The Role of Complexity in Addressing the Water Quality Challenge

Dissertation

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Summary

Poor quality of freshwaters is a widespread and challenging problem for humankind. The concept of complexity is a particularly promising concept to analyse and address this problem, and public policy problems more generally. The main reason is the concept's strength in unifying structural features of problems within a more comprehensive structural approach to political problem-solving. So far, however, these possible benefits remained hidden given the lack of a clear understanding of complexity, ultimately hampering a systematic analysis of the implications of complexity for solutions and governance strategies.

This study aims at strengthening the value of the concept of complexity for systematic comparative analyses of water-related problems and public policies in general. To achieve this goal, this work is to specify the concept of complexity as well as the implications of complexity for solutions and governance strategies, both from a theoretical and an empirical point of view. To this end, five main basic approaches are applied, referring to underlying premises, the role of an interdisciplinary approach, the European Water Framework as an empirical reference point, the integration of practical knowledge, and the focus on external validity. Main results are:

i. Operationalisation and measurement: This dissertation provides a detailed operationalisation of complexity related to the dimensions of goals, variables, dynamics, interconnections, and informational uncertainty. It also shows that freshwater pollution-related problems in Germany differ along these five complexity dimensions. This applies to 37 types of pollution-related problems and four clusters of problems, which refer here to tame, wicked, system complexity, and uncertainty problems.

ii. Implications of complexity for solutions: This dissertation suggests that relations between complexity and policy delivery can be both positive and negative and vary along dimensions of complexity and policy delivery. Regarding the analysed freshwater pollution problems, this work also shows various effects of complexity on policy delivery, both along the 37 types of problems, and along four clusters of wicked problems.

iii. Implications of complexity for governance: This dissertation suggests a differentiated theoretical approach to define governance for complex problem-solving, demonstrating that the role of diverse institutions, actors, and interactions differs for solutions along five key dimensions of complexity: goals, variables, dynamics, interconnections, and informational uncertainty, and different management strategies that are information gathering, modelling, using decision-support tools, prioritising of measures, conflict solving, deciding under uncertainty, and being adaptive and flexible.

Future research is recommended to build on these results, by providing further empirical evidence and contextualising the approach on governance for complex problem-solving. Following this path may help to contribute to turn the “logic of failure” (Dörner 1996) regarding complex problem-solving into a “logic of success” for addressing problems of varying complexity in public (water) policies.

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Sabrina Kirschke

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I. Framework paper

1. Introduction: Setting the problem

1.1 The practical problem: Addressing the water quality challenge

Poor water quality has become a prevalent problem of humankind. This concern has been highlighted on a global scale (UNESCO 2012), but particularly also for continents such as Europe (EEA 2012) and Asia (Evans et al. 2012). In the north-western part of Europe, for instance, the ecological status or potential of rivers and lakes is particularly alarming, with about 90 per cent of the respective water bodies not having a good status (EEA 2012, p. 38). Germany is representative here, with a notably large number of water bodies in less than a good status (BMU 2010).

Such prevalence of poor water quality is problematic, given its negative impacts on biodiversity of aquatic and terrestrial species as well as on the health and wealth of human beings. Freshwater species, for instance, have rapidly declined due to water pollution and flow modification, among others (Dudgeon et al. 2006). Waterborne diseases, especially diarrhoea, are one of the most important causes of death among small children (WHO 2002). Moreover, insufficient wastewater treatment might increase the risk of antimicrobial resistance, ultimately increasing the risk of heading into a post-antibiotic era (Caucci 2016).

Given these widespread, negative impacts of poor water quality, the qualitative status of waters has become a priority topic in the international discourse on sustainable development. Sustainable Development Goal (SDG) 6.3 explicitly calls for a better quality of freshwater resources (E/CN.3/2017/2). In the European Union, achieving a good ecological and chemical status of European freshwaters is a goal that has been formalised with the adoption of the European Water Framework Directive (WFD) in 2000. This directive aims at achieving a good status of waters by 2015 or 2027 at the latest (Directive 2000/60/EC).

Achieving SDG 6.3 on water quality and implementing respective legal frameworks such as the WFD require addressing a set of important pressures on surface waters and groundwater. On a European level, these pressures pertain, in particular, to diffuse and point source pollution, physical modifications, and the overexploitation of water. Concerning diffuse pollution, for instance, the input of nutrients such as nitrogen and phosphorus is a major problem. Regarding physical modifications, major problems relate to the straightening of rivers or migratory obstacles such as dams, among others (EC 2003).

Addressing these pressures has, however, turned out to be a challenging problem. Germany is a case in point. Despite various activities of German public authorities to address the water quality problem, more than 80 per cent of Germany's surface water bodies and more than 30 per cent of groundwater

bodies were not likely to achieve a good status by 2015 (BMU 2013). One example are the pressures from agriculture in the form of the input of nutrients into groundwater through leaching. Addressing such a problem is particularly challenging as it involves going beyond given codes of practice and implementing special measures such as catch crop or undersown cultivation (LAWA 2013).

1.2 Approaching the problem: Structural approaches and the concept of complexity in analysing public (water) problems

Failure in addressing the poor quality of freshwaters has increasingly been pinned on the complexity of the underlying problem. The basic idea is that (i) water resource management problems such as micro pollution or diffuse pollution linked to agriculture are complex, (ii) attempts to address such complex problems tend to fail, and (iii) there is a need for special, mostly participatory governance strategies, in order to address such complex problems in practice (e.g., Pahl-Wostl 2007, Patterson et al. 2013, Metz and Ingold 2014, Bjornlund et al. 2018). But what does the concept of complexity as a structural approach have to offer for analysing the water quality challenge?

Structural approaches have been typically used to analyse political problem-solving. Such approaches analyse the relationship between governance and solutions to problems depending on the intervening variable of the structure of problems. Put differently, they derive relevant governance strategies for problem-solving from the underlying analytical structure of problems (e.g., Peters 2005, Dose 2008, Peters and Pierre 2015). In public policy, examples for such approaches refer to the impacts of the general solvability of problems on the role of various governance strategies such as the use of contracts, partnerships, networks, and soft law (Peters and Pierre 2015). In the field of water management, researchers analyse, for instance, the impact of participation on addressing water-related problems along normative and informational uncertainty related to these problems (e.g., Newig et al. 2005).

Structural approaches are particularly relevant in the analysis of political problem-solving. First, and most generally speaking, problems and their solutions are predominant in policy field analysis (e.g., Peters 2005, Dose 2008, Hoppe 2011, Peters and Pierre 2015). Second, knowing about structures of problems helps to identify more effective governance strategies to address problems (Peters 2005, Dose 2008, Peters and Pierre 2015). The identification of problem structures can, for instance, be essential to understand and possibly change the responsibilities of public authorities for problem-solving. An example case is the problem of diffuse pollution of freshwaters by agriculture. Whereas water authorities are traditionally meant to address water pollution, an understanding of the problem structure ‘interconnections between water and soil’ suggests applying more complex institutional settings to address this problem (Peters 2005, Kurian and Ardakanian 2015). Third, structural approaches allow for analysing governance strategies along regional scales and policy (sub)-fields. This

is done by overcoming the problem of transferability of results produced in single case studies on the one hand and quantitative analyses on the other. The transfer and application of results of both single case studies and quantitative analyses rely in fact on various conditions. Structural approaches have, however, the potential to combine the benefits of case-specific and quantitative analyses for efficient problem-oriented analysis (Kirschke and Hagemann 2014, Hagemann and Kirschke 2017).

Given these benefits of structural approaches in problem-oriented governance analyses, researchers have identified several structures of problems which are likely to impact the relationship between governance and solutions to problems. In public policy analysis in general, there are numerous examples of structural approaches to problems (e.g., Rittel and Webber 1973, Peters 2005, Dose 2008, Peters and Pierre 2015, Alford and Head 2017). For instance, Peters (2005) suggests seven types of structures, namely solubility, complexity, the question of scale, divisibility, monetarisation, the scope of activity, and interdependencies. In the field of water management, examples refer to different types of uncertainty, in particular (e.g., Newig et al. 2005, Sigel et al. 2010). Newig et al. (2005), for example, differentiate two types of uncertainty: normative and informational. Based on this differentiation, the authors suggest varying participatory strategies to address these problems.

Hence, structural approaches to political problem-solving are pivotal when analysing public policy problems. Relevant studies have, however, a typical shortcoming: they only focus on analysing single or specific types of problem structures, ultimately hindering researchers from identifying a comprehensive set of governance strategies for addressing problems. Take, for instance, traditional differentiations along types of uncertainty. Whereas the differentiation of types of uncertainty enables systematic discussions of governance strategies related to uncertainty, such an analysis systematically excludes problem structures and related governance strategies that are independent of uncertainty. An example is the structural dimension of dynamics in political problem-solving. Some dynamics of problems are in fact well-known but are still neglected in problem-solving analyses as shown in the field of climate change (Sterman and Sweeney 2002, Amelung and Funke 2013).

To overcome such shortcomings of structural approaches in public policy analysis, an integrated view of problems is needed. The concept of complexity is particularly helpful in this regard. It has the potential to integrate most different structural features of problems within a comprehensive structural approach to political problem-solving. For instance, the concept can encompass normative and informational uncertainty as well as dynamics of real-world problems (e.g., Dörner 1996, Funke 2012). By consequence, the concept is also widely used and has recently been promoted as an overarching concept for discussing various structures of problems in public policy analysis (Peters and Pierre 2015).

