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Addressing Complexity in Environmental Management and Governance

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Abstract: Governance for complex problem solving has been increasingly discussed in environmental sustainability research. Above all, researchers continuously observe that sustainability problems are complex or "wicked", and suggest participatory models to address these problems in practice. In order to add to this debate, this study suggests a more differentiated theoretical approach to define governance for complex environmental problem solving than in previous studies. The approach consists of two vital steps: First, we operationalize complexity and define management strategies for solving environmental sustainability problems based on findings from psychology research. Second, we identify governance strategies that facilitate these management strategies. Linking those strategies suggests that the role of diverse institutions, actors, and interactions differs for five key dimensions of complexity: goals, variables, dynamics, interconnections, and informational uncertainty. The results strengthen systematic analyses of environmental sustainability problems in both theory and practice.

Keywords: complex problems; complex problem solving; governance; Integrated Water Resources Management; Water Framework Directive; wicked problems

1. Introduction

The concept of complexity has recently gained prominence in environmental sustainability research, in particular with regards to the political conditions for complex problem solving. First, researchers continuously observe that sustainability problems are complex or "wicked". Examples refer to various environmental fields such as the management of fresh waters [1–3], climate change [4,5], or food and agriculture [6–8], among others. Second, researchers suggest closely related political models to address complex or "wicked" problems. Popular concepts focus on reflexive [9,10], participatory-deliberative [7,11,12], and different forms of network or interactive forms of governance [13–16]. By implication, researchers also question more hierarchical, especially science-driven models of political problem solving [6,17].

We understand that such contributions are a valuable critique of simplistic planning approaches in political and administrative science. This research takes into account that most pressing societal problems in fact deny any easygoing solutions [18–21]. Indeed, public authorities have to deal with various uncertainties and need to learn continuously when addressing these problems [7,10,22–25]. To enable such learning processes, the above mentioned researchers convincingly argue that participatory instead of hierarchical modes of governance are essential. However, the inverse has been argued for as well. In the field of environmental management, participatory approaches apparently do not necessarily benefit complex problem solving [26,27]. Research suggests that the relevance of specific participatory approaches to address problems is dependent on particular goals and context factors [28], such as the degree of informational and normative uncertainty [29]. Moreover, it has been suggested that further governance dimensions such as precise rules can impact the achievement of environmental management goals [30].

Against such considerations, we see an important need for a more differentiated approach to governance and complex problem solving. Our core concern is that one-dimensional approaches in terms of governance and complexity do not sufficiently address the variety of complex environmental problems. A multi-dimensional approach in terms of governance and complexity could result in a much more nuanced and accurate picture of the relationship between governance and complex problem solving. Besides, it could pave the way for using complexity as a useful 'lens' through which policy problems can be systematically categorized and analyzed [31]. In fact, such systematic structural approaches to problem solving have repeatedly been advocated [17,32], but still lack in-depth research, given the apparently predominant role of both single variables, and explanations that are highly context-specific. Such structural approaches are not in contrast to, but complementary to those approaches and frameworks that focus on dimensions of politics in complex problem solving such as multi-stakeholder processes.

This study aims to further advance this debate by developing a differentiated structural approach to complex environmental problem solving. We suggest a theoretical framework that considers how specific types of complexity impact the role of specific governance strategies in order to address these specific types of complex problems. Thus, our framework is functional in the sense that it aims to facilitate the identification of governance strategies for complex problem solving, based on varying complexities of real world problems. The ultimate goal is to support scientists and practitioners in their aims to analyze and address complex problems effectively (e.g., by analyzing and identifying relevant participatory strategies or institutional settings). To build the framework, we refer to established research from the complementary fields of psychology and political and administrative science. To illustrate components of the framework, we mostly refer to concrete examples in the field of environmental management, especially water-related problems. We particularly focus here on the case of the implementation of the European Water Framework Directive (WFD) in Germany, given the existence of in-depth background information on its complexity, and the impacts related to this case [33]. Moreover, research related to the WFD particularly highlights the benefits and challenges of participatory and social-learning approaches that this research can build on and add to [15,29]. While we refer to the WFD case to illustrate our theoretical framework, we do not use this case to demonstrate all facets of the framework, which would go beyond the scope of this paper.

