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Research

Studying human-nature relations in aquatic social-ecological systems using the social-ecological action situations framework: how to move from empirical data to conceptual models

Laura Herzog [1], *Louis Tanguay* [2], *Beatrix E. Beisner* [2], *Claudia Pahl-Wostl* [1], *René Audet* [3] and *Maja Schlüter* [4]

ABSTRACT. Various analytical frameworks have been developed to examine the interactions between humans and nature in social-ecological systems (SES). When studies of SES do not make explicit how a framework is used to build conceptual models, they leave a black box for scholars aiming to use such frameworks. Our study highlights such a process, focusing on the analytical step of transitioning from empirical data to categories of the recently developed social-ecological action situations (SE-AS) framework. This framework, which proposes to study SES along configurations of action situations (AS), has so far been applied in few studies. Clarifying how data are analyzed and adapted within this framework is thus of relevance for anyone interested in using it. We compare two analytical methods used to identify AS configurations, each method serving for the analysis of one of two lake-catchment areas, located in Northern Germany and Canada. The first method is a qualitative interview content analysis based on text coding; the second is the analysis of causal loop diagrams (CLD) derived from interviews. Both data sources outline stakeholder social representations of their SES. We compare: (1) the suitability of the two analytical methods for identifying configurations of AS and their linkages, and (2) the potential and limitations of the SE-AS framework for assessing the inherent dynamics of emergent phenomena within SES. Our two-pronged data analysis methodology led to similar results despite the different analytical methods used. We conclude that the SE-AS framework can help illustrate different interactions within an SES while allowing for relatively simple, yet comprehensible system representations. We also identify challenges and limitations that we encountered. Challenges revolve around identifying AS and differentiating them from outcomes. Limitations include the representation of time and levels of governance, and weighting the relative importance of AS.

Key Words: *causal loop diagrams; complex systems; multidisciplinary methods; participatory research; SE-AS framework, social-ecological systems*

INTRODUCTION

One of the recurring challenges with social-ecological system (SES) analysis and governance is integrating the understanding of their multidimensional, complex nature into practical decision-making processes (Leenhardt et al. 2015). Studying SES 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). 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 illustrations of causal relationships between system variables, as seen, for instance, in causal loop diagrams (CLDs) (cf. Forrester 1961, Inam et al. 2015, Halbe and Adamowski 2019). However, such approaches fail to acknowledge that interactions responsible for explaining emergent social-ecological phenomena cannot be fully predicted based solely on a deterministic approach. Because key dynamics in a system can have repercussions on the system as a whole, just as systemic social-ecological phenomena can also affect system variables (Schlüter et al. 2019), recognizing these phenomena as well as their non-deterministic nature is essential to understand the overall systemic state and to anticipate their potential effects. Emergent phenomena can be, for example, the collapsing state of a system or an ecosystem governance regime shift.

Emergent phenomena in SES are difficult to predict and even more difficult to govern. There is thus a need for multidisciplinary research that identifies and evaluates SES dynamics that lead to specific phenomena of interest. The recently developed social-ecological action situations (SE-AS) framework (Schlüter et al. 2019) focuses on the action situation (AS) as a unit of analysis, like its predecessors the institutional analysis and development (IAD) framework and the SES framework (Ostrom 2005, 2007, McGinnis and Ostrom 2014). An AS, as stated by Ostrom (2005:32), exists "Whenever two or more individuals are faced with a set of potential actions that jointly produce outcomes (...)." The main difference with the IAD and the SES frameworks is what produces outcomes in the AS of the SE-AS framework. In the SE-AS framework, the concept of an AS is broadened to treat social actors and ecological elements on the same level, and to place their interactions at the center of the analysis. The SE-AS framework thus explicitly considers interactions between social and ecological elements and enables the analysis of those interactions. The focus on interactions among and across social actors and ecological elements allows the study of dynamics within an SES responsible for generating emergent phenomena, which include and affect both humans and ecological entities.

Using such a framework for SES research requires gathering knowledge about complex systems by combining different types of data. Three databases exist in which scholars gather data and knowledge on variables of SES in a structured way (these are the

[1]Institute of Geography, Research Centre Institute of Environmental Systems Research, Osnabrück University, Germany, [2]Groupe de recherche interuniversitaire en limnologie (GRIL), Département des sciences biologiques, Université du Québec à Montréal, Montréal, Québec, Canada, [3]Département de stratégie, responsabilité sociale et environnementale, Université du Québec à Montréal, Montréal, Québec, Canada, [4]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

IFRI and NIIS databases for the IAD framework, and the SES library and SESMAD for the SES framework; see Bernstein et al. 2019; https://seslibrary.asu.edu/). Despite the existence of these databases, systematically linking analytical frameworks to data collection practices is not yet customary in publications (Bernstein et al. 2019). Studies often do not address the nature of the underlying data and the actual data analysis process (Ratajczyk et al. 2016). When studies of SES do not make explicit how a framework is used to build a conceptual model, showing little to no coherence in how categories are used, measured, or derived from empirical data, they leave little support to guide scholars aiming to use or apply such a framework (Thiel et al. 2015). This strongly diminishes the potential reach of any given framework in SES research, especially for communication with decision makers or for consistency within the research field. We contribute to filling this gap in the literature by describing how categories of AS can be derived from empirical data, and we do this by using and comparing two analytical methods. We apply the recently developed SE-AS framework, thus contributing to the practicability of its use.

Our objectives are thus to (1) compare the suitability of an interview content analysis with that of a CLD analysis to identify action situations and their interactions within an SES, guided by the SE-AS framework, and to (2) evaluate the potential and limitations of the SE-AS framework for comprehending the dynamics of SES and the phenomena these create. The reason behind the proposed comparison is to evaluate whether the AS configurations based on the SE-AS framework can be successfully generated through different methods, or whether some methods might be more appropriate than others for such a purpose.

Our case studies focus on human-induced alterations within two north temperate shallow lake ecosystems in Germany and Canada: Lake Dümmer is a shallow lake with a surface area of 13.5 km² located in southeastern Lower Saxony, North-Western Germany; Lake St. Charles covers an approximate area of 3.6 km² and is located 20 km north of Quebec City, province of Quebec, Canada. Both lakes are used for recreation, offer a fishing site, are habitats for birds and other wildlife species, and are impacted by human use, i.e., road salts and sewage being the main source of pollution at Lake St. Charles and nutrients from agriculture causing eutrophication of Lake Dümmer. In our analyses, we focus on the lakes and their catchment areas, including the feedbacks between the ecological and the social systems, and we use data generated in the context of a participatory research project. The representations of SES and the studied emergent phenomenon, which in our cases is lake ecological integrity, defined as "unimpared structure, composition and function [of the ecosystem] and a capacity for self-renewal" (Schallenberg et al. 2018:367), thus derive from the social depictions of those same systems. These social depictions were themselves identified through collaborative efforts with relevant stakeholders. Furthermore, we develop more comprehensive representations of the studied SES than have SE-AS framework studies to date. Our analysis thus contributes to the discussion on how the SE-AS framework can help expose a more detailed understanding of SES and their emergent phenomena.

CONCEPTUAL BACKGROUND

Qualitative data analysis in social-ecological systems (SES) research

When analyzing qualitative data that inform SES representations, a coding protocol that keeps a record of the analytical criteria and steps guarantees consistency in the analysis process (Anderies et al. 2016). This is just one element in a set of methodological tools, also including selection criteria, codebook manual or intercoder reliability testing, that together ensure sound qualitative research and a transparent record of qualitative data analysis (Ratajczyk et al. 2016). A transparent record of the analytical process helps guide the analysis and interpretation of data in light of any given analytical scheme, such as the SE-AS framework. A coding and analysis protocol enables replicability and comparability across case studies and provides a common language for variables and terms.

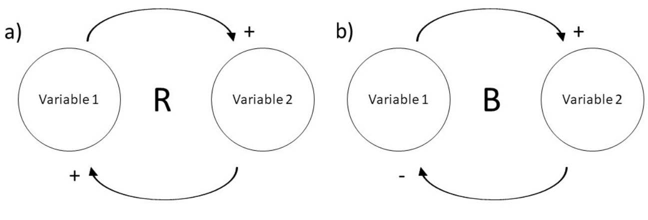
The study by Leslie et al. (2015) provides an excellent example of how to analyze an SES with qualitative and quantitative data within an analytical framework while transparently reporting the analytical steps. The SES library (https://seslibrary.asu.edu/) at Arizona State University and the Social-Ecological Systems Meta-Analysis Database (SESMAD) at Dartmouth College (SESMAD 2021) represent endeavors enabling comparisons of SES case studies based on databases of the studied variables and underlying coding manuals. These databases provide the grounds for comparable research on SES dynamics by relying on studies with transparent data operationalization and analysis processes. We further emphasize and illustrate this need for transparent data analyses when using frameworks in SES research.

Causal loop diagrams (CLDs)

We focus on the CLD modeling technique to (1) collect data and (2) lay the foundation of interrelated system variables, upon which we identify AS in the St. Charles case. A CLD presents a schematization of a system under study to reveal solutions for a focal problem (Haraldsson 2004) by describing system variables and events and the connections among and between them. 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.

Designing a CLD usually begins with the identification of a problem within a system, which gives the CLD its purpose (Richardson and Pugh 1981, Vennix 1996). The purpose can be to better understand the dynamics that surround the identified problem or to find potential solutions. Once the purpose is identified, the causes and consequences of the problem are identified as variables. Variables are linked through either a positively or negatively correlated relationship, signifying that a given first variable will affect a second variable in the same or opposite direction. Consequences of the problem are then linked back to causes either directly or through a series of variables. Loops in a CLD are formed when two (or more) variables are connected by links that form a circle comprising both variables (Fig. 1). Loops can be balancing (indicated with a "B") or reinforcing (indicated with an "R"). A reinforcing loop means a variation in one 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 over time as a result of negative correlation between two variables (Vennix 1996, Haraldsson 2004, Inam et al. 2015). Causal loop diagrams are drawn on a researcher-specified temporal scale, and important delays are marked on the affected causal links (Haraldsson 2004).

Fig. 1. Generic causal loop diagrams with a) a reinforcing loop and b) a balancing loop.



The social-ecological action situations (SE-AS) framework

The SE-AS framework (Schlüter et al. 2019) expands on the concept of an action situation (AS) from the institutional analysis and development (IAD) framework (Ostrom 1990) and combines it with ideas from complexity science and resilience thinking (Folke et al. 2010). The concept of an action situation as a unit of analysis with which to study the behavior and interactions of social actors in the context of multilevel complex systems was elaborated within the IAD framework (Ostrom 2005). In the IAD framework, an AS consists of participants, their positions, potential outcomes, a function turning actions into outcomes, the control of this function, information and costs, and benefits related to these actions and outcomes (Ostrom 2005). The AS and the participants therein contained thus generate actions and outcomes that feedback into the system. The IAD suggests that so-called exogenous variables that are part of the system under study also influence AS and participants. Examples are biophysical conditions, attributes of community, and rules. The IAD thus strongly focuses on social dynamics and institutions to understand SES and how actors act and behave in those.

The SES framework, a predecessor of the SE-AS framework, was developed from the IAD as a response to natural scientists who found that the IAD was reductive by condensing all ecological processes into exogenous variables. The SES framework thus integrates the ecological part of an SES actively into the analysis: it centers the action situation, within which actors interact and create outcomes that shape the SES, in the middle of the resource system, resource unit, governance system, and actors (McGinnis and Ostrom 2014). In this framework, the exogenous variables of the IAD have switched to the center of attention and the ecological side, i.e., the biophysical conditions, figures more prominently in SES studies using the SES framework.

The SE-AS framework proposes recognizing the social and ecological spheres equally in an SES study, offering AS that consist of social actors and/or ecological entities, interacting with each other within a specific context. Action situations are thus defined by the very nature and quality of the social, ecological, or social-ecological interactions therein. Action situations themselves shape the system, influencing each other through outcomes and creating AS configurations that generate a system's emergent phenomenon. Presented as a complementary approach to its predecessors, the SE-AS framework is thus able to capture dynamics, processes, and interactions within SES, on a variety of organizational levels (Schlüter et al. 2019). The framework has been created to analyze how emergent phenomena occur within SES.

The SE-AS framework maps configurations of AS, i.e., contextual interactions of system components that are hypothesized to underpin an emergent phenomenon of interest (Fig. 2). The SE-AS framework consists of (Schlüter et al. 2019):

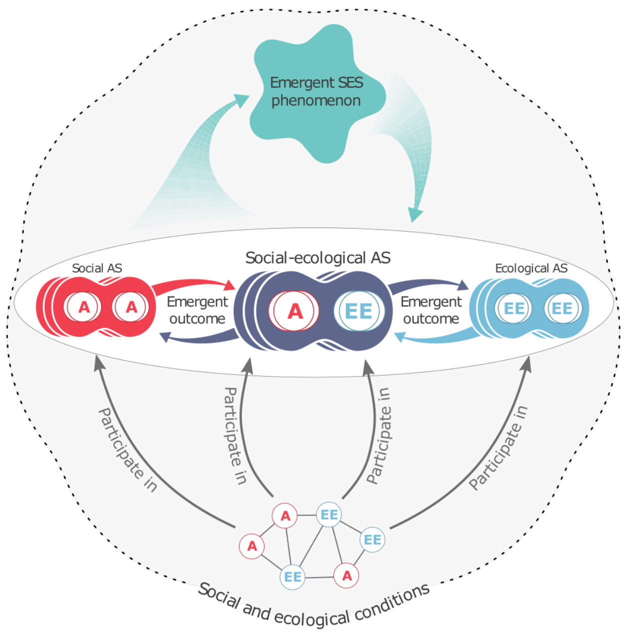
- actors (A) and ecosystem elements (EE) that interact with each other at the micro level;
- purely social or ecological action situations (S-AS and E-AS, respectively) which, within the frame of a given analysis, define exclusively social or ecological interactions;
- social-ecological action situations (SE-AS) within which the human-ecosystem interactions of interest occur;
- outcomes, generated by AS, that are connected to and 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, resulting from the links created by different outcomes between different action situations. The configuration of AS represents an assumption about how interactions and outcomes have produced the emergent phenomenon of interest;
- the emergent social-ecological phenomenon, which can be observed at the macro level, and which feeds back to influence the AS configuration.