Approaching the water quality challenge with the complexity lens thus makes sense if researchers aim at a comprehensive understanding and analysis of problems.

1.3 Deficits in applying the concept of complexity in the analysis of public (water) problems

Applications of the concept of complexity in the analysis of public (water) policies show, however, severe deficits. The main problem is a lack of a clear understanding of complexity (Peters 2017). This is not to so say that literature would not have provided plenty of conceptualisations. Examples refer to complexity conglomerates that encompass several essential features of complexity such as a large number of interrelated factors (e.g., Ingraham 1987, Wagenaar 2007). Further examples relate to qualitative binary concepts concerning simple or tame versus complex or wicked problems, partly based on single dimensions of complexity such as the number of influencing factors (e.g., Rittel and Webber 1973, Bathie 2008, Weber and Khademian 2008, Funke 2012). Furthermore, there are examples of gradual (numerical) concepts of complexity, highlighting gradual variations between simple and complex problems on a 0–1 scale (e.g., Ingraham 1987, Voss et al. 2007).

Even though these approaches provide critical qualitative and quantitative features of complexity, they do not combine these features within one concept. Considered separately, the approaches thus fail to differentiate clearly between both various dimensions and degrees of complexity. This is particularly problematic when it comes to describing public policy-, and especially water-related problems. Water-related problems in general (Lach et al. 2005, Lund 2012) or related (implementation) problems such as Integrated Water Resources Management (IWRM), an adaptive management (Imperial 2005, Pahl-Wostl 2007, Pahl-Wostl et al. 2012), diffuse water pollution (Patterson et al. 2013, Tan and Humphries 2018), micro pollution (Metz and Ingold 2014), an urban water management (Head 2014a) or the safe use of wastewater in agricultural production (Nölting et al. 2017, Dare and Mohtar 2018) seem to be highly complex or wicked indeed. However, their complexity degrees may differ in detail. Some sub-problems such as the reduction of migratory obstacles for fishes or the implementation of wastewater treatment plants may vary considerably in a range from simple to complex. Without a clear differentiation of various degrees and dimensions of complexity, it is not possible to precisely describe these differences between problems.

Due to this vague understanding of complexity, the implications of complexity for political problem-solving remain vague as well. Complexity has continuously been mentioned as the primary suspect for the failure of water-related policies. It has been continuously argued that structural features of complex problems such as connections of socio-ecological systems, system dynamics, and differing interests of stakeholders pose immense difficulties for public authorities when facing complex water-related problems. These assumptions have also triggered the investigation of new or more adequate

governance strategies to address this specific class of public policy problems (Pahl-Wostl 2007, Patterson et al. 2013, Head 2014a).

However, the specific impacts of complexity on solutions to water-related problems remain unclear. There may be a negative relationship between complexity and solutions to problems indeed. However, simplistic relationships between complexity, on the one hand, and failure to address complex problems, on the other hand, can be questioned. First, complexity could result in various types of outputs which impact problems more or less effectively (Newig 2003, 2007). For instance, complexity could result in non-actions or ineffective actions. Whereas non-action means that public authorities do not take any actions to address a problem, ineffective actions emphasise that actions taken by public authorities do not address problems effectively (Head 2014b). Second, such different types of failure may be related to various dimensions of complexity. For instance, research in the field of psychology suggests that humans are prone to ignore inherent dynamics and interconnections of problems which may eventually result in ineffective actions. In contrast, goal conflicts may prevent public authorities from taking actions in general (e.g., Dörner 1996).

In addition to an insufficient understanding of the implications of complexity for problem-solving, vague understandings of complexity also result in somewhat vague understandings of governance strategies to address these problems. There is a lively debate on governance and complex problem-solving indeed (Duit et al. 2010, Gerrits and Marks 2015). Researchers suggest closely related political models to address complex or "wicked" problems. Popular concepts focus on reflexive (Voss and Kemp 2006, Loorbach 2010), participatory-deliberative (Durant and Legge 2006, Wagenaar 2007, Jentoft and Chuenpagdee 2009), and network governance (Weber and Khademian 2008, Ferlie et al. 2011). By implication, researchers also question more hierarchical, especially science-driven models of political problem-solving (Bathie 2008, Head and Alford 2015, Head and Xiang 2016).

Such contributions provide valuable critiques of simplistic planning approaches in political and administrative science. They also convincingly argue that participatory instead of hierarchic modes of governance are essential. However, emphasising participation as a central mechanism to address complexity falls a bit short. First, proponents of upcoming design studies argue that sets of tools instead of single tools are required to address problems (Howlett 2014, Howlett et al. 2015). This particularly applies to the field of wicked problems (Head 2014b). Second, the benefits of participation in political problem-solving are not clear. In the field of environmental management, for instance, participatory approaches do not necessarily benefit complex problem-solving (Koontz and Thomas 2006, Newig and Fritsch 2009). Research instead argues here that the impact of specific participatory approaches on solutions depends on specific goals and contextual factors (e.g., Bryson 2013), such as the degree of

informational and normative uncertainty (e.g., Newig et al. 2005). Moreover, it has been suggested that further governance strategies such as the definition of precise rules can impact the achievement of environmental management goals (e.g., Biddle and Koontz 2014). Against such considerations, there is a pressing need for a more differentiated approach to governance and complex problem-solving in general, and with regard to water-related problems, more particularly.

1.4 Research goals and outline

Against this background, the overarching goal of this dissertation is to strengthen the value of the concept of complexity for systematic comparative analyses of public policies in general and freshwater quality-related problems, in particular. The overarching question is:

How can the value of the concept of complexity be strengthened for the analysis of public policies in general and freshwater quality-related problems, more particularly?

Based on the identified research lack, the primary way for strengthening the value of the concept of complexity is a *specification* of the concept of complexity itself and of its implications for solutions and governance. This encompasses three questions:

1. Operationalisation and measurement of complexity: How can the concept of complexity be operationalised for analysing public policies? How complex are freshwater quality-related problems?
2. Implications of complexity for solutions: Which impacts has complexity on solutions to problems, both from a theoretical perspective and based on empirical evidence regarding freshwater-related problems?
3. Implications of complexity for governance: Which impact does complexity have on the definition of governance strategies for problem-solving?

These three questions relate to three specific working goals:

1) Operationalisation and measurement of complexity: This work aims to operationalise and measure complexity in political problem-solving by differentiating relevant dimensions and degrees of complexity. A differentiated understanding of complexity goes beyond vague dichotomisations along simplicity and complexity, which is crucial when analysing the implications of complexity for political problem-solving.
2) Implications of complexity for solutions: This work seeks to specify the implications of complexity for solutions to problems by analysing the relationship between complexity and policy delivery. A more precise understanding of the impacts of complexity goes beyond vague

discussions along success and failure in complex problem-solving, which is particularly relevant to understand constraints in addressing problems.

3) Implications of complexity for governance: This work aims to specify the role of complexity in the relationship between governance and problem-solving by explicitly addressing causal mechanisms between complexity, governance, and solutions. This is to overcome simplistic discussions of the role of participation and hierarchy for addressing simple and complex problems, relevant to addressing complex problems in practice effectively.

These three questions and working goals regard both theoretical development and empirical insights. In terms of theoretical development, this work aims at innovations around the concept of complexity, hypotheses on the implications of complexity on solutions, and the role of governance strategies in addressing complex problems. In terms of empirical insights, this work seeks to provide in-depth analyses of complexities and their implications for solutions to problems, as well as examples of causal mechanisms between complexity, governance, and solutions.

The three questions and working goals are addressed in four research papers. The operationalisation and measurement of complexity are mainly addressed in papers 1 (Kirschke et al. 2017b) and 3 (Kirschke et al. 2019). The implications of complexity for solutions and policy delivery, more particularly, are mainly addressed in papers 2 (Kirschke et al. 2017a) and 3 (Kirschke et al. 2019). The implications of complexity for identifying governance strategies are mainly tackled in paper 4 (Kirschke and Newig 2017).

The following sections present basic approaches, key findings, and main contributions of these four research papers and in relation to these three questions and working goals. Section 2 elaborates on overarching methodological approaches to address the working goals. These basic approaches relate to all research papers and questions, and help us to both understand and locate this work in the range of analyses on governance and complex problem-solving. Section 3 then summarises the results of the four research papers of this dissertation along with the single papers and the three questions of this dissertation. Section 4 discusses the results and relevant questions for future research in the field of governance and complex problem-solving. Finally, section 5 concludes with the major contributions of this dissertation.

2. Basic methodological approaches

This section discusses basic approaches to answer the three questions of this dissertation. These basic approaches have guided all research papers and include theoretical and empirical aspects of this work. They refer to underlying premises, the role of an interdisciplinary approach, the European Water

Framework as an empirical reference point, the integration of practical knowledge, and the focus on external validity. The following sub-sections describe these approaches, illustrate their application in the research papers, and discuss their usability to answer the questions.

