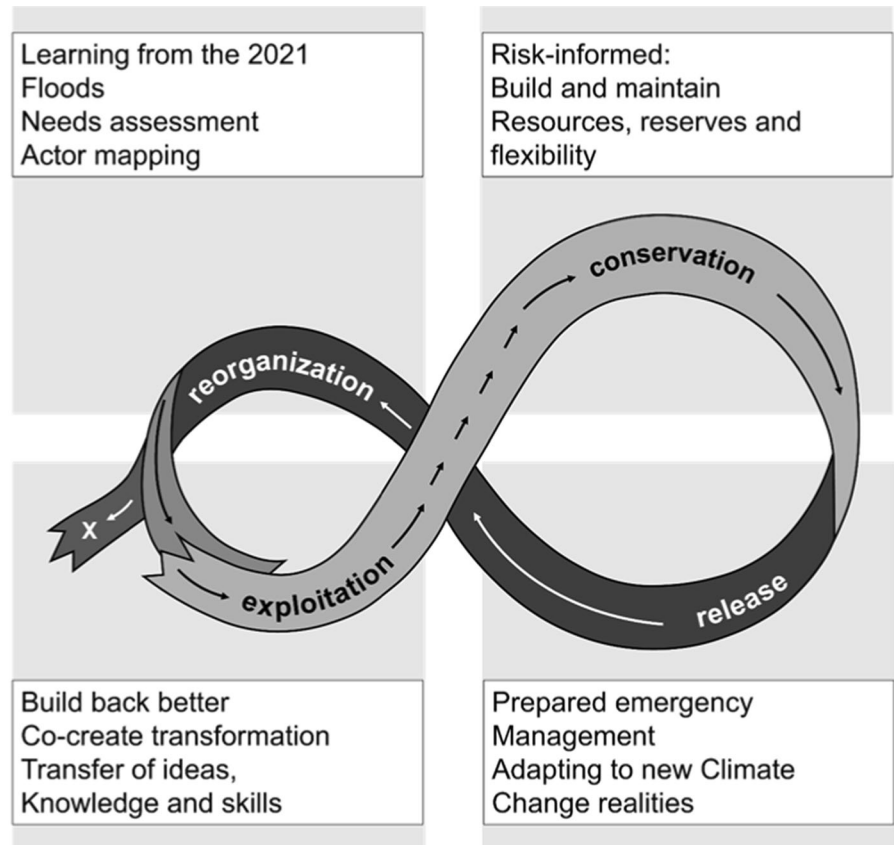
Apart from this abstract description of change, what real change is and what is not must also be scientifically analyzed. Some studies on transformation are already tackling this challenge and even the question of what fundamental or regime change means. A known philosophical challenge is whether the change of physical or observable structures can already constitute change (Cumming & Collier, 2005). The philosophical story of the ship of Theseus describes the example of when a ship's wooden planks would be slowly decaying and being replaced by new wooden boards, whether this still represents the original ship. It is the same example with human skin cells, which are replaced within a month, but the overall organism of skin persists. This also points to questions raised by resilience, e.g., whether an ecosystem is described as resilient

when it maintains its structure and function, even when some of its elements, such as the fish, do not survive.

The model of resilience is developed to portray systems in a dynamic ever evolving, and changing process while the system maintains basic functions. This means that there is never consistent stability or crisis. Still, there is a constant fluctuation between phases of stability before the collapse in a crisis occurs, then re-organization and an exploitation phase back to conservation and stability before the system can crash and be released after a crisis. The separation into phases is certainly helpful for application studies and can also be found in other representations of linear phases, such as in the disaster cycle (Baird et al., 1975; Coetzee & Niekerk, 2012). The disaster cycle represents the phases before, during, and after a crisis.

However, an important advancement of the disaster cycle is the conceptualization of resilience as an alternative to circular models by introducing a fluctuating dynamic rather than a linear dynamic (Fig. 3). Applying this to the flood example offers four stages

Fig. 3 Resilience in the panarchy understanding as a fluctuating system, captured in four stages (based on Holling, 2001)



of relative stability or imminent change that can be used to guide future flood risk management.

Combining systems changes and interventions

Several conceptual frameworks exist in science that try to differentiate security components, for example, into resources, conflicts, coordination, and knowledge components (Frei & Gaupp, 1978). Transformational research suggested a framework to analyze transformation by separating it into triggers, interventions, adjustments, and transformations (Fekete et al., 2022). Building upon this, we suggest a conceptual working framework to analyze the different components of this study.

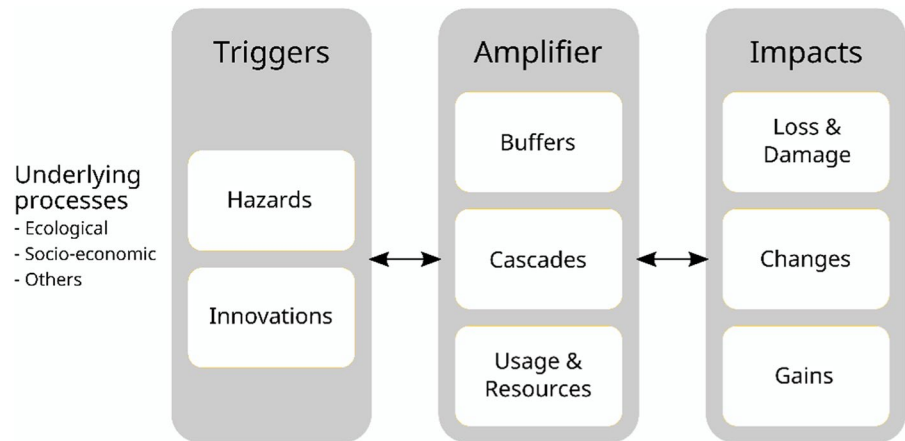
Figure 4 displays underlying processes, such as socio-economic or ecological processes, that are already occurring. This relates to research and frameworks about root causes that drive processes that finally lead to conditions where human beings become vulnerable. The same applies to geological

and geomorphological processes in natural sciences that ultimately lead to hazard events.

The left column symbolizes inputs to changes, such as triggering events or processes. These triggering processes can be an earthquake that triggers landslides. While this is an example of a sudden hazard, climate change is an example of a creeping hazard. Climate change can, as a process, trigger extreme events or hazards such as floods, heat, waves, or wildfires. As stated above, positive triggers and innovations, such as novel ideas or tools, are also important triggers.

Infrastructure can be an example of an amplification or catalyst component presented in the middle column of the Figure. Infrastructures are ambiguous because hazards or innovations can affect them. They can be utilized or used as resources that can buffer or amplify the effects of impacts. Infrastructure is understood as a combination of blue, critical, and green infrastructure. The column on the right represents the outcome or impact. Some impacts are understood here as negative, such as losses and damage from

Fig. 4 Conceptual framework for measuring transformation by an interaction of triggers, amplifiers, and impacts



disasters. Other outcomes are changes in many parts of affected areas and non-affected areas. That can also include positive outcomes, mainly of innovations, and not of hazards, such as gains through infrastructure usage, energy production, or other services derived from infrastructure. Feedback loops and interactions in many areas can also amplify impacts. This includes interventions, which can result from the notion or experience of innovations and hazards or reactions of infrastructure outputs. Interventions can generally be directed at any other component in this framework. Interventions are feedback mechanisms with a key or even triggering characteristic. Examples of interventions are new regulations or laws introduced that inhibit building houses into the floodplains. This

intervention would reduce losses and damages by removing houses from the exposure zone.