Schlüter et al. (2019) identified a non-exhaustive set of interactions that define the action situations and indicate their nature or characteristics. Consulting Pahl-Wostl et al.'s (2020) study of action situations in the context of water governance, we found that the list of the SE-AS framework's social AS derived from Schlüter et al. (2019) could be further expanded by some of the categories used by Pahl-Wostl et al. (2020), namely, coordination, planning, application of measures, conflict resolution, and enforcement of rules. We thus added these categories to our list of AS (see Table 1; see also Appendix 1 for the coding protocol, which includes more details on AS categories). We also included in Table 1 the AS that we created based on the analysis of our case studies.

Based on this section's concepts, we propose the following terminology:

- AS configurations: relate to the configurations of AS that are drawn for each case study, using the interview data and based on the SE-AS framework.
- Social representation: refers to a narrative of the SESs as perceived by the actors.
- SES representation: relates to the illustration of the SESs under study, presented through AS configurations and based on the actors' social representations of the system.

Fig. 2. A schematic representation of the social-ecological action situations (SE-AS) framework. A's represent social actors and EE's represent ecological elements; social action situations are colored in red; SE-AS are colored in dark blue; ecological action situations are colored in light blue; the emergent phenomenon shows in a turquoise star-form shape. Interconnections between social actors and ecological elements show in the network at the bottom of the figure, generating specific action situations as indicated by the arrows that guide to the three exemplary AS at the center of the figure. The AS are connected with each other through their outcomes. The configuration of AS in the center describes the pattern and dynamics that explain the system's emergent phenomenon (from Schlüter et al. 2019). Note: SES = social-ecological systems.



- Framework: relates to the SE-AS framework, unless stated otherwise.

METHODS

To gather our data, we conducted interviews with relevant stakeholders in the two case study regions, Lake Dümmer in Northern Saxony, Germany, and Lake St. Charles in Quebec, Canada. The interview questions were structured along the logic of causal loop diagrams, asking about a central issue, its causes and consequences, and their repercussions to form questions (see Appendix 2, Table A2.1 for the interview questionnaire). We did so because the technique of revealing links between an issue, its causes, consequences, and potential feedbacks is easily explained, and thus more accessible to participants. Although we are aware that this approach differs from the one used by Schlüter et al. (2019), the participatory nature of our study called for such an approach. We considered that explaining the concept of AS and having participants understand and use it effectively within the timeframe imposed by the interview process did not seem realistic. That said, although the interview questions were based on CLDs structure, we used two distinct analytical methods to conceptualize AS configurations, using one analytical method for each SES, and focusing on lake ecological integrity as the emergent phenomenon (see Fig. 3 for a summary of our methodology).

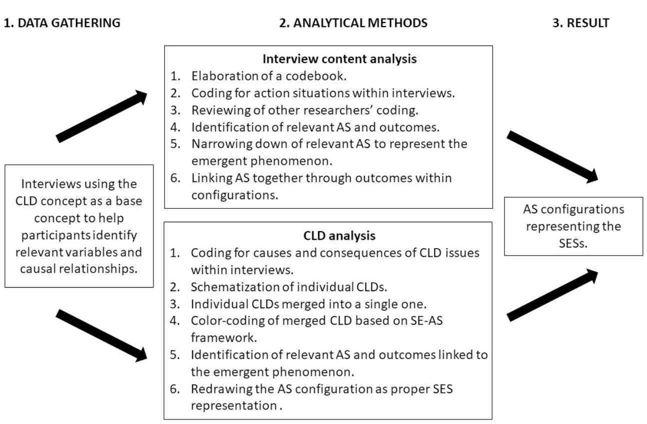
The first analytical method is based on the content analysis of interviews. For this, we applied a qualitative coding scheme to the transcribed interviews with which we assessed social, ecological, and social-ecological AS within the SES that the participants had described (for the coding scheme, see Table 1, with more information on the categories in Appendix 1). For the other method, we constructed causal loop diagrams that were merged into a unique CLD as a preliminary analytical step (CLD analysis) before identifying AS. The rationale for using two different analytical methods for identifying AS and their configurations was to examine whether different approaches can lead to comparable representations when those latter are based on the SE-AS framework, or whether one approach may be superior to the other in certain aspects.

It should be noted that, compared to the AS configurations originally presented by Schlüter et al. (2019), we focused on more detailed representations of the studied systems, with many AS integrated into our configurations instead of only a few main ones. As Schlüter et al. (2019) wrote, "[t]he framework is flexible with respect to the level of abstraction and detail of an analysis (...)." We opted for a more detailed analysis for three reasons: (1) we were interested in exploring the SE-AS framework suitability for different adaptations, beyond Schlüter et al. (2019) original proposition, (2) the data collected through interviews permitted detailed representations, and (3) with stakeholders directly involved in both cases, it was relevant to communicate our results with more detailed SES representations instead of broad generalizations that might be of little practical use to them.

Table 1: Categories of actions situations (AS) based on Schlüter et al. 2019[†], Pahl-Wostl et al. 2020[‡], and newly created ones for the purpose of this study[§].

Category	Description
Social-Ecological Action Situation	
Converting[†]	Changing sea or landscapes through technology (e.g., building a dam) or by restoring or converting use to protect ecosystems (e.g., protected areas/reserves)
Cultivating/Harvesting[†]	Cultivating crops, harvesting natural resources such as fish, timber, grass
Polluting[†]	Introducing substances into ecosystems
Recreating[†]	Spending time in nature, enjoying (physically, psychologically)
Ecological disservice[§]	Disservice brought by natural systems to human populations
Ecological manipulation[§]	Changing the food-web by regular interference, changing natural dynamics
Sparing[§]	A specific social action (e.g., a measure) that wilfully cares for or ameliorates an ecological component's state
Social Action Situation	
Conflicts[†]	Engaging in actions that aim to harm other actors
Deliberating[†]	Communicating, exchanging observations and views, reflections, assessing outcomes, persuading each other
Information sharing[†]	Sharing information or knowledge between actors
Investing[†]	Allocating financial resources to restore, conserve, or convert sea or landscapes
Lobbying[†]	Influencing political actors to follow one's own interests
Networking[†]	Creating and maintaining social ties
Rule making[†]	Developing operational ruler, e.g., the level at which individuals can harvest a resource; developing collective choice rules that determine who is involved in decision making
Application of measures[‡]	Application of specific measures or programs. Outputs are not plans but more tangible products
Conflict resolution[‡]	Social interactions specifically designed to resolve conflicts
Coordination[‡]	Social interactions specifically designed to support the coordinated development and implementation of strategies, plans, activities, instruments, monitoring processes, taking of measurements, etc.
Enforcement of rules[‡]	Monitoring the achievement of certain pre-defined goals, environmental targets etc. and procedures that assess the compliance with rules and their enforcement, and informal observation of others behaviour which might exert social pressure
Planning[‡]	Produce some kind of plans regarding the use of the resource
Ecological Action Situation	
Competition[†]	Individuals of the same or different species compete for a limited food resource or space
Reduction[§]	The presence of one ecological component (in a specific state, e.g., hotter, more abundant, ...) reduces the capacities of another ecosystem component
(Non-)Transporting[§]	A substance/particle in one ecosystem component is transported to another one, e.g., via wind; a natural flow between two ecosystem components is inhibited

Fig. 3. Summary of our methodological design with two analytical methods. Note: AS = action situations; SES = social-ecological systems; SE-AS = social-ecological action situations; CLD = causal loop diagrams.



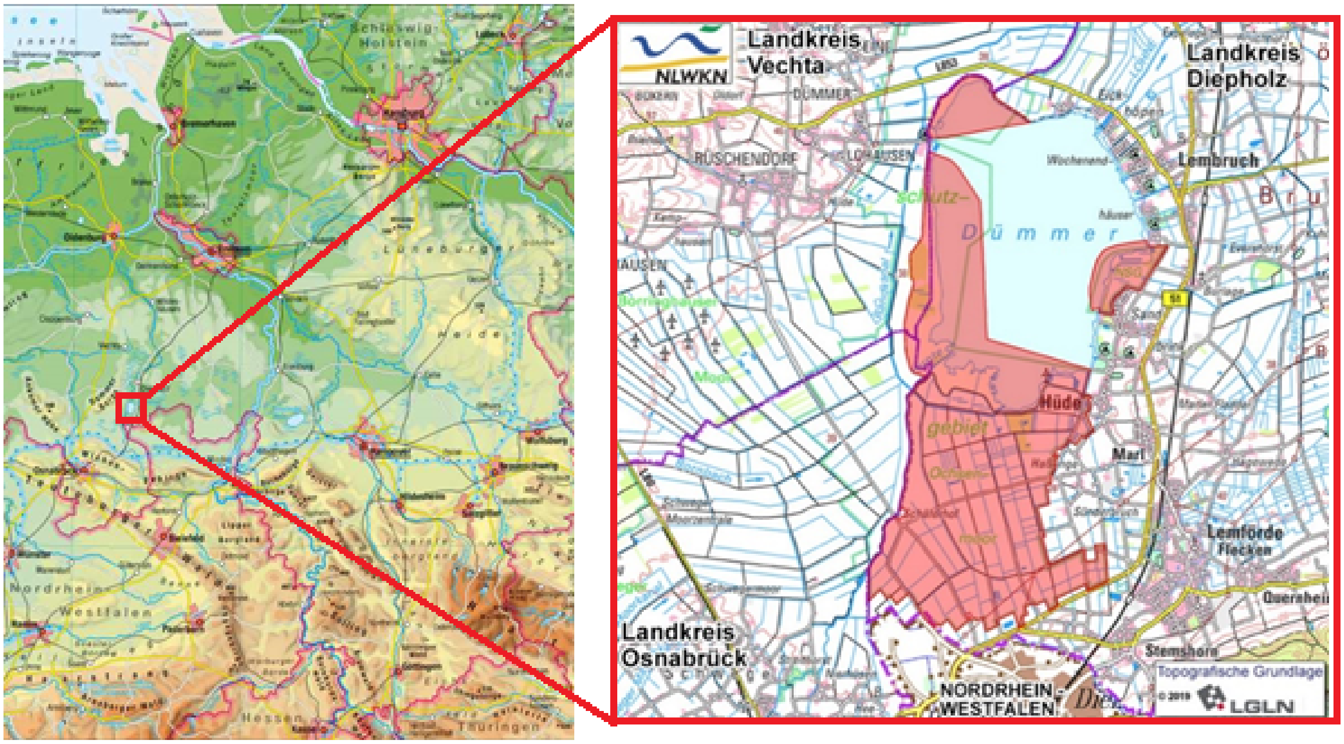
The two case studies

The watershed of Lake Dümmer covers an area of 346 km² (Hochschule Osnabrück 2013). Its waters are fed by the River Hunte, which runs from south to north through the lake. The western and southern shores, as well as the lowlands east and south of the lake, are nature reserves (Landkreis Diepholz 2020). The lake is administered by two districts in the federal state Lower Saxony, Germany, and around 8000 inhabitants live close to the lake (for the lake's location within Lower Saxony, Germany, see Fig. 4).

Currently, the lake stores water that is used to regulate the River Hunte levels, protecting downstream communities from floods. The lake further serves as a recreational area for many tourists throughout the year, while being home to a rich biodiversity, including a variety of iconic flora and fauna habit (FFH) species and migratory birds (Council of the EU 1992, Landkreis Diepholz 2018; FFH refers to the EU Council Directive on the conservation of natural habitats and of wild fauna and flora). A redevelopment project is underway for the lake to reduce nutrient loading resulting mainly from agriculture in the Hunte River Basin.

Lake St. Charles' watershed covers an area of 165.8 km² (Légaré 1998; Fig. 5). 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 550 km². The higher St. Charles River watershed, created by the water intake on the river downstream of the lake, covers around 348 km² over five municipalities: Stoneham-et-Tewkesbury, Lac-Beauport, Lac-Delage, Quebec City, and Saint-Gabriel-de-Valcartier, as well as over an urban territory of the Indigenous Huron-Wendat Nation, Wendake (APEL 2009, 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 falling under its jurisdiction, while the remaining belongs to Stoneham (APEL 2009). The population in the watershed of the upper St. Charles River was around 19,000 people in 2016, mainly concentrated along the tributaries and around the lakes (APEL 2019).

Fig. 4. Location of Lake Dümmer and the Hunte River in North-Western Germany (Diercke Weltatlas 2021), including in red, the nature reserves west and south of the lake (right, LGLN 2019).



The lake became a semi-natural reservoir, with a hydro-electric current capacity of 14.8 Mm^3, after the construction of the Cyrille-Delage dam in 1934 and reconstruction in 1948, which raised the water level approximately 3.6 m above natural historical 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 are home to a rich bird diversity and provide a handful of ecosystem services, notably recreational opportunities. In addition, Lake St. 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 provide drinking water to a population of more than 300,000 residents living in the Metropolitan Community of Quebec.

Common basis: interviews

At Lake Dümmer, XX interviewed 18 key stakeholders in the spring and summer of 2019, while YY interviewed 22 key stakeholders at Lake St. Charles in the fall of 2019. Interviews were semi-structured, following a list of questions, but leaving the interviewer the freedom to ask additional questions (for the questionnaire, see Appendix 2, Table A2.1). Interviews lasted between 45 minutes and 3 hours and most of them were recorded for the Dümmer case, while all were recorded for the St. Charles case.