2.1 Premises

A first basic approach relates to three underlying premises of this dissertation. These premises refer to the possibility to subjectively define problems, the possibility to address problems, and the interest of public authorities in addressing problems. 'Possibility to define problems' means that it is possible to at least subjectively determine complexity features of problems such as inherent conflicts between stakeholders or the number of factors that influence solutions to problems. 'Possibility to address problems' means that solutions are clear baselines for evaluating the success of governance strategies in addressing problems. Further, 'interests in addressing problems' means that public authorities are indeed interested in solving problems and thus cannot be described as sheer power-seeking entities, for instance.

These three premises relate to all three working goals. First, the possibility to define problems is a clear prerequisite for measuring complexity and evaluating implications of complexity for solutions and governance. Attempts to measure complexity only make sense if we accept the possibility to define problems; analysing the implications of complexity is only possible if we accept that the structure of problems can be described. Second, the premise of the possibility to address problems underlies the goal of operationalisation and is relevant to analysing the implications for solutions. Operationalisations and analyses of the implications seem in fact only to be relevant if we assume that operationalisations can have implications for solutions. Third, interests in problem-solving are in general crucial for defining and solving problems.

Applying these three premises is, however, challenging. Regarding problem definitions, there are arguments to suggest that humans are in fact limited to understand all relevant features of complexity. Psychology research has demonstrated that problem solvers are not fully aware of the complexity of problems so that they treat complex problems as simple problems. This particularly applies to the complexity dimensions of dynamics and interconnections (e.g., Sweeney and Sterman 2000, Sterman and Sweeney 2002, Cronin et al. 2009, Schmid et al. 2011). An example refers to climate engineering. Here, Amelung and Funke (2013) convincingly argue that humans are prone to critical errors when they try to address complex problems. However, a clear understanding of features of problems is relevant to identify effective governance structures to address these problems (Metz and Ingold 2014, Peters and Pierre 2015). Further, in agreement with Metz and Ingold (2014, p. 1998), indeed "difficulties cannot lead us to ceasing to try to understand the root causes of policy problems. It can only be

understood as a warning to reject any overly simplistic view and instead approach policy problems comprehensively".

Further, referring to solutions presupposes that there is agreement on both the current and the target state. This is a condition that is, of course, often not met (Durant and Legge 2006, Voss et al. 2007, Bathie 2008, Hoppe 2011). Second, even if there is agreement on the target state, it is often difficult to determine whether this state is achieved since complex problems tend to entail untraceable side effects of actions (Rittel and Webber 1973, Wagenaar 2007, Batie 2008, Weber and Khademian 2008, Funke 2012). Moreover, addressing solutions in the field of water management is particularly challenging given that some effects are delayed in time and are thus difficult to assess (Sigel et al. 2010) – a case that particularly applies to groundwater resources (Theesfeld 2010). However, failure to operationalise solutions is even less acceptable. For instance, researchers could confine themselves to discussing how to deal with complexity in a general way and thus give up the goal of defining useful strategies to address complex problems. This missing link between instruments and outcomes has in fact recently been criticised in the field of wicked problem-solving (Howlett and Lejano 2015).

Finally, assuming interests in solutions can be problematic as well. Politicians and public authorities can have several motives to act. For politicians, for instance, a vital motive can be re-election. However, this work still sticks to the underlying premise of interests in solutions since solving problems is at least in theory one core goal of politicians and public authorities.

2.2 Interdisciplinary approach

A second basic approach relates to the role of interdisciplinarity in answering the research questions. Interdisciplinarity means here to rely on knowledge from different scientific disciplines to answer the three questions. From a theoretical point of view, this work relies, next to knowledge in the field of political and administrative science, on knowledge provided by psychology research. From an empirical point of view, this work refers to research traditions that are more closely related to water management such as engineering and the natural sciences.

The approach of interdisciplinarity relates to all three research questions. First, psychology research is used to operationalise complexity, to define the implications of complexity for solutions to problems and to discuss the relationship between governance, complexity, and solutions. Second, the engineering and natural sciences serve to apply the operationalisation of complexity and to define implications of complexity for solutions.

Referring to psychology research to conceptualise complexity and its impacts has several advantages over predominant approaches in political and administrative science. First, relying on psychology

research allows us to differentiate clearly dimensions and degrees of complexity given a long-standing research tradition on complex problem-solving in psychology (e.g., Funke 2012). Second, relying on psychology research allows for identifying micro-foundations for the implications of complexity for solutions and governance strategies. One could critically argue that results from psychology research could not be transferred to political analyses, given that they result from laboratory experiments. However, many experiments this work refers to are based on so-called micro worlds which reflect real-world problems quite well (e.g., Dörner 1996).

Further, referring to different scientific disciplines such as engineering and the natural sciences to apply the concept of complexity is particularly important given the limitations of humans to recognise different facets of a problem. In fact, relying on interdisciplinary knowledge allows for a more substantiated understanding of real-world problems, which ultimately serves to validate results.

2.3 The case of implementing the European Water Framework Directive in Germany

A third basic approach refers to the empirical reference point of the implementation of the European Water Framework Directive (WFD) in Germany. The WFD is a major regulation for water management in Europe. Its primary objective is to achieve a good ecological and chemical status of European freshwaters by 2015. To achieve this goal, EU member states had to (i) evaluate the state of waters, (ii) plan how to address water quality-related problems, and (iii) implement measures to address these problems, among others. In case of failure to achieve water quality-related goals by 2015, two subsequent planning processes allow for adjustments of measures to achieve WFD's goals by the end of 2027 (Directive 2000/60/EC).

This dissertation refers to specific facets of the implementation process of the WFD in Germany. Technically speaking, it focuses on specific problems public authorities currently address to improve the status of waters. These problems relate to types of measures as defined by the *Bund-/Länderarbeitsgemeinschaft Wasser* (LAWA). These types of measures have different abstraction levels. On a macro level, LAWA differentiates key pressures, amongst them hydro-morphological alterations, point, and diffuse-source pollution. On a meso level, there are different sub-types of these key pressures. In the field of point and diffuse-source pollution, for instance, these sub-types refer to different polluter groups such as agriculture, mining, and urban wastewater discharge, among others. On a micro level, LAWA further differentiates about 100 types of sub-pressures. In the field of agriculture, for instance, there are various pathways and types of matters such as leaching of nutrients or the input of pesticides into groundwater (LAWA 2013).

This dissertation refers to a subset of these different types of problems to address all three research goals. First, 37 types of sub-pressures in the field of point and non-point pollution help to apply a clear-

cut operationalisation of complexity. Second, these 37 problems are used to analyse the implications of complexity for solutions. Third, this work refers to examples in the field of Integrated Water Resources Management in general, and various key and sub-pressures such as hydro-morphological alterations and non-point pollution in particular, to illustrate the relationship between governance, complexity, and solutions to problems.

There are both problem-related and theoretical reasons to take the implementation process of the WFD in Germany as a point of reference. From a problem-related point of view, the implementation process of the WFD in Germany refers to a major environmental problem in Germany. First monitoring cycles have shown that surface and groundwater bodies are in a somewhat poor condition (BMU 2010). Despite various activities of German public authorities to address this issue, more than 80 per cent of Germany's surface water bodies and more than 30 per cent of Germany's groundwater bodies were not likely to achieve a good status by 2015 (BMU 2013). This failure in achieving a good status of waters also influences other environmental fields negatively. An example is the eutrophication of coastal waters resulting from high nutrient loads of running waters (LAWA 2013). Further, referring to these 37 problems allows for addressing major issues in current water policy. Point and non-point source pollutions present two significant pressures on waters in Europe, in general (COM 2007), and in Germany, in particular (BMU 2010). The 37 types of sub-pressures also represent a predominant majority of problems German public authorities identified in addressing the issue of point and non-point pollution (LAWA 2013).

From a theoretical point of view, problems related to the implementation of the WFD in Germany are likely to vary in a range from simple to complex. The WFD is described as an attempt to implement an Integrated Water Resources Management (Dworak and Kranz 2005, Richter et al. 2013, Theesfeld and Schleyer 2013), which researchers reasonably describe as a complex problem (Imperial 2005, Pahl-Wostl 2007). However, there are arguments to suggest that specific problems of the WFD implementation differ in detail. This particularly applies to the level of sub-pressures in general and problems in the field of point and non-point pollution of groundwater and surface waters, in particular. For instance, research has suggested that some of these sub-pressures such as micro pollution (Metz and Ingold 2014) are particularly complex, going back to many polluters among others. Also, a varying number of monitoring sites and different flow velocities of groundwater and surface waters are likely to influence the degrees of informational uncertainty and dynamics. Comparative analyses of complexities in the field of sub-pressures are thus likely to result in variations. Such variations are necessary to demonstrate varying complexity degrees and to analyse their implications for solutions and governance strategies.

Further, referring to this case is also particularly relevant in terms of similar conditions for the analysis of problems and problem-solving. In fact, problems related to sub-pressures on waters seem to be comparable both in their scope and in their framework conditions for implementation. Regarding the scope, all types of problems refer to types of measures that public authorities have to implement on a federal state level. Concerning further framework conditions, federal states have to implement these measures within a set timeframe, and under the same overarching rules to address water quality-related problems.

2.4 Integration of knowledge provided by practitioners

A fourth basic approach relates to the integration of knowledge provided by practitioners to address the three working goals. This practical knowledge relates to the problems analysed in this dissertation, the measurement of their complexity, and outputs of problem-solving processes.

