Multilevel water quality management in the international Rhine catchment area: how to establish social-ecological fit through collaborative governance

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**ABSTRACT.** One major challenge of water quality management is that the source of pollution and its effects might be spatially disentangled. This cause-effect misfit has large implications on how surface water in a hydrological catchment area is managed and regulated. We argue in this paper that such misfit can best be addressed through interconnected and multilevel collaborative arrangements that support institutional capacity building. In line with recent literature, we presume that social-ecological fit can be enhanced through direct collaboration among actors managing the same or interconnected ecosystem units. To study the social-ecological fit, we analyze three subcatchments of the international river basin of the Rhine. Our data on actor collaboration, on inter-related subcatchments, and on actor and subcatchment connections are analyzed through network analysis and motif counts. Our results show social-ecological fit to emerge in less complex co-management situations, e.g., when one resource unit lies in the competence of two actors, or if one actor is responsible for two units. To a lesser extent, there is also evidence for more complex, multilevel collaboration arrangements among actors.

**Key Words:** collaborative governance; institutional capacity building; problem of fit; social-ecological networks

**INTRODUCTION**

The management of natural resources is challenged by complex social-ecological interdependencies (Treml et al. 2015, Vogel et al. 2015): human action, e.g., pollution, impacts the quality of ecosystems, e.g., water, and related services, e.g., drinking water. This can then again affect humans and other species, e.g., eco- or human-toxicological effects, and provoke feedback loops, which result in a complex causality chain. To account for these complexities, several scholars emphasize a need to fit, i.e., an alignment of the governance system (institutional arrangements addressing environmental problems or resource uses) with the characteristics of the respective ecosystem (Berkes et al. 2003, Ostrom 2005). In other words, reducing the misfit between the societal system and the ecosystem is fundamental to enhance environmental problem resolution (Young 2002, Folke et al. 2007, Galaz et al. 2008, Bodin et al. 2014).

We focus on collaboration among actors, which, as shown in previous studies, results in the reduction of misfit and improved environmental problem solving (Bergsten et al. 2014, Bodin et al. 2014). However, we argue that the establishment of such collaborative ties is substantially more difficult for ecosystems (here watersheds) that cross borders and scales and that are thus managed by actors belonging to different jurisdictions or decisional levels. This paper therefore makes at least two contributions to the literature of social-ecological misfit and transboundary governance: first, we focus on one international river basin to investigate the particular challenges to establish collaboration in one large common-pool resource problem situation. Second, we integrate methods and data from both natural and social sciences to do so.

To analyze the added value of collaboration among actors involved in resources management, we take a network perspective. More concretely, we study both, one ecological network that consists of the natural resource units (river catchments), and one social network including actors responsible for or affected by the resource units. We then look at the so-called “motifs” of social-ecological networks (see Bodin and Tengö 2012, Guerrero et al. 2015). That is, we define and conceptualize a set of potentially relevant configurations of interdependencies between social actors and ecological resource units. We are then able to analyze the frequency of these different social-ecological motifs and distinguish if a fit or misfit situation exists based on the present or absent collaboration tie (in the social network). By this, we aim to shed light on the question of which social-ecological configurations reflect collaboration among actors regarding the resource they manage. Identifying these configurations in turn permits us to evaluate the social-ecological misfit (or fit) of the governance of large-scale ecosystems.

To investigate collaboration between actors we focus on a particularly challenging case with several multilevel and connected interdependencies: water quality management in an international river catchment area. In such a context, the source and effects of water pollution are typically spatially disentangled, the most common example being one of an upstream user contaminating surface water of a river and the downstream user suffering from this water pollution. This spatial cause-effect misfit has substantial implications on how surface water quality in a hydrological catchment area is tackled and regulated. We argue that collaboration among actors who use the same resource system is an important precondition to reduce social-ecological misfit (Bodin et al. 2014, Guerrero et al. 2015). However, in the context of an international river catchment, actor collaboration is particularly challenged in four ways: (1) by actors located at different levels (local, regional, national, international); (2) by actors representing different jurisdictions of the same or different countries; (3) by water quality and degradation issues that are determined by natural river stream dynamics, most noticeable through the hierarchy of upstream and downstream users; (4) by institutional arrangements, country-specific regulations, and border effects.

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In this paper, we argue that a social-ecological misfit in surface waters can be addressed through cross-scale, e.g., different dimensions such as spatial or temporal scale (see Cash et al. 2006), and multilevel, e.g., units of analysis within one scale (see again Cash et al. 2006) collaboration. In line with Guerrero et al. (2015) we assume that social-ecological fit is enhanced if (a) two actors using the same ecosystem unit collaborate, (b) an actor is able to manage several, interdependent ecosystem units, and (c) if actors belonging to different jurisdictional levels collaborate in order to manage ecosystem units tangent to their respective territories.

This improvement due to collaboration has different reasons. Collaboration can be seen as the result of joint activities in general, and learning and increased mutual trust among actors in particular (Guerrero et al. 2015). Trust and learning in turn consolidate institutional capacity in terms of increased legitimacy and more effective implementation (Sabatier et al. 2005).

In this context, we presume that establishing collaboration across different ecosystem units, levels, and scales is more difficult than among actors belonging to the same level or managing a single resource unit (see also Young 2002, Treml et al. 2015). We analyze collaboration and social-ecological fit in three subcatchments integrated in the larger international river basin of the Rhine River. Our data consist of three different networks including societal (actors) and ecological (subcatchments) nodes and different qualities of ties (actors’ collaboration, downstream water flow, and actors’ area of competence) related to the particular water quality issue of micropollutants in surface waters. The first network comprises the collaboration among actors and is therefore entirely social. The second network is entirely ecological, representing the subcatchments’ downstream water flow. The third social-ecological network reflects the actors and their connection to the resource units in terms of jurisdictional and/or management competence. To investigate collaborative tie formation in these multiplex networks we count different motifs that include social and ecological nodes (Bodin and Tengö 2012, Bodin et al. 2014, Guerrero et al. 2015). However, our study is explorative and descriptive in nature, aiming at revealing existing collaboration patterns among actors while considering the resource unit each of the actors is linked to. By this, we introduce a small set of social-ecological motifs that can be identified in any social-ecological system and indicate respective social-ecological misfits or fits.

THEORETICAL BACKGROUND

Goverance and ecological systems are typically fragmented in terms of geographic spaces and time horizons (Galaz et al. 2008). The resulting social-ecological misfit is seen as a major barrier for effective resource management. Thus, reducing the misfit between the societal system and the ecosystem by aligning the governance system to the characteristics of the ecosystem is considered as fundamental to enhance environmental problem resolution (Young 2002, Folke et al. 2007, Galaz et al. 2008, Bodin et al. 2014). Assessing the misfit regarding the adjustment of the governance system involves at least three challenges. First, to understand the spatial extent of the environmental problem of the ecosystem under analysis, its exact sources and effects have to be identified (Elshafei et al. 2014). However, this is challenged by the complex feedback-loops within and a constant evolution of ecosystems. Second, in the socio-political system, collective action problems, formal authority, and top-down initiatives can collide with bottom-up and voluntary initiatives (Berardo and Scholz 2010, Feiock and Scholz 2010). Moreover, a broad variety of actors from different levels of decision making and implementation processes contribute to the institutional complexity of modern governance (Hooghe and Marks 2001, Lubell 2013, Lubell and Edelenbos 2013). Third, complex interactions are not only apparent within the socio-political and ecological system, but cross-system links enhance the misfit: socio-hydrological modeling has demonstrated that causation, prevalence, temporality, and the impacts of complex phenomena such as climate change, nuclear waste storage, or toxic chemicals in waters constantly interact with human and societal dimensions, which makes them difficult to identify and demands for a coupled human-water systems perspective (Sivapalan et al. 2012, Chen et al. 2016).