The blue, critical, and green infrastructure types can also be separated and analyzed regarding their different characteristics (Fig. 5). They reveal different types of inputs. For example, in a flood, blue infrastructure is a main source of floods, when rivers are, in fact, a main part of their hazard event. At the same time, blue infrastructure is a main source of buffering of the flood or as a retention basin (Ribbe et al., 2024). Green infrastructure mainly consumes water for irrigation and serves as a buffer when used as a retention or sponge. Floods mainly affect gray infrastructure, but dam breaks can also lead to flood waves.

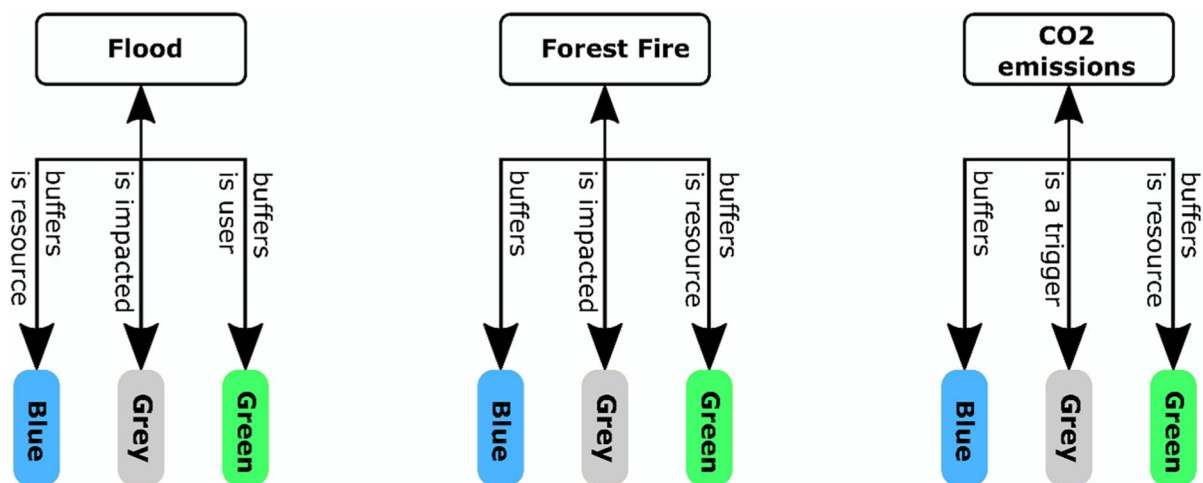


Fig. 5 Examples of interactions between triggers, buffers, and impacts of hazard examples with blue, green, and gray infrastructure

Using another example of wildfires shows that the relationships are similar, only slightly different. Blue infrastructure is mainly a buffer for wildfires. Green infrastructure is mainly a resource fueling wildfires by wood or other vegetation. It can also serve as a buffer to store water and moisture in rainy periods that can buffer wildfires and as a sponge against flooding. Gray infrastructure is mainly impacted by wildfires, but can also serve as a trigger when sagging power lines touch vegetation in summer and spark a fire.

The third example compares a creeping hazard to the above examples of all the sudden events. CO₂ emissions are buffered by blue infrastructure when they are used as carbon sinks. Green infrastructure is also mainly a carbon sink. On the other hand, it can be a source of CO₂ emissions when burned. Gray infrastructure, in this case, is mainly a hazard producer when industry and cars are CO₂ emitters.

Change criteria

System theory provides a framework to derive components and criteria to analyze these (Chorley & Kennedy, 1971). Table 1 displays the main conceptual components of systems to be analyzed in this study, whether or not transformation occurs. The first components are elements, and the related measuring criteria of changes cover a wide area of different resources (Table 1).

The resources include people, budgets, institutions, tools, and ecosystem resources. While these are countable and measurable physical elements, a system's non-physical elements can still be captured in a measurement now and in the future. This includes knowledge and plans. Certain techniques and skills are also observable or describable. For example, a system can be analyzed to identify whether the number or type of people has changed. The criterion of budget can be analyzed in the same way, for example,

Table 1 Criteria for measuring transformation of systems

Main conceptual component of transformation	Measuring criteria Change of/in
Elements	Resources: People/staff Budget Institutions/buildings Knowledge/awareness Plans Techniques/skills Tools Eco resources, nature-based-solutions
Boundaries	Sets of elements Natural boundaries or overlaps of boundary types Coordination change Distribution change
Internal relations	Regulations Communication Hazards, stressors, stimuli
External relations	Laws Communication Hazards, stressors, stimuli
Dynamics	Type, phase, length Linear Undulating Extremes Evolution/growth Fluctuating
Quality of the system: main idea/function/identity/quality/value	Value change Conflict Redefinition of target levels/agenda setting/elections

whether there is more or less budget for flood preparedness in a given system.

The next component is the system's boundaries, which include several measurement criteria. One criterion is the set of elements liable to change regarding how elements are grouped. For example, it is not just the number of people as such, but how people are organized in groups and how the group's composition changes over time. For example, 1,000 people are active as helpers in one flood event, and 80% are untrained volunteers. After the flood, they get better training and register at relief organizations. In the next flood, it will be the same number of people, but they will be reorganized under the umbrella of different organizations, and now the boundaries of how people are grouped have changed. Natural boundaries, such as rivers or coastlines, set another criterion. There are also overlaps of different boundary types, such as water catchments with administrative boundaries. Sometimes, they match, but very often, the different types of boundaries intersect each other. Boundaries can also be measured by the change of coordination, when administrative units are redefined, or by the distribution of boundaries.

Another component of systems is the relations or vectors between elements. There are internal relations within a system under observation. Measurement criteria include regulations, for example, in which topic areas and regions certain new flood preparedness laws or guidelines have been published. A major concept to keep in mind when looking at relations and communication in this context is that change related to climate change happens under post-normal scientific conditions, i.e., "facts are uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz & Ravetz, 1990). This means that research and researchers play an active and direct role in communicating with actors of any kind and adopt new roles and norms like participation and being public communicators with a license to display emotions (Brüggemann et al., 2020; Nicolaisen, 2022). The exchange between elements, especially people and actors of any kind, can therefore be measured by communication. Interrelations exist due to many factors, and hazards and stressors produce internal relations of relevance for our topic. Considering the involvement of different actors, including researchers, evaluation criteria for science communication that might need extension due

to the post-normal nature of climate change adaptation strategies can be considered. External relations are relations between different systems. This is very similar to internal relations, and since they are likely to be at a higher organizational level, it can be regulations but also laws. Taking scholarly communication into account, it can also contribute to the published body of scientific knowledge and bibliometric criteria could be applied.

The components so far mainly captured static aspects. Therefore, it is important to add dynamics as another component. Dynamics can be measured not only by different points in time but by different types, phases, and lengths of dynamics. Dynamics can be linear, undulating, characterized by extremes, and their character can be evolution and growth or fluctuating.

The last component is often not directly observable by physical components. Apart from aspects directly related to individual elements, certain qualities of the system respond to the overall system or system of systems. The system's quality can be the main idea or function, identity, all the values that drive the overall system, and especially human individuals and society. Such a designation of relevance and quality is necessary for a system to be identified as a system by humans.

Criteria to measure such qualities of a system include value change. Values may change when ideas from other countries are transferred, and then search and rescue for human beings can become the new priority. Another criterion is measuring a system's quality and how it can transform conflicts. Conflicts can indicate problems in a given system and will serve as a stimulus for change. The definition of target levels or agendas can also measure system quality changes. While this component overlaps with the previous components, it could be the top priority component, because without the overall idea, a system can become hollow. For example, maintaining a certain organization on paper to demonstrate activity can be detected as hollow and dysfunctional in real life. The organization as such and all the elements, structures, and even building sites may persist. But if the overall will for action or credibility of action is missing, all the other components become neglected. Even when a given institution's staff numbers or budget rises or shrinks, it will not immediately impact a real fundamental change.