This work refers to knowledge of practitioners in addressing all three research goals. First, it relies on practitioners such as representatives of public authorities to define 37 water-related problems and to measure their complexity degrees. Second, it relies on these problems and their complexity degrees as well as on data from public authorities on policy delivery to analyse the implications of complexity for solutions to problems. Third, it relies on problems as defined by public authorities to illustrate the relationship between governance, complexity, and solutions.

There are several reasons for relying on the definition of problems by public authorities. To start with, this work aims at contributing to problem-solving approaches. Consequently, research should also be interested in addressing real-world problems. Further, valid measurements of complexity are more likely to be achieved if problems are a daily business of public authorities and not virtually constructed. Moreover, referring to these problems allows us to measure the implications of complexity for solutions since reporting on policy delivery is related to these problems. Despite these arguments for referring to these problems, such an approach is also risky given that problem descriptions provided by public authorities can be limited. For instance, researchers describe the problem of micro pollution as a complex, diffuse-source problem which is particularly difficult to be addressed (Metz and Ingold 2014). However, public authorities define micro pollution as a point-source pollution problem which seems to be limited (LAWA 2013).

Second, including practical knowledge next to substantiated scientific knowledge through interviews on problem complexity serves the validation of the results on complexities. Technically speaking, knowledge in a specific practical domain gives value to a specific viewpoint (e.g., public authorities or river basin organisations) whereas a specific transdisciplinary background of interviewees ensures most

generic assessments of problem complexities. This is particularly important given the limitations of human beings to recognise all the different facets of problems (Daviter 2017b, Funke et al. 2018). Here, it should be highlighted that practitioners are meant to provide new types of knowledge, in addition to scientific knowledge. Whereas social scientists may provide scientific knowledge on implementation, practitioners may have more practical knowledge of implementation challenges (e.g., Meuser and Nagel 2009).

Finally, this work relies on data from public authorities on policy delivery related to these problems. These data are best suited to evaluate solutions to problems since public authorities were obliged to report on the status of implementation, based on standard indicators, and at the same moment in time. However, these data also include some uncertainties. It is, for instance, unclear which specific criteria public authorities applied to define the status of implementation. However, such deficits may not prevail given the vast amount of data related to policy delivery.

2.5 External validity

A fifth basic approach relates to the emphasis put on external validity to answer the research questions. This relates to theory in particular, but also to empirical results. In terms of theoretical development, this work relies on abstract operationalisations and hypotheses which do not refer to a specific topic or problem area. By consequence, respective approaches can be applied to most different water-related problems. In terms of empirical evidence, this work refers to different types of problems in Germany in general, and not to one specific problem in one specific region.

This approach of rather high external validity serves to address all three research goals. First, this work relies on an abstract operationalisation and different types of problems to address the issue of operationalisation. Second, it relies on general hypotheses and on these types of problems to analyse the implications of complexity for policy delivery. Third, this work relies on general hypotheses and types of problems in order to discuss the relationship between governance, complexity, and solutions.

In terms of theoretical development, the main reason for the focus on external validity is that the research gap relates to both water management and public policies in general. Further, the basic idea is that structural approaches bring forward the debate on problem-solving exactly because of their lacking relation to specific contexts. In terms of the empirical analysis, generic definitions of problems are particularly well-suited to analyse the impact of complexity based on a bigger amount of data. If just a small set of specific problems had been defined, it would have been difficult to derive any meaningful results on the implications of complexity on solutions.

3. Results

This section summarises the results of the research papers along the four single research papers (3.1) and the three questions of this dissertation (3.2).

3.1 Summary of research papers

This dissertation comprises four published research papers. The papers have each been assigned short titles, namely "Mapping complexity" (Kirschke et al. 2017 b – paper 1), "Impacts of complexity" (Kirschke et al. 2017 b – paper 2), "Clusters of complexity" (Kirschke et al. 2019 – paper 3), and "Governance and Complexity" (Kirschke and Newig 2017 – paper 4) (see table 1). The four papers are briefly summarised below.

Table 1: Four research articles of this dissertation

No	Paper	Short title
1	Kirschke, S., Borchardt, D., Newig, J. (2017b): "Mapping Complexity in Environmental Governance: A comparative analysis of 37 priority issues in German water management", *Environmental Policy and Governance* 27(6), 534-559.	"Mapping complexity"
2	Kirschke S., Newig J., Völker J., and Borchardt D. (2017a): "Does problem complexity matter for environmental policy delivery? How public authorities address problems of water governance", *Journal of Environmental Management* 196, 1-7.	"Impacts of complexity"
3	Kirschke, S., Franke, C., Newig, J., Borchardt, D. (2019): "Clusters of water governance problems and their effects on policy delivery", *Policy & Society.*	"Clusters of complexity"
4	Kirschke, S., Newig, J. (2017): "Addressing Complexity in Environmental Management and Governance", *Sustainability* 9, 983.	"Governance and complexity"

3.1.1 Paper 1: "Mapping complexity"

Paper 1, "Mapping complexity", mainly addresses the operationalisation and measurement of complexity. Based on psychological research, in particular, complexity is operationalised along five dimensions, namely 'goals', 'variables', 'dynamics', 'interconnectedness', and 'informational uncertainty'. These five dimensions can each have low, middle, and high values, referring to simple, complicated, and complex problems. This operationalisation is applied to the 37 water pollution-related problems in Germany. The complexity degree of these problems is analysed based on 65 expert interviews, resulting in 158 complexity assessments. The analysis shows that problems tend to have medium degrees of complexity. However, the analysis also reveals varying degrees of complexity, with certain problems such as micro pollution being particularly complex and other, mostly point-source problems, being rather simple. These assessments of complexity degrees are based on 30 types of

arguments for complexity, referring to various technical, natural, and social sources of complexity. The results will enable the systematic identification of governance strategies for complex problem-solving.

3.1.2 Paper 2: "Impacts of complexity"

Paper 2, "Impacts of complexity", mainly addresses the analysis of the implications of complexity for solutions to problems. Based on literature in the field of complex problem-solving, this paper formulates hypotheses on the relationship between complexity and solutions to problems. The analysis shows here that complexity can be correlated both negatively and positively with policy delivery, and that such relations can vary along dimensions of complexity and stages of policy delivery. The paper then tests the hypotheses based on data on problem complexity and policy delivery related to the 37 types of pollution-related problems. The quantitative analysis reveals a relative dominance of negative correlations between complexity and policy delivery. Moreover, there are sporadic positive relations, as well as slight variations between dimensions of complexity and stages of implementation. These results hint at more "complex" impacts of complexity on solutions to problems than have been assumed in the literature. Governance strategies may also be adapted to respond to such complex challenges for problem-solving.

3.1.3 Paper 3: "Clusters of complexity"

Paper 3, "Clusters of complexity", addresses both the measurement of complexity and the implications of complexity for solutions to problems, here referring to the concept of 'wickedness'. The empirical paper first applies the methodology of factor and cluster analysis to the data set of 37 pollution-related problems in Germany. The factor analysis reveals three factors of 'wickedness', namely 'goals', 'uncertainty', and 'system complexity'. Based on variations of these three factors, subsequent cluster analysis based on WARD reveals four completely homogeneous clusters of wicked problems. These refer to 'system complexity', 'uncertainty', 'tame', and 'wicked' problems. These four clusters consist of problems related to different types of sources, polluter groups, and types of waters. Further empirical analyses also reveal that the four clusters of problems vary in their effects on different dimensions of policy delivery. These empirical insights may contribute to a more systematic design of governance strategies for addressing pollution-related freshwater problems along specific features of wicked problems.

3.1.4 Paper 4: "Governance and complexity"

Paper 4, "Governance and complexity", mainly addresses the questions of governance strategies for addressing complex problems. This paper is designed as a theoretical framework paper, presenting a differentiated theoretical approach to define governance for complex problem-solving. The approach

consists of two main steps: in a first step, management strategies for addressing complex problems were defined, based on results from psychology research, in particular. The paper identified six management strategies, namely information gathering, modelling, prioritising, conflict solving, deciding under uncertainty, and being adaptive and flexible. In a second step, the paper provides governance strategies that facilitate the implementation of these management strategies. These governance strategies regard institutionalisation (obligation and precision of rules), the involvement of different kinds of actors (e.g., scientists, local and political experts, facilitators), and the implementation of different forms of interaction (deliberation, negotiation, hierarchy). Linking management and governance strategies demonstrates that institutions, actors, and forms of interactions facilitate solutions to problems depending on the complexity dimensions of goals, variables, dynamics, interconnections, and informational uncertainty.

3.2 Summary along overarching research questions

This section summarises the research results along the three questions of this dissertation. A summary is provided in Table 2. The table shows in which way the four research papers as depicted in Section 3.1 contribute to answering the three overarching research questions as elucidated in Section 1.4. The colours represent the type of contribution, with 'green' referring to a core theoretical or empirical contribution of a paper to answering a question, 'yellow' referring to providing a basis for answering a certain question, and 'red' referring to the uptake of respective results provided in other papers. The table shows that the question of operationalisation and measurement of complexity is mainly addressed in papers 1 ("Mapping complexity") and 3 ("Clusters of complexity"). The implications of complexity for solutions, and policy delivery, more particularly, is addressed in papers 2 ("Impacts of complexity") and 3 ("Clusters of complexity"). The implications of complexity for identifying governance strategies are discussed in paper 4 ("Governance and complexity"). Moreover, all four research papers contribute to answering the three questions by providing the basis for other papers.