One way to bridge fragmented social-ecological systems is through collaborative network arrangements: they bring public and private stakeholders together to engage in consensus-oriented decision making (Ansell and Gash 2008). Such deliberative, bottom-up ways of problem solving have shown to improve environmental outcomes (Berkes et al. 2003, Christensen et al. 2012, Newig 2012). This argument is based on the assumption, and some empirical evidence, that the participation of affected, concerned, and responsible actors enhances the acceptance of decisions, which consequently supports implementation, and therefore improves the quality of outcomes (Macnagthen and Jacobs 1997, Herzog and Ingold 2019). Although such collaborative forms of governance are increasingly adopted, there is no consensus yet regarding their effectiveness or performance (Sabatier et al. 2005, Gerlak et al. 2013). One way to study interrelated, multilevel and cross-sectoral actors’ arrangements and their performance is the analysis of (environmental) policy networks (Berardo and Scholz 2010, Lubell 2013). Following this literature, policy outputs and outcomes are the result of particular network configurations, including both public and private actors (Koppenjan and Klijn 2004, Henry 2011). These networks decisively impact the quality of natural resources management in terms of stakeholder involvement increasing information exchange, boundary organizations linking a variety of different actors, and knowledge transfers (Adger 2003, Crona and Bodin 2006, Duit and Galaz 2008, Prell et al. 2009, Crona and Parker 2012, Vignola et al. 2013).

Applying such a network perspective to assess the social-ecological misfit within a Kenyan fishery setting, a Madagascan forest conservation context, and watershed management in Costa Rica, Bodin et al. (2014) and Vignola et al. (2013) have demonstrated that collaboration among actors involved in the management and use of geographically distributed though interdependent ecological units reduces the social-ecological misfit and, as a consequence, enhances conservation outcomes. However, we argue that the establishment of such collaborative ties is substantially more difficult in watersheds that cross borders and scales and that are thus managed by actors belonging to different jurisdictional contexts. Moreover, this cross-scale management situation is further challenged by the upstream-downstream dynamics in surface waters (see also Sayles and Baggio 2017). The starting point of this research thus reads as follows: Collaboration among actors using or managing the same resource is more difficult to establish in settings where these actors
Motifs conceptualizing the social-ecological fit challenges.

**Type of fit challenge†**

- **Shared management of ecological resources**
  When two or more actors use or manage the same resource, collaboration (a2) among these actors prevents resource degradation or overexploitation.

- **Management of interconnected ecological resources**
  The management—either by a single actor (b2) or by multiple actors (bb2)—of interdependent resource units is crucial to enhance the social-ecological fit. This allows the detection and management of adverse effects beyond the unit of use.

- **Multilevel management to maximize cross-scale matching**
  The management of ecosystems requires the coordination of a broad range of actions taken on different levels. The fit regarding cross-scale matching is thus enhanced if actors from different levels collaborate (c2).

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**Social-ecological motifs‡**

| Type of fit challenge† | Misfit | Fit |
|-----------------------|--------|-----|
| **Shared management of ecological resources** | a1    | a2  |
| **Management of interconnected ecological resources** | b1    | b2  |
| **Multilevel management to maximize cross-scale matching** | bb1   | bb2 |

† The descriptions of the fit challenges follow Guerrero et al. (2015).
‡ The graphical representation has been adapted from Cushner et al. (2016). The actors (red nodes) are linked to each other (red lines) and/or (with blue lines) to the ecological resource unit(s) (green nodes). Interdependencies among ecological resource units are indicated with green lines. Red and white nodes in motifs c1a, c1b, and c2 indicate different levels of management and resource use.

act across different ecosystem units, levels, and scales compared with situations in which actors belong to the same level or manage one single resource unit.

**MOTIFS OF SOCIAL-ECOLOGICAL (MIS)FIT**

We subsequently discuss different social-ecological motifs related to the three fit challenges introduced above (see Fig. 1; see also Bodin et al. 2014, Guerrero et al. 2015). Motifs in our understanding are illustrations of social and ecological nodes and how their relation corresponds to either a fit or a misfit situation. Motifs a1 and a2 conceptualize the shared management and use of an ecological resource, e.g., a forest patch or a river section. Motif a1 shows the case of a misfit, that is, no collaboration between actors who share the same resource. In contrast, motif a2 illustrates a collaboration among actors who share the same resource indicating a fit between the social and the ecological system. Motif a2 is therefore expected to result in better environmental outcomes in terms of resource management and regulation than motif a1.

The second challenge relates to the management of interconnected ecosystems. Motifs b1, b2, bb1, and bb2 relate to the situation where two resource units are connected. In a “one-actor” situation, coherence in management can be achieved when this actor is not only related to one, but to both interconnected resources. In a multitactor situation, and related to our core argument, collaboration between two actors seems key as soon as each of them is connected to one of the two interconnected resource units.

The third set of motifs is related to the challenge of cross-scale matching in order to maximize the spatial fit. Higher level actors, e.g., on the national level, are often involved in the management and use of more than one resource unit and thus able to coordinate different geographical units, e.g., different regional jurisdictions. As soon as one resource crosses different jurisdictions, collaboration should involve actors from more than one level. This situation is conceptualized in motif c2.

In line with our key argument, collaboration among actors is more difficult to establish in settings where these actors act across different ecosystem units (bb2) and levels (c2) compared to situations in which actors belong to the same level (c1a and c1b) or manage one single resource unit (a2). Thus, we expect motifs bb2 and c2 to occur less often compared to the other corresponding motifs.
DATA AND METHODS

The international water basin of the Rhine River
We selected the Rhine River to study misfit challenges between actors and the respective resource units they use and/or manage and which furthermore cross different jurisdictional levels, borders, and diverse countries. The Rhine originates in the southern Swiss Alps and transcends Switzerland, Liechtenstein, Austria, Germany, France, and the Netherlands before flowing into the North Sea. The Rhine catchment area comprises major tributaries through which parts of Italian, Belgian and Luxembourgian territories become part of it as well. It has a total length of 1230 km and its catchment area comprises 185,000km² rendering the Rhine one of the major surface water streams of Central and Western Europe. The catchment area is characterized by mountain areas as well as flatlands, including dense urban areas and areas of agricultural use. Because of its use as a route for transport and for cooling purposes, heavy industries, especially from the chemical sector, located their major production sites on its shores (Kremer 2010). Overall, a broad diversity of human activities such as agriculture, industrial production, and large settlement areas challenge the water quality of the Rhine, which is at the same time a major source of drinking water for many urban settlements along the river (Kremer 2010).

Water quality management in the Rhine River catchment area
In our study, we focus on water quality management in the catchment area of the Rhine River. The specific water quality issue we look at are micropollutants, chemical and organic substances detected in surface waters at concentration levels ranging from nanograms per liter (ng/L) to micrograms per liter (µg/L). They are defined in contrast to aquatic macropollutants, compounds present at the level of micrograms per liter (µg/L) to milligrams per liter (mg/L; Stamm et al. 2016). Micropollutants are of emerging political concern because of their potentially negative impacts on the environment (Kid et al. 2007, Brodin et al. 2013, Petrie et al. 2015) as well as on human health (Cunningham et al. 2009, 2010). They challenge existing management and regulatory structures because they differ from traditional pollution problems. First, there exist thousands of different compounds with different environmental effects. Second, they have a multitude of possible sources (pharmaceuticals and personal care products from households, plant protection products from agriculture, biocides for material protection on buildings, etc.) and thus many different entry points into water bodies (Ternes 1998, Kolpin et al. 2002, Schwarzenbach et al. 2006). The respective substances enter the aquatic environment via diffuse or point-source pollution. This has a direct impact on the assessment of the extent of the problem: whereas diffuse sources such as herbicides and pesticides from agriculture cover a large area, point source pollution can be targeted at the entry point, that is, wastewater treatment plants. We account for both possibilities by including subcatchments of the Rhine that embrace both industrial and urban areas with wastewater treatment plants as well as rural areas with diffuse sources from agriculture. Finally, some micropollutants are persistent, which means they do not degrade and cannot be filtered yet and remain in surface waters, transcending jurisdictional borders and countries. This characteristic is particularly relevant here as we assess fit-challenges stemming from cross-scale and multilevel social-ecological interactions across large geographical distances.