The role of the analyst or moderator should be addressed in scientific studies (Bell et al., 2006; Fekete et al., 2012; IRGC - International Risk Governance Council, 2017; Klinke & Renn, 2006; Renn et al., 2011). Especially in research and transfer practice, where multiple actors interact and co-create, the role of the observer becomes blurred and should be documented. In the case of the project Co-Site, the university is the moderator of the transfer of ideas, knowledge, and skills represented by project staff. Even when the university only serves as a mediator, the goals of the project, the values and skills of the organization, and the individuals involved have a major impact on what is done and how it is done, especially considering the co-creative approach, meaning that the observer is part of or associated with the co-creative process (Jorgensen & Principles, 2020). This connects to the last component mentioned in Table 1 above. The observer and moderator’s motivation, will, and quality composition greatly impact the project outcome, even when the organization tries to hold back its interests and serve only as a moderator. A university is attributed to certain characteristics, such as scientific skills and a certain form of neutrality. But this perception can change when the university does not act from a neutral standpoint but tries to engage actively in a transformative change, including actions.

The observer also applies a certain observation lens on the system to be analyzed within a given system environment. First, the observed system consists of physical and nonstructural properties and different types of actors. The observer is one of the actors and, therefore, both part of the system and an observer of the system. Placing itself into the internal or external system boundary is important to state and analyze. The observation lens consists of different paradigms and methods for analyzing the overall process and project by which criteria. An example is this study’s conceptual considerations, measurement criteria, and frameworks provided above and below. The observer is also part of the system environment, which includes many more actors and processes than those captured by the system under observation.

Concept and method steps in this study

The study’s research design consists of a conceptual frame to derive generic and transferable components

and criteria to measure transformation. System theory is applied and related to the field of risk assessment. Stages of input and output stimuli into and out of a system are provided for both negative impacts, such as hazards and stressors, as well as positive stimuli (Chorley & Kennedy, 1971). Outcomes also can be both positive and negative. This conceptual frame mainly characterizes and measures systems at a given time and enables repeated measurements after a certain time.

As a next step, methods that enable the application of these criteria must be selected out of the many possibilities (Table 2). This study is about climate change and extreme events related to transformations of human infrastructure systems and how humans interact with blue, critical, and green infrastructure. It is important to focus on human actors because their perceptions and actions are major drivers for utilizing infrastructure to mitigate or adapt to climate change. Therefore, methods must be selected to capture the transformation criteria measuring actor groups’ type, composition, and interrelation.

A first method is actor-network mapping, which is selected to display and document actors’ set-ups and interrelations. There are multiple types of actors or stakeholder mapping and network analysis in the literature (Durrant et al., 2022; Gaillard & Maceda, 2009; Gopal & Clarke, 2015). As a first step, different interest and stakeholder groups are identified to provide an overview of possible actors to be involved or considered. In the second phase, actors’ power and interest (Johnsen & Scholes, 1999), considering climate change measures, will be evaluated

Table 2 Research design of this article

Step	Conceptual steps
1	Selecting a crosscutting topic to get started: infrastructure
2	Creating a conceptual model of system change: Boundaries, elements, relations, internal, external Dynamics/resilience type Measuring criteria
3	Analyzing transfer and transformation: (a) Actor mapping (i) Actor types and hierarchies (ii) Regional landscape (iii) Role of moderator and observer (b) Needs assessment © Spatial assessment (GIS)

to identify key stakeholders. Accompanying these steps, interrelations between actors are documented to analyze interconnected actor clusters and identify actors that should be connected. In addition, indicators for the transformation are derived from the data by analyzing the dynamic change of the network over time.

The needs assessment as a second method is selected to capture existing impacts and challenges related to climate change and infrastructure transformation (Jovel & Mudahar, 2010; Kaufman & English, 1979; World Bank, UN Development Programme, European Union, and GFDRR, 2018). Needs assessments allow us to capture the demands and perceptions of different actor groups and, later on, allow interventions and changes in needs to be documented by a follow-up needs assessment or assessment of achieved interventions and outcomes.

Needs assessments can be conducted through focus group discussions. These are conducted in the project as co-creative workshops, using co-designing methods to enable the exchange and transfer of knowledge. Since such focus groups typically consist of selected individuals, additional methods are applied to identify groups of people not participating in the focus groups. A survey is designed to capture the additional aspects of needs, demands, and ideas these groups bring to the table and send out to include many people. Further methods and formants will be employed during the project to garner them according to the needs of different actors, such as civil society, NGOs, partners from the private sector, and many more. The latter actors were identified before the project started, and it was jointly discussed how to include local populations especially. This will need more time, and only a few results of the above methods will already be reported in this study.

In addition to the social science methods presented above, semi-quantitative measurement of change is applied using spatial assessment and geographic information systems. This has the advantage of accessing data derived from airborne sensors and planning data, as well as including statistical and demographic data. While such quantitative and spatial data also has known constraints, the major advantage is that it is available from the same data sources for the project area. Spatial assessments allow us to analyze existing land use and settlement area changes, extending far before the project run time. Future

spatial data can easily be integrated, allowing for continuous monitoring of changes.

Ethics statement: The participants in this study including oral communication are active partners within the project. They provided written consent to the cooperation and joint work within a living laboratory and signed their consent for communication, participation, measurement and evaluation in the cooperation agreement. In addition, the ethics commission of the university has approved this study. The start of the recruitment period for this study was 01.01.2023 and the end 29.11.2023.

Results: operationalization at selected examples

The following are preliminary results from the first year of the project. They represent the outcomes of the first joint co-creative workshops and actor discussions. Names of persons and institutions are anonymized. The preliminary results will be complemented by more in-depth investigations and comparisons of changes after a further run-time into the project.

National and cross-regional level topic: the 2021 floods

The components and criteria to measure transformation can already be applied nationally for the 2021 floods in Germany. There has been huge interest from different national and international audiences to learn from the German flood disaster, especially whether something has changed in management and governance. This is a difficult question to answer because of all the complex underlying actor groups, governance structures, and pros and cons of all activities. Therefore, the components and criteria described above can help to dissect this complex picture.

With regard to the first column with the elements of the system of flood risk management in Germany, Tables 1 and 3 (Table 3 follows below) correspond, with the latter 'completing' the former by including the results of the analysis. The following results can be observed: Regarding people involved, at least one of the municipalities in the project has created a new staff unit responsible for guiding the reconstruction after the flood disaster. The existence of such a unit and the devotion of resources shows the significance

Table 3 Transformations after the 2021 floods (topics in flood-affected areas in Germany) as a result of the actor workshops

Main conceptual component of transformation	Measuring criteria Change of/in:	Results
Elements	Resources: People/staff Budget Institutions/buildings Knowledge/awareness Plans Techniques/skills Tools Eco resources, nature-based solutions	New staff unit reconstruction in one municipality Funds for reconstruction Only 30 of 4000 destroyed buildings will not be rebuilt in the same place Cell phone warning Helicopters get winches Planning of retention basins Renaturation of rivers
Boundaries	Sets of elements Natural boundaries or overlaps of boundary types Coordination change Distribution change	New competence center in which the federal states work together Coordination and structures remain Spontaneous helpers to be better integrated
Internal relations	Regulations Communication Hazards, stressors, stimuli	Resilience management concepts and contingency plans are being developed
External relations	Laws Communication Hazards, stressors, stimuli	Changes in legislation are foreseen and contribute from neighboring fields such as critical infrastructure
Dynamics	Type, phase, length: Linear Undulating Extremes Evolution/growth Fluctuating	Linear: it had to be rebuilt quickly Fluctuating: only at the next high water there is a surge of activity again
Quality of the system: main idea/function/identity/quality/value	Value change Conflict Redefinition of target levels/agenda setting/elections	Conflict: citizens do not want trees cut down for renaturation

of the task. How and in which areas this unit is effective must be analyzed further. Regarding the budget criterion, the federal states and other levels have provided funds for reconstruction, including the municipalities. Of around 4.000 buildings destroyed in the Ahr Valley in Rhineland-Palatinate, only about 30 are planned to be permanently relocated out of the flood-exposed zone (DKKV, 2022). This represents rather a non-transformation. Whether or how the about 4000 destroyed buildings are rebuilt better has to be analyzed later on. The reactivation and expansion of the warning infrastructure, e.g., with additional sirens or warnings on digital information boards, has increased since the flood. A technical means of warning that has been missing is now available and has been trained in an exercise with the whole population in Germany: the cell broadcast system on mobile phones (BMI & BMF, Bericht zur Hochwasserkatastrophe,