In order to develop our framework, the following two sections address the relationship between complex problems on the one hand, and governance on the other hand. From a structural point of view, we follow here our functional approach, showing how to identify relevant governance strategies for problem solving, based on the complex nature of the problems. Such an approach is different from causal logics of the factual problem solving processes, in which governance strategies precede problem solving processes. Technically speaking, the two sections identify specific sub-strategies in governance and complex problem solving, namely management strategies (e.g., information gathering, modelling) and governance strategies (e.g., participation, deliberation). Whereas management strategies refer to actions that directly affect complex problem solving, governance strategies enable or facilitate these management strategies. The section 'Deriving Management Strategies to Cope with Complexity' suggests management strategies that are based particularly on psychological literature on complex problem solving. Following our functional approach, this section takes the complexity of problems as a starting point to derive management strategies that contribute to the solution of these policy problems. The following section 'Governance strategies to Enable and Facilitate Management Strategies' then defines governance strategies, based on analyses in political and administrative science, in particular. This section defines governance strategies that are likely to facilitate the implementation of management strategies. Thus, we suggest the concept of "management strategies" as an important causal mechanism between the structural features of problems on the one hand, and governance strategies to address these problems on the other. They can encompass strategies such as information gathering, modeling or conflict solving. As such, they explicitly differ from (i) the structure of problems such as conflicting goals, dynamics, and the interconnectedness that underlies these management strategies, and (ii) governance strategies such as different forms of institutionalization, and involvements of actors and interactions that enable or facilitate these management strategies. Using these management strategies as a causal link is particularly important in order to understand which and why specific governance strategies can help in addressing specific features of complex problems.

As a result, we have identified both a set of management strategies to address complexity on the one hand, and a set of governance strategies to facilitate management strategies on the other. To be of analytical and empirical value, these strategies have to be combined, resulting in a direct link between the complexity of problems on the one hand, and governance strategies for addressing these problems on the other. This allows us to understand how a certain structure of problems can be addressed by a certain governance strategy, based on these causal mechanisms of management strategies. The following section establishes this link, and shows how governance strategies for complex problem solving can significantly differ along various types of environmental problems. The final section then discusses the approach presented in this paper, and suggests steps for further analysis. By doing so, we hope to contribute to turning the "logic of failure" [20] regarding complex problem solving, into a "logic of success" for addressing environmental problems of varying complexity.

2. Deriving Management Strategies to Cope with Complexity

The starting point of our analysis is the complexity of problems. Over the past decades, political scientists [22] and psychologists [31] have conceptualized the complexity of problems in various ways. For our purpose, we understand the complexity of problems in the sense used in psychology: Based on widespread discussions in this literature [34], we define 'problems' as discrepancies between the current and the target state that are difficult to overcome. Referring to Kooiman [16], they can be understood as articulated potential needs that have to be addressed in political terms. In our understanding, such discrepancies can be management problems, occurring at different stages of the policy process, e.g., at the stage of agenda setting, policy formulation, implementation, and evaluation. In the field of water management, for instance, this could be the implementation of an integrated water resources management strategy (IWRM) in general, or a wastewater treatment plant in particular. In fact, environmental authorities can face a lot of difficulties when they try to implement an IWRM or a wastewater treatment plant, amongst, for instance, conflicting interests of stakeholders or a lack of information on the qualitative status of water.

Further inspired by psychology research [31], we understand complexity as a predictor of how challenging problem solving is. For instance, one could reasonably argue that the implementation of an IWRM is more complex in terms of conflicting goals than the implementation of a wastewater treatment plant. Consequently, it would be much more difficult to implement an IWRM than a wastewater treatment plant.

According to Dörner [20], Funke [35], complexity further includes five dimensions:

1. Goal conflicts regarding values and means), including their number (how many goals exist) and relationship (how goals are related with each other);
2. Variables influencing the achievement of goals;
3. Dynamics of variables, meaning how strongly the variables develop independently of each other;
4. Interconnectedness of variables, describing in which way the different variables are interrelated;
5. Informational uncertainty, describing how much information is missing for problem solving.

For instance, one could argue that implementing an IWRM is complex in the sense that there are (i) several conflicting interests on how to use water, such as industrial or agricultural beneficiary interests; (ii) several variables such as different natural conditions and social factors that influence goals; (iii) several dynamically evolving variables such as the climate or demographic development; (iv) high interconnections, e.g., between the input of matters and market prices for fertilizers; and (v) high uncertainties on how different kinds of measures impact the quality of waters [33].