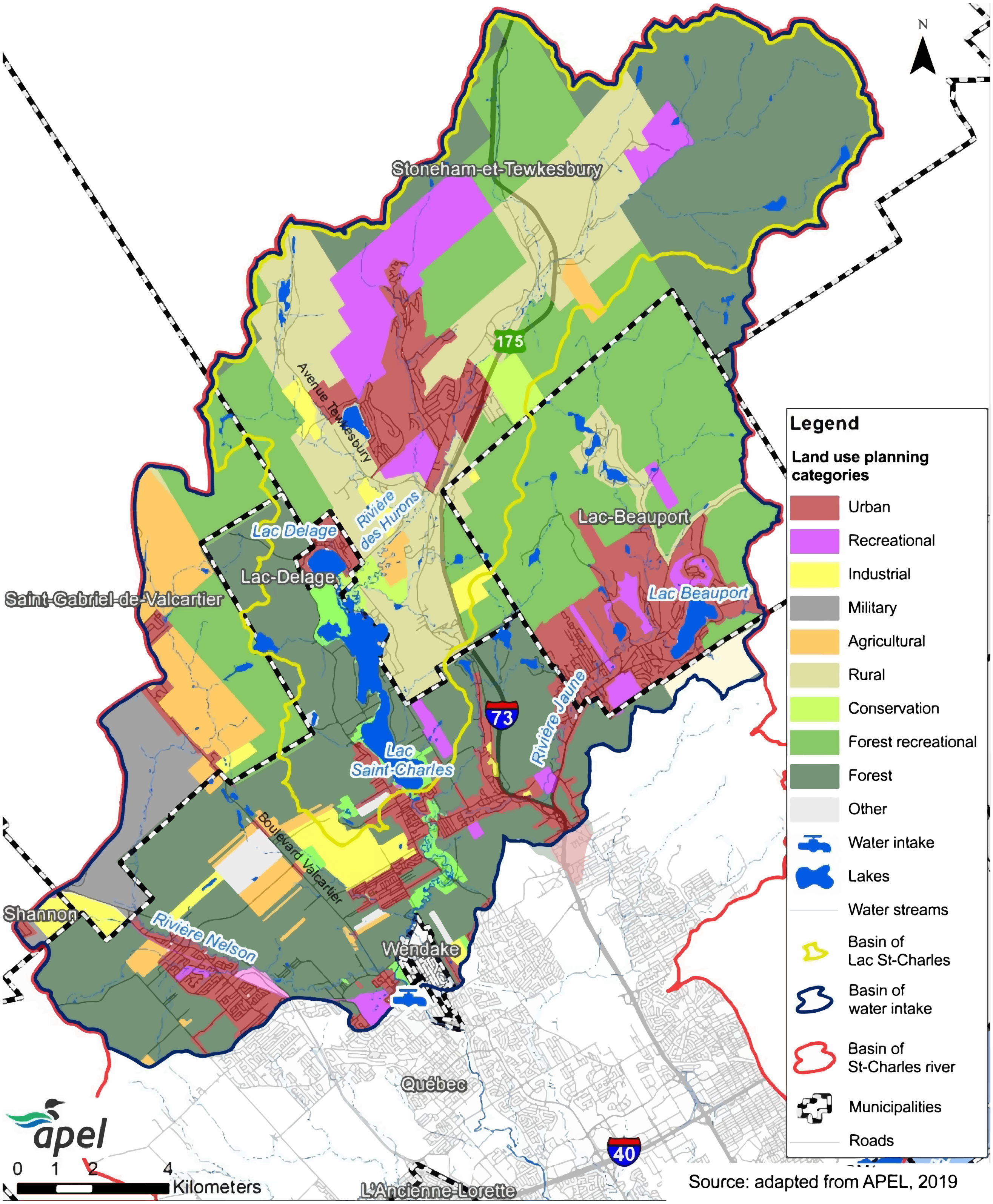
Using purposive sampling (cf. Palys 2008), interview participants were identified based on their organization's importance for either the management, the use, the protection or the assessment of each lake, their natural resources, and their catchment area. In the St. Charles case, guidance from a local NGO was also provided to identify which actors were the most actively involved in the lake watershed management or use. The interviewees included: 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 (for a list of the interviews of the Lake Dümmer case, see Appendix 3, Table A3.1; due to Quebec standards for maintaining participant confidentiality a similar list cannot be provided for the Lake St. Charles case).

Because CLDs are a convenient tool with which to represent a system's variables and their connections, we decided to structure the interviews along the logic of CLDs to identify the stakeholders' comprehension of the SES. We also explicitly asked stakeholders about the human-nature interactions they observed at the lakes. The purpose of the interviews was thus to construct each interviewee's social representation of the main issue within the studied SES, causes and consequences associated with this issue, and the relations and feedbacks between identified variables.

Identifying action situations through text coding: case study 1, Lake Dümmer

The interview recordings of Lake Dümmer's stakeholders were transcribed with the automatic transcription software AmberScript. To identify the interactions of actors and ecosystem components, three researchers coded the stakeholder interviews along the set of AS categories as defined by Schlüter et al. (2019)

Fig. 5. Water intake watershed at Lake St. Charles, Metropolitan community of Quebec City, Province of Quebec, Canada.



and Pahl-Wostl et al. (2020; see also Table 1; Appendix 1) and coded the outcomes these AS created.

The coding process was done via a qualitative content analysis using the qualitative text analysis software MaxQDA. The coders guaranteed intercoder reliability by reviewing each other's coding and discussing subsequent differences. The addition of new types of AS to the list was permitted if needed. The identification of action situations and their outcomes was thus an iterative deductive and inductive process: researchers met regularly to discuss the coding process, the necessity of newly created AS categories, the interpretation of AS, and their connections via outcomes. The coding protocol supported the coding process by recording our observations of the process itself, the main issues of discussion, and the decisions made. The protocol also included a guideline of how to code and a glossary of the terms action situation, outcome, and phenomenon (for the protocol, see Appendix 1). The process helped identify 34 AS categories within the interviews.

To determine the relevant AS that explain the phenomenon of interest within the SES, we first identified a core set of AS: we started with the SE-AS that were more frequently mentioned by the interviewees, appearing to be the focus of the social representations. We then laid out the other coded AS that related to these initial ones and the connections among them, as described by participants, thereby creating a first version of AS configurations. In the second step, we checked whether the AS were constituent for the emergent phenomenon of interest. If that was the case, we analyzed their elements and their interactions to define their outcomes and subsequently related AS. We continued in a similar manner until we could not find any new necessary AS to explain the emergent phenomenon. For the Dümmer case study, 19 action situations were considered relevant to the analysis (for an overview of the action situations identified, see Table 1; Appendix 1).

Identifying action situations through CLDs: case study 2, Lake St. Charles

During the interview process, we offered to create a CLD together with the interview participants, using a large sheet of paper and sticky notes. When participants expressed a preference for an oral discussion instead, CLDs were created later on, with recordings of the interviews inserted in ATLAS.ti 8 for coding. We used deductive coding to identify the perceived causes and consequences associated with the main issue discussed (cf. Crabtree and Miller 1999), thus identifying CLD variables. Generated CLDs were then transferred into digital visualizations using the software Vensim (Ventana Systems Inc.). To obtain an overall impression of stakeholders' social representations of the lake SES, we merged the individual CLDs, starting with the most comprehensive individual CLD and adding in elements from other CLDs until every relevant element had been incorporated (Appendix 4, Fig. A4.1; see Inam et al. 2015 for the six steps of how to merge CLDs, select relevant variables, and deal with controversies). Thus, a merged CLD does not embody one coherent, aggregated social representation of a given system, for there is no such thing as a single consistent representation of a system. A merged CLD is a bricolage of CLDs collected by a researcher and comprises the elements that constitute the most comprehensive representation of the system and its core challenges.

All variables were identified as either social, ecological, or social-ecological to prepare for the following analytical step, and all causal links between variables within the merged CLD were weighted based on the number of stakeholders who mentioned them. It should be noted that a merged CLD is not meant to simply aggregate all variables nor illustrate a consensual social representation of a system. It rather uses convergent perceptions between different social representations as a backbone to build upon, while divergent perceptions can be illustrated in several ways, such as through several conditional causal links.

Action situations and their outcomes were derived from the merged CLD, and a configuration of AS was hence constructed to explain the emergent phenomenon of interest, lake ecological integrity. When examined through the SE-AS framework lens, variables or groups of variables within a CLD can represent:

- the emergent SES phenomenon (macro level);
- configurations of several AS or some single AS (meso level);
- outcomes, interactions between and among actors and ecosystem elements, or single actors or ecosystem elements (micro level).

To facilitate the conceptualization of the AS configuration from the merged CLD, we color-coded the merged CLD variables or groups of variables based on whether they represented social AS, ecological AS, social-ecological AS, the emergent phenomenon, external AS, or emergent outcomes. We used the preliminary classification of CLD variables to guide the identification of the different types of AS. Variables were considered to be part of an AS if we could identify actors taking part in the described variables, and emergent outcomes if the variables were rather an expression of an ongoing process without any identifiable actors or interactions relevant for the analysis (Appendix 4, Fig. A4.2). More detailed examples of this process are given in the discussion.

As with the Lake Dümmer case, we classified AS according to the categories from Schlüter et al. (2019) and Pahl-Wostl et al. (2020; Table 1; Appendix 1), while remaining open to new categories that might not have been identified in previous publications; thereby adopting a primarily deductive approach completed by an inductive one. The selection of relevant CLD variables for constructing AS was based on those most frequently mentioned during the interviews, as well as those with the greatest number of causal links.

To evaluate how the identified AS and outcomes interact, we considered only the strongest causal links between variables, as illustrated within the merged CLD. The strength of causal links needed to be evaluated comparatively to others for each variable, because not all variables shared the same number of mentions during the interview process. Thus, no causal loop strength "limit" was established for the entire merged CLD. Furthermore, in instances when two AS were linked without any identified emergent outcomes in between, causal links were considered as additional outcomes and described accordingly to better translate the merged CLD into a configuration of AS. Once all AS and outcomes were identified in the merged CLD, the AS configuration was redrawn as an SES representation based on the SE-AS framework.

Table 2. Description of the action situation (AS) configurations for Lake Dümmer.

Process	Description
1.	The building of the dike (external factor), finalized in 1953, converted the former wetlands surrounding Lake Dümmer into arable land. This ecological manipulation (N°1) means the lake's water level is regulated and kept at an artificial height: low in winters, high in summers. This measure enables sailing (Recreating 1).
2.	High water levels in summer further disturb reed growth; the accumulation of water leads to greater concentration of nutrients in the lake (indicated with an arrow toward Competition 1).
3.	Nutrients arise from agricultural activity in the catchment: farmers fertilize (Polluting) the soil to increase harvests; nutrients, mainly phosphorus (P), get washed into the hydrological cycle (indicated with an arrow) and are transported into the lake water (Transporting). In the lake, macrophytes (aquatic plants) and cyanobacteria (noxious algae) feed on the nutrients (Competition 1).
4.	Overproduction of algae leads to oxygen deprivation in the water, killing smaller fish (Competition 2); creates undesirable odors and is potentially toxic to the touch and inhalation, thus hampering visitors who come to the lake to bike, fish, or swim (Recreating 2).
5.	Overproduction of macrophytes impedes sailing, but does provide spawning sites and habitat for fish (Competition 2).
6.	Heat waves (external factor) concentrate nutrients (P) in the lake by evaporation, favoring algae and macrophyte growth; high temperatures also favor growth. Owing to the dike, this overproduction of biomass remains in the lake causing continuous sediment accumulation (Non-Transporting) of the lake upon decomposition.
7.	Social action tackles these consequences of Polluting and artificial water regulation (Ecological manipulation 1) as indicated by the red AS. The Lower Saxonian Ministry of the Environment had commissioned the State Office for Water Management, Coastal Defence and Nature Conservation to prepare a concept designed for the remediation of the lake (ML and MU 2012; Rule making). The remediation plan contains 16 actions geared to diminish P loads in the Hunte R. and the lake.
8.	One main action is the implementation of voluntary measures in agriculture that reduces the use of nutrients and their runoff from fields (Application of measures). Another is the renaturalization of the Hunte R. to also reduce nutrient inputs (Converting and Planning). This measure aims to reverse the channeling of the lake's tributaries in the past (external factor).
9.	The implementation of the remediation plan is overlooked and advised by a council (Deliberating) comprised of representatives from various sectors, which meets three times a year and communicates the necessity of measures. As a result, emergency plans for immediate measures (Coordination) have been established.
10.	Based on those, different ecological manipulations (N°2-4) are carried out: fishing big fish out of the lake; adding oxygen to the lake in times of acute cyanobacterial blooms; installing barriers and diving barricades to keep algae from reaching beaches and; mowing of macrophytes to enable sailing. Annual sediment removal is another continuous measure of remediation (ML and MU 2012; Ecological Manipulation N°5).
11.	The Dümmer forum communicates information regarding the biological status of the lake and the process of the lake remediation plan to the public, inviting interested citizens and stakeholders to public hearings twice a year (Information sharing) (ML and MU 2012, LGLN 2019).

ACTION SITUATION CONFIGURATIONS BASED ON THE SE-AS FRAMEWORK

The two case studies revealed different anthropogenic actions, social-ecological interactions, and ecological processes affecting lake ecological integrity. Furthermore, we identified distinctive feedbacks within the SES, in which actors were involved in regulating and managing emerging dynamics and phenomena. It should be noted that, contrary to the phenomena illustrated in Schlüter et al. (2019), we illustrate a phenomenon (lake ecological integrity) that is more representative of the overall system state compared to a more measurable phenomenon such as eutrophication. The reason for this choice is that we included both AS responsible for eutrophication or for perturbing natural ecosystems, as well as measures taken to counter such negative effects. Therefore, our emergent phenomenon can express either the maintenance or the deterioration of the lake's ecological integrity.

Dynamics and feedbacks within the Lake Dümmer SES

The ecological integrity of Lake Dümmer is challenged by an oversaturation in phosphorus, which alters internal lake dynamics and affects the ecosystem services provided regarding recreation and repercussions on the system (Fig. 6; Table 2).