2021). This, indeed, is one of the most substantial real changes after the flood. Associations of relief organizations, experts, and other councils have collected demands for additional technical equipment. Winches for helicopters are high on the list since they were lacking in the 2021 operations. Many other similar technical demands are raised. The acquisition and financing of such customized technology tools and machines typically takes a long time and, therefore, must be analyzed in the future. The renaturation of rivers and planning of retention basins is an ongoing discussion and will be discussed later at a local level.

Regarding boundaries as a component, the new Competency Center of Civil Protection resembles a re-organization of how the federal states work together with the German state (BMI & BMF, 2021). But while representatives now have an office space, and therefore an option to physically work together

in a crisis and the preparedness phase, it still needs to be seen whether this will be a lived or theoretical change.

Germany's overall coordination and incident command system structures remain despite many discussions. While there has been a lot of critique of dysfunctional coordination and communication, the perception amongst the first responder organizations was that it has worked in principle and, therefore, will be sustained (Fekete & Sandholz, 2021). How to better integrate spontaneous helpers is expressed as an important demand in many of the lessons learned studies and strategy papers that came out after the 2021 floods by the federal states and other institutions after the floods (Broemme, 2022a, 2022b; Ministerium des Innern des Landes Nordrhein-Westfalen, 2022; Rheinland-Pfalz, 2021). Still, it needs to be seen whether, in a follow-up exercise or disaster event, this indeed will be different.

No major change can be observed regarding internal and external regulations and relations. The same applies to public perception beyond the directly affected people (aus dem Moore et al., 2022), which calls for changes in external communication across regions and actors. Also, the type of hazards and stressors of positive stimuli did not change.

Regarding the component of dynamics, a rather linear behavior can be observed when it comes to rebuilding quickly on site of the affected areas. However, the fluctuating dynamics also fit this topic, as activity surges typically only occur when the next flood comes and then subsides again. While some internal changes within administrations are planned or being developed, their implementation and evaluation will need more time. Some external changes, such as national laws or strategies, are currently published but were already developed years before the floods in 2021. However, new laws, such as those relating to critical infrastructure from the European Union (EC, 2022), will also have a major influence on neighboring fields such as disaster preparedness or energy transformation.

Regarding the last component, the quality of the system, only local conflicts can be observed that will be discussed further down. The floods have reiterated the overall value and perception of flood risk management and preparedness. Given the prevalence of lessons learned studies and the magnitude of the event, it is conceivable that it has left an impression

that could last slightly longer than in previous large floods. The structure used in this results section displays the conceptual approach and the analysis steps outlined in Table 2. Table 3 further demonstrates how the research design of the article (Table 2) achieves concrete results when applied to a real case. The column on the left shows the 'conceptual model of system change', while the other columns show how this model was applied and found to be present in the case study for 'analyzing transfer and transformation' (Table 1). Following the research design of the latter steps of the conceptual model, we first analyzed the 'actor mapping', then the 'needs assessment' and finally conducted the 'spatial assessment', as follows in the results sections below.

Actor mapping: infrastructure and climate change at the district level

The specific system composition of actors (see "[System composition](#)" section), administrative hierarchy and boundaries regarding the application in Cologne was analyzed using the systems theory approach. We identified several types and groups of actors that were involved from the beginning of the project, such as municipality administration, civil society groups active in the field of flood risk, critical infrastructure bodies such as the fire department, and companies consulting in risk and resilience management. In the first phase of the project, the main focus was on involving municipality actors, which is why the following example refers to this group of actors. More groups will be involved in the course of the project, ranging from insurance companies to industry, other segments of the society, the environmental management or the economy, but this is beyond the scope of this paper. Figure 6 illustrates the administrative levels within the district. At the top level is the district; the Cologne district comprises 11 counties and 99 municipalities. The district of Cologne is located within the federal state of North Rhine-Westphalia (NRW) in western Germany, which is characterized by relatively large districts and related governmental areas and population numbers. The federal state of NRW was the second most affected by the 2021 floods (Mohr et al., 2021). The neighboring federal state of Rhineland-Palatinate in the south experienced the highest casualties. Rhineland-Palatinate is characterized by a much larger number of districts, counties,

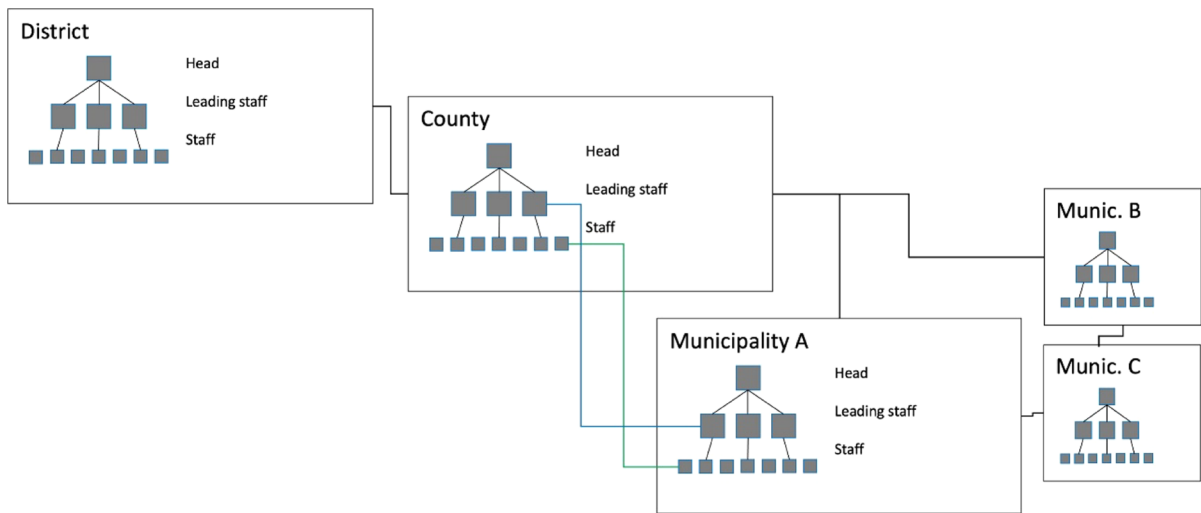


Fig. 6 Conceptual chart of an actor mapping hierarchical layout

and municipalities, all of which are smaller than those in NRW.

Apart from the abstract hierarchical structures of the administration, it is important to consider administrative boundaries and regional spatial relations. In a previous project from 2016 to 2019, we observed that administrative staff or utility providers in neighboring counties often had not communicated about special topics such as disaster preparedness or critical infrastructure (Fekete, 2019; Fekete et al., 2019). For example, the district of Cologne is characterized by the natural boundary of the river Rhine, a major stream that divides western and eastern areas. This natural boundary has an important influence on the planning of disaster relief as well as on the interaction between local actors and policymakers.