In sum, micropollutants are a challenging water quality issue that entered the political agenda only recently. We thus argue that the establishment of collaboration is probably more difficult for this type of water pollution than it would be in the case of another, more visible and less persistent water quality issue. So if we see potential for fit, this might then be equally or even more easily adaptable in other water quality management situations.

Case studies
From the catchment area of the Rhine River, we chose three case study areas to investigate our research question: Which social-ecological configurations reflect collaboration among actors regarding the resource they manage? Identifying these configurations enables us to evaluate the social-ecological misfit (or fit) of the governance of large-scale ecosystems. In order to be selected, the case studies had to fulfill the following selection criteria:

- They have to be positioned in a region with a considerable concentration of micropollutants in the water body;
- There should be different forms of sensitive water use in the region, e.g., drinking water purification;
- There should further be some regulatory framework regarding micropollutants already in place.

Subsequently, we give a short overview of the three case studies. Table 1 provides a brief summary of the three case study regions while Figure 2 shows a map of the catchment area of the Rhine River in which the three areas of the case studies are highlighted.

Table 1. Case study regions.

| No. | Case | River | Source of micropollutants | Countries | Cross-border region |
|-----|------|-------|---------------------------|-----------|---------------------|
| 1   | Basel| Rhine | Settlements, industry, agriculture | Switzerland, Germany | yes |
| 2   | Moselle| Moselle | Settlements and hospitals, agriculture (viticulture) | Luxembourg and Germany | yes |
| 3   | Ruhr | Ruhr | Settlements, industry, agriculture | Germany | no |

The Rhine at Basel
The first case study is the Rhine River’s catchment area around the Swiss city Basel and its urban agglomeration. Basel is located at the international tri-point where Switzerland, Germany, and France meet. The city is known for its pharmaceutical and chemical industries, which, together with the urban drainage, are major contributors for micropollutants in the river’s surface water. However, micropollutants are not only found in the area of Basel but in Swiss water bodies in general, many of which belong to the catchment area of the Rhine (Gälli et al. 2009). The persistent substances entering Swiss water bodies connected to the Rhine inevitably appear in the surface water in Basel. We therefore consider the river’s catchment area geographically upstream of Basel as part of the case study’s region. In our analysis of actors, we focus on the city of Basel and its
Fig. 2. The Rhine River catchment area and the case study regions, retrieved from: http://www.fgg-rhein.de/servlet/is/4230/BMU_DE_WA_CD%5B1%5D.jpg; own translation.
surroundings, narrowing the area in which water quality management occurs down to the place where the Rhine River’s waters leave the country of Switzerland and pass over from the High Rhine into the Upper Rhine.

The Moselle in Luxembourg and Germany
The Moselle is a western tributary of the Rhine, originating in the French Vosges and meeting the Rhine off Koblenz in Germany. Its catchment area is shared by France, Luxembourg, Germany, and Belgium. The case study region covers the territories of the Grand Duchy of Luxembourg and its two neighboring German Bundesländer Rhineland-Palatinate (RLP) and Saarland. All three political entities are responsible for the management of the river’s waters as the Moselle builds the natural and national border between Luxembourg and Germany (UNECE 2011). Micropollutants present in the Moselle’s catchment area on the Luxembourgian territory inevitably surface in the Moselle’s water on the German territory. We focus thus on collaboration in water quality management regarding micropollutants in the Grand Duchy of Luxembourg and the two German Bundesländer Rhineland-Palatinate and Saarland.

The Ruhr in Germany
The third case is the catchment area of the Rhine’s eastern tributary Ruhr in western Germany. Its catchment area gave its name to the biggest urban agglomeration in Germany and one of the most intense industrial areas in Germany in the 20th century: the Ruhr region. The Ruhr is thus a river prone to micropollutants stemming from both residential and industrial areas. Several pharmaceutical compounds have been detected above the threshold value of 0.1 µg/L throughout the last decade (RWTH Aachen 2008). Herbicide and biocide compounds were also found in the river’s waters, but did not exceed the maximum permissible concentrations (AWWR 2015). Water-related actors in the region are very sensitive to the issue of micropollutants as the river accounts for 20% of the region’s drinking water supply (MKULNV 2009). The overall goal of the federal state’s government is to keep concentrations of micropollutants below 0.1 µg/L.

Social-ecological networks: data gathering and network construction
Subsequently, we introduce the three networks analyzed for this study by explaining the data gathering procedure and the construction of the networks.

Network 1: Actors’ collaboration network
The basic argument of this study is that certain types of interactions among actors enhance the so-called social-ecological fit. We focus on collaboration as the key type of interaction among actors in natural resources management. Collaboration is defined as mutual (in contrast to one-way) engagement in a joint relationship that is crucial to assess a shared concern, responsibility, or competence of two actors regarding one specific ecosystem, ecological unit, or geographical area (Weible and Sabatier 2005, Lubell et al. 2010, Henry 2011, Ingold 2011).

We focus on the collaboration of collective actors and organizations like public authorities, private organizations, such as waterworks, and NGOs and interest groups that are involved in the use, management, and regulation of surface water (see also Knoke et al. 1996). Following approaches developed in the context of the SES framework (Sadoff and Grey 2005, Ostrom 2009), we identified the organizations in the respective regions that are direct or indirect users of surface water of the Rhine River, that are affected by or responsible for micropollutants in the rivers’ waters and that are in charge of the rivers’ regulatory management. To gather further information on the involved actors, we interviewed managers, CEOs, and heads of public offices of key organizations in the water sector in the respective region in spring and summer 2016. These key actors were asked to name those actors they consider important in water quality management in the respective areas, thereby applying the reputational approach (Laumann and Pappi 1976).

The resulting final actor list was used in a survey conducted in the Basel region between 18 April and 24 August 2016, in the Ruhr region between 5 September 2016 and 6 February 2017, and in the Moselle region between 25 September 2016 and 17 February 2017 (for additional information on the actors of each case study see Tables A1.1-1.3 in Appendix 1). Actors (nodes) were asked with whom they closely collaborate (ties) in terms of water quality management irrespective of agreeing on policy positions. We defined close collaboration as discussing findings, developing policy options, exchanging positions, and evaluating alternatives. Thus, collaboration between actors is based on the self-assessment of actors. The actors’ responses were transformed into a matrix in which 1s indicate that an actor collaborates with another actor and 0s signify no collaboration with the respective actor. This procedure provided us with an actor collaboration network for each case. We treat collaboration as undirected tie. Table A1.4 in Appendix 1 provides an overview of the number of actors contacted in each case study region, the number of returned questionnaires, and the resulting response rate. Tables A.1.5-1.7 in the Appendix provide an overview of the descriptive statistics of the three actor networks.