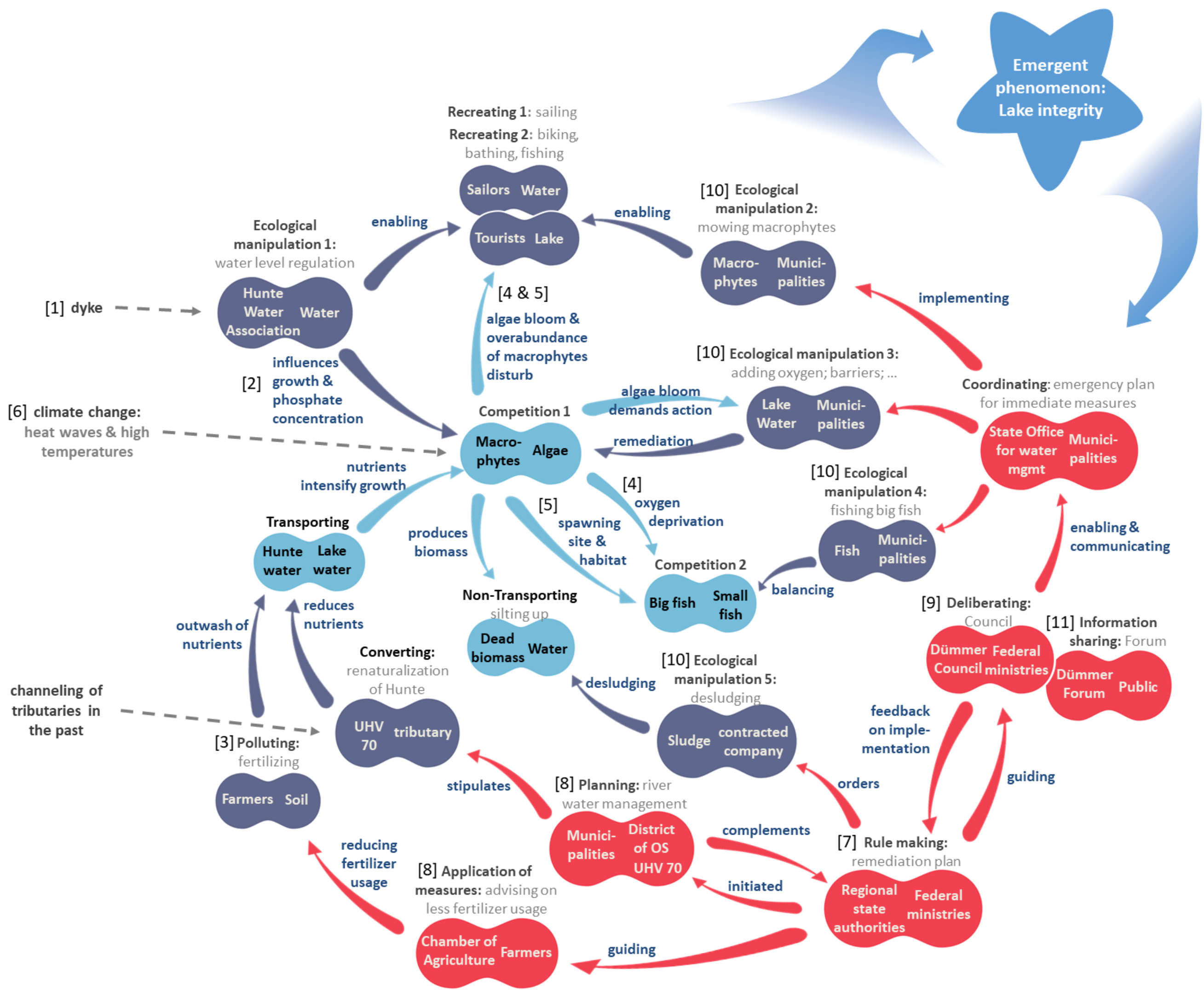
Overall, the AS configuration shows us that the eutrophication process of the lake, stemming mainly from agricultural activity nutrient input, comes with a range of negative consequences for the SES. Those are intensified by the artificial regulation of water levels. Both the source and the symptoms are counteracted by a range of measures. These measures are the result of a rule-making process and are continuously supported by ongoing coordination, planning, and deliberation of the actors involved in the lake's management.

Dynamics and feedbacks within Lake St. Charles SES

The ecological integrity of Lake St. Charles has long been of concern for interested parties, but it only truly became an urgent matter in 2006 when significant cyanobacteria blooms began to appear in the lake (APEL 2009). However, because the governance system surrounding Lake St. Charles was in a transition phase at the time of the interviews, participants expressed social representations of both the past and the future envisioned state of the system (see Appendix 4, Fig. A4.2). For the sake of the present study, the AS configuration solely includes a recent past and present depiction of the system (Fig. 7; Table 3), thus excluding measures that were proposed by stakeholders as potential solutions yet to be implemented to solve issues related to the state of the lake, or so-called "vision measures" (see Appendix 4, Fig. A4.2).

To summarize, the cycle of inadequate governance, followed by social conflicts and even more residential development, which lead to increased pressure on the lake and its resources, appears to be central to the deterioration of the lake ecological integrity. However, as seen in Figure 7, governance could also be a catalyst for ensuring the maintenance of this ecological integrity, notably through more coordination among stakeholders, which would help in taking different measures to decrease the effects of human actions on the lake.

Fig. 6. Action situation (AS) configuration of the social-ecological system (SES) of Lake Dümmer, with purely social AS in red, social-ecological AS in dark blue, and purely ecological AS in pale blue. Single events on the left side connected to AS through dashed arrows are external factors that were either established in the past or are recurrent events.



DISCUSSION

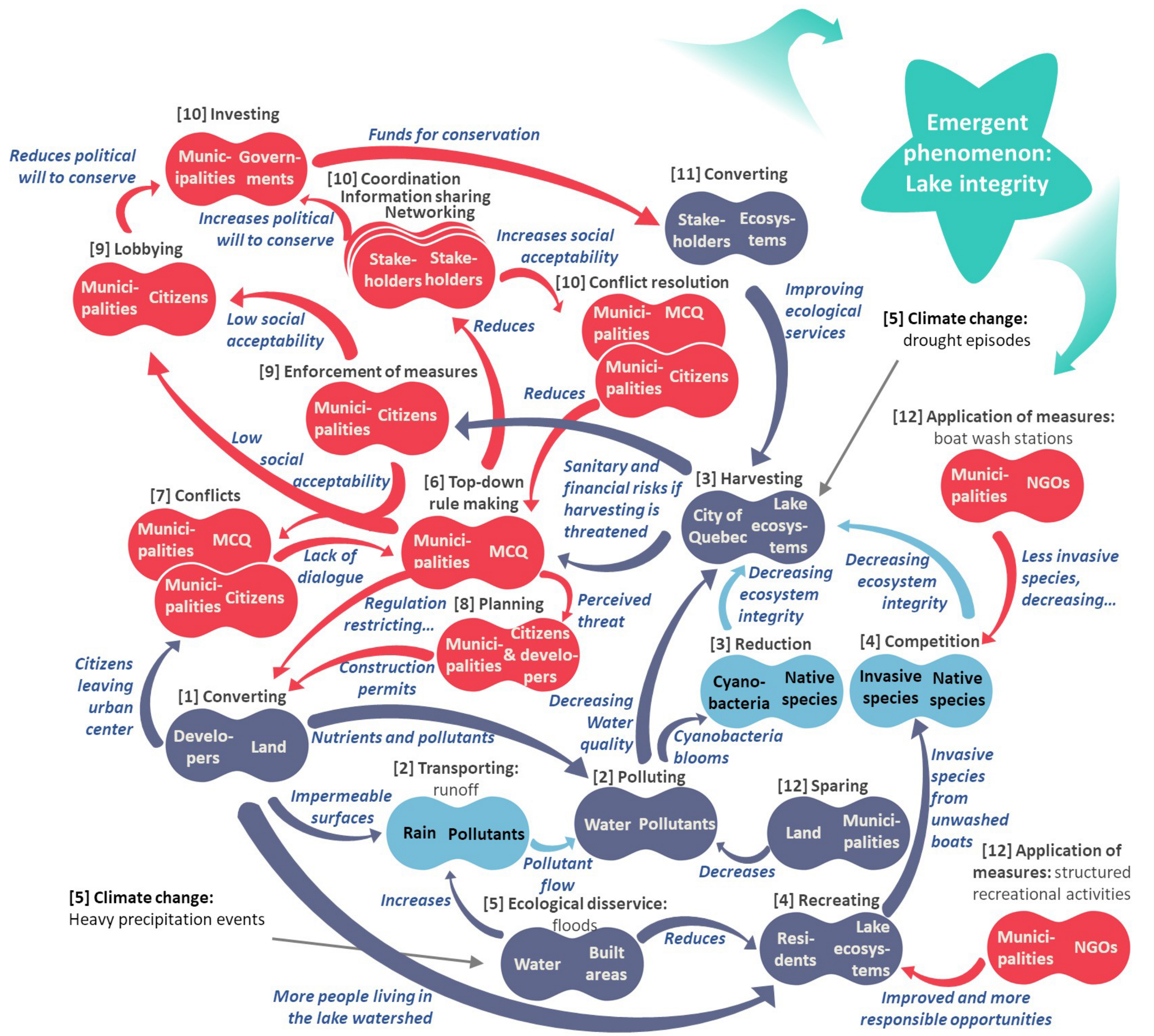
To discuss the practicability and relevance of the two analytical methods used to develop AS configurations based on the SE-AS framework, we start with an exploration of the comparability of the AS configurations identified for our two case studies. We then dive into the challenges of using qualitative data to construct such configurations and highlight the added value and limitations of the SE-AS framework for studying SES, as encountered in our two case studies.

Comparability of the two case studies

Developing AS configurations through the interview content analysis and the CLD analysis allowed us to identify key AS responsible for generating the emergent phenomenon under scrutiny, lake ecological integrity. Interviews were structured similarly for both case studies, and close collaboration between the teams helped to ensure that any differences in content between the two AS configurations successfully reflect real variation in the interview data rather than any differences in the methods used for developing the configurations. Such an observation is fundamental to highlight the practicability of the SE-AS framework because it underlines the fact that, despite being used in different contexts and with different analytical methods, it still allows for comparisons to be made between two different cases.

Although there are similarities between the two studied SES regarding ecosystem services (e.g., recreational activities), the handling of water levels, and the symptoms of water quality

Fig. 7. Action situation (AS) configuration of the social-ecological system (SES) of Lake St. Charles, with purely social AS in red, social-ecological AS in dark blue, and purely ecological AS in pale blue. Single events connected to AS through dashed arrows are external factors affecting the system.



degradation (presence of cyanobacteria), the AS responsible for the emergent phenomena are different. The main activity responsible for water quality degradation in Lake Dümmer is agriculture, as observed in the AS Polluting (Fig. 6), reflecting the interaction between farmers and the land. In the Lake St. Charles watershed, residential development, including associated road networks and wastewater, is responsible for deteriorating the water quality, as seen in the AS Converting (Fig. 7). Measures taken to counter the decrease in water quality are also quite dissimilar, with a remediation plan, 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 as measures that should be taken in the future.

The AS configurations also point out which of the three parts of the SES, i.e., social, ecological, or social-ecological, is most prominent in generating the emergent phenomenon. In the

Table 3. Description of the action situation (AS) configurations for Lake St. Charles.

Process	Description
1.	Although many causes degrading lake integrity were discussed by interview participants, the most prominent explanations provided involve the effects of high-impact development and land use, road network development, outdated septic tanks, and wastewater overflow from upstream treatment plants (Converting).
2.	Important nutrient release and greater runoff (Transporting) as a result of increased impermeable surface area led to more pollutants in the lake (Polluting).
3.	This in turn promotes cyanobacteria blooms that hampers lake biodiversity (Reduction) and reduces drinking water quality (Harvesting).
4.	Greater residential development increases the number of residents in the area who use the lake ecosystem for recreating. When using unwashed boats, visitors can introduce invasive species, increasing competition with local species and decreasing ecological services, hampering lake ecological integrity and water quality.
5.	Climate change also comes into play, since drought periods, more frequent episodes of intense precipitation and associated ecological disservice (Ecological disservice) such as floods, as well as generally higher temperatures are predicted to contribute to reducing lake integrity and water quality (Moss 2012, Jeppesen et al. 2014).
6.	In the past, when confronted with this degrading water quality, the Metropolitan Community of Quebec (MCQ), a body encompassing representatives from all municipalities in the Quebec City area, decided to impose severe constraints on development and urban planning in lake-associated municipalities through a series of interim control by-laws (ICBL; top-down rule-making). This eventually led, in 2016, to a prohibition of all residential development activities within 500 m 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.
7.	These ICBLs, and especially the 2016 one, were negatively received by municipalities within the upper St. Charles River watershed, eventually leading to conflicts (Conflicts) and legal proceedings that were won by the pursuant municipalities.
8.	Furthermore, when the 2016 ICBL was announced, there was a historical peak in construction permit requests (Planning) in one of the surrounding municipalities from developers and citizens alike who wanted to avoid the incoming restrictions, resulting in even more intensive residential development in the watershed.
9.	Water quality degradation also led to some restrictions over landowners' perceived rights (Enforcement of measures), leading to low social acceptability of those measures and to more conflicts, as well as to citizens lobbying (Lobbying) for their own self-interest, diminishing in turn decision-makers' desire for investing in conservation measures.
10.	Those restrictions, combined with top-down rule making, also hampered possibilities for more coordinated actions (Coordination) and sharing (Information sharing) among stakeholders, which could help find common goals and solutions (Conflict resolution), reduce the need for top-down rule making, and stimulate political will for investing (Investing) in conservation.
11.	That said, the social context has been improving steadily since 2019, and the City of Quebec started to invest more in conservation. So far, such investments have notably led to the acquisition of private lands along the lake shoreline for conservation purposes (Converting), thus favoring ecological services and lake water quality.
12.	Other measures that have been taken by stakeholders to diminish the effects of anthropic activities on the lake ecosystem include: the installation of boat wash stations and a better control over and structuring of recreation activities (Application of measures), although more efforts are still needed; reduced road salt use in winter months; the use of sediment retention infrastructure; and acquisition of contaminated sites (Sparing) either for decontamination or at the very least to reduce contamination risks through better management.

Dümmer case, ecological AS are limited to four while there are nine social-ecological AS and six social AS. In the St. Charles case, there are 3 ecological AS, 8 social-ecological AS, and 14 social AS. This reflects that, in terms of proportions, stakeholders from the Dümmer case focused more strongly on social-ecological AS, which they consider to be mostly responsible for influencing water quality, whereas in the St. Charles case, stakeholders attributed responsibility mostly to social AS, as a result of governance failure and of other potential social AS that were hampered by such failure.

Methodological challenges and comparison

The methods we used do have challenges.

