What can actors learn from social-ecological systems dynamics for managing ecosystem services? An application of the SE-AS framework.

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Abstract:
Human impact on ecosystems has intensified over the last decades, putting intense pressure on ecosystem service provision including clean drinking water, functioning biogeochemical cycles, and arable topsoil for agriculture. The extent to which ecosystems have degraded has been studied and documented by researchers and international scientific bodies, such as the IPBES. However, it is well known that stakeholders often manage ecosystems without being fully aware of their inherent dynamics and their repercussions on social systems, leading to our research question: How can representations of social-ecological system dynamics and of their potential repercussions on the social system inform actors for the management of ecosystem services and enhance their reflexive capacity to handle complexity and uncertainties?

We examine social representations of social-ecological system (SES) dynamics in which actors are integrated. To do so, we analyze land and water use, and the alteration and management of ecosystem services in two lake catchment areas in Northern Germany and Québec, Canada. For the data gathering process and the first analytical step, we use Causal Loop Diagrams (CLD) derived from interviews which outline stakeholders’ representations of the SES. The paper applies the SE-AS framework by Schlüter et al. (2019) which structures the study of social-ecological systems along configurations of action situations within such systems, as well as across them. In our study, we examine a) the effects of anthropogenic resource exploitation and use on ecosystem dynamics and services; b) feedbacks between different system variables and interactions; and c) resulting responses of social systems, i.e., actions undertaken by decision-makers responsible for managing ecosystems.

Keywords: SE-AS framework; anticipatory governance; adaptive resource management; social learning; Causal Loop Diagrams; social-ecological systems; SE-AS framework

1 Please note that this is a paper draft with preliminary results. The case study analyses are not yet completed. The study is part of the BiodivERsA research project LimnoScenES, funded by the Belmont Forum.
1. Introduction

Humans rely on ecosystems for survival and well-being, a truth acknowledged by intellectuals and philosophers around the world and across the ages, from Leopold (1949) to as far back as Plato, and even before (Mooney and Ehrlich 1997). Ecosystems render provisioning services like drinking water, food and timber; they ensure regulating services over processes related to climate, waste treatment, water purification and disease control; they offer cultural services such as recreational spaces and spiritual benefits; and they provide supporting services including photosynthesis, nutrient cycling and soil formation (Ash et al. 2010, xi; Millenium Ecosystem Assessment 2005).

Humans alter ecosystems continuously via urbanization and economic activities such as mining, agriculture, livestock farming, logging, fishing, damming for hydroelectricity or flood management. Such alterations tend to affect the capacity of ecosystems to generate essential services (Costanza et al. 1997; Daily 1997). For instance, altered ecosystem dynamics may bring about uncertainties regarding resource availability and quality. Actors thus need to adapt their management plans and actions to these new realities of growing uncertainties about the ecosystems’ state and evolution. In other words, systems need to increase their resilience (Folke et al. 2016).

Different approaches to tackle such issues have been developed in parallel in the last decades. Two of them, adaptive management – also known as adaptive resource management – and anticipation, have received a particularly great deal of attention from many fields of studies (Folke et al. 2005; Miller, Poli, and Rossel 2013; Hasselman 2017). The two concepts have also converged towards another concept called anticipatory governance (Boyd et al. 2015). Such concepts underline the importance, for actors and decision-makers, to be aware of the effects of one’s interventions and actions on ecosystems, on the services they provide and on the well-being of those who depend upon those services. Reflection on such dynamics must be considered as an integral part of the continuing management process (Folke et al. 2005, 443). Those approaches reflect the need to view natural resource use as part of a single overarching system in which humans and nature interact: a social-ecological system (SES) (Berkes and Folke 1998, 2–4).

One of the recurring challenges with SES analysis is to integrate their multidimensional, complex nature into practical decision-making (Leenhardt et al. 2015). Studying social-ecological systems requires a multi-disciplinary analytical framework, a scheme through which one gains a focus on the structure and the elements that underlie complex systems (Ostrom 2009). Adaptive management and anticipatory governance also necessitate such a comprehensive and transformative structure to be efficiently implemented (National Research Council 2004; Pahl-Wostl 2007; Boyd et al. 2015). To gather knowledge about complex systems, differing data need to be combined. A variety of analytical frameworks has been developed to study SES, each one with specific benefits regarding the focus and the purpose of the study (Binder et al. 2013). Notably, it has become customary in the literature to represent SES dynamics through illustration of causal relationships between system variables, as seen in Causal Loop Diagrams (CLDs) (cf. Forrester 1961; Inam et al. 2015; Halbe and Adamowski 2019). However such approaches fail to explain encompassing, emergent social-ecological phenomena, which can in turn have an effect
on the system variables (Schlüter et al. 2019). Such emergent phenomena can be, for instance, the collapsing state of a system or the governance regime that manages an ecosystem. Emergent phenomena of social-ecological systems are difficult to predict and even more difficult to govern. Thus, the need to find new units of analysis for multidisciplinary research in order to evaluate and analyse SES dynamics leading to specific phenomena cannot be overstated. The social-ecological action situations (SE-AS) framework (Schlüter et al. 2019) used in this paper proposes a new unit of analysis centered on the actors – both social and ecological –, their interactions, the outcomes of such interactions and the SES phenomenon these create.

In this paper, we propose a methodology to use data generated in participatory research and apply the SE-AS framework on it. Thereby we show the relevance of focussing on action situations as units of analysis when studying SES dynamics and the added value of identifying a SES's emergent phenomenon. We do so by studying two cases as examples for our methodological approach. We examine human-induced alterations within two north temperate shallow lake systems located in Germany and Canada, as well as the resulting feedback loops between the ecological and the social systems. In doing so, we aim to: a) reveal dynamics and changes within the two SES; b) understand how ecosystem services are affected; and c) contemplate how participatory research could inform resource management and anticipatory governance, potentially leading to purposefully reflexive relationships between the researchers and the researched systems. The paper thus raises the following research question: How can representations of social-ecological system dynamics and of their potential repercussions on the social system inform actors for the management of ecosystem services and enhance their reflexive capacity to handle complexity and uncertainties?

To reach our objectives, we use a participatory approach, which is key to successful sustainability research (Kasemir et al. 2003), by: 1- relying on a structured qualitative content analysis of interviews with key stakeholders of two different lake ecosystem management regimes²; 2- creating CLDs out of these analysis, and; 3- applying the SE-AS framework to the generated data. We examine the effects of resource use on lake ecosystems, the changed dynamics within the lake systems and associated feedbacks back into the social systems, as well as the social systems’ subsequent reactions. We demonstrate the usefulness of the SE-AS framework to unravel and better elucidate SES dynamics and changes in SES and the induced emergent phenomena. We argue that actors could, through the framework, reflect on the effect and effectiveness of their actions, adapt their management to foresee and handle unexpected dynamics and changes, and coordinate their decisions, all in an effort to deepen their understanding of the SES responses, hence spurring anticipatory governance.