Needs assessment

During the first workshops in the project in the district of Cologne, different administrative units and actors expressed various needs, activities, or topics concerning transformations. Overall, the topic has shown great interest since it addresses needs provided by the last flood experience in the area, future demands of transferring to more sustainable and green resource consumption, and the creation of new jobs to compensate for phasing out of brown coal mining.

The county's representatives have expressed the need to develop a spatial strategy for disasters and

transformation processes that would match existing strategies for climate change, adaptation, and sustainability in the region. Another demand was a better connection between data and information systems. Digital twins are current trends, but they are also necessary in case of a blackout and to better monitor and document disaster risk as well as green and blue infrastructure potential for retention areas and more.

Participation processes with the population are an ongoing need. While some formats have been tried by the municipalities, attracting local citizens to engage and stay informed is still challenging. Developing digital parks to generate new jobs and income is one project in the county. The pros and cons of critical infrastructure dependency on those parks and whether digital parks or compounds create more jobs must be analyzed.

The region is also characterized by a major ongoing transformation of land use by brown coal mining. Whole villages have been deconstructed to dig out the brown coal for decades. Protests of climate change activists have brought this to greater national attention in recent years and months. Phasing out of coal mining is the demand of the protesters that are backed up by scientists—generally as well as locally—and those areas that have already been dug out will need to be changed for future usage. One plan is to fill them with water and create artificial lakes and a recreation area. This also needs assessments of how to direct future tourism and other aspects. The last topic

mentioned was the current trend in exploring alternative sources of energy for car mobility in the form of hydrogen extraction. While this is mainly an assessment of opportunities generated by it, it could also benefit from a risk assessment.

Municipality A in the project framework has been severely affected by the floods in 2021. Reconstruction and related flood protection concepts are, therefore, a major priority. In line with that, the dialogues revealed that the fire protection plan should be updated to include better sirens and warning systems for different types of hazards, including floods and heavy rain. A measurable change that can already be observed is that the municipality has created and operates a recovery incident command unit. As in many other municipalities, a climate change manager has been employed. Since these are new and often single persons, feasible topics and tasks must still be identified, and strategies and activities must be designed.

Municipality B provided ideas for the conversion of an industrial area. That is a current need and could be analyzed further on how this relates to blue, critical, and green infrastructure climate change adaptation ideas. The municipality also had some flood exposure issues and plans to develop a flood protection concept for a hospital. Additionally, they created a climate board and intend to participate more in communication and interaction with local civil society.

A concrete first action within the Co-Site project is to analyze the potential of nature-based solutions, such as green and blue infrastructure. Municipality B has started another project already analyzing the redesigning of green roofs for bus stops and unsealing the city trees. Additional ideas to generate sponge city features include the upkeep of playgrounds and not selling them for built areas. It has to be analyzed how effective and large all these areas can be combined and which potential they have to mitigate floods or droughts.

Municipality C has also been heavily affected by the 2021 floods. Houses, hospitals, schools, kindergartens, and industrial compounds were affected. The city has proposed to naturalize the straightened course of a stream in an alley flooded in 2021 to create more retention space. However, to achieve this, the existing 300 alley trees must be felled and new trees planted somewhere else instead. The municipality already

tried different information and participation formats, such as a local community gathering, an online meeting, and student projects in the streets to engage with the citizens. Online participation was the highest, and many ideas and demands could be documented using the text chat function. The project Co-Site will further analyze how and to which extent naturalization in the street can help in floods and whether upstream retention areas could be more effective. In a field visit, experts from the project on nature-based solutions already discovered that the street area is too narrow to diminish flood peaks sufficiently. The upstream area up to the stream's source was visited on the field visit, and an inter-mix of river training, natural river course, and river channeling was observed. Elderly citizen homes, playgrounds, and a car repair shop were in the exposure zone, displaying different types of social and economic vulnerability and secondary hazards such as contamination.

Further upstream, the narrow valley provided some areas for potential retention basins. However, most are privately owned and, therefore, difficult for the municipality to use. One large area of a former oil company had already been restored, and the contaminated soil had been cleared. But there are plans to place a new fire station there, and it must be analyzed further whether this could also be a conflict of interest. As with any retention areas, this would represent a spatial risk transfer, not a local risk solution for the people in the affected streets.

Communication with and participation in civil society is a major need in this municipality. Co-Site strives to support this process with co-creative approaches as well as an accompanying science communication strategy. Other topics for the project to work on are the droughts experienced in 2022, demands for urban green irrigation, and a heat action plan. Table 4 shows a summary of the findings.

Spatial assessment of risk and transformation potential

One focus of analysis within the Co-Site project is assessing how the region is affected by climate change and which potential it has to adjust or transform towards living with the impact of climate change, as well as mitigating it by more sustainable usage of resources. Various methods will be employed over the project run time to address this. Apart from actor

Table 4 Results of first workshops, where the actors expressed their needs and interests

Actor	Needs, activities, or topics concerning transformations	Transformations
County (Senior admin. for structural change, broadband, digitalization, regional and structural development)	Developing a spatial strategy for disasters and transformation processes—and resilience management for the county Needs for information systems/digital twin Participation processes with the population Developing digital parks to generate new jobs and income Conversion of former coal mine to recreation area of two lakes Extracting hydrogen for future car mobility	Cross-sectoral cooperation
Municipality A (Senior admin.)	Flood protection concept Fire protection plan, sirens Training for staff in administration Integration into resilience management of the county Cybersecurity and energy planning	Climate manager employed Cross-sectoral cooperation Recovery command staff built
Municipality B (Senior admin. Urban planning, climate and environment, junior admin sustainability)	Contribution of green area development to climate change adaptation Climate board and participation of civil society Nature-based solutions (green roofs for bus stops, unsealing for city trees)	Sustainability manager employed
Municipality C (Senior admin. Planning and building, mobility, climate protection, flood protection, climate manager, water authority, sustainable urban planning, utility companies)	Houses, hospitals, schools, kindergartens, and industrial compounds affected by the 2021 floods Conflict with suggested naturalization of a stream in an alley Drought 2022 and irrigation for urban green, heat action plan Communication and participation of civil society (co-creation and science communication)	Cross-sectoral cooperation Climate Protection Officer (manager) employed

analysis and other data, geographic information systems (GIS) potential is also investigated. The following map and GIS assessment show a preliminary scenario of areas that could have the potential to mitigate or adapt to climate change, regions that already are transforming, and areas potentially affected by climate change extreme events, such as floods and forest fires (Fig. 7).