The interview content analysis

When coding the AS from the interviews, several new questions arose. The first one was related to the level of detail to apply. For instance, while we initially decided to code implicit AS mentioned in the participant discourses, we eventually realized that they were not relevant for explaining the emergent phenomenon. In the course of the coding process, we also recognized the need for two new AS categories. The first was (Non) transporting, an ecological AS for which there was no equivalent in the list of AS extracted from the literature, to describe the movement of an ecosystem element transporting another element or substance within the system space. Secondly, Ecological manipulation was created to account for regular perturbations with potential effects for food web dynamics, e.g., by inhibiting pest species or supporting desired ones. This AS category was distinguished from the AS category Converting, which considers ecosystem change through technology or by restoring or converting use to protect ecosystems. Our novel category accounts for the more dynamic nature of ecological manipulation. Finally, we also realized that some interactions could be assigned to several AS categories because some of them represent broader categories. For example, interactions that describe an ecological manipulation or a conversion were often additionally coded as an application of measures. However, the former categories (either Ecological manipulation or Conversion) were favored in the AS configuration because they described those interactions more precisely. For instance, in Figure 6, Ecological manipulation 2 (mowing macrophytes) is, in fact, a measure applied by stakeholders. But stating that this is an application of measures would be less precise and less informative than stating that it is an ecological manipulation.

The CLD analysis

We found that producing a configuration of AS based on a CLD was a relatively fast process. We also found that, once the merged CLD based on interview data was completed, it could be reused relatively efficiently to develop AS configurations based on different emergent phenomena under scrutiny. Still, because we had to construct CLDs before identifying the AS configuration, we were faced with all known limitations associated with creating and merging CLDs. However, these limitations have been extensively covered in the literature (e.g., Haraldsson 2000, Schaffernicht 2010, Inam et al. 2015, Bureš 2017), and we could rely on this accumulated knowledge to ensure proper use and merging of CLDs.

Apart from elaborating CLDs, the main challenge to developing an AS configuration based on CLDs was the dissimilarity in structure. Converting a series of diverse variables and causal links into interactions between actors or elements and the emergent outcomes was not a straightforward process and was somewhat subjective. However, using a primarily deductive approach helped reduce subjectivity because AS categories described in the literature could be found relatively easily in the merged CLD by isolating relevant variables or grouping them with their causal links when necessary. Only when important variables failed to fall into previously described AS categories did we use an inductive approach to describe a new type of AS.

Another challenge came from translating the CLD variables and links, which were mostly devoid of actors, into AS involving mainly actors and their interactions. This required an additional level of interpretation in which we had to bring appropriate actors back into the relevant AS by referring to the interview data when necessary. For instance, the CLD variables "residential development" and "road network" were combined to express the AS "Converting" in which developers were brought back as actors who interact with the land, the ecosystem element. One of the outcomes of this AS, represented by the CLD variables "outmigration from the city center" and "attractiveness of the living environment" were combined as a single emergent outcome from AS "Converting." That is because, even though migration does imply some actors, no relevant interactions existed within these latter variables that would have helped analyze the lake ecological integrity. Rather, the other AS that influenced outmigration, which are social conflicts and recreation, were more relevant for understanding the dynamics affecting the phenomenon of interest. They were thus described as AS, whereas migration remained an outcome, described as "citizens leaving urban center."

Comparing the two analytical methods

Although no analytical method was preferred over the other because both methods were used for analyzing a given case study, comparisons can be drawn from our study. The most obvious advantage of the interview content analysis over the CLD analysis is that it allows for translation of the interview data directly into AS configurations. It is thus less subject to information loss that may happen when transferring raw information (such as interview data) into a model (such as the SE-AS framework). In the interview content analysis, this process of translation is done only once, whereas it needs to be done twice for the CLD analysis, i.e., from the interview data to the merged CLD, and from the merged CLD to the AS configuration. This second analytical method might thus be more prone to information loss during the analysis.

The CLD analysis also has benefits compared to the interview content analysis. First, we found the CLD concept to be easier to explain to participants in an interview context than the SE-AS framework. Thus, we could structure the interview a priori in a way to make the interview data easy to integrate into CLDs. Second, it was easier to define links between AS when those AS were based on CLD variables because the latter were already structured in causal relationships. This is especially true when compared to the interview content analysis for which establishing links between AS, solely based on the interviewees' responses, added another level of complexity during the analysis.

Despite these comparative strengths and weaknesses in our two analytical methods, what our two-pronged methodology demonstrates is that the SE-AS framework can be used successfully with different analytical approaches to link empirical data with the stylized models proposed by the SE-AS framework. According to our experience, we found no real "superior" analytical method to identify AS and create AS configurations. The need and familiarity of researchers with specific methods might thus be the most important element to consider for identifying AS. Indeed, despite the high level of complexity revealed by our case study analyses, they were made comparable through the use of AS configurations, as described in the SE-AS framework.

Methodological limitations

A first limitation comes from the fact that variables mentioned as important during the interviews were likely more representative of the better-known variables rather than those with greatest influence on the systems. Although these variables could be the same, we cannot assume this. To work around this, we engaged with diverse involved stakeholders to ensure that different types of knowledge were included in our system representations, and we also remained transparent that our AS configurations reflect the stakeholders' social representations of the SES and are thus not meant to be comprehensive nor consensual. Other limitations relate to data gathering methods and the nature of AS.

Data gathering

The fact that interviews were structured around the generation of a CLD could have limited, to some extent, the data obtained. Participants were asked about human-freshwater interactions they observed, but they were mainly asked to think in causal links rather than in terms of interactions between elements and actors of the SES. Hence, subtleties of any given interactions might have been lost. However, having stakeholders think through causal links helped identify a diverse array of system variables, producing a complete picture of their social representation of the system's main issue. Also, based on our experience, we estimated that CLDs would be more accessible to participants, being easily explained and generated within the time allowed by the interview process. In comparison, it would have been difficult to structure interviews around the concept of AS and their outcomes, while not knowing beforehand what phenomenon we were looking for and which interactions were responsible for its manifestation.

The nature of action situations

We mentioned at the beginning of the discussion how social and social-ecological AS were perceived as more important by interviewees for generating the emergent phenomenon in our case studies. Still, it should be highlighted that regime shifts in our case studies are produced by ecological AS and their outcomes, hence by ecological non-linearities, which can trigger a change in the ecological integrity of the lakes under study. The SE-AS framework is an attempt to bring the social-ecological into focus because these interdependencies are of great importance (see Lade et al. 2013, 2015, Martin et al. 2020). However, what is considered most relevant in an AS configuration of an SES depends on both the purpose of the analysis and, in our case, on the point of view of interviewees. If the purpose is to find ways to manage or govern an environmental problem, interactions that can be manipulated or influenced will be of more importance than those that are out of human's control (e.g., the phosphorous in the sediments). Similarly, because most of the stakeholders involved in our study are interested in the management of the lake and are less knowledgeable of its ecological aspects, it probably influenced their stronger focus on social elements of the systems.

General strengths and limitations regarding the use of the SE-AS framework for studying SES

As stated by Schlüter et al. (2019), AS configurations of an emergent phenomenon open space for discussing the mechanisms underlying the phenomenon, challenging common sense knowledge about alleged causes, generating insights about formerly unknown factors influencing the SES, or juxtaposing different AS conceptualizations of a phenomenon. The framework advises to "(...) clarify different understandings as a basis for further exploration and learning."

Strengths

First, in our cases, the SE-AS framework was useful for illustrating the main dynamics underlying an emergent phenomenon in a simple yet comprehensive manner. As mentioned, although we used different analytical methods to develop AS configurations from our two case studies, we concluded that the two AS configurations permitted comparisons of the cases. The SE-AS framework also helped in pointing out which of the three AS archetypes, i.e., social, ecological, or social-ecological, were perceived as the most important in each case to generating the emergent phenomenon, lake ecological integrity.

Second, the SE-AS framework provided an essential tool to make sense of the information provided by Lake St. Charles' merged CLD. Indeed, the SE-AS framework allows disentangling variables for which causal relationships are undefined or non-linear, by treating and interpreting such situations as single ASs. The framework is thus especially useful to help deal with highly complex and dense CLDs, which can result from merging many different CLDs. An especially eloquent example of the SE-AS framework added value for analysis and communication can be observed by comparing the AS configuration for the St. Charles case (Fig. 7) to the equivalent system CLD (Appendix 4, Fig. A4.1). Although the former can be understood fairly rapidly, including necessary measures to counter the deterioration of the lake ecological integrity and involved actors, the latter is much harder to grasp. Similar analytical interpretations about the system dynamics might be derived from both CLD and SE-AS system representations but it is much harder to derive insights from CLDs when they are overly complex.

Third, one of the main arguments we see for using the SE-AS framework is its potential for interdisciplinary and cross-sector communication. It provides a tool allowing the combination of ecological and social elements into a coherent whole while focusing on the interactions between those elements instead of treating them as isolated entities. Its basic unit of analysis, the action situation, helps communicate the role of stakeholders and ecosystem elements in generating the phenomenon under scrutiny. The framework thus highlights areas in the SES in which future actions need to be taken, thereby informing decision-making processes. The added value for policy communication is that using the SE-AS framework enables rapid understanding of an SES state and dynamics and the location of the collective actors in the system responsible for them. Action situation configurations may facilitate sustainable resource governance by indicating whose actions need to be altered and where in the system measures should be implemented. The SE-AS framework is thus also superior to CLDs in this regard because it helps position actors and highlight their roles in the management of SESs, hence it communicates a clear message for decision makers.

Fourth, the SE-AS may help to explain governance failure within a system. Because the AS configurations of our case studies are the result of analyzing SESs' social representations of interview participants, these configurations reflect a subjective understanding of the system rather than an objective one. Thus, the SE-AS framework is a suitable tool to show how social representations of the lake and scientifically described social-ecological processes converge or differ. These differences may reveal to resource managers and resource management scholars how their view of common SES compares to different perspectives with differing emphases. Such divergence may lead to suboptimal decisions and may eventually explain pitfalls of lake governance and decision making in the face of social-ecological issues.

Limitations

Despite the strengths of the SE-AS framework, we did encounter limitations that should be acknowledged in future research. First, the SE-AS framework cannot, in itself, elucidate which AS are the most crucial for generating any given phenomenon, nor was it created for such a purpose. This must be well understood by researchers interested in using it. In our case, identifying relevant AS was accomplished as a result of data analysis, as well as through researchers' knowledge and understanding of the focal systems. However, our analytical methods presented their own challenges. For instance, in the Dümmer case, identifying AS based on the interviews led to a large number of observed AS, illustrating a diverse array of interactions between different actors and ecosystem elements within the SES. Defining the emergent phenomenon at stake and the AS relevant to explain it 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 analyses of the interview data.

Second, the distinction between AS and outcome is often unclear. The definition of outcome by Schlüter et al. (2019) remains rather vague: "Outcomes of one AS may affect rules, structures, or participants of another AS." In some of the outcomes we identified, their elements intermingled with elements of other action situations or could be interpreted as interactions themselves. To overcome this, we discussed the specific cases among researchers to decide whether we would interpret the observed action (or interaction) as an outcome of an AS or as a new interaction. One example is the AS Transporting in which river and lake water interact. We discussed whether the "outwash of nutrients", which is the outcome of AS Polluting, would be sufficient to describe the process of nutrients entering the lake water. It became problematic when we identified the AS Converting (re-naturalizing the tributary) which benefits the river water quality. In this case, we found that transporting of river water into lake water needed to be identified as an AS itself. The AS Converting affects the AS Transporting through the outcome “reduces nutrients”. This aspect may reflect that in an SES, the elements and their relations to each other are in a continuous state of change, implying that the interactions and their interrelations through outcomes are in an evolving process. From such a perspective, what one defines as an AS, or process of an interaction, and what one defines as an outcome then depends on the researcher’s perspective and might be relative to time, other AS, or even, as in the example below, a question of the resolution the researcher chooses to capture the AS and their interrelations.

Third, regarding the assignment of the AS categories to the identified interactions, we observed that some interactions could be interpreted through several AS categories. The Dümmer council, for instance, represents a deliberating as well as a networking interaction of actors. The researcher needs to decide which of the interpretations better express the AS contributing to the emergent phenomenon, or whether both should be included as two separate yet interlinked AS. The same accounted for the social AS categories Information sharing and Deliberating, which were often coded together, and the ecological AS Facilitation and Species-habitat interaction. A thorough discussion of the specific interactions in question is needed to assign them to their AS category.

Fourth, interactions in an SES may happen at different organizational levels (local, regional, national). The framework, however, does not easily allow to distinguish the levels at which AS occur in its SES representation. Schlüter et al. (2019) suggested how to reflect on the local and the global level in their representation of the potential triggers of a global outbreak of H5N1 avian influenza. However, that representation is less detailed than what we present. Other AS configurations may comprise more levels and more AS. Researchers focusing specifically on different levels may want to consider this point and find a workaround for using the framework.

Fifth, we found that, as is the case with CLDs, the time component was hard to express within the SE-AS framework, even more so than in CLDs. The framework simply does not cover time spans. If one studies an SES in which AS occurred at different points in time but are still affecting each other, it is difficult to illustrate this time difference in the representation. For instance, in the St. Charles case, interview participants had described both past and future variables in their representation of the system. Hence, different time periods were expressed in the merged CLD, and we found no convincing way to translate this idea into the AS configuration. Therefore, we chose not to include so-called “vision measures”: variables representing potential measures proposed by participants as ways to improve the overall lake SES. Components that happened in the past in the Dümmer case study were indicated as external factors (see Fig. 6). One possible workaround for such a limit could be to have different AS configurations for different time spans.

Finally, the SE-AS does not propose a set of prescribed AS meant to be comprehensive in explaining emergent phenomena. It is, on the contrary, open to new AS categories that may be relevant for any given research needs. This might be seen as a weakness because it reduces the analytical capabilities of the framework, but it gives it more flexibility, which can also be seen as a strength. Either way, it needs to be understood by researchers, so they can take full advantage of the SE-AS framework and use it accordingly. For instance, in our case, we observed the lack of a social AS that explicitly described the establishment of trust, social coherence, and mutual understanding; aspects important in resource management, which do not necessarily manifest in an AS. However, they are relevant to understanding social dynamics. In the St. Charles case, the trust variable, as well as lack of trust, were considered to be part of the AS Conflict resolution and Conflicts, respectively; social coherence was included in the AS Networking. For future research, we encourage SES scholars to explore possibilities for including AS that describe the state of mind of actors within interactions, regardless of whether those be conflictive or consensual.