The paper is structured as follows: first, we present and define relevant concepts, focussing on resilience, adaptive management, anticipatory governance, CLDs and the SE-AS framework; we then describe the methodological approach, including a brief

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² By lake ecosystem management regime, we understand an informal network of actors who because of their mandate or their interest in the lake and its catchment area are working on or implementing measures that ought to regulate and protect the lake (cf. Pahl-Wostl 2009, 356).
description of the case studies and of the data gathering process. The subsequent sections present the analysis and results for each case study, a reflection on hypothesized information transfer to relevant actors through our research process, methodological limits and overall contributions.

2. Theoretical and Conceptual Background

We ground our methodological study on the two theoretical concepts of resilience and anticipatory governance as well as on Causal Loop Diagrams and the SE-AS framework as analytical tools.

2.1 Resilience in SES

Social-ecological resilience is defined as the capacity of a system to persist, adapt and transform to maintain its key functions (Folke et al. 2016). A resilient system continues to regenerate itself, to maintain its functions, and to provide its services despite the perturbations occurring and the internal changes it undergoes (Folke et al. 2005, 442f.). To achieve resilience within a social-ecological system, actors thus need to be able to adapt their management modes to changes and disturbances that occur in the ecological and in the social system (Folke et al. 2005, 444; Pahl-Wostl 2009, 355). The aim of efficient ecosystem management is to ensure the resilience of the ecological and the social system (Biggs, Reinette (O.) et al. 2015). As Turner and Daily (2008, 25) state, being able to “efficient[ly] and effective[ly] manage[…] ecosystems can sustain the provision of vital ecosystem services […]. To do so, scholars of resilience and sustainability research have emphasized the need to view the social system that influences ecosystems through its resource uses and exploitations as intertwined with the ecological system (Berkes and Folke 1994, 2f., 1998, 3f.; Folke et al. 2005, 443). They furthermore highlighted the need of the social system to “(…) respond to environmental feedback, to learn and store understanding, and be prepared and adaptive to allow for change.” (Folke, Colding, and Berkes 2003, 354). One way to do so is through anticipatory governance.

2.2 Anticipation, adaptive management, anticipatory governance and social learning

Anticipation is often associated with SES resilience, and the former is broadly seen as a necessity for the latter to be observed within a system (Miller, Poli, and Rossel 2013; Boyd et al. 2015). Rosen’s (2012, 313) original definition of anticipation from his classic book first published in 1985 states that “[a]n anticipatory system is a system containing a predictive model of itself and/or its environment, which allows it to change state at an instant in accord with the model’s predictions pertaining to a later instant.” Since its original mention, the concept has been used in many disciplines, from physics to future sciences and biology (e.g. Dubois 2000; Fuerth 2009; Louie 2009) to the point where certain authors argue anticipation to be a discipline in its own right (Miller, Poli, and Rossel 2013; Boyd et al. 2015). An anticipatory SES can thus be understood as how the living and non-living system components are able to project themselves into the future.
and to adapt, purposefully or not, their actual behaviour based on such projection (Fuerth 2009; Quay 2010).

If anticipation is turned towards the future, adaptive management responds to the past to shape a desirable future. Adaptive management relates to actors’ ability to systematically and continuously improve their instruments and practices by learning from the management strategies they implemented in the past (Pahl-Wostl 2007, 51). The concept implies that actors change the existing structures and characteristics of their management system and their behaviors to deal with changes occurring in the respective ecosystem and the stresses these changes imply (Pahl-Wostl 2007, 52, 2009, 355). Those who ought to adapt need the organizational and institutional flexibility, the social capital and social memory to do so (Folke et al. 2005, 444). Adaptive governance, coined by Dietz et al. (2003), put emphasis on the importance of such flexible adaptive response strategies to deal with disturbances and crisis (Boyd et al. 2015). Adaptive governance has been notably pointed out as a requirement for adaptive management to be implemented successfully (Chaffin, Brian, Gosnell, and Cosens 2014) and as “an emergent, self-organised process of an SES that changes form as systems undergo periods of crisis and stability” (Chaffin, Brian C. and Gunderson 2016). Both, adaptive management and adaptive governance, thus focus on the adaptiveness of a system without the requirement to foresee changes as observed in anticipation studies.

Anticipatory governance emanates from this shortcoming by combining adaptive governance with anticipation studies. Anticipatory governance “involves changing short-term decision making to a longer-term policy vision, including the notion of foresight.” (Boyd et al. 2015). This involves envisioning different future scenarios and a diverse array of possible actions to maintain the system in a desirable state, while actively monitoring the system to observe changes and adapt management accordingly in a sort of feedback structure (Fuerth 2009; Quay 2010). While adaptive governance can be seen as a necessity for adaptive management, anticipatory governance can be seen as a requirement for a resilient, anticipatory SES, while also encompassing adaptive governance.

The distinctions between anticipatory, adaptive or purely reactive systems – i.e. deprived of anticipation or adaptive management and strictly reacting to stresses based on fixed policies (National Research Council 2004; Garmestani 2014) – will be analysed through the application of the SE-AS framework. Notably, using anticipatory governance lenses for analysis purpose, we test how the framework can inform researchers on the nature of the SES under scrutiny, and whether it allows to analyze the type of governance stakeholders apply. Moreover, we expect the framework to offer stakeholders an illustration of the SES that inspires them on how to evolve their resource management towards anticipatory governance. We expect anticipatory governance to arise from social learning, through what Yang (2015, 448) called participants reflexivity, thus considering participants to be self-reflexive entities, as proposed by Smith (1994).

Based on the literature on anticipatory governance, we derive the following six criteria to assess governance within the case studies’ SES and evaluate presence of anticipatory structures (Fuerth 2009; Quay 2010; Boyd et al. 2015):
1- regulation and law-making are flexible while offering solid foundational structures;
2- there is a foresight system in place, integrated within policy and management;
3- multiple short-term and long-term future scenarios are considered with identified key precursors;
4- monitoring of changes in the system is carried out to ensure adaptive management in a feedback structure;
5- cooperation among different actors is instituted for decision making;
6- institutional culture is open-minded and integrate different types of knowledge.

To outline the dynamics of the two social-ecological systems we study and the governance structure therein, we use Causal-Loop-Diagrams in a first, preliminary analytical step, by establishing causal links and resulting feedback loops between social, ecological and social-ecological variables defined within our data.

2.3 Causal Loop Diagrams (CLDs)
CLDs present a schematization of a system under study to reveal a focal problem (Haraldsson 2004, 19f.) and by describing system variables and events and the connections among them in time and space (daily/monthly/yearly timescales; at local, regional or entire-system level). A CLD represents “a dynamic system’s causal structure: variables, causal links with a polarity and symbols that identify feedback loops” (Schaffernicht 2010, 653). A CLD thus reveals a system’s relevant elements, their relationships and their repercussions.3

2.4 The social-ecological action situations (SE-AS) framework
The SE-AS framework has its origins in the social-ecological system (SES) framework and the Institutional Analysis and Development (IAD) framework by Ostrom and her colleagues (McGinnis and Ostrom 2014; Ostrom 2005). Presented as being complementary to its predecessors, the SE-AS framework is able to capture dynamics, processes and interactions within SES, and on different levels (Schlüter et al. 2019). The framework’s purpose is to map the interactions of social and ecological elements and the effects among them that lead to the emergence of a phenomenon of interest that is either characteristic of the SES’s state or indicating a new state of the studied system, like a shift or an exceeded tipping point.