Table 2: Contribution of the four research papers to answering the three overarching research questions on the definition, impact, and governance of problems*

Paper	Operationalisation and measurement of complexity	Implications of complexity for solutions	Implications of complexity for governance
Paper 1: "Mapping complexity"	Original operationalisation of complexity; Original mapping of 37 types of problems	Basis for the analysis of impacts by operationalising and mapping complex problems	Basis for the analysis of governance strategies by operationalising and mapping complex problems
Paper 2: "Impacts of complexity"	Uptake of the operationalisation of complexity and the empirical results	Original definition of policy delivery; Original analysis of impacts of complexity on policy delivery	Basis for the analysis of governance strategies by clarifying the impacts of complexity on policy delivery
Paper 3: "Clusters of complexity"	Original analysis of clusters of complex problems	Original analysis of impacts of clusters of complex problems on policy delivery	Basis for the analysis of governance strategies by clarifying clusters of complex problems and their impacts on policy delivery
Paper 4: "Governance and complexity"	Uptake of the operationalisation of complexity	Uptake of the assumption of negative impacts of complex problems on solutions to problems	Original analysis of governance strategies for addressing complex problems

* The colours refer to different types of contributions of the single research papers to answering the questions of this dissertation, with 'green' signifying an original contribution, 'yellow' a supporting contribution, and 'red' an uptake of results provided in other papers.

3.2.1 Operationalisation and measurement of complexity

The first question regards the operationalisation and measurement of complexity in the context of political problem-solving by differentiating various dimensions and degrees of complexity. This question is mainly addressed in papers 1 (Kirschke et al. 2017b) and 3 (Kirschke et al. 2019). The operationalisation and empirical results provided in paper 1 were taken up in paper 2 (Kirschke et al. 2017b) and – on a more general level – also in paper 4 (Kirschke and Newig 2017).

Regarding the operationalisation of complexity, research depicted in paper 1 combines qualitative (e.g., Rittel and Webber 1973, Ingraham 1987, Wagenaar 2007, Bathie 2008, Weber and Khademian 2008, Funke 2012,) and quantitative understandings of complexity (Ingraham 1987, Voss et al. 2007). As a result, different dimensions and degrees of complexity are differentiated clearly. The dimensions of complexity refer to 'goals', 'variables', 'dynamics', 'interconnections', and 'informational uncertainty'. Each of these dimensions can have three possible values that refer to simple, complicated, and complex problems. Consequently, 15 possible categories are identified, referring to different dimensions and

degrees of complexity. In theory, these categories can be combined in various ways, resulting in a wide range of different complex problems. This allows for very specific, comparative analysis of complexity degrees of problems in contrast to analyses based on either one of the qualitative and quantitative concepts alone.

In terms of empirical evidence, paper 1 (and in part also paper 2) maps 37 water-related problems German public authorities address in order to implement the WFD in Germany. To map problems, this research relies on the knowledge of experts from different scientific fields and practical work contexts. Results demonstrate the applicability of the operationalisation concept. First, numerical assessments suggest a tendency towards middle-range occurrences. However, the analyses also reveal slight varieties in complexity degrees. Second, the analyses show that there are various types of arguments for complexity. These two main results regard the 37 types of problems as well as problem groups, namely types of polluters (e.g., agriculture, mining), types of sources (diffuse and point sources), and types of water bodies (surface waters and groundwater). These two main results also apply to the five dimensions of complexity, namely goals, variables, dynamics, interconnections, and informational uncertainty.

Subsequent factor and cluster analyses in paper 3 further reveal that there are four types of complex (here called wicked) problems (complex systems, uncertainty, tame, and wicked problems), based on variations of three factors of wickedness (goals, uncertainty, and system complexity). The paper shows in fact that the five dimensions of wickedness can be reduced to three factors, namely factor 1 ('system complexity'), factor 2 ('goals'), and factor 3 ('informational uncertainty'). Factor 1 is influenced by the dimensions 'variables', 'dynamics', and 'interconnections', whereas factor 2 is mainly coined by the dimension 'goals', and factor 3 by the dimension 'uncertainty'. Cluster analysis based on WARD uncovers four clusters of wicked problems. These four clusters are completely homogenous ($F < 1$), and differ clearly along the three factors 'system complexity, 'goals', and 'informational uncertainty'. The clusters include problems of different types of waters (surface waters and groundwater), sources (diffuse sources and point sources), and polluters (agriculture, mining, abandoned sites, constructed areas, urban wastewater, stormwater, industry, and others).

In sum, the improved operationalisation of complex problems provided in this dissertation enabled the systematic comparison and clustering of freshwater-related problems along their complexity degree. These results provide the basis for analysing implications of complexity for solutions and governance.

3.2.2 Implications of complexity for solutions

The second question of this dissertation regards the specification of the impacts of complexity on solutions to problems, by analysing the relationship between complex problems on the one hand and policy delivery related to these complex problems on the other. This research question is addressed in papers 2 (Kirschke et al. 2017a) and 3 (Kirschke et al. 2019), in particular. Paper 1 (Kirschke et al. 2017b) provides the basis for this analysis and paper 4 (Kirschke and Newig 2017) takes up the assumption of negative impacts of complex problems on solutions to problems.

From a theoretical point of view, and taking stock of literature in the field of complex problem-solving, relations between complexity and policy delivery can vary significantly, based on various conditions such as emotions, interests, abilities, and framework conditions. Paper 2, in particular, discusses general relationships between complexity and policy delivery as well as the impacts of single dimensions of complexity and different stages of policy delivery on such a relationship. Regarding the general impacts, problem complexity can be correlated both negatively and positively with policy deliver. In terms of the impacts of dimensions of complexity and stages of policy delivery, there can be stronger correlations between the complexity dimensions 'dynamics' and 'interconnection of variables' on the one hand and policy delivery on the other hand when compared to the other three dimensions of complexity. Further, stronger correlations between complexity and (specific stages of) implementation than for goal formulation were expected.

In terms of empirical results, the analyses in paper 2 reveal a relative dominance of negative correlations between complexity and policy delivery, sporadic positive relations, and slight variations between dimensions of complexity and stages of implementation. This partly supports the assumptions as spelt out above. Most importantly, predominantly negative correlations between complexity on the one hand and goal formulation and indicators of high levels of implementation on the other hand support assumptions of negative correlations between complexity and policy delivery. Moreover, a significant positive correlation between the complexity dimension 'goals' and the policy delivery aspect 'goal formulation' supports assumptions on positive correlations. Furthermore, results suggest some variation in the effects of dimensions of complexity on (different stages of) policy delivery.

Turning to the effects of clusters, the results of paper 3 suggest that clusters of wickedness matter for policy delivery. The results also hint at more complex effects of wickedness on solutions beyond simple dichotomies of success and failure of wicked and tame problems. Most importantly, clusters which represent problems of particularly low and high degrees of wickedness are rather similar in their effects on goal formulation and implementation. Clusters which rather represent intermediate forms between tame and wicked problems have particularly significant impacts on policy delivery. Furthermore, we

observe more significant results on goal formulation than on implementation, namely if problems are particularly wicked or tame, problem solvers would rather formulate goals to address these problems. Finally, we find significant impacts regarding measures 'in construction', possibly going back to the degree of informational uncertainty.

In sum, the papers operationalised solutions to complex problems along the concept of policy delivery, defined hypotheses on the implications of complexity for solutions, and measured the implications of complexity for solutions along the 37 types of problems and clusters of wicked problems. This analysis of implications of complexity was enabled by the operationalisation and measurement of complexity provided in papers 1 and 3 and justifies further analysis of the implications of complexity for governance strategies as provided in paper 4.

3.2.3 Implications of complexity for governance

The third question of this dissertation regards the implications of complexity for governance, by clearly considering causal mechanisms between complexity, governance, and solutions. This research goal is mainly addressed in paper 4 (Kirschke and Newig 2017). Papers 1 to 3 (Kirschke et al. 2017 a, b, Kirschke et al. 2019) provide the basis for the analysis of governance strategies by operationalising and mapping complex problems as well as by clarifying the impacts of complexity on policy delivery.

As a main result, paper 4 demonstrates a multi-dimensional approach to governance and complex environmental problem-solving. This one consists of a functional "how-to" procedure, consisting of two steps. First, management strategies for addressing complex problems were defined, based on results from psychology research, in particular. The paper identified six basic strategies, namely information gathering, modelling, prioritising, conflict solving, deciding under uncertainty, and being adaptive and flexible. Second, the paper provides governance strategies that facilitate the implementation of these management strategies. These governance strategies regard institutionalisation (obligation and precision of rules), the involvement of different kinds of actors (e.g., scientists, local and political experts, facilitators), and the implementation of different forms of interaction (deliberation, negotiation, hierarchy). Linking management and governance strategies demonstrates that institutions, actors, and forms of interactions facilitate solutions to problems depending on the complexity dimensions of goals, variables, dynamics, interconnections, and informational uncertainty.