Network 2: Ecological network
The ecological network consists of the subcatchments of each case study region. Links between two subcatchments exist as soon as a potential downstream flow, and thus a potential passage of micropollutants from one subcatchment to the other, is possible. Despite the directionality implied by downstream flows, we nevertheless treated the links between two subcatchments as undirected (see also Sayles and Baggio 2017). Although water pollution in the case of micropollutants follows a downstream flow direction, fish migration or drinking water interdependencies include an upstream element. The information for the ecological network is based on the river and catchment database for Europe (Vogt et al. 2007) dividing the Rhine into more than 30,000 primary catchments and river segments (see also Ingold et al. 2018). In order to limit the number of catchments, only the river networks with Strahler stream order ≥ 4 were considered and the primary catchments were merged accordingly, resulting in 336 subcatchments with an average size of 477 km² for the entire Rhine River basin (for a map of the Rhine River catchment area illustrating the 336 subcatchments see Figure A1.1 in Appendix 1).

These subcatchments were then further limited to the three case study regions. For the Basel case, all upstream subcatchments of the Rhine River, starting from the source of the Rhine and including the subsequent catchments of the Anterior and
Posterior Rhine, Alpine Rhine, the Rhine in the Upper and Lower Lake of Constance, and the High Rhine, were included. For the Basel case, the ecological network ends in the city of Basel where the High Rhine descends into the Upper Rhine. The Moselle case includes all subcatchments of the Moselle River on Luxembourgian and German territory and is delimited by the city of Koblenz where the Moselle discharges into the Rhine. Finally, the Ruhr case consists of all subcatchments for the Ruhr River and ends at the city of Duisburg, where the Ruhr flows into the Rhine River. This results in 74 ecological nodes for the Basel case, 31 nodes for the Moselle case, and 11 nodes for the Ruhr case. The nodes and their links form the ecological networks that represent the respective subcatchment area of each case study. Descriptive statistics for the three ecological networks are provided in Tables A1.8-1.10 in the Appendix; Figures A1.2-4 show maps of the catchment areas of the three cases indicating their subcatchments of Strahler stream order ≥ 4 and the connection among these sub-catchments.

Network 3: Social-ecological network
Network 3 is a two-mode network that affiliates actors (node 1) from Network 1 to the subcatchments (node 2) from Network 2. A link between an actor and an ecological node is established as soon as an actor is accountable, uses, or manages the subcatchment that node 2 represents. More concretely, actors were assigned to a subcatchment if their area of competence or resource use geographically overlaps with a subcatchment. If this area includes three subcatchments, this resulted in three links between the actor and the three ecological nodes, respectively. The geographic area of competence or use of the actors resulted from the actors’ self-assessment in the survey and was defined as the area in which actors have formal regulatory, implementation, or consulting competences. The following six options regarding actors’ geographic area of competence or use were given in the questionnaire: (1) a single community, (2) a region consisting of several communities, (3) a federal state, (4) a nation state, (5) a transboundary region (6) a subcatchment of the Rhine River, and (7) the whole Rhine catchment. For each option, further specification, e.g., name of the community, was demanded.

To match the subcatchments with the respective competence area of an actor, a spatial approach was taken. First, the respective areas were (re)coded in terms of administrative units (community, federal states, nation state). Second, the spatial data of both, the subcatchments as well as the administrative units of the actors, were drawn on a map. Third, with the help of geographic information software, we identified the intersections of the subcatchments and the competence area of each actor. Because of the lower resolution (100 x 100m) of the catchment area data, a minimum threshold of 5% of geographical overlap for the competence area and the subcatchment area was defined to account for an intersection. Fourth, the intersections between a subcatchment and an actors’ competence area were transposed into three two-mode network matrices (one for each case study region) where “0” indicates no intersection, and “1” indicates an intersection between the actor’s competence area and the subcatchment.

Methods and data analysis
In accordance with Bodin and Tengö (2012) the social-ecological motifs, i.e., a set of social actors linked to ecological units (see Fig. 1), were counted. Therefore, the frequency of each motive in the empirically observed network was compared to the frequency of 10,000 randomly generated networks, each with 10,000 samples, to estimate the number of subgraphs. This procedure enables us to check which motifs prevail in our original networks at a significant level by comparing them to their distribution in the random networks. In addition to the motifs outlined in Figure 1, we included two additional “control” motifs-labelled BC3 and BC4 (see Figs. 3-5), according to the analysis by Guerrero et al. (2015). Different than in our analysis where we only include motifs that include one single resource units (Figure 1), these authors also added motifs where more than one resource unit is managed by one or more social actors.

The motifs were analyzed using the FANMOD software package. FANMOD is capable of analyzing a broad set of motifs including motifs with different node and tie attributes. The analyses are carried out for motifs with the same number of nodes as well as for a fixed number of different node attributes and types of ties. For instance, an analysis of motifs consisting of three nodes included simultaneously motifs a1, b1, a2, b2, c1a, c1b, and c2 but not the remaining ones. However, FANMOD imposes certain limitations to the analysis of motifs that go beyond the size of five nodes. For motifs with more than five nodes, the number of node attributes is limited to 1. Thus, the calculation of motifs for multilevel or two-mode networks including more than five nodes is not possible. Table A1.11 in Appendix 1 lists the statistics of the motifs with 3, 4, and 5 nodes for each case study.

RESULTS
Figures 3-5 summarize our results. The first column indicates the observed frequency (in %) of the respective motif. In Figure 3, motif a1 occurs in 22% of all possible cases that include three cross-scale nodes. The second column represents the mean frequency of the motif in the randomly permuted networks. We chose a 1% significance level, and significant results (bold in the figure) indicate that a motif occurs more frequently than expected by chance. The difference between the first (observed frequency) and the second column is thus indicative in terms of higher or lower occurrence.

In the Moselle region (Fig. 3), the three misfit motifs a1, BC3, and c1b have a higher frequency than expected by chance. This means that actors who are connected to the same subcatchment are not collaborating with each other (a1). Furthermore, a single actor connected to various unrelated resource units is not addressed through further collaboration among actors in the social network (BC3). Finally, two actors related to the same subcatchment are of the same jurisdictional/operational level, e.g., regional, even though the subcatchment is embedded in a hierarchy of different levels, e.g., national and regional (motif c1b). Even though motif BC3 occurs at a significant frequency, it only figures as “control motif” in our model.

Figure 3 further outlines that the fit motifs a2, b2, and c2 are significant in the Moselle case. Thus, looking at the interplay between the baseline motif a1 and its respective fit motif a2, there is a considerable chance for actors exploiting the same resource unit to also collaborate. From a multilevel perspective, there is a smaller frequency of two actors that are linked to the same subcatchment but operate at different levels to collaborate (c2). Another significant, but less frequent fit motif is the one of one actor who is connected to two interrelated subcatchments (b2).
Fig. 3. Motif analysis of the Moselle case. Notes: green nodes indicate ecological units, red nodes social actors (in c2 the empty dot indicates national actors, the red dot subnational actors); blue lines indicate social-ecological (SE) links, green lines indicate links between ecological nodes (EE), blue lines indicate links between social nodes (SS); frequency in the third column indicates the frequency of the motif in the empirical network; mean-frequency indicates the mean frequency of the motif in the random networks; standard deviation is from the mean frequency; Z-scores are defined as the original frequency minus the random frequency divided by the standard deviation; the p-value of a motif is the number of random networks in which it occurred more often than in the original network, divided by the total number of random networks. Bold numbers indicate significant results at a 1% significance level.