The social-ecological action situations framework represents a configuration of action situations, i.e. interactions of components of a system that are hypothesized to generate an emergent empirical phenomenon of interest (Figures 1a and b). Interactions can occur

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3 The loops in a CLD come into play when two (or more) variables are connected by links that form a circle, i.e. create a loop comprised of the variables. Such a loop can be balancing (indicated with a “B”) or reinforcing (indicated with an “R”). A reinforcing loop means a variation in any variable leads to an intensification of the initial deviation of this variable throughout the loop; a balancing loop means that a variable within the loop dampens the intensification of a causal link, limiting an increase in the loop variables as a result of negative correlation between two variables (Haraldsson 2004, 22; Inam et al. 2015, 254; Vennix 1996, 45f).
between ecosystem components (EC), actors (A) and actors and ecosystem components. Action situations generate outcomes that influence other action situations, creating any given configuration of action situations linked through their respective outcomes (see Figure 1 for a depiction of the SE-AS framework). Action situations are embedded in a wider social and ecological context of neighboring ecosystems, higher-level governance systems, and societal norms. The framework aims to represent only those interactions that have generated the emergent phenomenon of interest to the researcher. The SE-AS framework consists of (Schlüter et al. 2019):

- **actors** (A) and **ecosystem components** (EC) that interact with each other at the micro-level;
- **social-ecological action situations** (SE-AS) within which the human-ecosystem interactions of interest occur;
- **purely social or ecological action situations** (S-AS and E-AS respectively) which, within the frame of a given analysis, define exclusively social or ecological interactions;
- **outcomes**, generated by action situations (AS), that influence other action situations and that can also influence the very action situation that produced them.
- **A configuration of action situations**, situated at the *meso-level*, which results from the links created by different outcomes between different action situations. The configuration of AS represents a hypothesis about how interactions and outcomes have produced the emergent phenomenon of interest;
- the **emergent social-ecological phenomenon** which can be observed on the *macro-level*, and which feeds back to influence the AS configuration (Schlüter et al. 2019).

**Figure 1**: Depiction of the SE-AS framework through a) pictures and b) descriptions (Schlüter et al. 2019)
3. Methods

We combined several methods to reach our research objective. First, we conducted interviews with relevant stakeholders in the two case study regions. We used CLDs to structure interviews and gain insights into stakeholders’ social representation of the local SES. We then coded the interviews regarding social, social-ecological and purely ecological interactions mentioned by stakeholders. Based on those codes, we constructed the configurations of action situations within the two aquatic social-ecological systems, thereby applying the SE-AS framework. In the following subsections, we present each step in further details, after a brief introduction of the case studies.

3.1 Case studies: lake Dümmer and Lake Saint-Charles

The two lakes and their surroundings that serve as SES case studies are Lake Dümmer in southeastern Lower Saxony, North-Western Germany, and Lake Saint-Charles, north of Quebec City, province of Quebec, Canada.

3.1.1 Lake Dümmer

Lake Dümmer is a shallow lake with a surface area of 13.5 km² (Figure 2). Its waters are fed by the River Hunte that runs from south to north through the Dümmer. The western and southern shores of the lake, as well as the lowlands east and south of the lake, are nature reserves (Landkreis Diepholz 2020). The lake’s area belongs to the administrative district Diepholz while its catchment area, the Hunte basin, lies within the administrative district Osnabrück; both of which lying in the federal state Lower Saxony, Germany. A community of around 8,000 inhabitants lives close to the lake.

In the 1950s, the lake was diked, and seasonal water level dynamics are no longer occurring. The dyke allowed agriculture to prosper in the former wetlands and in the lake’s watershed, covering around 70% of the area (NLWKN 2010, 3). Today, the lake serves as a storage pond to regulate the water level of the Hunte and to protect downstream communities from flood. It further serves as a recreational area and as a spot for holidays for many tourists throughout the year (Seen.de), while being home to a rich biodiversity, including a variety of iconic FFH species and migratory birds (Council of the EU 1992; Landkreis Diepholz 2018). However, the lake has an impoverished submersed vegetation and aquatic fauna due to eutrophication and silting. Stress factors affecting the ecosystem include recreational activities (e.g. water sports), drainage, fertilization, and the destruction of wet meadows. Also, the dyke prevents dead vegetation (mostly from reeds) from being transported out of the lake, into the wet meadows. As a result, the significant biomass of decomposing vegetation remains in the lake, and the resulting sludge sediments must be pumped out regularly.
A redevelopment project is underway for the lake. Its main objectives are to reduce nutrient loading resulting mainly from agriculture in the Hunte basin, and to consistently remove the accumulated sediments at the bottom of the lake. As part of the project, the Bornbach, a tributary of the Hunte, was diverted in 2009. This intervention reduced the phosphorus input by 55% (ML and MU 2012, 8). The regional wastewater treatment plants were modernized with a third treatment stage for the same purpose (ibid., 8). However, the resulting phosphorus concentration in the lake is still roughly three times the value that the lake can tolerate, causing significant development in plankton, including cyanobacterial blooms. To further reduce this nutrient load, a polder of reeds will be built to filter out most of the phosphorus in the Hunte river’s surface water before it enters lake Dümmer. The reed polder and a change of land-use management in the basin are required to improve the lake’s water quality.

3.1.2 Lake Saint-Charles

Located 20 km north of Quebec City, Lake Saint-Charles covers an approximate area of 3.6 km², while its watershed covers an area of 165.8 km² (Légaré 1998) (Figure 3). St. Charles River flows from the lake into the St. Lawrence River, hence the lake also lies in that river’s watershed, which extends up to 348 km² and over six municipalities: Stoneham-et-Tewkesbury, Lac-Beaupré, Lac-Delage, Quebec City, Saint-Gabriel-de-Valcartier, and Wendake (APEL 2017).
Although Stoneham occupies the greatest extent of land area in the watershed (41%), Quebec City owns most of the riparian area around the lake, with around 80% of the shoreline that falls under its jurisdiction, while the remaining belongs to Stoneham (APEL 2009). The population around Lake Saint-Charles, including all households in the watershed of the high St. Charles River, was around 19,000 people in 2016 and mainly concentrated along the tributaries and around the lakes of the area (APEL 2019).

The lake became a semi-natural reservoir, with a hydro-electric current capacity of 14.8 Mm³, after the construction of the Cyrille-Delage dam in 1934 and its reconstruction in 1948, which raised the water level approximately 1.5 to 2 m above natural levels (APEL 2009; OBVC 2015). The northern part of the lake drains an important protected wetland known as the Northern Marshes, which together with the lake and the watershed is home to a rich bird diversity and seven fish species, while providing a handful of ecosystem services, notably recreational opportunities. In addition, Lake Saint-Charles is the major water source (up to 60% during summer) for the drinking water filtration facility located 11 km downstream on the St. Charles River (APEL 2017). The distribution networks

Figure 3: Water intake watershed at Lake St. Charles, Metropolitan community of Quebec City, Province of Quebec, Canada.
provide drinking water to a population of more than 300,000 residents living in metropolitan Quebec City.