The map provides a first impression of the region's spatial distribution of blue, critical, and green infrastructure. For better differentiation and related to the extreme event of forest fire analyzed, green infrastructure is highlighted only by forest and not by agricultural area. Forests are more prevalent in the southwestern and western parts of the region. The middle part is characterized by agriculture (not shown on the map). Rivers and lakes are distributed all over the district. A flood scenario of a 250-year return period

plus the failure of existing dike and mobile systems shows large areas in blue around major rivers. These rivers run more or less from south to north, and the river Rhine flowing through Cologne, for example, is a 1.232 km long river originating in Switzerland and entering the North Sea up north in the Netherlands. Heavy rain flood scenarios must be captured here, which would not be well visible at this spatial resolution. Gray infrastructure is shown on the map by settlement, industrial and commercial areas, and the road network. In later research on the project, critical infrastructure types, such as energy lines, and points of interest, such as hospitals, will be analyzed. The brown areas indicate the brown coal mining fields northwest of the district, the Rhenish mining area. They cover large areas and will be transformed into lakes for re-creation after brown coal mining has ended. The orange areas are buffer areas showing the

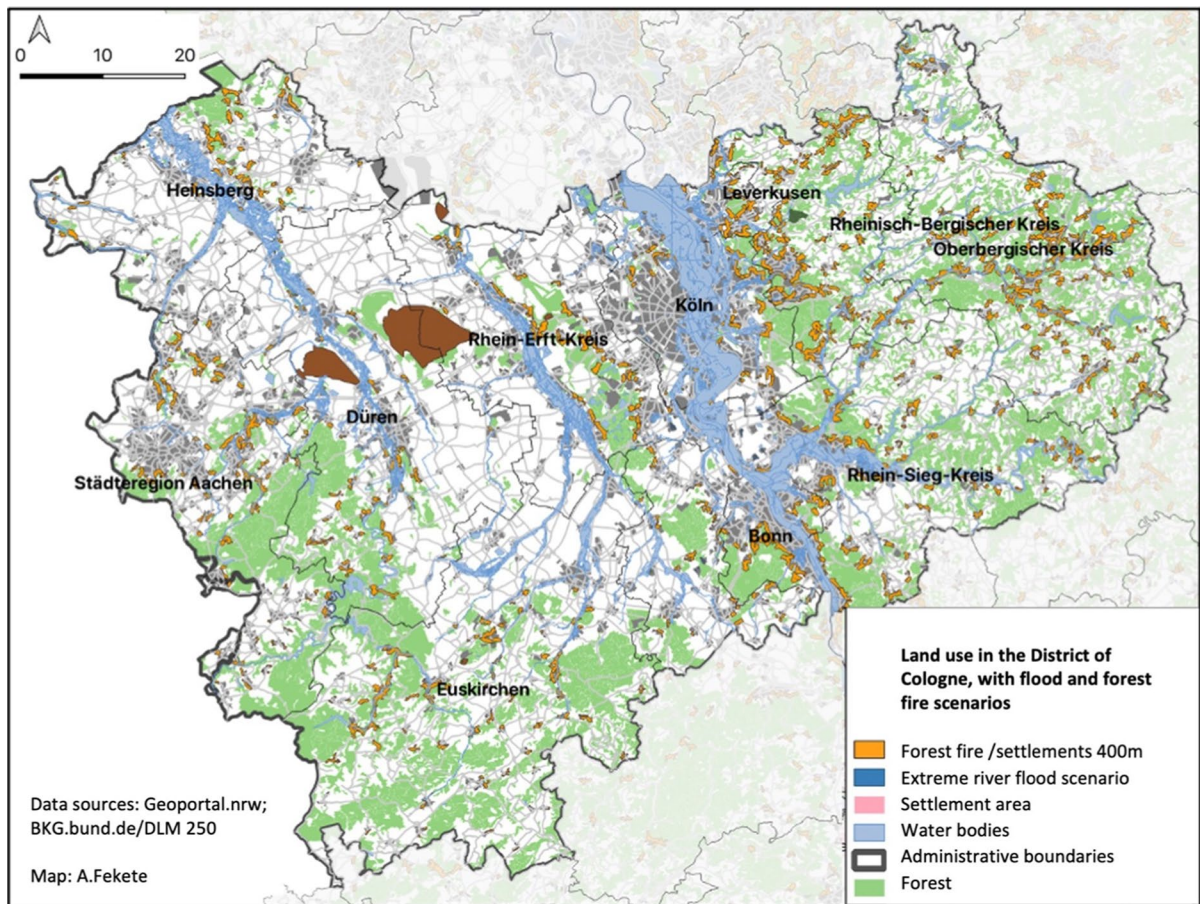


Fig. 7 Map of the Cologne district displaying forest area, riverine extreme flood scenario, gray infrastructure, and brown coal mining areas

wildland-urban interface of settlement borders overlapping with forest borders in a 400 m zone. This provides an additional scenario for potential forest fire risk to the flood scenario on the map. The 400 m has been derived in a previous study by comparing international studies on ignition distances between forests and settlements (Fekete & Nehren, 2023).

The area was affected by severe flooding in 2021, a heavy rain event that contributed to flash floods and riverine flooding. The covered area matches well with some of the blue areas shown in the map as a hypothetical scenario but also differs in some parts and had covered larger areas in 2021 outside of the river embankments due to heavy rain.

The GIS calculated the total and relative area of blue, critical, and green infrastructure and flood and forest fire areas per county. Table 5 shows that the

counties vary in size (first column). The five largest areas are highlighted in bold. The different sizes of the total area indicate different potentials for providing green and blue infrastructure space to better adapt to climate change or to provide mitigation areas such as carbon sinks. But while larger counties have such a general potential, it also has to be compared with the area covered already by settlement. The second column shows the size of the settlement area in km² per county. The top five are not the ones with the highest total area, but rather large cities such as Aachen, Köln (Cologne), and three counties with a mixed coverage of the rather medium and smaller size of cities and towns. Comparing it with the third column, which shows the relative settlement area per county size, shows that the cities of Bonn and Leverkusen would also appear in the top five. These larger cities have

Table 5 Spatial analysis of area potential in the Cologne district for blue, critical, and green infrastructure

	Total county area in km	Settlement area in km	% Settlement area per county (%)	Forest area in km	% Forest area per county (%)	% flooded per settlement area (%)	% forest-fire exposed settlement per county area (%)
Aachen	704,448,804	138,550,418	19.67	218,234,399	30.98	2.26	13.53
Bonn	141,581,312	61,383,397	43.36	41,016,069	28.97	14.12	9.96
Düren	940,487,187	80,247,565	8.53	181,986,218	19.35	6.92	2.01
Euskirchen	1,250,217,760	76,853,305	6.15	465,311,186	37.22	6.89	2.20
Heinsberg	627,304,533	93,645,643	14.93	59,058,044	9.41	3.54	2.78
Köln	406,662,445	144,175,971	35.45	52,301,101	12.86	26.72	4.71
Leverkusen	78,780,272	32,632,179	41.42	7,415,715	9.41	17.75	9.41
Oberbergischer Kreis	918,258,057	97,830,169	10.65	357,995,062	38.99	4.68	7.40
Rhein-Erft-Kreis	703,091,262	114,081,932	16.23	78,980,703	11.23	7.75	3.04
Rhein-Sieg-Kreis	1,152,453,721	157,429,178	13.66	340,044,177	29.51	15.51	4.12
Rheinisch-Bergischer Kreis	438,093,010	75,469,601	17.23	151,481,883	34.58	4.55	11.28

less area to convert into blue and green due to high existing residential and other settlement areas. They are also potentially more exposed to spatially distributed risk—be it a natural hazard, such as a flood, wildfire, industrial accident, etc. The forest area in total is mainly located outside the large cities except for Aachen. However, Aachen is a special county since it is a combined area of the city and surrounding settlements. Aachen is also one of the few cities with no river in its center or main settlement area.

The potentially flooded settlement area is highest for Bonn, Cologne, Leverkusen, the Rhein-Erft-Kreis, and the Rhein-Sieg-Kreis, as indicated in the map. Meaning these cities have the highest potential flood exposure. The cities of Bonn, Cologne, Leverkusen, and other counties have been affected by floods. In 1993 and 1995, river floods occurred in Cologne, and flash floods in the 2000s in Bonn and Leverkusen. In 2021, it was Leverkusen, the Rhein-Erft-Kreis, and the other counties affected in the district. The last column shows the percentage of forest fire-exposed settlements per county area. The top five only partly overlap with the counties affected by floods. But both extreme event types would affect the city of Bonn and Leverkusen. In addition, Aachen, Oberbergischer Kreis, and Rheinisch-Bergischer Kreis are under the top five of forest fire exposure.