Defining the implementation of an IWRM or the sustainable management of water as a complex problem, based on this five-dimensional understanding of complexity, is also consistent with the results of other researchers that have applied different understandings of complexity [1,15,36]. However, we go one step further by assuming that these five dimensions of complexity are not static or in contrast to simple problems. Instead, these dimensions can vary gradually between low and high values [31,37,38], thereby building a multi-dimensional continuum with two extremes: if all dimensions are maximized, a complex problem exists; if all dimensions are minimized, a simple problem exists. Between these two extremes, numerous intermediate forms are possible that vary between simple and complex problems [33].

Take, for instance, our former example in the field of water management. Whereas the general implementation of an IWRM is reasonably described as a complex problem, some sub-problems public authorities deal with when implementing an IWRM, can have different degrees of complexity. Examples are the reduction of migratory obstacles for fish, or the implementation of wastewater treatment plants. These problems seem rather simple, even though there may be conflicts around goals (economic vs. ecologic interests) and informational uncertainty (e.g., in terms of the impact of measures on the qualitative status of waters). Figure 1 illustrates these variations, based on generic examples of problems with different degrees of complexity. Here, we use the term 'complicated' to describe problems that are neither simple nor complex.

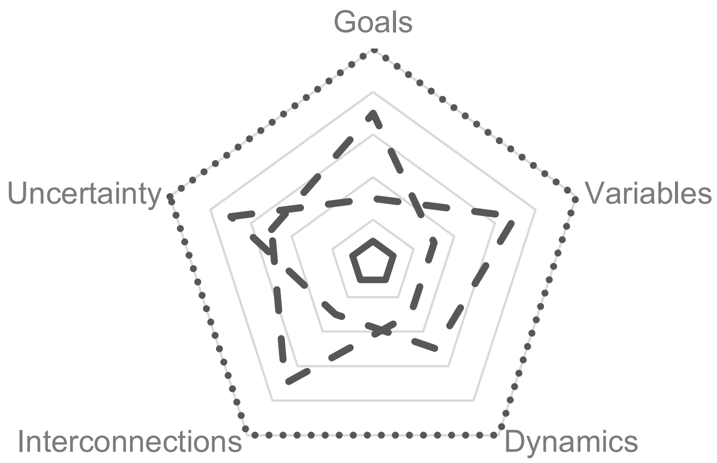

Figure 1. Variations of problem complexity across five dimensions. Depicted are four generic examples of complex (dotted line), complicated (dashed lines) and simple (solid line) problems, based on Kirschke et al. [33].

This approach to conceptualizing the complexity of problems has several advantages over predominant approaches in political and administrative science [33]. First, dimensions of complexity are clearly separated in contrast with the rather general complexity conglomerates that prevail in parts of the literature [12,32]. Second, understanding complexity as a continuum is very different from understanding it as an opposite of simple or tame problems, as it has frequently been conceptualized [6,14,18,35]. Moreover, our approach adds to gradual (numerical) concepts [32,39] and definitions of specific types of complex problems [17] since we further operationalize degrees of dimensions of complexity. This has important advantages for analyzing real world problems. Most importantly, we are able to describe similarities and differences of problems, such as the reduction of migratory obstacles for fish or the implementation of wastewater treatment plants, in a much more specific way. This eventually helps us to define specific management strategies to address these problems such as conflict solving or modeling, instead of generally referring to a varying degree of uncertainty, among others [7,32].

In the following, we specify management strategies that are functionally linked to these five dimensions of complexity. Traditionally, researchers have discussed such management strategies in a rather general way. Most importantly, they have emphasized the need to learn and act under conditions of (informational) uncertainty. They have also acknowledged that various problems lead to different needs for action under uncertainty [7] and learning for solutions [10,40]. Interestingly, however, both psychological research and political cooperation theory suggest more differentiated management strategies for solutions depending on different dimensions of complex problems. For instance, if problems are defined by dynamics (e.g., climate and demographic change), modeling is a useful strategy to address the problem (e.g., implementing cost-effective water treatment plants). If problems are characterized by high conflicts (e.g., on the usage of water in a water scarce region), conflict solving strategies are important to address the problem (e.g., fostering rural development) (see Table 1). The following sub-sections further develop on these strategies, along the five dimensions of complexity.

Table 1. Complexity and Management Strategies. 'X' signifies that a given management strategy helps to address the respective complexity dimension.