| Motifs associated with social-ecological misfits | Frequency (%) | Mean frequency (%) of 10,000 random networks | Standard deviation of 10,000 random networks | Z-score | p-value |
|---|---|---|---|---|---|
| a1 | 21.855 | 21.039 | 0.00095028 | 8.5844 | 0.0001 |
| b1 | 2.3086 | 4.0302 | 0.0018981 | -9.0702 | 1 |
| BC3 | 2.4595 | 2.0687 | 0.00036212 | 10.791 | 0 |
| BC4 | 0.39919 | 0.55131 | 0.00041211 | -3.6913 | 1 |
| c1a | 0.404 | 0.50532 | 0.0031171 | -3.2503 | 1 |
| c1b | 6.7911 | 4.7136 | 0.00064288 | 32.15 | 0 |

| Motifs associated with social-ecological fit | Frequency (%) | Mean frequency (%) of 10,000 random networks | Standard deviation of 10,000 random networks | Z-score | p-value |
|---|---|---|---|---|---|
| a2 | 9.9269 | 7.2281 | 0.0015225 | 17.726 | 0 |
| b2 | 2.501 | 1.2359 | 0.0010125 | 12.494 | 0 |
| bb2 | 0.0095329 | 0.032196 | 8.2559e-005 | -2.74151 | 0.9995 |
| c2 | 2.318 | 1.979 | 0.00077442 | 9.7205 | 0 |
Fig. 4. Motif analysis of the Ruhr case. Notes: green nodes indicate ecological units, red nodes social actors (in c2 the empty dot indicates national actors, the red dot subnational actors); blue lines indicate social-ecological (SE) links, green lines indicate ecological nodes (EE) links, blue lines indicate links between social nodes (SS); frequency in the third column indicates the frequency of the motif in the empirical network; mean-frequency indicates the mean frequency of the motif in the random networks; standard deviation is from the mean frequency; Z-scores are defined as the original frequency minus the random frequency divided by the standard deviation; the p-value of a motif is the number of random networks in which it occurred more often than in the original network, divided by the total number of random networks. Bold numbers indicate significant results at a 1% level.

| Motifs associated with social-ecological misfit | Frequency (%) | (%) of 10,000 random networks | Z-score | p-value |
|------------------------------------------------|---------------|-------------------------------|---------|---------|
| a1                                             | 32.88         | 31.585                        | 20.84   | 0       |
| b1                                             | 0.20752       | 0.21258                       | -0.37788| 0.6258  |
| BC3                                            | 0.22139       | 0.19701                       | 3.5115  | 0       |
| BC4                                            | n.a.          | n.a.                          | n.a.    | n.a.    |
| c1a                                            | 0.12682       | 0.12494                       | 7.1313  | 0       |
| c1b                                            | 12.705        | 12.564                        | 1.781   | 0       |

Motifs associated with social-ecological fit

| Motifs associated with social-ecological fit | Frequency (%) | (%) of 10,000 random networks | Z-score | p-value |
|------------------------------------------------|---------------|-------------------------------|---------|---------|
| a2                                             | 15.598        | 14.443                        | 7.1179  | 0       |
| b2                                             | 3.1819        | 3.0133                        | 15.499  | 0       |
| bb2                                            | n.a.          | n.a.                          | n.a.    | n.a.    |
| c2                                             | 2.7669        | 2.508                         | 2.5116  | 0       |
**Fig. 5.** Motif analysis of the Basel case. Notes: green nodes indicate ecological units, red nodes social actors (in c2 the empty dot indicates national actors, the red dot subnational actors); blue lines indicate social-ecological (SE) links, green lines indicate ecological nodes (EE) links, blue lines indicate links between social nodes (SS); frequency in the third column indicates the frequency of the motif in the empirical network; mean-frequency indicates the mean frequency of the motif in the random networks; standard deviation is from the mean frequency; Z-scores are defined as the original frequency minus the random frequency divided by the standard deviation; the p-value of a motif is the number of random networks in which it occurred more often than in the original network, divided by the total number of random networks. Bold numbers indicate significant results at a 1% level.

| Motifs associated with social-ecological misfit | Frequency (%) | Mean frequency (%) of 10,000 random networks | Standard deviation of 10,000 random networks | Z-score | p-value |
|------------------------------------------------|---------------|---------------------------------------------|---------------------------------------------|---------|---------|
| a1                                             | 20.052        | 20.553                                      | 0.00083213                                  | -6.0136 | 1       |
| b1                                             | 0.18059       | 0.3432                                      | 5.2471e-005                                 | -30.989 | 1       |
| BC3                                            | 27.05         | 25.103                                      | 0.0016823                                   | 11.572  | 0       |
| BC4                                            | 0.058838      | 0.016233                                    | 2.9338e-005                                 | 14.522  | 0       |
| c1a                                            | 3.3413        | 4.3546                                      | 0.00086203                                  | -10.71  | 1       |
| c1b                                            | 0.43453       | 0.60946                                     | 0.00095271                                  | -1.8362 | 1       |

| Motifs associated with social-ecological fit    |               |                                             |                                             |         |         |
|------------------------------------------------|---------------|---------------------------------------------|---------------------------------------------|---------|---------|
| a2                                             | 6.7819        | 5.47                                        | 0.0015634                                   | 8.391   | 0       |
| b2                                             | 1.8206        | 1.6815                                      | 5.4801e-005                                 | 25.381  | 0       |
| bb2                                            | 0.00011381    | 0.00023713                                  | 1.3278e-006                                 | -0.9288 | 0.8199  |
| c2                                             | 2.9161        | 1.7214                                      | 0.0016353                                   | 7.3057  | 0       |
Results are very similar in the Ruhr region (Fig. 4) with one exception: the clb motif occurs significantly at a lower frequency. This is interesting, because both multilevel misfit motifs occur more frequently than expected by chance (cla and clb) and there is statistical evidence that in some cases actors manage to break up the single-level collaboration and engage in multilevel interaction to manage the same resource unit (c2).

The Basel region (Fig. 5) differs substantially from the other two cases. Motif a1 as one typical baseline misfit configuration is still rather frequent (over 20%), but at a nonsignificant level. Besides BC3, which is very frequent in the Basel region, at 27% (and significant in all three cases), BC4 occurs as well more frequently than expected by chance, but not very often at all. The significant and frequent fit functions, a2, b2, and c2, are the same in Basel as in the other two cases.

**DISCUSSION AND CONCLUSION**

Collaboration is seen as a key mechanism to tackle the misfit between the societal system and the ecosystem and thus to prevent environmental degradation and resource overexploitation (Young 2002, Folke et al. 2007, Galaz et al. 2008, Bodin et al. 2014). Although previous research found support for enhanced collaboration and a concomitant social-ecological fit (Bodin et al. 2014, Guerrero et al. 2015), our analysis cannot fully confirm this trend. Comparing water quality management among three regions along the River Rhine, social-ecological misfit seems at least as prominent as social-ecological fit. More concretely, even though there is a tendency of two actors to collaborate as soon as they use or manage the same resource, the contrary, the absence of collaboration, is more frequent. However, there is also good news: three out of the four fit functions we tested are significant in all three regions. For example, multilevel management occurs more often than would be expected by chance. Only collaboration between multiple actors responsible for interconnected resources seems particularly challenging (motif bb2).

We can think of three major reasons for why we observe more misfit than fit in our cases: first, and in line with the literature on complex social-ecological interdependencies (see for instance Elshafei et al. 2014), the investigated environmental problem of micropollutants is a diffuse one. Micropolllutants are invisible substances in waters, a characteristic that makes it difficult to conceive and to target the problem. Establishing collaborative ties between authorities, polluters, and target groups of a largely unknown or invisible problem thus seems to be one particular challenge. Second, our data only conceives direct collaborative links among actors. However, some of the actors in our network might be indirectly linked through waterbody associations. Accounting for actors’ connections through such platforms, thus considering the ecology of games actors are part of (see Lubell 2013), might reveal more fit than only accounting for actors’ direct collaboration. Different studies highlighted the potential of so-called platforms when it comes to manage natural resources (see Fischer and Leifeld 2015). Third, we can see a hierarchy between the different fit and misfit situations. This hierarchy reflects our expectation that collaboration among actors is more common in a single resource unit (see motif a2 in Fig. 1) or a single actor (see motif b2) situation. In contrast, we expected multiresource (see motif bb2) and multilevel (see motif c2) collaboration situations to occur less often. The frequency analysis confirms this expectation: collaboration among two actors, each responsible for interconnected resources, was not found to be significant and frequencies of this motif are very low. The multilevel motif, representing the multilevel management of one subcatchment, is less frequent than other collaborative arrangements among actors in this cross-scale network situation. However, there is a significant but still low frequency of two actors collaborating that belong to different jurisdictional levels and are both responsible for or acting in the same subcatchment of the Rhine. This last result highlights that enlarging jurisdiction, for example, through the establishment of inter-regional and transboundary water or ecosystem associations, might be one way to foster collaboration across borders, countries, and cultures.