Similar assessments are carried out for droughts affecting agricultural and forest areas, interacting with blue and green infrastructure (Fig. 8).

The analysis results can only indicate the first measures to capture the spatial potential for areas to adapt to or mitigate climate change. It also can help planners see which counties have higher exposure to extreme events at the district level. Finally, areas that are already transforming, such as the brown coal area, are important for learning about ongoing transformation and how the population, industry, and nature deal with a planned type of large-scale transformation. Overall, the region represents a living laboratory for ongoing and planned transformation and experience with extreme events.

Discussion

Benchmarking transformation: transformation goals and hollow change

Measuring transformation is already a challenge, but how to measure whether transformation crosses a threshold to be regarded as effective or successful?

There are several ideas on how to approach this, but this article is yet far from being able to answer.

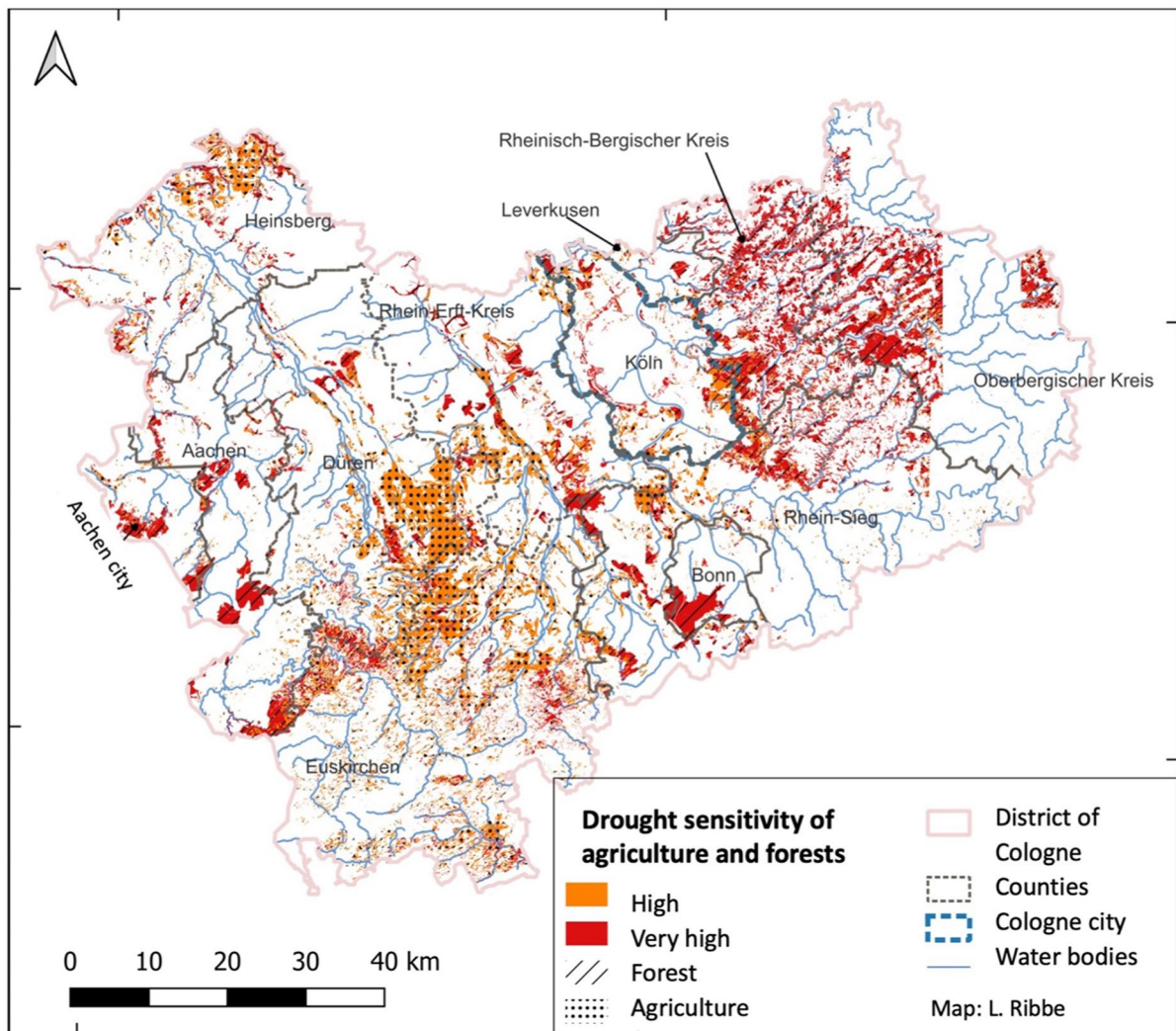


Fig. 8 Map of Cologne district showing drought vulnerability of agriculture and forestry

Returning to the basic definition of transformation, including a fundamental or political regime change, the fundamentality must be defined. One conceptual idea of conducting this is captured within the protection goals or risk management goal idea (Fekete et al., 2012). A transformation definition would need to be broken down into ambitions and underlying values that must first be elicited from different actor groups. For example, for one actor group with an economic interest, their economic progress would be the main motivation for the transformation, the basis for measuring change, and how the group values it. From an emergency management point of view, the survival of humans would be a key value and way to measure

success. In addition to the values, the goals would also need to capture a threshold. These thresholds could be derived from the conceptual components of the system and changes as described in this article. For example, changes in the numbers and volumes of elements, such as persons, budgets, or institutions, could serve as quantifiable targets that calculations or joint agreements could determine.

While this quantification approach seems straightforward, it also has many limitations and constraints, as can be shown from neighboring fields like disaster risk, which already has great difficulties in correctly assessing the number of casualties after a disaster. Other elements of the

conceptual components described above could be used, such as the number or quality of interrelations and, thereby, how the overall governance structure changed, for example. Fundamental regime change could be defined by a new mix of different actor groups joining under a certain organization, such as a parliament.

But, as has been shown in neighboring fields, such as critical infrastructure research, whether it is a relevant and significant result is not only determined by quantities or descriptions of static elements (Fekete, 2011). The time factor also greatly influences whether the transformation was effective. Is it long-lasting, sustainable, or just short-term, briefly replaced, or abandoned?

Finally, a third generic quality criterion underlies and overrules all quantifiable and even temporal criteria. It is captured in the last conceptual component as a rather invisible and less quantifiable quality dimension. In critical infrastructure research, this is symbolized by water supply interruptions. If, in a given water supply system, all the elements, actors, technical pipes, and distribution channels persist after a disruption, the water can still only be usable when not contaminated or when trust in water quality is present. This can be translated into transformation definitions, where any change could be considered hollow. Even when persons, institutions, or budgets change dramatically, it could still be seen as a hollow change that does not change other fundamental aspects. These other fundamental aspects could be the overall mindset or other boundaries and constraints that are not changed, such as the political regime, territory, bureaucracy, limitations of personal freedom, or similar.

Transformation goals could be defined to capture and measure changes in entire systems, including humans and the environment. Measurement is to be understood as both quantifiable and non-quantifiable documentation of change. To achieve a change understood as a real fundamental transformation, the number, temporal aspect, and quality of the system must change in a way that these three generic criteria, in combination, achieve a state considered fundamental by the observers. Therefore, in advance, these fundamental thresholds need to be defined. This requires a methodological process derived from protection and risk management goals. It includes an elicitation of different underlying values of the actors. It needs a

second step of identifying critical changes whereby criticality is measured in the three generic criteria.