	Management Strategies for Problem Solving					
Complexity Dimension	**Gathering Information**	**Modeling and Using Decision Support Tools**	**Prioritizing of Measures**	**Conflict Solving**	**Deciding under Uncertainty**	**Being Adaptive and Flexible**
Goals	x			x		
Variables	x		x			
Dynamics	x	x				x
Interconnections	x	x				x
Uncertainty	x		x		x	x

2.1. Number and Relationship of Goals

The dimension of goals can be addressed by using two management strategies. First, conflict solving will play a role in finding a solution, since conflicts around goals negatively influence the likelihood of maximizing all goals [41]. Second, conflict solving also calls for gathering symmetrical information, this being an important condition for confidence building and subsequently for cooperation, as classical studies in the field of international cooperation theory [42] have shown.

To be more specific, if there are several highly important and contradictory goals, problem solvers first should determine which goals should be dealt with and when, and thus conflict resolution and symmetrical information will enable the solution to be reached. The new generation of framework directives of the European Union (EU) such as the European Water Framework Directive, exemplifies such 'normative uncertainty' [29]. If there is just one goal or a few hierarchical and non-contradictory goals, it is clear which goals should be dealt with in which order. In this case, realizing the prioritized goal quickly enables the solution to be reached. Typical examples are EU edicts which are to be implemented at a national level. Next to these extremes, there can be different needs for conflict solving, e.g., based on few goals with the same priority that do not contradict each other, and a few goals that are hierarchical but contradictory.

2.2. Number of Variables

The dimension of variables can be addressed by applying two management strategies. First, information gathering and processing is relevant for finding solutions. Relevant information regards the occurrences of these variables (more or less of a given variable) and their relation to solutions (strength and direction of influence). This information is relevant, since variables are all potential points of intervention, and occurrences and relations can influence which kind of action enables solutions. Second, prioritizing which information on variables has to be gathered is relevant for finding a solution. Such prioritization is necessary, since material and temporal resources are limited [35].

Consider, for instance, problems related to the input of matters in surface waters and groundwater. If the problem is to reduce inputs of matters in general, there are numerous variables that possibly enable solutions such as various types of matters, polluter groups, natural and non-natural framework conditions as well as options to address a problem. The quantity of variables makes it necessary to generate a lot of information (e.g., which kind of measure has which impact on an effective reduction of pollutants) and this can eventually overburden the temporal and monetary resources of problem solvers (e.g., sophisticated simulations to ensure the right combination of measures,) so that priority setting is necessary to arrive at solutions (e.g., focusing on certain types of matters such as persistent organic matters). Considering sub-problems of the overall problem of pollution reduces the number of variables to different degrees. For instance, the goal of reducing the input of pesticides has significantly less influencing variables than the goal of reducing the input of micro-pollutants in general), but more influencing variables than the goal to reduce the input of nitrogen from agriculture. Consequently, information gathering and prioritizing can enable solutions to be reached, to different degrees.

2.3. Degree of Dynamics

Dynamics generally increase the importance of coping with temporal developments, meaning that the variable's next states have to be anticipated [38]. Such anticipations increase the importance of systems thinking and thus information gathering and modeling as well as interactive decision-making environments for finding a solution [35,43–45]. Further, dynamics increase the importance of adapting to changing conditions based on learning. These strategies are useful, since humans face fundamental problems in dealing with dynamics [19,43,44]. This even applies to low dynamics. For instance, rather simple problems such as estimating water amounts in the presence of continuous inflow and outflow cause severe problems for humans [43,46]. Funke [38] showed that two developing variables suffice to impact a system's control negatively. Dörner [19] (p. 91) further emphasized a fundamental "inability to deal with exponential functions". This implies, for instance, "that someone who reads in the newspaper (…), that 6% economic growth is possible in the long run is not in the position to understand this piece of information" [19] (p. 91). Unfortunately, these deficits don't only apply to novices, but to experts as well [31,47].

Highly dynamic variables are very common in different environmental problem areas. Considering climate change, for instance; there is an exponential relationship between CO_2 emissions and temperature. To address such dynamics, modeling the variable's next state and adapting to changing conditions is relevant [21]. However, other problems in the field of environmental policy include variables which develop in a less dynamic way. Take, for instance, the relationships between demographic developments and the input of nutrients in the context of urban wastewater treatment planning. Such relationships are likely to develop in a rather linear way, thus simple demographic scenarios may suffice to address this sub-problem. Also, some problems include variables that do not evolve dynamically for a certain period in time. Take, for instance, fixed subsidies for farmers' practices to reduce the application of fertilizers, or for technologies to support climate change adaptation. In such cases, decisions can be made based on the status quo, and do not have to be adapted for a certain period in time.