One added value of this research is that for the first time to our knowledge, we applied social-ecological network analysis to a large cross-scale resource system. Furthermore, our ecological network has the specific characteristic of up-and down-stream interdependencies. Even if responsibilities were distributed more or less equally among the different actors in the social network, affectedness would still be clearly one directional: the water pollution investigated here does affect downstream jurisdictions (and actors therein) more severely than upstream ones. Further research is needed to scrutinize such differences in problem affectedness in upstream/downstream settings and how this difference affects the resources management. In general, this analysis could be strengthened by including more information about the actors: for instance, distinguishing whether they are private organizations or public authorities or polluters or actors suffering from water quality shortages. With this information, it would be easier to clearly identify the location of misfit and to apply further tools, such as visualizations (see Sayles and Baggio 2017, Ingold et al. 2018). Visualizations are then a good way to communicate scientific results to practitioners and make a concrete contribution to natural resources management.

Our results did not reveal significant differences between the three cases, even though one is a typical cross-border (Basel), one an international (Moselle), and one a single-country case (Ruhr). To benefit from this cultural and contextual diversity, future investigations could include more attributes of the resource units and of the actors, respectively. Finally, new applications are needed that account for such an enhanced nodal complexity and allow for a more flexible modeling of relevant network configurations.

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[1] Strahler stream order of a river network is a numerical method to define the stream size based on the tree structured hierarchy of the river tributaries. The smallest upstream tributaries are designated with Strahler order 1. Only if two tributaries with the same Strahler order join the resulting river segment, the Strahler order increases by 1. We decided to restrict our ecological network to catchments with Strahler order ≥ 4 because those correspond to a size of tributaries that is big enough for actors involved in surface water management to be aware or concerned about water quality issues.
Responses to this article can be read online at: http://www.ecologyandsociety.org/issues/responses.php/11087

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# Appendix 1

Table A1.1: Actors’ list of the case study Basel

| N° | Acronym   | Actor’s name                                                                 | Actor type                           | Nationality |
|----|-----------|------------------------------------------------------------------------------|--------------------------------------|-------------|
| 1  | ADMLoerr  | District administration of the city of Lörrach                              | Regional political actor             | G           |
| 2  | AIBBL     | Cantonal Office for Industrial Companies, Basel Landschaft                   | Regional political actor             | CH          |
| 3  | ALSACENAT | Alsace Nature                                                                | Environmental NGO                    | F           |
| 4  | APRONA    | Association for the protection of the groundwater of the Alsatian plain      | Environmental NGO                    | F           |
| 5  | AQUAEXP   | Union of Laboratories of Swiss Drinking Water Provider                       | Scientific institution               | CH          |
| 6  | AQUAVIV   | Prevention of Water Pollution Northwest Switzerland                           | Environmental NGO                    | CH          |
| 7  | AUEBL     | Cantonal Office for Environmental Protection and Energy, Basel Landschaft    | Regional political actor             | CH          |
| 8  | AUEBS     | Cantonal Office for the Environment and Energy, Basel Stadt                  | Regional political actor             | CH          |
| 9  | AWBR      | Association of Waterworks Lake Constance-Rhine                               | Water association                    | Internat.   |
| 10 | CERCL     | Association of the cantonal experts of water biology and chemistry           | Scientific institution               | CH          |
| 11 | CITYWeil  | City of Weil am Rhein; Waterworks Südliches Markgräflerland                 | Service provider                     | G           |
| 12 | EAWAG     | Swiss Federal Institute of Aquatic Science and Technology                    | Scientific institution               | CH          |
| 13 | ESPECS    | Environment, spatial planning and energy committees of the members of the Swiss parliament | National political actors | CH          |
| 14 | FOEN_W    | Federal Office for the Environment, Water Division                           | National political actor             | CH          |
| 15 | FSVO      | Federal Food Safety and Veterinary Office                                    | National political actor             | CH          |
| 16 | HKBB      | Basel Chamber of Commerce                                                    | Polluter                             | CH          |
| 17 | IAWR      | International Association of Water Works in the Rhine Basin                  | Water association                    | Internat.   |
| 18 | ICPR      | International Commission for the Protection of the Rhine                     | Water association                    | Internat.   |
| 19 | IWB       | Industrial Works Basel (Drinking water provider in Basel)                    | Service provider                     | CH          |
| 20 | KI        | Organization of municipal infrastructure                                      | Service provider                     | CH          |
| 21 | KI.SSV.SGV| Swiss Association of the Municipalities                                       | Regional political actor             | CH          |
| 22 | LABBL     | Cantonal Laboratory Basel-Landschaft                                         | Scientific institution               | CH          |
| N° | Acronym | Actor’s name | Actor type | Nationality |
|----|---------|--------------|------------|-------------|
| 23 | LABBS  | Cantonal Laboratory Basel City | Scientific institution | CH |
| 24 | LUBW  | Regional institution for the environment, measurement and nature conservation, Baden-Württemberg; Department prevention of water pollution | Regional political actor | G |
| 25 | NOVARTIS | Novartis International - Chemical company | Polluter | CH |
| 26 | PRONA | Pronatura – Environmental Protection Organization | Environmental NGO | CH |
| 27 | ROCHE | F. Hoffmann-La Roche plc – Chemical company | Polluter | CH |
| 28 | SBrV | Swiss Association of well craftsmen | Service provider | CH |
| 29 | SFA | Swiss Fishery Association | Consumer organization | CH |
| 30 | SVGW | Swiss Gas and Water Industry Association | Water association | CH |
| 31 | TZWK | German Water Centre, Karlsruhe | Scientific institution | G |
| 32 | VSA | Swiss Water Association | Water association | CH |
| 33 | WWB | Hardwasser plc (Drinking water provider in Basel) | Service provider | CH |
| 34 | WWF | World Wide Fund for Nature, Switzerland: regional group Basel | Environmental NGO | CH |
| 35 | WWR | Water Works Reinach and surrounding area | Service provider | CH |
| 36 | WWTPBasel | WWTP Basel, ProRheno plc | Polluter | CH |
| 37 | WWTPBirs | WWTP Birs, Birsfelden | Polluter | CH |
| 38 | WWTPChem Basel | Industrial WWTP, ProRheno plc | Polluter | CH |
| 39 | WWTPRhein | WWTP Rhein, Schweizerhalle | Polluter | CH |