CONCLUSION

We compared two analytical methods to use interview data and develop AS configurations based on the SE-AS framework developed by Schlüter et al. (2019), examining two case studies centered on lake SES in Germany and Canada. We illustrated how different SES dynamics could be observed within simple representations of the case studies’ SES. Using the SE-AS framework to do so revealed several benefits. The framework helps disentangle variables for which causal relationships are ill-defined or non-linear, thereby creating clarity in the analysis of complex systems. It serves interdisciplinary research of the social-ecologically intertwined nature of SES through the possibility of combining ecological and social knowledge and variables. Moreover, it could potentially provide a communication tool outside academia that illustrates the role of stakeholders and ecosystem elements in an SES, while stimulating discussions on the underlying mechanisms of SES.

In terms of analytical limitations, we found that different organizational levels of AS (local, regional, national) are difficult to represent and that the time factor cannot be illustrated easily in a single diagram. Further aspects to consider when using the SE-AS framework are that the definition of “outcome” remains vague and that identifying outcomes properly in the SES can be challenging. Also, several AS categories may describe a single interaction in the studied SES. It is up to the researcher to decide which category is more significant to include in the AS configuration. Finally, future studies may need to include social AS that reflect actors’ trust, social coherence, and mutual understanding to better illustrate social dynamics, all of which, it should be noted, are aspects included in Ostrom’s questions and variables used throughout her studies. Adding some of these variables to the SE-AS methodology would enrich the analytical capturing of interpersonal relations.

The need for research that goes beyond coupling social and ecological data, by putting social-ecological interactions at the center of data gathering and data analysis, is increasing rapidly as climate change and its resulting uncertainties and imbalances manifest in a plethora of SES around the globe. Future research could study how AS configurations can inform computational models to design simulations of the systems under study, as suggested by Schlüter et al. (2019). Translating the identified interactions and their respective outcomes into quantifiable measurements would be indispensable as a next research step. The methodology introduced here can help comprehend complex systems and organize knowledge of diverse stakeholders of the system 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 developing greater resilience in any SES system, such as freshwater bodies, facing increasing climatic disturbances and uncertainties.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13268

Author Contributions:

LH drafted data collection methods under the supervision of CPW. LH and LT refined the data collection methods and collected and analyzed the data. LH and LT also drafted and wrote the manuscript with inputs from all authors. BB, CPW, and MS coordinated the overall direction of the research project under which this study was undertaken.

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Data Availability:

The data/code that support the findings of this study are available on request from the lead authors. None of the data/code are publicly available because they contain information that could compromise the privacy of research participants. Ethical approval for this research study was granted by the university of the second lead author.

LITERATURE CITED

Anderies, J. M., M. A. Janssen, and E. Schlager. 2016. Institutions and the performance of coupled infrastructure systems. International Journal of the Commons 10(2):495-516. https://doi.org/10.18352/ijc.651

Bernstein, M., M. del M. Mancha-Cisneros, M. Tyson, U. Brady, C. Rubiños, H. C. Shin, S. Vallury, S. Smith-Heisters, and E. Ratajczyk. 2019. Mapping Ostrom's common-pool resource systems coding handbook to the coupled infrastructure systems framework to enable comparative research. International Journal of the Commons 13(1):528–552. http://doi.org/10.18352/ijc.904

Binder, C. R., J. Hinkel, P. W. G. Bots, and C. Pahl-Wostl. 2013. Comparison of frameworks for analyzing social-ecological systems. Ecology and Society 18(4):26. https://doi.org/10.5751/ES-05551-180426

Bureš, V. 2017. A method for simplification of complex group causal loop diagrams based on endogenisation, encapsulation and order-oriented reduction. Systems 5(3):46. https://doi.org/10.3390/systems5030046

Council of the European Union. 1992. Richtlinie 92/43/EWG Des Rates Vom 21. Mai 1992 Zur Erhaltung Der Natürlichen Lebensräume Sowie Der Wildlebenden Tiere Und Pflanzen. Council of the EU, Brussels, Belgium. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1992L0043:20070101:DE:PDF

Crabtree, B. F., and W. M. Miller, editors. 1999. Doing qualitative research. Second edition. Sage, Thousand Oaks, California, USA.

Diercke Weltatlas. 2021. Diercke Weltatlas - Kartenansicht - Physische Übersicht. Westerman Group, Brunswick, Germany. https://diercke.westermann.de/content/physische-%C3%BCbersicht-978-3-14-100754-1-3-1-0

Folke, C., S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström. 2010. Resilience thinking: integrating resilience, adaptability and transformability. Ecology and Society 15(4):20. https://doi.org/10.5751/ES-03610-150420

Forrester, J. W. 1961. Industrial dynamics. MIT Press, Cambridge, Massachusetts, USA.

Halbe, J., and J. Adamowski. 2019. Modeling sustainability visions: a case study of multi-scale food systems in Southwestern Ontario. Journal of Environmental Management 231:1028-1047. https://doi.org/10.1016/j.jenvman.2018.09.099

Haraldsson, H. V. 2000. Introduction to systems and causal loop diagrams. LUMES, Lund University, Lund, Sweden.

Haraldsson, H. V. 2004. Introduction to system thinking and causal loop diagrams. LUMES, Lund University, Lund, Sweden. http://cmap.crs.org.pl:4444/rid=1244140954250_1167059429_1461/Introduction%20to%20Systems%20and%20Causal%20Loop%20Diagrams.pdf

Hochschule Osnabrück. 2013. Der Dümmer und sein Einzugsgebiet in Nordwestdeutschland - eine ökologische Perspektive. Hochschule Osnabrück, Fakultät Agrarwissenschaften & Landschaftsarchitektur, Osnabrück, Germany. https://docplayer.org/75236855-Der-duemmer-und-sein-einzugsgebiet-in-nordwestdeutschland-eine-oekologische-problemregion.html

Inam, A., J. Adamowski, J. Halbe, and S. Prasher. 2015. Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: a case study in the Rechna Doab watershed, Pakistan. Journal of Environmental Management 152:251-267. https://doi.org/10.1016/j.jenvman.2015.01.052

Jeppesen, E., M. Meerhoff, T. A. Davidson, D. Trolle, M. Søndergaard, T. L. Lauridsen, M. Beklioglu, S. Brucet, P. Volta,

I. González-Bergonzoni, and A. Nielsen. 2014. Climate change impacts on lakes: an integrated ecological perspective based on a multi-faceted approach, with special focus on shallow lakes. Journal of Limnology 73(S1). https://doi.org/10.4081/jlimnol.2014.844

Lade, S. J., S. Niiranen, J. Hentati-Sundberg, T. Blenckner, W. J. Boonstra, K. Orach, M. F. Quaas, H. Österblom, and M. Schlüter. 2015. An empirical model of the Baltic Sea reveals the importance of social dynamics for ecological regime shifts. Proceedings of the National Academy of Sciences 112(35):11120-11125. https://doi.org/10.1073/pnas.1504954112

Lade, S. J., A. Tavoni, S. A. Levin, and M. Schlüter. 2013. Regime shifts in a social-ecological system. Theoretical Ecology 6 (3):359-372. https://doi.org/10.1007/s12080-013-0187-3

Landesamt für Geoinformation und Landesvermessung Niedersachsen (LGLN). 2019. Dümmerforum 2019 II Auf Dem Schäferhof. LGLN, Hanover, Germany. https://www.arl-lw.niedersachsen.de/duemmerforum/dummerforum-2019-ii-auf-dem-schaferhof-203569.html

Landkreis Diepholz. 2018. Verordnung Über Das Landschaftsschutzgebiet "Dümmer" in Der Samtgemeinde "Altes Amt Lemförde." Landkreis Diepholz, Germany. https://www.diepholz.de/downloads/datei/OTAwMDA3ODYyOy07L3d3dy92aHRkb2NzL2Ntcy9sa2RoL21lZGllbi9kb2t1bWVudGUvbHNnX2RoXzE0X2R1ZW1tZXJfbmV1LnBkZg%3D%3D

Landkreis Diepholz. 2020. FFH-Gebiet Nr. 065 Dümmer: Kurzfassung Des Meldebogens Des FFH-Gebietes Sowie Verfahrensstände. Landkreis Diepholz, Germany. https://natura2000.diepholz.de/schutzgebiete/steckbriefe-aller-ffh-gebiete/duemmer/

L'Association pour la protection de l'environnement (APEL). 2009. Étude limnologique du haut-bassin de la rivière Saint-Charles, rapport final. Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord, Quebec City, Canada. https://agiro.org/wp-content/uploads/etude_limnologique.pdf

L'Association pour la protection de l'environnement (APEL). 2017. Faire autrement pour une protection des milieux naturels et des ressources en eau: recommandations règlementaires et non règlementaires visant à améliorer la gestion des milieux naturels et des ressources en eau à l'intérieur du bassin versant de la prise d'eau de la rivière Saint-Charles. Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord, Quebec City, Canada. https://agiro.org/wp-content/uploads/Developper_protection_milieux_naturels_eau_APEL-201702.pdf

L'Association pour la protection de l'environnement (APEL). 2019. Diagnose du lac Saint-Charles 2016. Association pour la protection de l'environnement du lac Saint-Charles et des Marais du Nord, Quebec City, Canada. https://agiro.org/wp-content/uploads/Diagnose-du-lac-Saint-Charles-2016.pdf

Leenhardt, P., L. Teneva, S. Kininmonth, E. Darling, S. Cooley, and J. Claudet. 2015. Challenges, insights and perspectives associated with using social-ecological science for marine conservation. Ocean and Coastal Management 115:49-60. https://doi.org/10.1016/j.ocecoaman.2015.04.018

Légaré, S. 1998. Étude limnologique du lac Saint-Charles 1996-1997. Université Laval, Quebec City, Quebec, Canada. https://agiro.org/publications/etude-limnologique-du-lac-saint-charles-1996-1997-stephane-legare-1998/

Leslie, H. M., X. Basurto, M. Nenadovic, L. Sievanen, K. C. Cavanaugh, J. J. Cota-Nieto, B. E. Erisman, E. Finkbeiner, G. Hinojosa-Arango, M. Moreno-Báez, S. Nagavarapu, S. M. W. Reddy, A. Sánchez-Rodríguez, K. Siegel, J. J. Ulibarria-Valenzuela, A. H. Weaver, and O. Aburto-Oropeza. 2015. Operationalizing the social-ecological systems framework to assess sustainability. Proceedings of the National Academy of Sciences 112(19):5979-5984. https://doi.org/10.1073/pnas.1414640112

Martin, R., M. Schlüter, and T. Blenckner. 2020. The importance of transient social dynamics for restoring ecosystems beyond ecological tipping points. Proceedings of the National Academy of Sciences 117(5):2717-2722. https://doi.org/10.1073/pnas.1817154117

McGinnis, M. D., and E. Ostrom. 2014. Social-ecological system framework: initial changes and continuing challenges. Ecology and Society 19(2):30. https://doi.org/10.5751/ES-06387-190230

Moss, B. 2012. Cogs in the endless machine: lakes, climate change and nutrient cycles: a review. Science of the Total Environment 434:130-142. https://doi.org/10.1016/j.scitotenv.2011.07.069

Niedersächsisches Ministerium für Ernährung, Landwirtschaft, Verbraucherschutz und Landesentwicklung (ML) and Niedersächsisches Ministerium für Umwelt, Energie und Klimaschutz (MU). 2012. Dümmersanierung: Rückblick und Ausblick. Niedersächsisches Ministerium für Ernährung, Landwirtschaft, Verbraucherschutz und Landesentwicklung and Niedersächsisches Ministerium für Umwelt, Energie und Klimaschutz, Hannover, Germany.

Organisme des bassins versants de la Capitale (OBVC). 2015. Bassin de la rivière Saint-Charles/Lacs - Organisme des bassins versants de la Capitale. OBVC, Quebec City, Quebec, Canada. http://www.obvcapitale.org/bassin-de-la-riviere-saint-charles-lacs#cplacstcharles

Ostrom, E. 1990. Governing the commons: the evolution of institutions for collective action. Cambridge University Press, Cambridge, UK.

Ostrom, E. 2005. Understanding institutional diversity. Princeton University Press, Princeton, New Jersey, USA.

Ostrom, E. 2007. A diagnostic approach for going beyond panaceas. Proceedings of the National Academy of Sciences 104 (39):15181-15187. https://doi.org/10.1073/pnas.0702288104

Ostrom, E. 2009. A general framework for analyzing sustainability of social-ecological systems. Science 325 (5939):419-422. https://doi.org/10.1126/science.1172133

Pahl-Wostl, C., C. Knieper, E. Lukat, F. Meergans, M. Schoderer, N. Schütze, D. Schweigatz, I. Dombrowsky, A. Lenschow, U. Stein, A. Thiel, J. Tröltzsch, and R. Vidaurre. 2020. Enhancing the capacity of water governance to deal with complex management challenges: a framework of analysis. Environmental Science and Policy 107:23-35. https://doi.org/10.1016/j.envsci.2020.02.011

Palys, T. 2008. Purposive sampling. Pages 697-698 in L. M. Given, editor. The Sage encyclopedia of qualitative research methods. SAGE, Thousand Oaks, California, USA. https://doi.org/10.4135/9781412963909.n349

Ratajczyk, E., U. Brady, J. A. Baggio, A. J. Barnett, I. Perez-Ibarra, N. Rollins, C. Rubiños, H. C. Shin, D. J. Yu, R. Aggarwal, J. M. Anderies, and M. A. Janssen. 2016. Challenges and opportunities in coding the commons: problems, procedures, and potential solutions in large-N comparative case studies. International Journal of the Commons 10(2):440. https://doi.org/10.18352/ijc.652

Richardson, G. P., and A. L. Pugh. 1981. Introduction to system dynamics modeling with dynamo. MIT Press, Cambridge, Massachusetts, USA.