2.4. Degree of Interconnectedness

Interconnectedness can be addressed by three management strategies for finding a solution: First, information gathering is needed to define the degree and direction of interconnectedness. Second, modeling enables the evaluation of consequences of actions, as it illustrates mutual dependencies. Third, adaptive decision making is relevant for dealing with side effects [35,45], which can be both negative and positive [48]. These management strategies are based on the difficulties humans encounter in dealing with interconnectedness. Humans tend to think "in causal series instead of in causal nets", that is, main effects are considered whereas (delayed) side effects are neglected [19] (pp. 91ff.). Most importantly, this is due to difficulties in anticipating "all possible consequences of a given situation" [37] (p. 187). Unfortunately, side effects are even more difficult to detect than dynamics [38].

Take, for instance, the goal of enhancing well-being in a certain region in emerging and developing countries. As demonstrated by Dörner and colleagues for the fictitious region of Tanaland, such a goal can include several variables that are intensely interconnected. In fact, those researchers simulated about 50 tightly interconnected variables (e.g., artificial fertilizers, food supply, population growth and famine), so that information gathering (e.g., positive and negative impacts of variables), modeling (e.g., impact of food supply on population growth and vice versa) and adaptive decision making (e.g., less food supply to reduce population growth) enabled solutions (e.g., well-being) [20,37]. However, some sub-problems can be quite different in terms of interconnectedness, and thus also in terms of the management strategies that contribute to successful solutions. For instance, problems such as high prices for animal feed in closed societies have influencing variables with fewer and weaker linkages compared with the general development (e.g., wheat production factors, demand for animal feed), so that less information has to be gathered, simpler models developed, and less adaptive decisions made. Other, small-scale problems such as low wheat production have only a few interconnected variables (e.g., sun, rain, soil), so that the corresponding information gathering, modeling, and adaptiveness are less relevant for finding solutions.

2.5. Degree of Informational Uncertainty

Informational uncertainty can be addressed by three management strategies: First, information gathering is useful for finding solutions since without sufficient information on the problem and its solution options, a problem cannot be solved. Second, there is a need for prioritizing which kind of information has to be gathered, based on limited temporal and monetary resources for information gathering. This also results in a need for deciding under uncertainty. Third, there is a need for adapting to new knowledge to find a solution since decisions are rarely based on complete information [20].

Consider, for instance, the former example of the European Water Framework Directive implementation process. Sigel et al. [49] have pointed out several different degrees of informational uncertainty and its consequences. For instance, they have indicated a low degree of informational uncertainty with regard to the definition of water quality status and specific pollution sources. In contrast, the authors have highlighted a high degree of informational uncertainty with regard to the role of certain measures in achieving a better status of water resources. In between these two extremes, a number of measures for implementing the Water Framework Directive reflect different degrees of informational uncertainty with respect to both technical and economic knowledge.

3. Governance Strategies to Enable and Facilitate Management Strategies

Which governance strategies are likely to facilitate management strategies for solutions? Traditionally, researchers have suggested participatory approaches to address uncertainty in complex problem solving, in contrast to hierarchical modes of governance for solving simple problems [23]. Following Duit et al. [23], we propose going beyond these suggestions by applying a broader understanding of governance. The term governance refers here to all modes of coordinating social action aimed at setting and implementing collectively binding rules [50]. Governance thus serves as an "organizing framework" [51] (p. 18) that includes various forms of coordination such as non-hierarchical and hierarchical modes of governance. Strictly speaking, we consider three main dimensions of governance:

1. Institutions that guide the problem solving process, amongst obligatory and precise rules [52–55];
2. Actors that participate in the problem solving process. Here, we consider the general number and different types of actors [56] such as institutions of the political-administrative system (e.g., legislative actors of different scales), experts (e.g., scientists and locals), and moderators.
3. Interactions, referring to specific modes of communication between participating actors [56,57] such as hierarchic forms of communication, deliberation and negotiation.

These dimensions can all be understood as governance strategies in order to address problems. Take, for instance, the goal of a good qualitative status for water. To achieve this goal, politicians and public authorities could aim for both obligatory and precise rules on how to use waters. To define such rules, they could involve different actors such as public authorities from the local or basin scale, natural, engineering, and social scientists, as well as various local stakeholders such as farmers and industries. Further, moderators could be involved to facilitate deliberative processes between these actors.