Abbreviations: CH = Switzerland; F = France; G = Germany; Internat. = International actor; WWTP = Waste Water Treatment Plant
Table A1.2: Actors’ list of the case study Moselle

| N° | Acronym          | Actor's name                                           | Actor type        | Nationality |
|----|------------------|--------------------------------------------------------|-------------------|-------------|
| 1  | Aluseau          | Luxembourgian association of water services             | Service provider  | LUX         |
| 2  | City.LUX         | Luxembourg City                                         | Regional political actor | LUX         |
| 3  | CoA.LUX          | Chamber of Agriculture, Luxembourg                      | Polluter          | LUX         |
| 4  | CoA.RLP          | Chamber of Agriculture, RLP                             | Polluter          | G           |
| 5  | DEA              | Water Distribution of the Ardennes                      | Service provider  | LUX         |
| 6  | EVS              | Association of the Disposal of Waste Water Saar        | Polluter          | G           |
| 7  | Fish.SAAR        | Fishery Association Saar                                | Consumer organization | G           |
| 8  | FLPS             | Luxembourgian Fishery Association                       | Consumer organization | LUX         |
| 9  | Hospitals. LUX   | Hospital Center Emile Mayrisch                          | Polluter          | LUX         |
| 10 | LDEW             | Regional Association of the Supply Industry, Hesse/RLP  | Water association | G           |
| 11 | LIST             | Luxembourg Institute of Science and Technology          | Scientific institution | LUX         |
| 12 | MinAgri.LUX      | Ministry of Agriculture, Viticulture & Consumer Protection, Luxembourg | National political actor | LUX         |
| 13 | MinDev.LUX       | Ministry for Durable Development & Infrastructure, Luxembourg | National political actor | LUX         |
| 14 | MUEEF.RLP        | Ministry for the Environment, Energy, Food & Forest, RLP | Regional political actor | G           |
| 15 | MUV.SAAR         | Ministry for the Environment & Consumer Protection, Saarland | Regional political actor | G           |
| 16 | MWVLW.RLP        | Ministry of Economy, Transport, Agriculture & Viticulture, RLP | Regional political actor | G           |
| 17 | NaturEmw         | natur & ëmwelt                                         | Environmental NGO  | LUX         |
| 18 | OffEnv.LUX       | State Office of the Environment, LUX                    | National political actor | LUX         |
| 19 | OffNat.RLP       | State Office of the Environment, RLP                    | Regional political actor | G           |
| 20 | OffNat.SAAR      | State Office of the Environment & Safety Protection at the Workplace, Saarland | Regional political actor | G           |
| 21 | SEBES            | Union of the Waters of the Esch-sur-Sûre Dam            | Service provider  | LUX         |
| 22 | SES              | Union of the Water of the South Koerich                 | Service provider  | LUX         |
| 23 | SGD              | Office of Structure and Approval North, RLP             | Regional political actor | G           |
| 24 | SIDEN            | Intercommunal Union of Waste Water Treatment of the North | Polluter          | LUX         |
| N° | Acronym  | Actor’s name                                | Actor type     | Nationality |
|----|----------|---------------------------------------------|----------------|-------------|
| 25 | SIDERO   | Intercommunal Union of Waste Water Treatment of the West | Polluter       | LUX         |
| 26 | SIDEST   | Intercommunal Union of Waste Water Treatment of the East | Polluter       | LUX         |
| 27 | SIVEC    | Intercommunal Union of the Ecological Purpose | Polluter       | LUX         |
| 28 | StGB.RLP | Association of Communities and Cities, RLP  | Regional political actor | G           |
| 29 | SWT      | City’s Department of Public Works Trier     | Service provider | G           |
| 30 | TUKais   | Technical University of Kaiserslautern      | Scientific institution | G           |
| 31 | ULC      | Luxembourgian Union of Consumers             | Consumer organization | LUX         |
| 32 | UNI.LUX  | University of Luxembourg                    | Scientific institution | LUX         |

Abbreviations: G = Germany; LUX = Luxembourg; RLP = Rhineland-Palatinate
Table A1.3: Actors’ list of the case study Ruhr

| N° | Acronym    | Actor’s name                                      | Actor type                              | Nationality |
|----|------------|---------------------------------------------------|-----------------------------------------|-------------|
| 1  | ARW        | Association of Waterworks Rhine                   | Water association                       | G           |
| 2  | AWWR       | Association of Waterworks Ruhr                    | Water association                       | G           |
| 3  | BMG        | Federal Ministry of Health                        | National political actor                | G           |
| 4  | BMU        | Federal Ministry for the Environment,              | National political actor                | G           |
|    |            | Nature Conservation, Building and Nuclear Safety, |                                        |             |
|    |            | Germany                                           |                                        |             |
| 5  | BUND.NRW   | Friends of the Earth Germany, regional group NRW  | Environmental NGO                       | G           |
| 6  | CoA.NRW    | Chamber of Agriculture, NRW                        | Polluter                                | G           |
| 7  | CompCent.  | Competence Centre Micro-pollutants, NRW           | Scientific institution                  | G           |
|    | NRW        |                                                   |                                        |             |
| 8  | DA.Duess   | District authority Düsseldorf, NRW                 | Regional political actor                | G           |
| 9  | DEW21      | Dortmund Energy and Water Supply Ltd              | Service provider                        | G           |
| 10 | EAWAG      | Swiss Federal Institute of Aquatic Science and    | Scientific institution                  | CH          |
|    |            | Technology                                        |                                        |             |
| 11 | Fish.NRW   | Fishing union NRW                                 | Consumer organization                   | G           |
| 12 | Fish.RUHR  | Cooperative association of fishing in the Ruhr     | Consumer organization                   | G           |
| 13 | Gelsen.plc | Gelsenwasser plc – Drinking water provider        | Service provider                        | G           |
| 14 | InstHyg.Gelsen | Institute of Hygiene, Gelsenkirchen              | Scientific institution                  | G           |
| 15 | IVA.NRW    | Agricultural-industrial association, NRW          | Polluter                                | G           |
| 16 | IWW        | IWW Water Centre, Water Research Institute        | Scientific institution                  | G           |
| 17 | MKULNV     | Ministry for Climate Protection, Environment,     | Regional political actor                | G           |
|    |            | Agriculture, Nature & Consumer Protection, NRW    |                                        |             |
| 18 | Paper.NRW  | Industrial federation of the paper industry,      | Polluter                                | G           |
|    |            | NRW                                               |                                        |             |
| 19 | RLV        | Rhenish Agricultural Association                   | Polluter                                | G           |
| 20 | RV         | Ruhrverband – Non-profit water management company | Polluter                                | G           |
| 21 | RVR        | Regional association of the Ruhr region           | Regional political actor                | G           |
| 22 | RWTHAach   | Rhenish Westphalian Technical University Aachen    | Scientific institution                  | G           |
| 23 | RWW        | Rhenish Westphalian Waterworks Ltd                | Service provider                        | G           |
| Nº | Acronym  | Actor’s name                                    | Actor type             | Nationality |
|----|----------|-------------------------------------------------|------------------------|-------------|
| 24 | UBA      | Federal Environmental Agency                    | National political actor | G           |
| 25 | UNI.Boch | University Bochum                               | Scientific institution  | G           |
| 26 | UNI.Duis | University Duisburg-Essen                        | Scientific institution  | G           |
| 27 | VKU.NRW  | Association of Municipal Enterprises, NRW        | Service provider        | G           |
| 28 | WLV      | Westphalian Agricultural Association             | Polluter                | G           |
| 29 | WWW      | Waterworks Westphalia                            | Service provider        | G           |

Abbreviations: CH = Switzerland; G = Germany; NRW = North Rhine-Westphalia
Table A1.4: Number of actors, number of returned questionnaires, response rate

|                | Basel | Moselle | Ruhr | Total |
|----------------|-------|---------|------|-------|
| N              | 51    | 44      | 39   | 134   |
| Questionnaires returned | 39    | 32      | 29   | 100   |
| Response Rate  | 76.5% | 72.7%   | 74.4%| 74.6% |

Table A1.5: Case study Basel: Descriptive statistics of the actor network

|                              |       |
|------------------------------|-------|
| Network size (no. of actors) | 51    |
| Network density (%)          | 0.139 |
| (no. of ties)                | (355) |
| Degree centralization (%)    | 0.508 |
| Reciprocity (%)              | 0.315 |
| Transitivity (%)             | 0.389 |