Also, the empirical papers 1, 2 and 3 question simplistic participatory approaches to address the complex challenges in water management and complex problem-solving in general. The papers hint at the relevance of various governance strategies to address different challenges of different types of complex or wicked problems. For instance, regarding specific dimensions of complexity such as

dynamics and interconnections, or specific types of wicked problems such as 'system complexity' problems, specific modes of participation such as participatory modelling might be more effective than the prevailing general roundtable formats meant to address complex problems in general.

4. Discussion

4.1 Main contributions of this dissertation

All in all, these results strengthen the value of the concept of complexity for systematic comparative analyses of public policies in general and water-related problems, in particular. This strengthening of the value of the concept of complexity is based on a nuanced understanding of complex problems and of the implications of complexity for solutions and governance. Research in the field of water management and public policy, in general, has long focused on general complexity conglomerates that negatively impact solutions to problems, and that participatory governance may address. While this research has strengthened governance research by paying attention to complexity as a structural approach to political problem-solving, this research also tends to be vague in its outputs. This dissertation helps to overcome this vagueness by specifying complexity and its implications for solutions and governance strategies. By doing so, this dissertation also contributes to more systematic structural approaches in political problem-solving than have been discussed so far.

The first main contribution in this regard is the operationalisation of the concept of complexity in political problem-solving. By differentiating more clearly between different dimensions and degrees of complexity, it is possible to better define complexity degrees of real-world problems than it has been the case in the literature on water-related problems and public policies in general. Water-related problems, in particular, were described as particularly complex (e.g., Pahl-Wostl 2007, Patterson et al. 2013, Metz and Ingold 2014). However, this research has shown that there are differences between water-related problems indeed, both with regards to 37 types and four clusters of pollution-related problems. Problems such as micro pollution or leaching in agriculture are systematically different from problems such as upgrading a wastewater treatment plant for better removal of phosphorus (Kirschke et al. 2017b, 2019). Based on such knowledge, it is also possible to better analyse the impact of complexity on policy delivery and governance strategies. While these results relate to water management problems in Germany, other problems or similar problems in other areas may also vary in their complexity degrees.

The second main contribution in this regard is the specification of implications of complexity for solutions to problems. This work identified specific implications of complexity on solutions that go beyond simplistic ideas of failure. In contrast to the general tone in the literature that emphasises

general negative impacts of complexity (e.g., Rittel and Webber 1973), this work shows that impacts on solutions can be both negative and positive, and depend more significantly on different dimensions and degrees of complexity. Water-related problems may thus not just fail, but fail in various ways, and due to various structural reasons (Kirschke et al. 2017a, Kirschke et al. 2017, 2019). While these results relate to water management problems in Germany, other problems or similar problems in other areas may have various impacts on solutions as well.

The third main contribution is the specification of governance for complex problem-solving. This work provides a particularly nuanced approach to governance and problem-solving, by differentiating different dimensions of complexity and governance. This is particularly interesting for analyses in the field of water governance, given the current focus on participatory approaches to address water-related problems (WFD, Art. 14), and given that these participatory approaches may also fail to sufficiently address these problems (Koontz and Thomas 2006, Newig and Fritsch 2009). It is also relevant for public policies in general, given that participatory approaches are at the forefront in the analysis of complex problems and public policies in general (e.g., Duit and Galaz 2008). As Howlett and colleagues stated (e.g., Howlett and Lejano 2015, Howlett et al. 2015), there has been a strong focus on network governance in public policy analysis, which hampers broader design thinking. This work contributes to revitalising this line of research by providing a clearer picture of the role of different governance strategies in complex problem-solving (Kirschke and Newig 2017). Given the abstract nature of this approach, such strategies for complex problem-solving may be applied to most different problems in the field of water and beyond.

In addition to its scientific contributions, this work contributes to the call for a more "substantiated science-policy interface" in water management (Borchardt et al. 2013: XIV). This goes back to (i) the clear focus on problems, (ii) the practical applicability of the concept of complexity in order to understand problem structures and failures to address them, and (ii) the provision of a method to systematically use governance strategies to address these failures. An important contribution in this regard is the application of the concept of complexity itself. In fact, some interviewees highlighted that the concept of complexity was particularly helpful for 'out-of-the-box' thinking. At the beginning of the interviews, some interviewees described problems as being rather simple. However, at the end of the interviews, they highlighted that problems are particularly complex. Such interviewees were aware of goal conflicts and uncertainties from the beginning, but rather neglected dynamics and interconnections of variables. Applying the concept of complexity seemed to help these interviewees to grasp these facets of complexity better.

4.2 Future research

This research has shown that the concept of complexity is useful for the analysis of public policy problems in general and freshwater-related problems, in particular. Future research is recommended to build on these results, focusing on the practical applicability of the approach, by both providing empirical evidence (4.2.1) and contextualising the approach (4.2.2).

4.2.1 Empirical analysis: Governance strategies and qualitative dimensions of solutions

Empirical analysis of the role of governance strategies for complex problem-solving

From an empirical point of view, this dissertation focused on the mapping of complex problems, and the impact of complex problems on policy delivery. Following up on this, future research can illustrate the practical applicability of the identified set of governance strategies based on a single case study design. An interesting example here is the problem of the input of nutrients in one specific river basin district in Germany since such inputs are widespread and have particularly negative impacts on freshwater resources (BMU 2013, LAWA 2013). Moreover, the role of governance strategies for problem-solving is recommended to be tested based on a comparative case study approach. Such approaches can relate to most similar problems within one cluster or to two most different types of problems such as tame and wicked problems from different policy (sub-)fields (Kirschke et al. 2019).

Measuring the effectiveness of solutions to complex problems

This dissertation argued for solutions to complex problems as one 'strategy' for dealing with complex problems (Daviter 2017a), and defined and analysed solutions along a quantitative concept of 'policy delivery'. An interesting way forward here is to go beyond the implementation of decisions in certain moments in time by also analysing the qualitative dimension of solutions. In the field of water management, for instance, it is interesting to see if the measures implemented within the context of the WFD also have an impact on the status of freshwater resources. While this qualitative question is challenging to address, its consideration is also important in order to check if governance strategies for complex problem-solving result in different types of (non-)solutions, such as effective or symbolic policies.

4.2.2 Contextualisation: Governance strategies and qualitative dimensions of solutions

Complexity and conditions for problem-solving

This work showed that the concept of complexity has implications for both solutions and governance strategies. Further research can build on these results, by clarifying how the concept of complexity can be put in relation to further conditions for political problem-solving. One important way forward here

is to further relate the concept of complexity to other structural dimensions of problems such as scales of problems, as suggested by Peters (2005), among others. A second way forward would be to understand better which role structural approaches have in contrast to other conditions of problem-solving which are rather independent of the specific nature of problems. One example for such a combined approach in the field of water management regards the summary of management factors that can indicate the implementation process of the WFD in Germany (Kirschke et al. 2015, 2016a).

Complexity and democratic theory

Another way for future research is to better situate the role of structural approaches to problems along a broader approach in democratic theory. The main goal here would be to understand if specific systems are particularly well-suited for implementing structural approaches. Such research would first have to define prerequisites for implementing such structural approaches to problems. It would then be necessary to test to which degree different political systems or administrative cultures or features of political systems fulfil these criteria. In principle, it would be reasonable to assume that the implementation of structural approaches needs flexibility, highly skilled personnel at public authorities, significant funding for understanding problems, as well as basic openness for participation to be implemented. Whereas some of these features can be implemented in most different systems and administrative cultures, others such as participatory approaches may not work easily in these different types of settings. However, water-related research has also suggested that participatory approaches to problem-solving may also be implemented successfully in more closed cultures and political systems (Kirschke et al. 2016b).

5. Summary and conclusion

Poor quality of freshwaters is a widespread and challenging problem for humankind. The concept of complexity is a particularly promising concept to analyse and address this problem, and public policy problems more generally. The main reason is the concept's strength in unifying structural features of problems within a more comprehensive structural approach to political problem-solving. So far, however, these possible benefits remained hidden given the lack of a clear understanding of complexity, ultimately hampering a systematic analysis of the implications of complexity for solutions and governance strategies. This study has strengthened the value of the concept of complexity for systematic comparative analyses of public policies in general and water-related problems, in particular. Based on both theoretical and empirical analyses, and the applications of different methodological approaches such as interdisciplinarity and the integration of practical knowledge, this work specified the concept of complexity as well as the implications of complexity for solutions and governance strategies:

i. Operationalisation and measurement: This dissertation provides a detailed operationalisation of complexity related to the dimensions of goals, variables, dynamics, interconnections, and informational uncertainty. It also shows that freshwater pollution-related problems in Germany differ along these five complexity dimensions. This applies to 37 types of pollution-related problems and four clusters of problems, which refer here to tame, wicked, system complexity, and uncertainty problems.

ii. Implications of complexity for solutions: This dissertation suggests that relations between complexity and policy delivery can be both positive and negative, and vary along dimensions of complexity and policy delivery. Regarding the analysed freshwater pollution problems, this work also shows various effects of complexity on policy delivery, both along the 37 types of problems, and along four clusters of wicked problems.

iii. Implications of complexity for governance: This dissertation suggests a differentiated theoretical approach to define governance for complex problem-solving, demonstrating that the role of diverse institutions, actors, and interactions differs for solutions along five key dimensions of complexity: goals, variables, dynamics, interconnections, and informational uncertainty, and different management strategies that are information gathering, modelling, using decision-support tools, prioritising of measures, conflict solving, deciding under uncertainty, and being adaptive and flexible.