Over the years, urbanization has significantly changed the lake ecosystem from a mesotrophic to a meso-eutrophic status (APEL 2019). Urban development continues to threaten the health of the lake ecosystem due to the increasing level of sediment and salt transported by the tributaries. Aging septic tanks and two municipal treatment facilities also release an increasing quantity of nutrients (nitrogen and phosphorus) and emerging contaminants. Stressors including invasive species, cyanobacteria, and water demand, in tandem with climate change, risk changing irreversibly the ecological characteristics and jeopardizing the provision of services by the watershed. Notably, four dominant genera of cyanobacteria have become more predominant in the lake, especially since 2006 (APEL 2019).

Municipalities, with the support of local NGOs, provide the necessary support to implement and deliver the province’s Integrated Water Resource Management approach, endorsed by the Province of Quebec in 2002 through the adoption of the National Water Policy (ROBVQ 2020). However, that approach has yet to provide the expected level of sensitization across relevant stakeholder groups to promote the definition of desired and sustainable watershed resource scenarios around La Lake Saint-Charles.

### 3.2 Interviews and CLDs

The first two authors conducted semi-structured interviews, each at one of the two case study sites. At Lake Dümmer, 18 stakeholders were interviewed in spring and summer of 2019, while 22 stakeholders were interviewed at Lake Saint-Charles in the fall of the same year. Using purposive sampling (cf. Palys 2008), respondents were identified based on their organization’s importance for either the management, the use, the protection or the assessment of Lake Dümmer and Lake Saint-Charles, their natural resources and their catchment area. Guidance from local NGOs was also provided when necessary. The interviewees comprised state authorities from the federal, regional and municipal levels, conservation and other nature-oriented NGOs, collective actors from the tourism sector, private entrepreneurs, Chambers of Agriculture, consulting firms, and water associations.4

Interviews had the purpose to construct a CLD of respondents’ representations of the main issues within the studied SES, their associated causes and consequences, and the relations and feedbacks between these identified variables (see Table S3 for the interview guidelines). Notes were taken and most of the interviews were recorded. The recordings were transcribed with the automatic transcription software AmberScript, revised by two student assistants for the Lake Dümmer case, and analysed using ATLAS.ti 8 for the Lake Saint-Charles case study and MaxQDA for the Lake Dümmer case study.

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4 For a list of the interviews of the lake Dümmer case, see Table S2 in the Annex. A similar list could not be provided for the Lake Saint-Charles case because of Quebec standards for maintaining participant confidentiality.
During the interview process, the two interviewers – one for each case – offered to create a CLD together with participants, using a poster and sticky notes of different colors. When respondents expressed a preference for an oral discussion instead, CLDs were created later on by the interviewer, using deductive coding (cf. Crabtree and Miller 1999) of the recordings to identify CLD variables. Generated CLDs were then transferred into digital visualizations using the software Vensim (Ventana Systems Inc.).

To obtain an overall impression of stakeholder social representations of the lakes’ SES, we merged the individual CLDs, starting with the most comprehensive individual CLD and adding in elements from other CLDs until every element had been incorporated (see Inam et al. 2015, 256, for the six steps of how to merge CLDs). The case studies’ merged CLDs gave insight into a) stakeholder social representation of the lakes’ SES status quo, and b) diverging perspectives on the system and its social-ecological dynamics. They were used in a subsequent step to guide the application of the SE-AS framework.

3.3 From interview analysis to conceptualizing SE-AS framework applications

3.3.1 The Lake Dümmer case study

To identify the interactions of actors and ecosystem components, we coded the stakeholder interviews along a set of action situation categories derived from the literature (Pahl-Wostl et al. 2020; Schlüter et al. 2019). The coding process was done via a qualitative content analysis using the qualitative text analysis software MaxQDA. The three coders guaranteed intercode reliability by recoding each other’s coded texts. We left ourselves the freedom to add new types of action situations to the list if needed. The identification of action situations was thus an iterative deductive and inductive process. To identify the relevant action situations of the SES, we started with the most striking social-ecological action situations that were mentioned often times by the interviewees and appeared to be at the center of attention of stakeholder SES representations. We then laid out the other coded action situations that related to these initial social-ecological action situations and the connections among them, thereby creating a first version of configurations of action situations; in a second step, we narrowed down the action situations to those needed to explain the emerging phenomenon of interest.

For the Lake Dümmer case study, we considered 15 AS as being relevant to the analysis.5 These AS describe the essential interactions between and within the social and ecological spheres, as well as their effects, to understand the emergent phenomenon of the lake’s eutrophication and the resulting troubles for the inhabitants of the lake ecosystem and its surroundings.

3.3.2 The Lake Saint-Charles case study

In the Lake Saint-Charles case, action situations were derived from the CLD merged across all stakeholder SES representations and configurations of action situations were constructed to explain the emergent phenomenon of interest, the lake’s water quality.

5 For an overview of the categories of action situations identified for Lake Dümmer, see Table S1 in the Annex.
CLDs can be examined through the SE-AS framework lens and might represent interactions occurring at one of several levels:

- the SE-AS framework in its entirety – that is, they might exhibit the emergent SES phenomenon (macro level);
- a configuration of several action situations or some single action situations (meso level);
- interactions between actors and ecosystem components (micro level).

To facilitate such translation, we identified themes within the merged CLD by grouping similar variables through a combined deductive and inductive process called selective coding (cf. Strauss 1987; Strauss and Corbin 1990). We thereby derived several thematic models from the merged CLD, in an approach reminiscent of Inam et al. (2015). We then identified a list of actors – both human and non-human – within these more focused, thematic models, and the interactions describing relationships between identified actors, and outcomes resulting from those interactions. As with Lake Dümmer case, we also used categories of action situations derived from the literature (Schlüter et al. 2019; Pahl-Wostl et al. 2020) to classify identified interactions, while remaining open to new categories that might not have been identified in previous publications, hence adopting a mixture of deductive and inductive approaches.

4. SE-AS frameworks and analysis of case studies

The comparison of the two case studies revealed different anthropogenic actions affecting the water quality of the aquatic ecosystems. We furthermore identified different feedbacks between the ecological and social spheres, in which actors are actively involved in regulating and managing the emerging dynamics and phenomena.

4.1 Dynamics and feedbacks within the Lake Dümmer SES

Figure 4 shows the application of the SE-AS framework for the Lake Dümmer case study. The resources of Lake Dümmer and its catchment area are used for different purposes and thus provide a variety of ecosystem services. The building of the lake’s dyke (external factor), finalized in 1953, converted the former wetlands surrounding Lake Dümmer into arable land. In the years after World War II, there was a great demand for agriculture. In this vein, agriculture was intensified in the region surrounding Lake Dümmer and its catchment area, the Hunte River basin south of the lake (ML and MU 2012, 12). Farmers produce crops, vegetables and animal feed for livestock farming. A result of this agricultural activity is the “polluting AS” in which farmers apply fertilizers on soil to get rid of slurry and to increase harvest. The nutrients, mainly phosphorus (P), in the soil get washed into the water of the rivers and creeks of the lake catchment (indicated with an arrow) and transported into the lake water (transporting AS).
The high amount of phosphorus stimulates the growth of macrophytes on one hand and the increase of cyanobacteria on the other (facilitation AS 1&2). A strong growth of macrophytes hampers sailing (indicated with the arrow “disturbance”). In the years in which cyanobacteria dominate, the algal blooms cause other types of problems: the cyanobacteria’s decomposition may release toxins, causes undesirable odors and deprives the water column of oxygen (indicated with the arrow “oxygen deprivation”). As a result, fish die due to the sudden dead zones in the lake – a battle for life that big fish species win easier than small fish species (competition AS). Bathing guests and tourists can no longer enter the lake, nor desire to stay nearby (arrow “disturbance” and recreating 2 AS).