We assume that all dimensions can vary between low and high values. First, rules can be more or less obligatory and precise. In terms of obligation, for instance, we can differentiate pure recommendations, laws with exceptions or laws without exceptions [52]. In terms of precision, rules can be highly vague, partly ambiguous or highly precise [52]. Second, varying amounts of actors can be involved in the process. Here, we differentiate between the involvement of none, a few or many actors in general or of specific groups in particular. Finally, communication can be more or less intense [55,57], ranging from hierarchic communication, to deliberation right through to negotiation [57].

Given these variabilities, diverse combinations of governance between two extremes are possible: On the one hand, there is "high density governance" where highly obligatory and precise rules guide negotiation processes of all relevant actor groups. On the other hand, there is "low density governance" where imprecise recommendations guide pure information sharing of public authorities via a single, small actor group which does not further discuss such information in a deliberative or negotiating manner. Between these two extremes, numerous intermediate forms represent more or less dense forms of governance. For instance, governance can be similar in terms of institutions, but differ in terms of actors and their interactions.

Such varying governance dimensions are a feature of the implementation process of the European Water Framework Directive. The Directive has some prevailing governance dimensions, for example regarding the role of participation in river basin management planning [58]. However, when it comes to addressing various sub-problems such as establishing buffer strips in agriculture or implementing more effective wastewater treatments plants, rules can be more or less obligatory, and actors can be involved to different degrees, among others.

This approach to operationalizing governance has several benefits. Most importantly, an analytical understanding of governance allows for analyzing the role of a wide range of governance dimensions in complex problem solving, instead of just focusing on the involvement of actors. The involvement of actors is certainly important, since this governance dimension is prominent in complex problem solving analyses [23]. However, further dimensions such as institutions are also likely to have an important impact on solutions to problems [41,52,53]. We thus assume that the discussion of institutions and interactions is particularly helpful to define more differentiated governance strategies for complex problem solving. On the other hand, limiting ourselves to the dimensions of institutions, actors and interactions also prevents the approach from becoming too complex. For instance, integrating further sub-dimensions of governance such as different moderation techniques might be useful to address complex problem solving, but it is also prejudicial to our goal of outlining the principle logic of the approach.

Based on this understanding of governance, we now aim at identifying those governance strategies that facilitate the implementation of management strategies as identified in Section 2. We ask, for instance, if the governance strategy of involving actors is useful, in order to gather information, or to model dynamics. This also makes it clear that our understanding of governance differs from work which understands governance as an umbrella term for (i) further aspects of planning such as management [59], and specific strategies to address problems such as flexibly adapting to changing conditions [8], among others. In our understanding, management strategies explicitly differ from (i) the structure of problems such as conflicting goals, dynamics, and interconnectedness that underlie these management strategies and (ii) governance strategies such as those involving different types of actors that enable or facilitate these management strategies.

To identify these governance strategies that facilitate management strategies, we consider those analyses that relate to our operationalization as provided above. Given the complexity of our framework, this includes analyses of different fields of research such as policy field analyses and international relations theory. Within this literature, we refer to those governance strategies that seem plausible, both from a theoretical and an empirical point of view. To this end, we refer to literature reviews such as synthesis papers and meta-analyses, as well as to classical studies in the fields. Single case studies usually serve to further exemplify respective governance strategies. In presenting the governance strategies, we stick to summarizing main strategies and arguments of this literature instead of replicating sophisticated discussions in terms of the pros and cons of specific strategies. This is based on our goal of providing a multidimensional approach to governance and complex problem solving. In fact, our strategy of presenting governance strategies allows an illustration of how different governance strategies can concur in a common, overarching framework to address complexity.

Table 2 illustrates this point. For instance, precision and obligation seem rather useful in terms of gathering information, but can also be counterproductive in terms of adaptation and flexibility. At this point we want to highlight that even if researchers identified alternative governance strategies for facilitating management strategies (e.g., different roles of obligation and precision for gathering information), one can reasonably argue that manifold governance strategies can impact management strategies, and thus have to be considered in respective analyses of complex environmental problem solving. In the following, we discuss these governance strategies along six management strategies for problem solving. This helps to increase the traceability back to the complexity degree of problems.

Table 2. Governance Strategies facilitating Management Strategies. The table shows how different governance strategies—grouped into institutions, actors and interactions—facilitate the implementation of different management strategies.