Future research is recommended to build on these results, by providing further empirical evidence and contextualising the approach on governance for complex problem-solving. Following this path may help to contribute to turn the “logic of failure” (Dörner 1996) regarding complex problem-solving into a “logic of success” for addressing problems of varying complexity in public (water) policies.

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II. Research papers

Paper [1]: Mapping complexity

Kirschke, S., Borchardt, D., Newig, J. (2017b): "Mapping Complexity in Environmental Governance: A comparative analysis of 37 priority issues in German water management", *Environmental Policy and Governance* 27(6), 534-559.

Publication status: Published, available via: Doi.org/10.1002/eet.1778.

Paper [2]: Impacts of complexity

Kirschke S., Newig J., Völker J., and Borchardt D. (2017a): "Does problem complexity matter for environmental policy delivery? How public authorities address problems of water governance", *Journal of Environmental Management* 196, 1-7.

Publication status: Published, available via: Doi.org/10.1016/j.jenvman.2017.02.068.

Paper [3]: Clusters of complexity

Kirschke S., Franke, C., Newig, J., Borchardt, D. (2019). “Clusters of water governance problems and their effects on policy delivery”, *Policy & Society.*

Publication status: Published, available via: Doi.org/10.1080/14494035.2019.1586081.

Paper [4]: Governance and complexity

Kirschke, S., Newig, J. (2017): "Addressing Complexity in Environmental Management and Governance", *Sustainability* 9, 983.

Publication status: Published, available via: Doi.org/10.3390/su9060983.

Annex

Annex 1: Overview of the electronic data and information annex

Contains confidential information, partly available upon request.

The electronic annex comprehends relevant background information and data with regards to the empirical analysis. It consists of three main parts: information and data on (1) the analysis of complexity, (2) the implications of complexity on solutions, and on (3) the analysis of clusters and their implications. In the following, the data and information included in the electronic annex are briefly described.

1. Complexity analysis

The first folder contains information and data on the complexity of problems, namely background information on the analysis of complexity, interview finals, as well as information on the qualitative and the quantitative analysis of interview results.

1.1 Background info interviews

This folder contains background information on the interviews on complexity of water-related problems in Germany, namely an overview of the analysed problems (1.1.1), the background document for the interviewees (1.1.2), the full list of interviewees (1.1.3) and a comparison of types of interviewees (1.1.4).

1.1.1 Problems

This document gives an overview on all 37 types of problems that have been analysed. This information is depicted in table 1 'Pollution of water resources from point and diffuse sources in Germany', containing information on the numbering of the problem, the short title of the problem, and a short description of the problem. This table has been published in Kirschke S., Newig J., Völker J., & Borchardt D. (2017). Does problem complexity matter for environmental policy delivery? How public authorities address problems of water governance. *Journal of Environmental Management* 196, 1-7, Annex A Table A.1. The original information stems from the platform WasserBLIcK and was translated by the authors.

1.1.2 Survey on complexity and the WFD

This document is a background document that was given to interviewees for their individual preparation of the interviews. The document provides general background information on the survey, a brief introduction to problem complexity and its operationalization, an example on how to apply this operationalization in the field of linear continuity (based on an expert interview), a questionnaire, and an overview on all problems that are of relevance in the study. This document has been sent to all interviewees before the interview, as a preparatory document.

1.1.3 List of interviewees

This list provides an overview on the 62 interviewees that have explicitly agreed on being mentioned in this study. The list contains information on the full names as well as the affiliations of the interviewees, and is ordered by their last name.

1.1.4 Types of interviewees

This excel chart provides background information on the types of interviewees. First, this chart includes information on the group the interviewee belongs to. The criterion for group membership is the general working context. I generally differentiated here practitioners and scientists and also added a group called 'inter', as a group with unclear working context. I also specified sub-groups, referring to different types of disciplines and practical working contexts. Moreover, this table chart includes information on gender (male/female), the place of interviews (interview by phone or face-to-face), the length of interviews in minutes, the preparation of interviewees (here referring to their readings of the background information as provided in 1.1.2), as well as the number of problems that have been defined in total, with regards to overarching problems and specific problems as relevant for the analysis.

1.2 Interviews finals

This folder contains the interview summaries of all 62 interviewees that agreed to be mentioned in this study. The list of summaries is ordered by time of approval. Each summary contains general information on the interview (contact information, information of the date and length of the interview, the discussed problems, and a clause on confidentiality), as well as a written summary of the interview (short introduction, summary along the five dimensions of complexity, a summary including a summarizing figure). This information was provided either on every problem individually (first round of interviews), or, in order to be more efficient, in a summary text for all problems as long as most of the information applied to several problems. The summaries were prepared based on extensive notes during the interviews, and were read and approved by the interviewees.

1.3 Qualitative analysis interviews

This folder contains information on the qualitative analysis of the summaries of the interviews. It contains three types of information, referring to three steps in the analysing process, namely focus group documents (1.3.1), coding documents (1.3.2), and a summary of numerical evaluation of codes (1.3.3).

1.3.1 Focus group documents

This folder contains so called focus group documents. In these documents, all information on the specific problems are summarized. Content-wise, this information is the same as provided in 1.2. However, the information is structured along the types of problems and not along interviewees. This was necessary since interviewees usually provided information on more than one problem (see 1.1.4). In terms of problem 16, 17, 22, 23, 26, 40, 42, 43, two focus group documents exist, because the problem was analysed in two steps. All focus group documents contain information on the interviewee, supporting the interpretation of the argument provided in terms of its relevance for defining the general complexity degree (see 1.3.2 and 1.3.3). The numbers provided in this document are continuous and do not represent the numbering of problems in the published paper.

1.3.2 Codings

This folder contains five excel sheets on the coding process, representing the five dimensions of complexity, namely goals, variables, dynamics, interconnections, and informational uncertainty. Each excel sheet contains several sub-sheets, representing different sources of complexity. For instance, the excel sheet on variables contains eight sub-sheets, representing different types of variables, namely matters, solutions options, natural locational factors, non-natural locational factors, actors and their interests, responsibilities, Governance, and general assessments. Each excel sub-sheet contains information on i) the problem, ii) the interviewee, iii) the text segment, iv) a fist general summary of the text segment, v) a second, more abstract, summary of the text segment, vi) a summary of all text segments of one interviewee per problem, vii) an assessment of the generic complexity degree based on the source of complexity (if applicable), and viii) an assessment of the context-specific complexity degree based on the source of complexity (if applicable). Steps i) to iii) are outputs of a coding process implemented with the help of MAXQDA; steps iv) to viii) represent further analyses, aiming at identifying i) clear sources of complexity and ii) understanding to which degrees these sources of complexity contribute to the general complexity of a problem. The identified sources of complexity are published in the paper „Mapping complexity“.

1.3.3 Summary numerical evaluation of codes

The excel sheet ‚1.3.3_Summary numerical evaluation of codes‘ contains two sub-sheets: i) an overview of numerical values for each source of complexity along types of problems and interviewees and ii) an explanatory table of IDs used in sub-sheet 1. Technically speaking, sub-sheet 1 contains context information (IDs on problems and interviewees), as well as generic (g) and context-specific (c) numerical evaluations of five dimensions of complexity as provided by the interviewees (Q1) and generic (g) and

context-specific (c) numerical evaluations of sources of complexity (Q2), both along a scale from 0 (simple) to 1 (complex).

1.4 Quantitative analysis interviews

The excel sheet ‚1.4_Quantitative analysis interviews' contains four sub-sheets: i) the generic numerical evaluations of five dimensions of complexity of each interviewee as well as average values of the generic numerical evaluations of five dimensions of complexity per problem, ii) the average values of the generic numerical evaluations of five dimensions of complexity per problem (condensed information of sub-sheet i), iii) the assignment of the average values of sub-sheet ii) to five groups of simple (I), simple to complicated (II), complicated (III), complicated to complex (IV) and complex problems (V) as well as respective occurences and percentages, and iv) average complexity degrees along groups of problems, namely diffuse and point sources, surface waters and groundwater, as well as different polluter groups.

2. Implications of complexity

The excel sheet ‚2_Implications of complexity' contains two sub-sheets: i) the average complexity degrees per problems and the respective number of measures not yet started, in planning, in construction and completed for the complete number of measures, the measures delayed and the measures not delayed and ii) the average complexity degrees per problems and the respective complete number of measures not yet started, in planning, in construction and completed, as well as a set of indicators for policy delivery.

3. Clusters and their implications

The excel sheet ‚3_Clusters and their implications' contains four sub-sheets: i) the assigment of the average complexity degrees per problems (N = 37) and of the respective indicators for policy delivery to clusters, ii) the assigment of the average complexity degrees per problems (N = 34) and of the indicators for policy delivery to clusters, iii) an overview of formulated goals per cluster (based on an index as well as on the total number), and iv) the average number of problems not yet started, in planning, in construction and completed per cluster of problems as well as the degree of implementation index per cluster of problems.