Another human influence on the lake ecosystem is the water level regulation (ecological manipulation 1 AS), which was made possible by the dyke. The lake serves as a retention basin for flood management. The higher levels of water during summer enabled water sports such as sailing, surfing and pedal boating (recreating 1 AS), thereby boosting regional tourism. Dammed-up water volumes on the other hand intensify the concentrations of nutrients in lake water (indicated with the arrow “intensification”).

Lake Dümmer’s oversaturation with phosphorus leads to the emergent phenomenon of lake eutrophication with modifications of internal lake dynamics and repercussions on the lake’s ecosystem services regarding recreation and a balanced ecosystem.6

6 The dyke furthermore disrupts the lake’s water flow: dead biomass, from macrophytes and cyanobacteria alike, cannot be washed out of the lake. Thus, silt builds up over time threatening to fill the lake (not shown in Fig. 4). Every year, the annual amount of new sediment added is dredged out of the lake as a continuous measure against this silting process (ML and MU 2012, 9).

7 In fact, the yearly load of P in Lake Dümmer is around 14t, a little more than three times the amount (3.8t) the lake can accept without major changes to the lake ecosystem state (Interview N°3).
Stakeholders at the federal and the regional level have reacted to these alterations. The Lower Saxonian Ministry of the Environment had commissioned the Lower Saxonian State Office for Water Management, Coastal Defence and Nature Conservation (Betriebsstelle Sulingen), to prepare a framework design for the remediation of the lake (ML and MU 2012, 36) (Rule making AS). The remediation plan proposed for Lake Dümmer contains 16 actions geared to diminish phosphorus loads in the Hunte River and the lake. One main action area that tackles the cause is the implementation of voluntary measures in agriculture to reduce the use of nutrients and their runoff from fields (application of measures AS). The most cost-intensive and challenging measure, currently being evaluated, is the construction of a reed polder that would filter water from the Hunte River before it enters the lake.

Immediate measures that fight the symptoms are organized by municipalities and the Federal State Office for water management (coordination AS). They include the addition of oxygen to the lake in times of acute cyanobacterial blooms; installing barriers and diving barricades in the lake to keep the algae from reaching beaches and swimming grounds (ecological manipulation 2 AS); or mowing macrophytes (ecological manipulation 1 AS) to enable sailing.

Two entities that support and accompany the implementation of the remediation plan are the Dümmer council and the Dümmer forum (deliberating AS). The council, founded in 2011, comprises regional stakeholders from various sectors, including agriculture, the tourism branch, nature conservation organizations, and public authorities (NLWKN 2013). The council meets three times a year to discuss the process of the remediation plan and to advise the federal authorities supervising its implementation. The Dümmer forum communicates information regarding the biological status of the lake and the process of the lake remediation plan to a broad public, inviting interested citizens and stakeholders to public hearings twice a year (ML and MU 2012, 35; LGLN 2019).

4.2 Dynamics and feedbacks within Lake St. Charles SES

The emergent phenomenon of Lake St. Charles’ SE-AS framework application is water quality, as this is the main overarching theme mentioned by stakeholders that could encompass every other issue mentioned. The framework is constructed in two parts: a first one with only five AS representing past issues with lake governance that led to decreasing water quality, and a second part with 17 AS showing both the preceding structures as well as the necessary structure to reach a governance state that would help prioritize actions and allow the lake to recover, as described by stakeholders (Figure 5).
Water quality in Lake St. Charles has long been of concern for interested parties, but it only truly became a more urgent one in 2006 when significant cyanobacteria blooms began to appear in the lake (APEL 2009). While many causes for these blooms were proposed by interview respondents, the most prominent explanations involve the effects of high-impact residential developments, road development, outdated septic tanks, and wastewater overflowing from treatment plants located upstream of the lake (converting AS in Figure 5a). These can all be encompassed under high-impact development, leading to pollution and water quality degradation (polluting AS). Confronted with this degrading water quality, the Metropolitan Community of Quebec (MCQ), a body encompassing representatives from all municipalities in the Québec City area, decided to stop all pollution sources that could potentially affect the lake’s water quality, thereby imposing severe constraints on development and urban planning in lake-associated municipalities through a series of Interim Control By-Laws (ICBL) (rule making AS). This eventually led, in 2016, to a prohibition of all residential development activities within 500m of the Lake
St-Charles shoreline, and all development on the MCQ’s territory had to first be approved by this latter entity, hence denying local municipalities their usual autonomy. These ICBLs, and especially the 2016 one, were badly received by the municipalities bordering on the lake, eventually leading to conflicts and legal proceedings that were won by the pursuant municipalities (conflicts AS). The top-down rule making approach taken by the MCQ did not improve the lake condition. In fact, one respondent mentioned that for several months following one of the ICBL implementation, there was a historical peak in construction permit requests in some of the surrounding municipalities because developers knew of the coming ICBL before it became law and this resulted in even more intensive residential development in the watershed (converting AS).

At the time of the interviews, stakeholders followed up on several efforts to increase cooperation and social acceptance of development regulations. As a result the SES representation of many respondents reflected the need for more integrated governance, more cooperation, and more awareness, leading to a somewhat idealistic state of the SES (Fig. 5b). In this envisioned case, ecological monitoring (ecological monitoring AS) would be pursued by researchers and other capable entities such as local NGOs and the provincial Ministry of Environment. The monitoring would lead to better knowledge of the state of the lake and of its SES (knowledge generation AS), which would in turn be shared among all relevant stakeholders (Information sharing AS) and be linked and enhanced through inclusive governance networks (networking AS). This would allow for more trust between involved actors and foster informed deliberation (deliberating AS), thereby creating consensual regulations on which all parties were able to agree, at least to some point (rule making AS). Application of such regulation and urban planning would go through a collaboration process, allowing actors to fix optimal objectives for the lake and its watershed (planning AS), to coordinate efforts at the level of the watershed for congruent actions to be made (coordination AS), and to apply the consensual measures (Application of measures AS) with the availability of necessary funding (Investing AS).

These measures, as mentioned by respondents, concern two main aspects of the SES. First, urban and land planning would focus on low-impact development with a high percentage of vegetation cover that would be kept intact, and large areas of ecosystems protected from all development (protecting AS); second, wastewater management would be improved by connecting septic tanks to the municipal sanitary sewers, modernizing wastewater treatment plants, or connecting them downstream of the water intake on St. Charles river (sparing AS). These measures, the respondents argued, would help preserve the lake from further pollution and would give it time to recover from past anthropogenic disturbances.