Table A1.6: Case study Moselle: Descriptive statistics of the actor network

|                              |       |
|------------------------------|-------|
| Network size (no. of actors) | 44    |
| Network density (%)          | 0.158 |
| (no. of ties)                | (298) |
| Degree centralization (%)    | 0.396 |
| Reciprocity (%)              | 0.263 |
| Transitivity (%)             | 0.528 |

Table A1.7: Case study Ruhr: Descriptive statistics of the actor network

|                              |       |
|------------------------------|-------|
| Network size (no. of actors) | 39    |
| Network density (%)          | 0.179 |
| (no. of ties)                | (265) |
| Degree centralization (%)    | 0.610 |
| Reciprocity (%)              | 0.233 |
| Transitivity (%)             | 0.519 |

Note: Network density is defined as proportion of observed relations in relation to all possible relations. Degree centralization indicates the dependence of the network on one or a small number of actors. Reciprocity shows the share of ties (dyads) in the network that are "confirmed" between two actors. Transitivity displays the degree of ordered triplets in which i \(\rightarrow\) j and j \(\rightarrow\) k. All network measurements were calculated using dichotomized data. Before calculating network centralization, the data were symmetrized.
Table A1.8: Case study Basel: Descriptive statistics of the ecological network

| Network size (no. of sub-catchments) | 74 |
| Network density (%) (no. of ties) | 0.014 (73) |
| Degree centralization (%) | 0.014 |
| Reciprocity (%) | 0.000 |
| Transitivity (%) | 0.000 |

Table A1.9: Case study Moselle: Descriptive statistics of the ecological network

| Network size (no. of sub-catchments) | 31 |
| Network density (%) (no. of ties) | 0.032 (30) |
| Degree centralization (%) | 0.038 |
| Reciprocity (%) | 0.000 |
| Transitivity (%) | 0.000 |

Table A1.10: Case study Ruhr: Descriptive statistics of the ecological network

| Network size (no. of sub-catchments) | 11 |
| Network density (%) (no. of ties) | 0.091 (10) |
| Degree centralization (%) | 0.144 |
| Reciprocity (%) | 0.000 |
| Transitivity (%) | 0.000 |

Note: Network density is defined as proportion of observed relations in relation to all possible relations. Degree centralization indicates the dependence of the network on one or a small number of actors. Reciprocity shows the share of ties (dyads) in the network that are “confirmed” between two actors. Transitivity displays the degree of ordered triplets in which \(i \rightarrow j\) and \(j \rightarrow k\). All network measurements were calculated using dichotomized data. Before calculating network centralization, the data were symmetrized.

Table A1.11: Motif statistics

| Case Study | Number of identified motifs with 3 nodes | Number of identified motifs with 3 nodes (level attributes) | Number of identified motifs with 4 nodes | Number of identified motifs with 5 nodes |
|------------|------------------------------------------|----------------------------------------------------------|----------------------------------------|----------------------------------------|
| Basel      | 9                                       | 27                                                       | 43                                     | 277                                    |
| Moselle    | 9                                       | 27                                                       | 43                                     | 212                                    |
| Ruhr       | 9                                       | 25                                                       | 39                                     | 79                                     |
**Figure A1.1:** The catchment area of the Rhine River, divided into sub-catchments of Strahler stream order ≥ 4 (there are no sub-catchments indicated on the Dutch territory)

- Number of catchments: 336
- Mean area: 477 km²
- Min area: 3 km²
- Max area: 4237 km²
Figure A1.2: Catchment area of the Basel case, indicating its 74 sub-catchments of Strahler stream order $\geq 4$ and their connection among each other.
Figure A1.3: Catchment area of the Moselle case, indicating its 31 sub-catchments of Strahler stream order ≥ 4 and their connection among each other.
Figure A1.4: Catchment area of the Ruhr case, indicating its 11 sub-catchments of Strahler stream order ≥ 4 and their connection among each other.
ERRATUM – added 14 January 2020

The subsequent erratum addresses two shortcomings of the paper “Multilevel water quality management in the international Rhine catchment area: how to establish social-ecological fit through collaborative governance”. First, the discussion and interpretation of the results reported in the RESULTS and CONCLUSION sections, Figures 3-5 are incomplete in terms of a full discussion of under-represented misfit motifs. Second, the authors were made aware of a potential misleading interpretation of the values reported as p-values in Figures 3-5. These deviate from standard statistical use of p-values as a test statistics. Indeed the authors themselves overlooked the two-tailed implication of the p-value as it is defined in the analysis (see e.g. notes to Figure 3). Consequently, p-values of “1” (or close) have erroneously not been considered as significant results. Therefore, the frequency values in Figures 1–3 might have been slightly overemphasized, in particular regarding the comparison between the empirical and the random networks. In two out of the three cases, these differences are only minor in absolute values, as outlined in detail below.

Generally, these shortcomings do not change the major conclusions of the paper. Only one conclusion with respect to the similarity of the three cases had slightly to be adapted. However, for reasons of full transparency the authors decided to disclose shortcomings in this erratum.

RESULTS SECTION

In the Moselle region (Figure 3), we outline in the paper that the three misfit motifs $a_1$, $BC3$, and $c1b$ have a higher frequency than expected by chance. However, particularly in the case of $a_1$, outlining that actors who are connected to the same sub-catchment are not collaborating with each other, the difference in terms of frequency is minimal. We need to conclude that this indicates a rather small substantial difference.

Additionally, we discuss here the misfit motifs $b1$, $BC4$ and $c1a$. They occur more often in the random networks. Thus, the under-representation indicates lower misfit than expected. Again, the observed effect regarding frequency is rather small in the case of $BC4$ and $c1a$.

Results for the Ruhr region (Figure 4) are described correctly. But generally we have to add that, in terms of frequency, the differences between the empirical and the random networks are rather small.

For the Basel region (Figure 5), motif $a_1$ as one typical baseline misfit configuration is rather frequent (over 20%), but slightly less as in the random networks. In the original paper, this result was described as not significant although—following the p-value definition—it is significant. Similarly, the misfit motifs $b1$, $c1a$, and $c1b$ occur significantly less often in the empirical network compared to the random networks. The under-representation of these misfit motifs indicates a stronger overall fit in the Basel region.
DISCUSSION AND CONCLUSION SECTION

We stated in the original paper, that three out of four fit motifs occur significantly more often in the empirical networks than in the random networks. This statement has to be completed by the observation that in the Moselle and the Basel regions, the misfit motifs occur less often compared to the random networks thus indicating a sign of fit. This under-representation of misfit motifs could not be observed in the Ruhr region. Hence, we have to revise our conclusion stated in the last paragraph of the paper that there were no significant differences between the three case studies. Actually, there are and we have an overall trend to misfit in the Ruhr region, and fit in the regions of Basel and Moselle. The Ruhr is the only single-country case with no strong cross-border and international dynamics. It is thus rather a counterintuitive finding, that fit in a jurisdictionally non-fragmented region is lower than in fragmented ones. And this needs further investigation. But an explanation for the enhanced fit in the two trans-boundary regions of Basel and Moselle is that this cross-border setting gives more incentive for collaboration and finally fit. While in a single country context the borders of environmental problems remain mainly invisible, national borders—even when they do not match with environmental problem borders—could initiate some culture or demand for cross-border collaborative resource management or at least change the perception of collaboration by the involved actors. Thus, upstream- and down-stream dynamics as well as international treaties and commissions (such as the International Commission for the Protection of the Rhine) require cross-border and trans-national coordination of actions in the Rhine. To conclude, problem pressure and trans-national institutions might be important triggers for collaboration and social-ecological fit.