Annex 2: Overview of articles included in this cumulative Ph.D. thesis

(in accordance with the guideline for cumulative dissertations in Sustainability Science [January 2012], in the following termed "the guideline")

Title of Ph.D. thesis: The Role of Complexity in Addressing the Water Quality Challenge

Papers included:

[1] Kirschke, S., Borchardt, D., & Newig, J. (2017). "Mapping Complexity in Environmental Governance: A comparative analysis of 37 priority issues in German water management", *Environmental Policy and Governance*, 27(6), 534-559.

[2] Kirschke S., Newig J., Völker J., & Borchardt D. (2017). "Does problem complexity matter for environmental policy delivery? How public authorities address problems of water governance", *Journal of Environmental Management* 196, 1-7.

[3] Kirschke, S., Franke, C., Newig, J., & Borchardt, D. (2019). "Clusters of water governance problems and their effects on policy delivery", *Policy & Society*.

[4] Kirschke, S., & Newig, J. (2017). "Addressing Complexity in Environmental Management and Governance", *Sustainability*, 9(6), 983.

Authors' contributions to the articles and articles publication status (according to §16 of the guideline):

Article #	Short title	Specific contributions of all authors	Author status	Weighting factor	Publication status	Conference contributions
[1]	Mapping complexity	SK: Research design, literature review, data collection and analysis, interpretation of results, writing of the paper, production of figures (70%) DB, JN: Commenting on research design, the interpretation of results and editing of manuscript (15% each)	Co-author with predominant contribution	1.0	Published by *Environmental Policy and Governance* 27(6), 534-559 (2016 Impact Factor = 2.032)	ICPP 2015
[2]	Impacts of complexity	SK: Research design, literature review, data collection and analysis, interpretation of results, writing of the paper, production of figures (60 %) JN: Commenting on research design, interpretation of results, writing parts of the paper, thorough editing of manuscript (20%) JV, DB: Commenting on research design, data provision, commenting on the interpretation of results, editing of manuscript (10 % each)	Co-author with predominant contribution	1.0	Published by *Journal of Environmental Management* 196, 1-7 (2016 Impact Factor = 4.010)	HKU-USC-IPPA 2016

[3]	Clusters of complexity	SK: Research design, literature review, data collection and analysis, interpretation of results, writing of the paper, production of figures (60 %) CF: Choice of research methods (factor and cluster analysis), analysis of data (factor and cluster analysis), production of one figure (clusters of problems), editing of manuscript (30 %) JN, DB: Commenting on research design and editing of the manuscript (5% each)	Co-author with predominant contribution	1.0	Submitted to Policy & Society (2016 Impact Factor = 1.115)	IRW 2016
[4]	Governance and complexity	SK: Research design, literature review, writing of the paper, production of figures (70%) JN: Commenting on research design; repeated discussion of paper structure and thorough editing of manuscript (30%)	Co-author with predominant contribution	1.0	Published by *Sustainability* (9, 983) (2016 Impact Factor = 1.789)	WCPS 2014, EPSA 2014, SWEFN 2014
			Sum:	4.0		

Explanations

Specific contributions of all authors

SK = Sabrina Kirschke, DB = Dietrich Borchardt, JN = Jens Newig, JV = Jeanette Völker, CF = Christian Franke

Author status

according to §12b of the guideline:

Single author [Allein-Autorenschaft] = Own contribution amounts to 100%.

Co-author with predominant contribution [Überwiegender Anteil] = Own contribution is greater than the individual share of all other co-authors and is at least 35%.

Co-author with equal contribution [Gleicher Anteil] = (1) own contribution is as high as the share of other co-authors, (2) no other co-author has a contribution higher than the own contribution, and (3) the own contribution is at least 25%.

Co-author with important contribution [Wichtiger Anteil] = own contribution is at least 25%, but is insufficient to qualify as single authorship, predominant or equal contribution.

Co-author with small contribution [Geringer Anteil] = own contribution is less than 20%.

Weighting factor

according to §14 of the guideline:

Single author [Allein-Autorenschaft]	1.0
Co-author with predominant contribution [Überwiegender Anteil]	1.0
Co-author with equal contribution [Gleicher Anteil]	1.0
Co-author with important contribution [Wichtiger Anteil]	0.5
Co-author with small contribution [Geringer Anteil]	0

Conference contributions

ICPP 2015	2nd International Conference on Public Policy, organized by the International Public Policy Association (IPPA), taking place July 1–4, 2015 in Milan (Italy). Webpage: http://www.ippapublicpolicy.org/conference/icpp2-milan-2015/8 (accessed 25.01.2018)
HKU-USC-IPPA 2016	HKU-USC-IPPA Conference on Public Policy, organized by the University of Hong Kong (HKU), the University of Southern California (USC) and the International Public Policy Association (IPPA), taking place June 10–11, 2016 in Hong Kong (China). Webpage: http://www.socsc.hku.hk/cpphk/ (accessed 25.01.2018)
IRW 2016	Intensive Research Workshop "Governance of wicked problems", organized by Wageningen University & Research, taking place October 27–28, 2016 in Wageningen (the Netherlands). Webpage: https://www.wur.nl/en/newsarticle/Call-for-abstracts-Governance-of-wicked-problems-.htm (accessed 25.01.2018)
WCPS 2014	23rd World Congress of Political Science, organized by the International Political Science Association, taking place July 19–25, 2014 in Montréal (Canada). Webpage: http://www.ipsa.org/events/congress/montreal2014 (accessed 25.01.2018)
EPSA 2014	4th Annual General Conference of the European Political Science Association, organized by the European Political Science Association, taking place June 19–21, 2014 in Edinburgh (Great Britain). Webpage: http://www.epsanet.org/conference-2014/ (accessed 25.01.2018)
SWEFN 2014	Sustainability in the Water-Energy-Food Nexus, organized by the Global Water Systems Project (GWSP), among others, taking place Mai 19–20, 2014 in Bonn (Germany). Webpage: http://wef-conference.gwsp.org/programme.html (accessed 25.01.2018)

Declaration (according to §16 of the guideline)

I avouch that all information given in this appendix is true in each instance and overall.

Detailed authors' contributions to the articles (according to §16 of the guideline):

[1] Kirschke, S., Borchardt, D., & Newig, J. (2017). "Mapping Complexity in Environmental Governance: A comparative analysis of 37 priority issues in German water management", *Environmental Policy and Governance*, 27(6), 534-559.

Author	Share (%)	Details of contribution	Signature
Sabrina Kirschke	70	Research design, literature review, data collection and analysis, interpretation of results, writing of the paper, production of figures	
Dietrich Borchardt	15	Commenting on research design, the interpretation of results and editing of manuscript (15% each)	
Jens Newig	15	Commenting on research design, the interpretation of results and editing of manuscript (15% each)	

[2] Kirschke S., Newig J., Völker J., & Borchardt D. (2017). „Does problem complexity matter for environmental policy delivery? How public authorities address problems of water governance", *Journal of Environmental Management* 196, 1-7.

Author	Share (%)	Details of contribution	Signature
Sabrina Kirschke	60	Research design, literature review, data collection and analysis, interpretation of results, writing of the paper, production of figures	
Jens Newig	20	Commenting on research design, interpretation of results, writing parts of the paper, thorough editing of manuscript	
Jeanette Völker	10	Commenting on research design and the interpretation of results, editing of manuscript	
Dietrich Borchardt	10	Commenting on research design and the interpretation of results, editing of manuscript	

[3] Kirschke, S., Franke, C., Newig, J., & Borchardt, D. (2019). “Clusters of water governance problems and their effects on policy delivery”, *Policy & Society*.

Author	Share (%)	Details of contribution	Signature
Sabrina Kirschke	60	Research design, literature review, data collection and analysis, interpretation of results, writing of the paper, production of figures	
Christian Franke	30	Choice of research methods (factor and cluster analysis), analysis of data (factor and cluster analysis), production of one figure (clusters of problems), editing of manuscript	
Jens Newig	5	Commenting on research design and editing of the manuscript	
Dietrich Borchardt	5	Commenting on research design and editing of the manuscript	

[4] Kirschke, S., & Newig, J. (2017). “Addressing Complexity in Environmental Management and Governance”, *Sustainability*, 9(6), 983.

Author	Share (%)	Details of contribution	Signature
Sabrina Kirschke	70	Research design, literature review, writing of the paper, production of figures	
Jens Newig	30	Commenting on research design; repeated discussion of paper structure and thorough editing of manuscript	

Annex 3: Erklärungen gem. § 9 Abs. 2 e)-f) und Versicherung gem. § 9 Abs. 3 der Promotionsordnung 2009 oder 2010 oder 2011 *)

Hiermit erkläre ich, dass ich mich bisher keiner anderen Doktorprüfung unterzogen oder zu einer solchen Prüfung angemeldet habe.

Hiermit erkläre ich, dass die Dissertation in der gegenwärtigen oder einer anderen Fassung noch keiner anderen Hochschule zur Begutachtung vorgelegen hat.

Ich versichere, dass ich die eingereichte Dissertation „The Role of Complexity in Addressing the Water Quality Challenge“ selbständig und ohne unerlaubte Hilfsmittel verfasst habe. Anderer als der von mir angegebenen Hilfsmittel und Schriften habe ich mich nicht bedient. Alle wörtlich oder sinngemäß anderen Schriften entnommene Stellen habe ich kenntlich gemacht.

Sabrina Julie Kirschke