	Governance Strategies		
Management Strategies	**Institutions**	**Actors**	**Interactions**
Gathering Information	Obligation, precision	Involvement of actors in general, involvement of institutions, scientific and local experts, moderators	Deliberation
Modeling/Using Decision Support Tools		Involvement of scientific, local, and political experts	
Prioritizing		Involvement of scientific experts	Deliberation
Conflict Solving	Obligation, precision	Involvement of actors in general, involvement of institutions, scientific experts, veto players, moderators	Deliberation/negotiation
Deciding Under Uncertainty	Lower obligation, precision	Involvement of scientific experts, veto players, but lower involvement of institutions	
Being Adaptive and Flexible	Lower obligation, precision	Lower involvement of experts, veto players	Deliberation/hierarchy

3.1. Governance Strategies Facilitating Information Gathering

Information gathering refers to all complexity dimensions. Equally, all governance dimensions can facilitate this management strategy.

First, institutionalization can have positive effects on information gathering: To start with, obligatory information gathering is likely to foster the willingness of actors to gather cost-intensive information, since non-compliance with obligatory rules necessitates justification, and thus increases the costs of non-compliance [60]. The effectiveness of obligatory rules has been demonstrated repeatedly: for example, in environmental management when tackling water quality issues [61]. Admittedly, however, there is also evidence to suggest that actors can also comply with non-binding rules [53]. Further, precision (e.g., type of information, deadlines) can increase rule legitimacy and thus compliance with these rules. For instance, research in the field of environmental management has shown that setting specific goals (pollution reduction targets for water) leads to better attainment of such goals [30]. Also, research has shown that different forms of specificity, such as the number of goals and target- and time-specifications, impact goal achievement rates across federal agencies in the United States [41].

Second, involving different kinds of actors can facilitate information gathering [62,63]. To start with, scientists effectively provide analytical "know-why" knowledge [64]. In contrast, locals or lay-persons contribute practical "know-how" knowledge [56,64]. However, locals also have access to scientific knowledge. For instance, Beierle [57] shows that in 74% of almost 150 cases of environmental decision making in the USA, participants indeed had high degrees of scientific capacity and resources. Yet, given different key knowledge fields between scientists and locals, a combination of both scientific and local knowledge is emphasized in environmental management [65]. Furthermore, in terms of actors, professional moderators and scientists can foster the generation, but also the integration and structuring of shared knowledge, and thus make information gathering not only more effective, but also more efficient [63,66], for example by using appropriate techniques for generating information [67,68]. Finally, research in the field of international cooperation theory has suggested that delegation to common institutions is an effective way to foster the exchange of information, by building trust among the relevant parties if these institutions are assumed to be impartial [42].

Third, there is evidence to suggest that deliberation has an effect on information gathering and processing: In fact, studies have repeatedly suggested that good deliberation increases participants' knowledge [69]. For instance, deliberation enhances experimental knowledge flow in disadvantaged neighborhood policies [12]. In contrast, hierarchical modes of communication such as "closed" questions seem less useful for eliciting information [63], even though they seem to be more efficient. Traditionally, such evidence is based on "the egalitarian, reciprocal, reasonable and open-minded exchange of language" [70] (p. 153). However, we admit that humans tend to search for evidence that will confirm their own views [71], as well as that groups tend to exchange known facts [70] and support defense routines for given hypotheses, leading to group thinking and thus limited learning based on new facts [45].

3.2. Governance Strategies Facilitating Modeling and Decision Support Tools

Modeling is necessary to handle dynamics and interconnectedness. To facilitate modeling, it is useful to involve different kinds of experts. Most importantly, scientists can ensure the scientific rigor of models, as demonstrated in the field of environmental modeling [66]. However, even scientists have difficulties in developing adequate models [31]. For example, "one can estimate a solution for large linear equation systems, but it can be anywhere from very difficult to impossible to solve an equation system that contains non-linearities" [31] (p. 19). Further, other experts than scientists can facilitate modeling [66,72]. Among others, decision makers can improve models and make them more applicable [45]. This applies particularly to cases of conflicting interest [72]. For instance, participatory modelling has resulted in new and applicable solutions to historically conflicting water pollution issues in Vermont [73].