5. Discussion

5.1 Comparison of case studies

While there are similarities in the two aquatic social-ecological systems regarding ecosystem services (e.g. recreational activities), the handling of water levels, and the symptoms of water degradation (presence of cyanobacteria), the AS responsible for the
emergent phenomena are dissimilar. The main activity responsible for water quality degradation in Lake Dümmer is agriculture, while in the Lake St. Charles watershed it is residential development (including associated road networks and wastewater) that is considered the cause for the increase in pollution. Measures taken to counter the decrease in water quality are also quite dissimilar, with an overall concept, volunteer farmer actions, ecological manipulation, and hydrological alteration as the main solutions already in place for the Lake Dümmer case, while stakeholders from Lake St. Charles proposed an integrated governance system, better wastewater management and ecosystem protection to be installed in the future.

Sketching the main AS and their composition and relations that are said to account for the emergent phenomenon is the framework’s key feature. The SE-AS configuration also points out which of the three spheres – social, ecological, or social-ecological – show to be most involved in generating the emergent phenomenon. While we observe a relative balance between the three spheres in Lake Dümmer’s framework configuration, ecological AS are almost absent from the AS configurations of the Lake St. Charles case study. This reflects that stakeholders here focus strongly on 1- social-ecological AS which they consider to be mostly involved in degrading water quality, and on 2- both social-ecological AS and even more importantly social AS, as a result of the newly proposed governance system, which need to be involved to improve water quality in the lake.

The framework application further revealed that the framework can be used to study and display configurations of action situations that have existed in the past (Fig. 5a), that describe a current situation (Fig. 4), or that could happen in the future (Fig. 5b). The SE-AS framework thus allows to study SES at different moments in time, and even project future potential AS configurations.

5.2 Hypothetical social learning for anticipatory governance

Although actual social learning in stakeholders and decision-makers still need to be tested, we can propose assumptions on how the SES representation through the SE-AS framework could potentially inform stakeholders thereby triggering social learning. Our estimations are based on the six criteria for anticipatory governance previously defined in section 2.2.

Looking at Figure 5a, which illustrates Lake St. Charles’ SES recent past, we observe only one action situation that relates to one of the six investigated criteria (1- flexible yet solid regulation, 2- integrated foresight system, 3- multiple scenarios with identified key precursors, 4- monitoring of changes, 5-cooperation, 6-integrated knowledge) and is thus reminiscent of anticipatory governance. The “ecological monitoring” AS falls into the 4th criterion. Since the SE-AS framework focuses on the very AS responsible for the emergent phenomenon under scrutiny – in our case, decreasing water quality – this does not imply that anticipatory governance was not present under any other form at that time in Lake St. Charles’ SES. Instead, it means that if other criteria were indeed present, stakeholders did not attribute them a significant enough effect to mention them as an element of the social-ecological system.
Figure 5b, an idealistic state of Lake St. Charles’ SES, shows that, although anticipatory governance was scarcely observed in previous states of the system, stakeholders are aware of many of the necessary steps required to bring the system closer to anticipatory governance and to help improve water quality. Both flexible and consensual regulation are considered key to an integrated governance system as envisioned by stakeholders; changes in the system are monitored; cooperation is put forward in the deliberating, planning and coordination processes; and, different types and different sources of knowledge are integrated and shared among all actors for better, more informed decision-making. Thus, eight AS can be identified as being an expression of anticipatory governance: “ecological monitoring”, “knowledge generation”, “information sharing”, “networking”, “deliberating”, “rule making”, “planning”, and “coordination”. We did not observe the anticipatory governance criteria 2- integrated foresight system and 3- multiple scenarios with identified key precursors.

Differences between Figures 5a and 5b and the fact that the MCQ holds a strong position in the management of lake water and land development express that for this case, anticipatory governance structures may tend to be bypassed in favour of a top-down approach by concerned and little informed deciding entities. With currently observed trends, and taking into account that climate change might in fact accelerate a decrease in water quality, anticipatory governance structures might tend to be set aside, hence diminishing the SES resilience towards climate change. That, we believe, is in itself a fact worth sharing with stakeholders and decision-makers, and a fact that might help generate insightful social learning.

At Lake Dümmer, we observe the 5th and 6th criteria of anticipatory governance within the Dümmer council and the Dümmer forum. Stakeholders belonging to the Dümmer council cooperate across sectors when discussing the process of the lake's remediation plan and further steps needed to fulfill it. In this vein, they have been looking at various potential measures and communicated them to the public through the Dümmer forum, thus accounting for open-mindedness and the integration of different knowledges. Although not shown in the framework configuration, the lake is currently under monitoring, the lake water’s bathing quality and the concentration of phosphorus are measured regularly. Actors thus consider changes in these two parameters which are key indicators for the measures’ effectiveness (criterion 4). To which degree regulations and law-making are flexible is impossible to estimate based on the current analysis; the remediation plan, however, provides clear guidelines that structure the implementation of measures (criterion 1). Just as in the case of Lake St. Charles, criteria 2 and 3 could not be observed.

Communicating the characteristics of anticipatory governance to stakeholders in both aquatic SES and indicating which of them they already use and which they do not yet consider could help inform them about the potential of anticipatory governance and how they as well as the ecological system could profit from it.
5.3 Limits and challenges in applying the SE-AS framework

The paper proves the relevance of the SE-AS framework by applying it to two lake SESs, showing how it can help understand which actors and interactions are responsible for a given emergent phenomenon of interest to researchers and stakeholders.

We analyzed the Lake Dümmer and the Lake St. Charles case studies with the same methods, emphasizing them differently in each case study analysis: the social-ecological system of Lake Dümmer was mainly analyzed through an interview analysis, the case’s merged CLD serving as orientation; the Lake St. Charles case study was analyzed based on the merged CLD, with the stakeholder interviews giving in-depth information when needed. However, the SE-AS framework application is not straightforward, and we identified several limits and challenges associated with it.

First, the SE-AS framework cannot, in itself, elucidate which AS are the most crucial for generating any given phenomenon. It was never created for such a purpose either, but this needs to be well understood by any researcher interested in applying it. In our case, identifying relevant AS was accomplished as a result of preliminary data analysis, as well as through researchers’ knowledge and understanding of the systems under scrutiny, as discussed in the “Methods” section. However, those preliminary analyses presented their own challenges. For instance, in the Lake Dümmer case, identifying AS based on the interviews led to a great amount of observed AS. Defining the emergent phenomenon at stake and the AS relevant to explain this was not an intuitive process and required a great understanding of insights provided by stakeholders. A coding protocol helped to guide the analysis and avoid differing analysis of the interview data. In the Lake St. Charles case, although frequency of variables and of causal links identified in the merged CLD already showed some trends illustrating the most important interactions to consider, translating those links and feedbacks, which were mostly devoid of actors, into AS involving mainly actors, required an additional level of analysis. We had to bring back appropriate actors into the relevant interactions and AS by referring to the interview data when necessary.

Second, the framework configurations show mostly generalized interactions and topics. Presenting such generalizations to stakeholders with the expectation to generate social learning can lead to mixed reception. We presented some of the results with a relatively high level of abstraction to stakeholders. Although reactions were not in themselves negative, one stakeholder argued that these were mere generalizations that would not help improve practical application of such knowledge in any way. In cases where data generalizations are necessary, researchers thus need to ensure that they communicate the use of such framework configurations of SES for stakeholders.