Schaffernicht, M. 2010. Causal loop diagrams between structure and behaviour: a critical analysis of the relationship between polarity, behaviour and events. Systems Research and Behavioral Science 27(6):653-666. https://doi.org/10.1002/sres.1018

Schallenberg, M., M. D. de Winton, and D. J. Kelly. 2018. Indicators of ecological integrity. Pages 367-393 in D. P. Hamilton, K. J. Collier, J. M. Quinn, and C. Howard-Williams, editors. Lake restoration handbook: a New Zealand perspective. Springer International, Cham, Switzerland. https://doi.org/10.1007/978-3-319-93043-5_11

Schlüter, M., L. Haider, S. Lade, E. Lindkvist, R. Martin, K. Orach, N. Wijermans, and C. Folke. 2019. Capturing emergent phenomena in social-ecological systems: an analytical framework. Ecology and Society 24(3):11. https://doi.org/10.5751/ES-11012-240311

SESMAD. 2021. Social-ecological systems meta-analysis database. Dartmouth College, Hanover, New Hampshire, USA. https://sesmad.dartmouth.edu/

Thiel, A., M. E. Adamseged, and C. Baake. 2015. Evaluating an instrument for institutional crafting: how Ostrom's social-ecological systems framework is applied. Environmental Science and Policy Part B(53):152-164. https://doi.org/10.1016/j.envsci.2015.04.020

Vennix, J. A. M. 1996. Group model building: facilitating team learning using system dynamics. John Wiley and Sons Ltd., West Sussex, UK.

APPENDIX 1 – CODING PROTOCOL

1. The analysis' aim

Using the SE-AS framework to describe the emergent phenomenon of our two case studies, i.e. lake ecological integrity, we aim to illustrate:

- Social-ecological dynamics, whether they are induced by human actions or ecological elements in the lakes catchment areas;
- Social dynamics that can affect ecological elements, and inversely, ecological dynamics that can affect social actors;
- Repercussions of those dynamics on ecosystems and their services, as well as on social actors and on the whole social-ecological system.

2. Definition of key terms (from Schlüter et al., 2019)

a. Action Situation (AS)

i. "(…) we expanded on Ostrom's concept of an action situation (AS). In particular, we extended the action situation beyond a purely social interaction context (social action situation, S-AS), to two other types of contexts: one that captures interactions between humans and nonhumans entities such as fish in a lake, a field, or a particular landscape, which we call a social-ecological action situation (SE-AS); and one that captures relations or interactions between ecological or biophysical elements such as predation of one species on another or the impact of a crop on soil quality, which we call an ecological action situation (E-AS)." (Schlüter et al. 2019)

ii. "(…) an action situation refers to the social space where participants with diverse preferences interact, exchange goods and services, solve problems, dominate one another, or fight (among the many things that individuals do in action arenas)." (Ostrom 2005: 14)

b. Outcomes (from Schlüter et al. 2019)

i. "(…) can be material or nonmaterial, such as a fish catch or a harvest, a perception, new knowledge, or meaning created through sense of place."

ii. "(…) are the result of actions and interactions that are enabled and constrained by rules and diverse agency, interests and goals of participating actors"

iii. "Human actors may adjust their behavior based on those outcomes (...) while ecological entities may disappear or change their functioning."

c. Phenomenon (from Schlüter et al. 2019)

"We use the term social-ecological phenomenon to refer to an empirical observation one wants to understand and explain, such as the collapse of the Baltic cod stock or a poverty trap."

3. The analytical steps

a. Lake Dümmer case

Text analysis software: MaxQDA

Number of coders: 3

i. Coding the interactions of actors, of ecological elements and of social and ecological elements the stakeholders mentioned in the interviews:
   - Individual coding: each coder codes six interviews;
   - Regular discussions on the action situations identified, their outcomes and their links; if reasonable, merging of action situation categories (codes); discussing whether some coded text is merely an assessment and no interaction;
   - Inter-coder reliability: cross-coding of the interviews among the three and checking whether coding is coherent.

ii. Assessing the action situations:
   - What do the action situations and their linkages – the configuration of action situations – tell us? Do they inform reduction of ecosystem services? Do they inform about change in dynamics in the ecosystem? Do we see an overarching phenomenon?
   - Reducing the action situations to a core set of relevant action situations that reflect the emergent phenomenon.

iii. Linking the action situations to each other; identifying the outcomes.

iv. As a final step, we go through the coded text passages, code by code and AS group by AS group (Social-Ecological, Ecological, and Social) to see if any new relevant AS emerges that we do not yet have considered; and to see which of the AS already identified might be confirmed by further identification in other interviews.

b. Lake St. Charles case

CLD analysis software: Vensim

Number of coders: 1

i. Identify the merged CLD variables as either social, ecological or social-ecological.

ii. Regroup single variables or group of variables that together illustrate the emergent phenomenon, action situations or outcomes by:
   - Selecting relevant CLD variables based on those most frequently mentioned during the interviews, as well as those with the greatest number of causal links;
   - Considering variables as part of an AS if actors or ecosystem elements can be identified within, and as outcomes if the variables were an expression of an ongoing process;
   - Color-coding the variables or groups of variables based on whether they represent social AS, ecological AS, social-ecological AS, the emergent phenomenon, external AS, or emergent outcomes.

iii. Identifying links, hence outcomes, between AS, through CLD variables causal links by:

- Considering only the strongest causal links between variables;
- When two AS were linked without any identified emergent outcomes in between, consider causal links as additional outcomes and describe them accordingly.

iv. Redrawing the AS configuration as an SES representation based on the SE-AS framework.

4. Coding rules

i. We code both explicit and implicit action situations observed in stakeholders' discourse.
ii. We identify actors within the interactions while coding.
iii. If we find a direct effect from one action situation to another, we note the outcome while coding.
iv. We can put several codes on one interaction and later discuss which code best represents the interaction.
v. We weigh the action situations (regarding their importance – times mentioned, for instance) to understand which ones are the most critical according to stakeholders.
vi. Some categories build upon each other, meaning that they may occupy the same space in an action situation configuration. We must keep this in mind when coding and when analyzing the interactions.
vii. We must remain aware of the levels encountered when coding, as described in the SE-AS framework:
    - micro-level – the actors and the ecological elements;
    - meso-level – the action situations and their configurations;
    - macro-level – system level, emergent phenomenon.
viii. We also include AS describing hypothetical, future measures, adding either a "POT" (referring to "potential") or a different color with the code.

5. List of action situations used as codes

Categories of Actions Situations are either theory-driven, based on Schlüter et al. (2019) (†) and Pahl-Wostl et al. (2020) (‡), or data-driven (§), hence newly created ones for the purpose of this study. General examples are given for each category, plus examples from the Lake Dümmer case when the category was observed there, and the included CLD variables from the Lake St. Charles case when applicable.

Name	Description	Example	Example at Lake Dümmer	Included CLD variables from Lake St. Charles case
Social-Ecological Action Situations				
Converting †	Changing sea or landscapes through technology (e.g. building a dam) or by restoring or converting use to protect ecosystems (e.g. protected areas/reserves)	Changing the lake level through dam construction, changing the littoral zone (landing stages), construction on the shoreline (building/real estate), hydrological manipulation	• Dyke built in 1953: hinders the transportation of dead biomass out of the lake; changed water level; • Converting a creek in 2009 to reduce phosphorus load of lake	• Revegetalization of lake shores • Acquisition of natural areas for conservation purposes • Protection of natural areas and of the lake • High-impact development • Road networks
Cultivating / Harvesting †	Cultivating crops, harvesting natural resources such as fish, timber, grass, and livestock	Fishing, drinking water extraction		• Amount of water available - at water intake - per capita • Quality of water at water intake • Quality of water in wells • Need to find other source of water
Cultural activities †	Performing cultural or spiritual activities in nature	School excursions, wedding celebration, work retreats, identify with the lake		
Ecological disservice §	Disservice brought by natural systems to human populations	Floods, pests, natural disasters		• Floods • Flooding
Ecological manipulation §	Changing the food-web by regular interference, maybe also Changing natural dynamics, e.g. by inhibiting pest species or supporting desired ones	Biomanipulation (planting of macrophytes, trawling whitefish)	• Desludging the lake; • Restoring to nature of Hunte River; • water level regulation; • mowing macrophytes;	

Name	Description	Example	Example at Lake Dümmer	Included CLD variables from Lake St. Charles case
			• adding oxygen to lake water; • barriers against algae	
Ecological monitoring †	Observing or measuring ecological conditions	Studies, regular reporting, iconic species observation, measurement		
Polluting †	Introducing substances into ecosystems	Nutrients, plastics, inorganic compounds from agricultural, industrial, or water sewage treatment activities (private septic tanks, communal)	Farmers apply nutrients (phosphorus) on fields	• Overflow of wasterwater from treatment plants • Aging septic tanks • Overflow of wastewater from aging sepctic tanks • Erosion; road salt; contaminated runoff • Presence of contaminated sites
Recreating †	Spending time in nature, enjoying (physically, psychologically)	Swimming, boating, hiking, bird watching	• Water sports like sailing • Biking • Bathing • Fishing	• Recreational activities • Accessibility to the lake and natural ecosystems • Contaminated boats and material • Uncontrolled access
Sparing §	A specific social action (e.g. a measure) that wilfully cares for or ameliorates an ecological component's state	The application of less or ecological friendly fertilizer on soil in order to reduce the entry of nutrients into soil and water cycle		• Management of contamination risks • Optimal management of road network • White (salt less) roads • Sustainable management of rain water • Sediment retention infrastructure
Social Action Situations				
Application of measures ‡	Application of specific measures or programs. Outputs are not plans but more tangible products	Payment schemes, reduced pesticide application rates, a new filter technique, or a new governmental authority.	Advising farmers to implement voluntary measures to reduce fertilizer usage.	• Installation of boat wash stations • Structuring of recreational activities

Competing †	Aiming to do better than other actors, may involve interfering with their activities to reduce their performance; active demand by two or more actors or groups of actors for some environmental resource/s (Merriam Webster Dictionnary)	Advertisement for lake tourism, campaigning for own action/achievements like reducing pesticide use or restoring shores		
Conflicts †	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 (Merriam Webster Dicitionnary)	One sector coming up with a project/plan that disturbs the actions of another sector (e.g. construction of a dam that inhibits fishing/swimming/sailing)		• Tense political climate • Trust between stakeholders • Disputes/conflicts
Conflict resolution ‡	Social interactions specifically designed to resolve conflicts.	Legal procedures (law case), round tables (regular seminars), mediation between conflicting parties by an independent third actor		• Tense political climate • Trust between stakeholders • Disputes/conflicts
Coordination ‡	Social interactions specifically designed to support the coordinated development of strategies, plans, activities, instruments, monitoring processes, taking of measurement, etc.	Facilitation of meetings and communication channels by state offices or associations that accompany the specific task	Municipalities coordinate the implementation of immediate measures together with the state office for water management, coastal protection and nature conservation	Mobilization, sensitization and accountability of citizens and professionals towards the environment and the impact they exert upon it
Deliberating †	Communicating, exchanging observations and views, reflections, assessing outcomes, persuading each other	Water associations informing their members, chambers of agriculture informing their members, deliberation within forums (see above)	Dümmer council oversees, reports on and advises the implementation of the lake’s rehabilitation concept	
Enforcement of rules ‡	Monitoring the achievement of certain pre-defined goals, environmental targets etc. and procedures that assess the compli-	State offices for the environment taking regular measurement of water quality, environmental NGOs counting species and re-		Imposed regulation

	ance with rules and their enforcement, and informal observation of others behaviour which might exert social pressure	porting the numbers, state offices checking on technical standards (e.g. of sewage treatment plants) or controlling the sale of pesticides to agricultural actors, etc. Sanctions in case of non-compliance, reporting on compliance, self-reporting		
Evaluating †	Evaluating outcomes of action situations	Reports of projects and council/association meetings, independent evaluation of the implementation of measures/policy instruments by a consultancy		
Information sharing †	Sharing information or knowledge between actors	Water council meetings, encounters of actors in so-called forums (i. e. working groups, regular meetings of different sectors, conferences, etc.)	Distributing information about the lake's state to the public through a public forum twice a year	• Education of citizens, professionals and politicalactors • Information/knowledge transfer
Investing †	Allocating financial resources to restore, conserve, or convert sea or landscapes	EU-financed projects to delineate reserves, national plans for renaturalisation of rivers and lakes		Budget available for conservation actions
Knowledge generation (and its distribution among actors) ‡	Produce knowledge regarding ecosystem dynamics and relevant to other governance functions and possibly also to operational activities	Information about ecosystem dynamics (e.g. pH-value, concentration of substances, residence time of water, etc.) to inform about lake's status and the potential measures to be taken to improve its status; about new techniques that clean a lake's waters.		
Lobbying †	Influencing political actors to follow one's own interests	Information campaigning (e.g. by Greenpeace, etc.), petitions, direct lobbying of interest groups at decision-making meetings (e.g. parliamentary sessions)		Citizen pressure in defense of individual rights

Networking †	Creating and maintaining social ties	Stakeholders meet in forums (annual meetings of associations, workshops, councils) and keep contact outside the forum, stakeholders meet due to a common project (e.g. the installation of a polder, see Dümmer case)		• Consultation and harmonization within a same municipality • Consultation and cooperation between different municipalities and citizens • Consultation between decision makers, munici palities and stakeholders
Planning ‡	Produce some kind of plans regarding the use of the resource	strategic plans, operational water management plans, etc.	The water management plan for the Hunte River (as part of the remediation plan)	Interpretation of gray zones within regulation
Rule making †	Developing an operational rule, e.g. the level at which individuals can harvest a common pool resource; developing collective choice rules that determine who is involved in decision making	Supra-national directives (e.g. WFD), national and regional water law, sewage treatment regulation, policies	Remediation plan for the lake	• Standardized framing/horizontal regulation • Strict regulation/urbanistic constraints • Top-down approach from MCQ
Social monitoring †	Monitoring compliance of others	Compliance of different stakeholders with regulations or norms		
Trading †	Exchanging goods or services between two or more actors, selling products at markets	Fish selling (private business, cooperatives, patron-client), fishing licences, concessions to water extraction, boat-renting		
Ecological Action Situations				
Competition †	Individuals of the same or different species compete for a limited food resource or space	Algae-Macrophytes light and nutrient competition	• Algae and macrophytes compete for nutrients and habitat • Fish species fight for habitat and food and for oxygen	• Invasive species • Biodiversity
Facilitation †	Individuals of one species facilitate growth or reproduction of another species	Macrophytes facilitate pike reproduction		

Infection †	One organism infects another organism with a disease			
Predation †	Individuals of one species prey on another	Zooplankton on phytoplankton, bream on zooplankton, pike on bream		
Reduction §	The presence of one ecological component (in a specific state, e.g. hotter, more abundant, …) reduces the capacities of another ecological component	A high amount of macrophytes in a lake ecosystem reduces the light climate within the lake		• Cyanobacteria • Biodiversity
Species-habitat interaction †	Generation of offspring, facilitated by suitable ecological environment	Bream disturbs macrophytes and the sediment		
(Non-) Transporting §	A substance/particle in one ecological element is transported to another ecological element, e.g. via water flow, wind…; A natural flow between two ecological elements is inhibited, therefore there is a "non-transportation" between them	Phosphor in and on soil is washed off by rain and into streams and lakes. A dyke inhibits the natural flow of water in and out of a lake. The water does not transport biomass out of the lake any longer.	• Phosphorus that has been washed off the fields and into stream water is transported into lake water • Biomass cannot be washed out of the lake	• Impervious surfaces • Rainwater runoff
Vegetation - soil interaction †	Vegetation growth stabilizes soil; soil quality affects vegetation growth and vice versa	Macrophytes stabilize soil		

6. References

Ostrom, Elinor. 2005. *Understanding Institutional Diversity.* Princenton, NJ: Princeton University Press.