Finally, defining benchmarks where actors consider change relevant or even fundamental is important. Benchmarks can be derived in different ways. One way is statistical or modeling, which has scientific definitions of what validation and evaluation need to be composed of. However, such numerical modeling and statistics often can only represent patterns, which are insignificant without relation to logical and causal hypothesis definitions. These hypotheses need causal explanations, which need to be derived empirically from the reality of the actors. There are examples of numerical calculations of quantitative thresholds, which have been summarized elsewhere. For example, the temperature threshold in time change negotiations is used as a communication means to convey acceptable or non-acceptable changes in temperature rises that can be measured by the proxy of temperature. A 0.5° increase in temperature is a different fundamental change than a 2° threshold. Other examples of using such quantitative goals are known from transportation accidents, which are reduced by a variety of measures, including safety belts, road construction, and car safety feature designs that have helped reduce the number of casualties from tens of thousands per year to four-digit numbers in Germany, for example. As a leading goal, zero targets of casualties are visions that drive overall activities and make them sustainable, although reaching a real zero seems rather ambitious or even unrealistic. Transformation goals and related benchmarks could follow similar ideas.

But very often, benchmarks can appear from empirical insights in reality. What is considered a fundamental or credible political regime change is often dependable and liable to societal definitions that can quickly change over time. But most of all, they have yet to be collected or scientifically addressed, so there should be rich opportunities to identify them. In the Co-Site project, we have held workshops with actors from municipalities' administrations in some counties. One example of how they would consider a transformation or introduction of a new measure successful is described in the following. Providing green roofs at bus stops could be criticized by residents. They could question how and whether the municipality has funds for such a measure without investing them in repairing infrastructure or improving local

services such as the service point for daily needs. This example could be an interesting benchmark for measuring transformation. Which measure is effective and over which period, and how can this be measured and thereby be transparent and credible to a local community? Combining all bus stop rooftops in the municipality will certainly not decrease precipitation runoff or boost the local climate so that people can directly feel it in a heavy rain or heatwave situation. But that wildlife, such as local bees and insects, profit from it, and the whole community profits from preserving biodiversity needs to be measured and put into a long-term benefit that is obvious and effective. Therefore, accompanying the project activities with science communication as well as identifying which formats and approaches work out how in which situation, region, and for which measure is needed and performed.

This also applies to larger undertakings. For example, creating new retention basins at a large scale to save distant streets in a city downstream. This measure also needs, first of all, acceptance by those affected by it. They also need credible documentation and measurement of which dimension of flood this can manage. This relates to one of the main dramas in disaster preparedness that there is "no glory in prevention." If the retention basin is designed big enough, populations spared of being flooded will probably not notice it. But if the retention basin needs to be bigger or is breaching, it will be regarded as useless, although it will have diminished some of the flood peak waves. The question of when a measure providing a fundamental change to flood impact, for example, is regarded as fundamental and effective, will provide much room for further research and knowledge transfer.

Reflections from an advisory board

The preliminary work results with the municipalities and county were also discussed with the project's advisory board. The representatives reflected on the project's approach versus the first expressions of interests and topics suggested by the actors in the regional administrations. One expert recognized that transformation is a kind of a *chiffre* for development. Transformation attempts to express urgency for specific developments outside the daily business. In contrast, tasks and topics provided by the administrations

are daily development tasks. These tasks can become transformative and future-oriented when combined with additional goals, such as post-fossil, sustainable, and resilient actions regarding infrastructure. The interaction with other external actors and their daily needs even aggravates this institutional performance gap. There is knowledge about the problem of climate change, but the actions are ineffective; a transformation of roles and duties is necessary. The readiness for implementation is hampered not only by financial needs but also by the governance and performance of the institutions.

Another problem is that the highly sectoral interests of actors can dominate. Ambitions interfere with the realities of the individual interests of actors and their narrow sectoral practices. A solution is to transfer examples from areas that have already experienced disasters and by imitating and learning from these best practices or their lessons learned. This emphasizes the need to work with examples.

One expert argued that while best practices can inspire new developments, it also needs so-called next practices. However, these future-oriented next practices and their novel approaches must be compatible with pre-existing situations.

In summary, the feedback from the transfer advisory board emphasized that the project and the topic of transformation are very ambitious. To avoid getting lost in the different day-to-day needs expressed by actors, it is important to develop jointly a shared vision of ambitious goals for the future. At the same time, these ambitious planning scenarios must be bridged with concrete examples based on administrations' day-to-day needs. Additionally, further actors need to be included, such as the private sector and citizens. Virtual reality, social media, and other forms of communication are also deemed important. Especially certain gaps can be addressed by using science communication, such as the gap between short and long-term actions or between the large range of scientific data models and local effects. More concrete visualizations of realities and actions can foster change. Actor assessment and needs assessments are examples of methods applied in several sites.

The scientific members of the board emphasized the different thematic interests prevalent at all sites. At the same time, these topics are relevant and comparable for all other communities and counties in Germany, too. Therefore, enabling mutual learning

and the exchange of lessons is important. It is also important to emphasize these crosscutting themes as well as methods used, such as communication strategies or approaches addressing blue, critical, and green infrastructure.

Conclusion

Climate change is becoming increasingly a reality, not only by the advent of physical events, but also by pressures on institutions to adapt and society to transform. This development leads to an increasing demand in science to formulate concepts and categories of monitoring and measuring such changes and transformations to address climate change, among other crises. The results presented from an ongoing project in western Germany reveal that cooperation with administrations and other actors is one solution to address this. Conceptual understandings of the transfer of knowledge, ideas, and methods underpin this approach. Singular events, such as major flood damages in Germany in 2021, triggered more awareness and research about change that is deemed necessary after such a significant event.

The interim results presented in the study consist of a conceptual model of parameters that can be used to identify and measure change. This encompasses qualitative categories, addressing changes observed when working with institutions. It also involves spatial assessments using geo-information that enables separate and independent quantitative data sources to analyze hazard and risk zones as well as potential areas for nature-based solutions to mitigate hazard extremes as well as adapting to climate change, and not just curbing emissions of CO₂. Applying the conceptual components directly at two spatial levels, cross-regional and district, this study shows that it is applicable. In fact, working with empirical findings from expert interviews and field observations with project partners helped to advance and complement the conceptual components of the study. Findings include that the 2021 floods had a major impact in stimulating many areas of changes across the regional level. Also, at the district level, working with three cities and municipalities, as well as with one county, demands for changes and needs identified predominate over real changes and fundamental transformations already implemented. However, this

is a limitation of the study: at this interim stage, many transformations will need more time. Yet it is important research to reveal how ongoing changes can already be documented and later compared after more years to follow whether these intended changes, once formulated, had really taken place. Another finding is that some of the immediate changes in institutions, such as publishing national strategies or regional concepts, had been developed many years before the end of the event. This is important for similar studies to separate which type of documents and decisions after a significant disaster are only partly related to the most recent event. The demand for measuring transformation is expressed in the assessment reports of the IPCC. But what defines a fundamental or regime change still seems to be missing in application. This study contributes to this new line of research that tries to complement conceptual notions of transformation with empirical findings on the ground. The study has shown that more conceptual development is necessary to bridge the general and broad definition of transformation with conceptual categories of transformation. It shows that when applying it in a multifaceted understanding of different aspects of administration actors and at different spatial levels, more demands emerge to advance the conceptual models. With this research, we want to encourage fellow researchers to advance to conceptual development and to measure transformation already, while changes are just slowly emerging to document both intended challenges and processes that accompany them, as well as reveal changes many years after planning has started. This will contribute to performance measurement of transformation, but will need a more detailed, conceptual understanding of transformation and transfer of knowledge and ideas between actors.

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Declarations

Conflict of interest The authors declare no conflict of interest.

Human and animal rights This research involves human beings, see attachments: Ethics board approval, Consent document.

Informed consent The project participants have signed a consent document—see attachment.

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