Third, the framework is not ideal for studying anticipatory governance characteristics within the social sphere of a SES. Features of resource governance comprise not only actor interactions – the framework’s focus –, but also tools, structures, and institutions. An SES study of solely stakeholder governance (and its repercussions on the ecological system) would require the researcher to translate the governance criteria used for the analysis into types of actor interactions beforehand and ideally complement the interview data with data derived from documents that are part of or describe the governance system.
That being said, once limits are well understood the SE-AS framework demonstrates strength in being able to illustrate innovative units of analysis which allow stakeholders to instinctively and promptly localize themselves within the system. The framework helps illustrate complex systems in a simple manner by focussing on specific phenomena and their potential causes, thereby showing which areas and which interactions are to be considered in any given circumstance for management of the phenomenon under scrutiny.

6. Conclusion

In this paper, we proposed an approach to use interview data and translate them through applications of the SE-AS framework developed by Schlüter et al. (2019). We used two case studies centered on lake SES in Germany and Canada to illustrate our approach. In doing so, our purpose was to underline how this framework could help reveal emergent phenomena in social-ecological systems and the interactions within the system that generate them; help induce social learning with insights on the SES; and notably by illustrating anticipatory governance structures within the system that could enhance system resilience.

For both case studies, the analytical approach of data analysis through a structured coding of interviews and the generation of CLD in order to identify SE-AS configurations proved successful. We illustrated how different SES dynamics could be observed within simple representations of the case studies’ SES. Comparing those representations allowed us to understand how the two SES differ, which spheres between the social, ecological and social-ecological ones are considered most prominent, and how governance plays out in place in each case.

The need for approaches such as the one proposed is increasing rapidly as climate change and its resulting uncertainties and imbalances manifest in a plethora of SES around the globe. The methodology introduced can help comprehend complex systems in an elegant manner, simple enough for decision-makers to grasp their essential parts, yet comprehensive enough to provide a fundamental understanding of dynamics behind any given phenomenon of interest. The SE-AS framework can help inform decision-makers on the governance structure in place, which can become key to develop greater resilience in any SES system facing increasing climatic disturbances and uncertainties.

Acknowledgements

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7. References


### Table S1: Categories of Action Situations identified at the Lake Dümmers case study

*Action situations in italic are not part of the framework configuration (Fig. 4)*