Pahl-Wostl, Claudia, Christian Knieper, Evelyn Lukat, Franziska Meergans, Mirja Schoderer, Nora Schütze, Daniel Schweigatz, Ines Dombrowsky, Andrea Lenschow, Ulf Stein, Andreas Thiel, Jenny Tröltzsch, and Rorigo Vidaurre. 2020 "Enhancing the capacity of water governance to deal with complex management challenges: A framework of analysis." *Environmental Science and Policy* 107: 23-35.

Schlüter, Maja, L. J. Haider, Steven J. Lade, Emilie Lindkvist, Romina Martin, Kirill Orach, Nanda Wijermans, and Carl Folke. 2019. "Capturing Emergent Phenomena in Social-Ecological Systems: An Analytical Framework." *Ecology and Society* 24 (3).

APPENDIX 2 – INTERVIEW QUESTIONNAIRE

Table A2.1: 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 polices** 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?

APPENDIX 3 – INTERVIEWEES

Table A3.1: List of Interviews – Lake Dümmer case study

n°	German Name of Organization	English Name of Organization	Time	Place
1	Natur- und Umweltschutzvereinigung Dümmer e.V. (NUVD)	Nature and Environmental Protection Association Dümmer	April 24, 2019	Hüde
2	Gewässerschutzberatung der Landwirtschaftskammer Niedersachsen	Water protection consulting of the Chamber of Agriculture of Lower Saxony	May 3, 2019	Osnabrück
3	Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN)	Lower Saxony State Agency for water management, coastal and nature conservation	May 16, 2019	Sulingen
4	Landesamt für Geoinformation und Landesvermessung Niedersachsen (LGLN)	Lower Saxony State Office for Geoinformation and Surveying	May 16, 2019	Sulingen
5	Wettfahrtgemeinschaft Dümmer e.V.	Racing community Dümmer	May 20, 2019	Hüde
6	Gewässerexperte	Expert on Lake Dümmer	May 22, 2019	telephone call
7	Naturschutzstation Dümmer, Einrichtung des NLWKN	Nature conservation station Dümmer, establishment of the NLWKN	May 28, 2019	Hüde
8	Tourismusverband Dümmerland e.V.	Tourist office Dümmerland	May 28, 2019	Lemförde
9	Hunte Wasserverband, Landkreis Diepholz	Hunte water board, County Diepholz	May 28, 2019	Diepholz
10	Samtgemeinde Lemförde	Joint municipality of Lemförde	May 29, 2019	Lemförde
11	Wasserverband Obere Hunte (K.ö.R.)	Water Association N° 70 „Upper Hunte“	May 29, 2019	Osnabrück
12	Stadt Damme	City of Damme	June 3, 2019	Damme
13	Naturschutzring Dümmer e.V.	Nature conservation ring Dümmer	June 5, 2019	Hüde
14	Amt für regionale Landesentwicklung Weser-Ems, Geschäftsstelle Osnabrück, Dezernat 4 „Flurbereinigung, Landmanagement“	Office for Regional Land Development Weser-Ems, Osnabrück Office, Dep. 4 "Land Consolidation, Land Management	June 7, 2019	Osnabrück
15	Anglerverband Niedersachsen	Anglers‘ Association Lower Saxony	June 11, 2019	Hannover
16	Fachdienst 67 Kreisentwicklung, Landkreis Diepholz	Specialist Service 67 District Development, County Diepholz	June 18, 2019	Diepholz
17	Untere Wasserbehörde, Landkreis Osnabrück	Lower Water Authority, County Osnabrück	June 24, 2019	Osnabrück
18	Landwirtschaftskammer Niedersachsen, Bezirksstelle Nienburg	Chamber of Agriculture of Lower Saxony, Nienburg District Office	Sep. 17, 2019	Nienburg
19	Niedersächsisches Ministerium für Umwelt, Energie, Bauen und Klimaschutz	Lower Saxony Ministry for Environment, Energy, Building and Climate Protection	June 5, 2020	Hannover

APPENDIX 4 – THE MERGED CLD OF LAKE ST. CHARLES

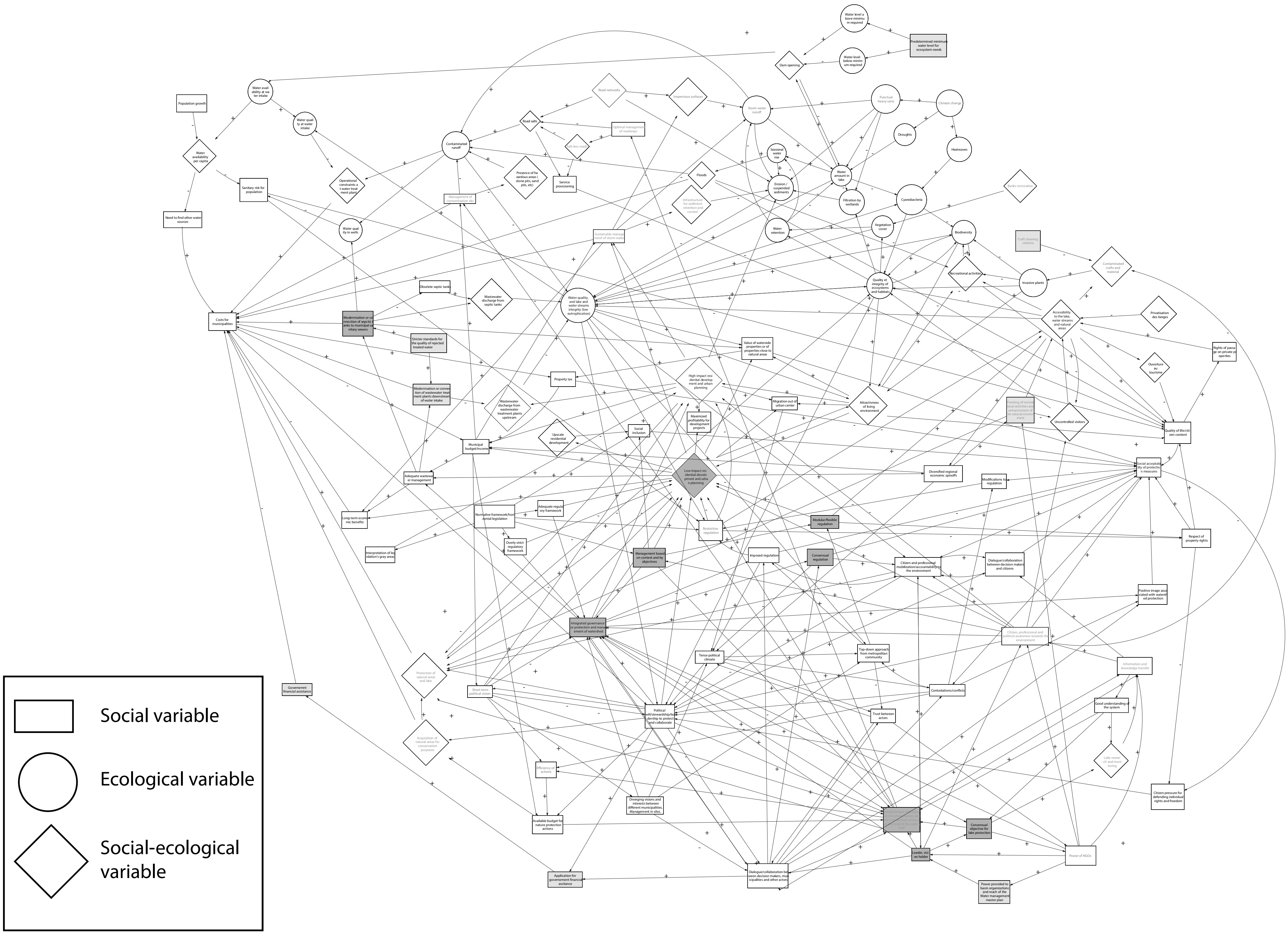

Figure A4.1: The merged CLD representing the Lake St. Charles' SES, based on the stakeholders' social representation of the system. This figure is not meant to be used to improve the understanding of the Lake St. Charles SES system but is merely presented here to showcase the complexity of the merged CLD as a whole, and the benefits brought a bout by the SE-AS framework to simplify the system representation while improving its comprehensibility.

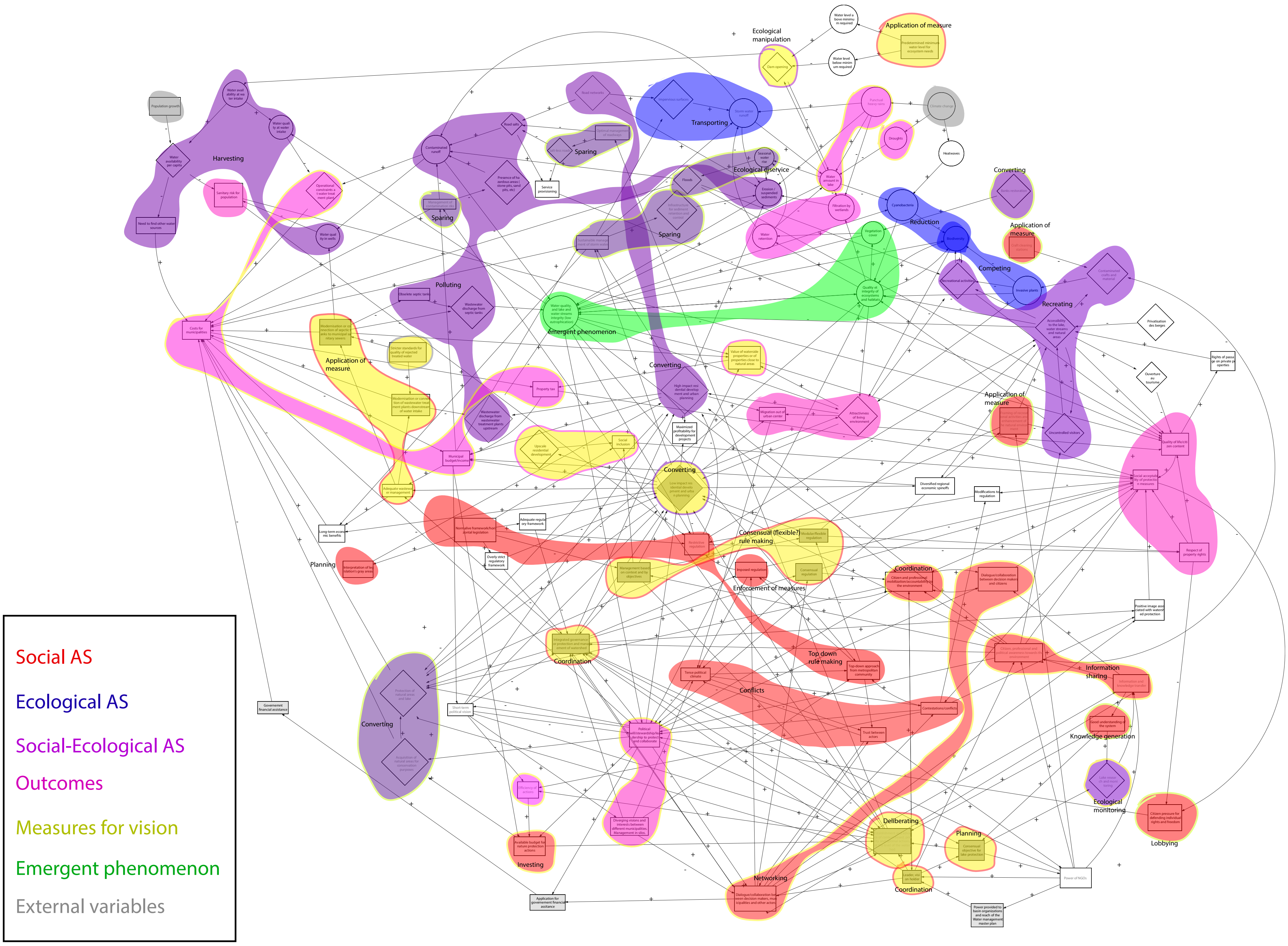

Figure A4.2: Color coding of Lake St. Charles' merged CLD for the SE-AS framework application. Colored "bubbles" are isolated or grouped variables that represent action situations (AS) or emergent outcomes. Variables which are not colored are excluded from the SE-AS framework representation, as are AS that express potential measures to reach the vision. This figure is presented to showcase how action situations and outcomes were derived from the merged CLD.