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Example at Lake Dümmers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Social-Ecological Action Situation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cultivating / Harvesting</td>
<td>Cultivating crops, harvesting natural resources such as fish, timber, grass</td>
<td>Agriculture</td>
</tr>
<tr>
<td>Converting</td>
<td>Changing sea or landscapes through technology (e.g. building a dam) or by restoring or converting use to protect</td>
<td>Dyke built in 1953: hinders the transportation of dead biomass out of the lake; changed water level</td>
</tr>
<tr>
<td>Cultural activities</td>
<td>Performing cultural or spiritual activities in nature</td>
<td></td>
</tr>
<tr>
<td>Recreating</td>
<td>Spending time in nature, enjoying (physically, psychologically)</td>
<td>Water sports like sailing; biking; bathing; fishing</td>
</tr>
<tr>
<td>Ecological monitoring</td>
<td>Observing or measuring ecological conditions</td>
<td>Water level, water quality, flora and fauna are measured</td>
</tr>
<tr>
<td>Polluting</td>
<td>Introducing substances into ecosystems</td>
<td>Farmers apply nutrients (phosphorus) on their fields (which are washed into the Hunte and the lake)</td>
</tr>
<tr>
<td>Ecological manipulation</td>
<td>Changing the food-web by regular interference, changing natural dynamics</td>
<td>Desludging the lake; restoring to nature of Hunte River; water level regulation; mowing macrophytes; adding oxygen to lake water; barriers</td>
</tr>
<tr>
<td><strong>Social Action Situation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rule making</td>
<td>Developing an operational rule, e.g. the level at which individuals can harvest a common pool resource; developing collective choice rules; etc.</td>
<td>Remediation plan for the lake</td>
</tr>
<tr>
<td>Information sharing</td>
<td>Sharing information or knowledge between actors</td>
<td>Distributing information about the lake's state to the public through a public forum twice a year</td>
</tr>
<tr>
<td>Deliberating</td>
<td>Communicating, exchanging observations and views, reflections, assessing outcomes, persuading each other</td>
<td>Dümmers council oversees, reports on and advises the implementation of the lake's rehabilitation concept; Dümmers forum offers space for discussion and information sharing</td>
</tr>
<tr>
<td>Knowledge generation</td>
<td>Produce knowledge relevant to other governance functions and possibly also to operational activities</td>
<td>Regular measurements of the lake’s and the Hunte’s water quality</td>
</tr>
<tr>
<td>Coordination</td>
<td>Social interactions specifically designed to support the coordinated development and implementation of</td>
<td>Municipalities coordinate the implementation of immediate measures together with the state office for water management, coastal protection and nature conservation.</td>
</tr>
<tr>
<td>Networking</td>
<td>Creating and maintaining social ties</td>
<td>Dümmers forum and Dümmers council offer opportunities to maintain contacts and establish trust</td>
</tr>
<tr>
<td>Planning</td>
<td>Produce some kind of plans regarding the use of the resource</td>
<td>The development of the 16 actions of the remediation plan</td>
</tr>
<tr>
<td>Application of measures</td>
<td>Application of specific measures or programmes. Outputs are not plans but more tangible products</td>
<td>Voluntary measures by farmers in the Hunte basin to reduce the use of fertilizers by 30%</td>
</tr>
<tr>
<td>Category</td>
<td>Description</td>
<td>Example at Lake Dümmer</td>
</tr>
<tr>
<td>------------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Social Action Situation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investing</td>
<td>Allocating financial resources to restore, conserve, or convert sea or landscapes</td>
<td>Voluntary measures by the farmers is financed by the state of Lower Saxony; municipalities pay for restoration of the Hunte River; municipalities &amp; the federal state pay for the immediate measures</td>
</tr>
<tr>
<td>Enforcement of rules and measures</td>
<td>Monitoring the achievement of certain pre-defined goals, environmental targets &amp; procedures assessing the compliance with rules &amp; their enforcement; informal observation of others behaviour</td>
<td></td>
</tr>
<tr>
<td>Evaluating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trading</td>
<td>Exchanging goods or services between two or more actors, selling products at markets</td>
<td>The federal state buys compensation area to offer to the owners of land on which the reed polder should be built</td>
</tr>
<tr>
<td>Lobbying</td>
<td>Influencing political actors to follow one's own interests</td>
<td></td>
</tr>
<tr>
<td>Competing</td>
<td>Aiming to do better than other actors, may involve interfering with their activities to reduce their performance; active de-mand by two or more actors or groups of actors for some environmental resource/s</td>
<td></td>
</tr>
<tr>
<td>Conflicts</td>
<td>Engaging in actions that aim to harm other actors; emotional disputes between actors; mental struggles resulting from incompatible or opposing needs, drives, wishes or external or internal demands</td>
<td></td>
</tr>
<tr>
<td>Conflict resolution</td>
<td>Social interactions specifically designed to resolve conflicts.</td>
<td>In its beginning, the Dümmer council was a forum for stakeholders to solve their conflicts</td>
</tr>
<tr>
<td><strong>Ecological Action Situation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Competition</td>
<td>Individuals of the same or different species compete for a limited food resource or space</td>
<td>Fish species fight for habitat and food and for oxygen – big fish adapt better to the difficult circumstances</td>
</tr>
<tr>
<td>Predation</td>
<td>Individuals of one species prey on another</td>
<td>Cormorants eat middle-size fish</td>
</tr>
<tr>
<td>Facilitation</td>
<td>Individuals of one species facilitate growth or reproduction of another species</td>
<td>Macrophytes provide habitat &amp; spawning sites for fish; cane brake is habitat for aquatic birds; phosphorus enhances growth of algae and macrophytes</td>
</tr>
<tr>
<td>Reduction / Taking over</td>
<td>The presence of one ecological component reduces the capacities of another ecological component, inducing an imbalance of the system</td>
<td>Cyanobacteria being abundant / algae bloom; high water levels in summer disturb the growth of the cane brake and less cane brake means less habitat for birds</td>
</tr>
<tr>
<td>Infection</td>
<td>One organism infects another organism with a disease</td>
<td></td>
</tr>
<tr>
<td>Species-habitat interaction</td>
<td>Generation of offspring, facilitated by suitable ecological environment</td>
<td>Macrophytes provide spawning site and habitat for fish</td>
</tr>
<tr>
<td>Vegetation – soil interaction</td>
<td>Vegetation growth stabilizes soil; soil quality affects vegetation growth &amp; vice versa</td>
<td></td>
</tr>
<tr>
<td>(Non)Transporting</td>
<td>A substance in one ecological component is transported to another one, e.g. via wind; a natural flow between two ecological components is inhibited</td>
<td>Phosphorus that has been washed off the fields and into stream water is transported into lake water</td>
</tr>
<tr>
<td>No.</td>
<td>German Name of Organization</td>
<td>English Name of Organization</td>
</tr>
<tr>
<td>-----</td>
<td>----------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>Natur- und Umweltschutzvereinigung Dümmer e.V. (NUVD)</td>
<td>Nature and Environmental Protection Association Dümmer</td>
</tr>
<tr>
<td>2</td>
<td>Gewässerschutzberatung der Landwirtschaftskammer Niedersachsen</td>
<td>Water protection consulting of the Chamber of Agriculture of Lower Saxony</td>
</tr>
<tr>
<td>3</td>
<td>Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN)</td>
<td>Lower Saxony State Agency for water management, coastal and nature conservation</td>
</tr>
<tr>
<td>4</td>
<td>Landesamt für Geoinformation und Landesvermessung Niedersachsen (LGLN)</td>
<td>Lower Saxony State Office for Geoinformation and Surveying</td>
</tr>
<tr>
<td>5</td>
<td>Wettfahrtgemeinschaft Dümmer e.V.</td>
<td>Racing community Dümmer</td>
</tr>
<tr>
<td>6</td>
<td>Gewässerexperte</td>
<td>Expert on Lake Dümmer</td>
</tr>
<tr>
<td>7</td>
<td>Naturschutzstation Dümmer, Einrichtung des NLWKN</td>
<td>Nature conservation station Dümmer, establishment of the NLWKN</td>
</tr>
<tr>
<td>8</td>
<td>Tourismusverband Dümmerland e.V.</td>
<td>Tourist office Dümmerland</td>
</tr>
<tr>
<td>9</td>
<td>Hunte Wasserverband, Landkreis Diepholz</td>
<td>Hunte water board, County Diepholz</td>
</tr>
<tr>
<td>10</td>
<td>Samtgemeinde Lemförde</td>
<td>Joint municipality of Lemförde</td>
</tr>
<tr>
<td>12</td>
<td>Stadt Damme</td>
<td>City of Damme</td>
</tr>
<tr>
<td>13</td>
<td>Naturschutzzing Dümmer e.V.</td>
<td>Nature conservation ring Dümmer</td>
</tr>
<tr>
<td>15</td>
<td>Anglerverband Niedersachsen</td>
<td>Anglers’ Association Lower Saxony</td>
</tr>
<tr>
<td>16</td>
<td>Fachdienst 67 Kreisentwicklung, Landkreis Diepholz</td>
<td>Specialist Service 67 District Development, County Diepholz</td>
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<tr>
<td>17</td>
<td>Untere Wasserbehörde, Landkreis Osnabrück</td>
<td>Lower Water Authority, County Osnabrück</td>
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<tr>
<td>18</td>
<td>Landwirtschaftskammer Niedersachsen, Bezirksstelle Nienburg</td>
<td>Chamber of Agriculture of Lower Saxony, Nienburg District Office</td>
</tr>
<tr>
<td>19</td>
<td>Niedersächsisches Ministerium für Umwelt, Energie, Bauen und Klimaschutz</td>
<td>Lower Saxony Ministry for Environment, Energy, Building and Climate Protection</td>
</tr>
</tbody>
</table>
Table S3: LimnoScenES Interview Questionnaire – English version

1. **General information**

1.1 What does your organization do (reason of its existence/long-term objective/s; daily tasks; ...)?

1.2 Which ecosystem services does the lake provide?

1.3 What is your/your organization’s stake in the lake and its ecosystem?

2. **Human-freshwater interactions and the lake’s issue/s**

2.1 Do you observe human-freshwater interactions at the lake? If so, what are they like?

2.2 Which challenges do you observe regarding the different uses of the lake’s different resources and ecosystem services?

3. **The CLD questions** (write the answers on post-its and fix them on a poster)

3.1 What is the main issue at the lake? (e.g. a specific user conflict? pollution? over-use of one of its resources? ...)

3.2 How has the problem developed over time?

3.3 What are the main direct and indirect causes of the problem’s development? How do causes and problem relate to each other (link polarities)?

3.4 What are the consequences of the problem?

3.5 What are main feedback processes between the causes and the consequences? Where are they situated in in the “CLD picture” (that just evolves)?

3.6 What kind of short-term policies do you think can be adopted to solve this problem?

3.7 What kind of long-term policies can be adopted to solve this problem?

3.8 Which policies exist that aim at solving the problem?

3.9 What are the main hurdles in the success of these policies?

4. **The other stakeholders**

4.1 Is there anyone missing on the list who is important for the lake?

4.2 Is there anyone on the list who has no stake whatsoever in the lake and its ecosystem services?

4.3 Who do you consider most relevant regarding the lake’s issue/s and its/their (potential) solutions?

5. **The workshops**

As said in the beginning, within the project we plan to do workshops with the stakeholders of the lake to understand which human-freshwater interactions exist, what kind of pressures influence the lake and its ecosystem (and biodiversity), what kind of visions the stakeholders have regarding the lake’s future, etc.

5.1 What would you like such a workshop to offer?

5.2 Which topics regarding the lake and its ecosystem services do you think should be discussed in such a workshop?

5.3 What focus/objective should a workshop have

- Information generation & exchange
- Discussion and development of potential policies; mediating conflicts
- Getting to know other stakeholders better; learning about their different interests in the lake and the intentions behind them

5.4 What else would you like to learn in such a workshop?