3.3. Governance Strategies Facilitating Prioritizing

Prioritizing refers to several dimensions of complexity, including, in particular, informational uncertainty. Prioritizing explicitly differs from conflict solving: Whereas conflict solving is about the goals to be pursued, prioritizing addresses the means utilized to reach a goal. It is thus a "conflict" over means rather than goals. To facilitate prioritization, actors and interactions can be of relevance.

First, actors can facilitate prioritization. Most importantly, scientists can assess the relative role of information in a given situation, and thus contribute to solving conflicts concerning prioritization. In fact, prioritizing information gathering could be considered as an attempt to enhance information asymmetry. In such cases, experts that are perceived as being objective could play a legitimizing role by determining the relevance of information. Further, scientists could add to prioritizing by clearly communicating informational uncertainty. In fact, providing specific information on uncertainties seems to be crucial for decision makers as demonstrated in the context of environmental management in the Netherlands [74].

Second, deliberation can facilitate prioritization: If there is no need to prioritize, hierarchical interaction seems plausible, since there is no evidence at hand to support any cost-intensive and thus less efficient forms of interaction, such as deliberation or bargaining. However, if there is a need to prioritize, deliberation may be useful because of its role in discussions on facts and truth [69,70].

3.4. Governance Strategies Facilitating Conflict Solving

Conflict solving refers to the dimension of goals in particular. All governance dimensions can facilitate this management strategy:

First, we consider the kind of institutionalization conflict solvers could strive for in order to settle their conflicts. Interestingly, there seems to be a "tradeoff between the advantages of flexibility in achieving agreement and its disadvantages in ensuring performance" [53] (p. 446). On the one hand, higher degrees of institutionalization in terms of obligatory and precise rules increase the credibility of commitments. This could be explained by the assumed impact of precise rules on behavior, amongst other things [41]. On the other hand, lower degrees of institutionalization in terms of obligation and precision are likely to foster compromise by easing bargaining problems. For, if a certain rule is both obligatory and precise, actors have to consider all relevant consequences of these rules, thus enhancing transaction costs for an agreement. To solve this trade-off, higher degrees of institutionalization are useful when there is high potential for opportunism. This is supposed to be the case in situations of consecutive performance, or when non-compliance is hard to detect [53].

Second, involving actors is likely to facilitate conflict solving. In environmental management, for instance, participation can increase innovative ideas in negotiations and mediations [57], foster the integration of interests [68] and increase acceptance of decisions [27]. However, participation can also run the risk of identifying new conflicts [68,75]. In terms of relevant actors, "those actors should be involved that have a clear interest in the issue at stake" [29] (p. 339), amongst veto players and scientists, in particular: Veto players can enhance the chance of implementing decisions. Scientists can contribute knowledge widening action options, consequently softening hardened negotiation positions as classical studies have suggested [76]. Further, there is evidence to suggest that mediators, in a broad sense, facilitate conflict solving [59,65,66]. In general, participation should be restricted to these actor groups if an efficient solution is to be achieved, since higher numbers of actors increasingly complicate decision making. This has been demonstrated in various contexts, such as in the field of international cooperation [77].

Third, interactions are likely to facilitate conflict solving in different ways. If there is no conflict, hierarchic interaction seems plausible, since there is no reason for more cost-intensive and thus less efficient forms of interaction. If there is a conflict, deliberation can help to reach agreement [78]. This might apply especially to cases of low or medium degrees of conflict regarding facts and truth. Here, deliberation has been suggested to impact empathy and changes in opinion [69,70]. In social dilemma situations, for instance, communication significantly fosters cooperation [79]. However, we admit that evidence for opinion change is not consistent [70], and especially that pre-deliberation preferences strongly impact post-deliberation preferences [80]. Moreover, research suggests that a collaborative governance is rather unlikely to succeed if there is a "prehistory of antagonism among stakeholders" without further measures of trust building, among others [59] (p. 554). Further, Mendelberg [70] argues that in cases of deep value-laden conflicts, deliberation can even have negative effects [70]. In long-standing conflicts, for instance, language may not raise new arguments, but be used as a "linguistic weapon" [70] (p. 171). In such cases, bargaining seems more useful [70].

3.5. Governance Strategies Facilitating Decision Making under Uncertainty

Decision making under uncertainty is particularly relevant for dealing with informational uncertainty. In general, decision making under uncertainty means that decisions have to be taken even though there are uncertainties. Take, for instance, our former example of implementing the European Water Framework Directive. Here, decision makers have to implement measures such as establishing buffer strips and expanding wastewater treatment plants even though the specific impact of such measures on the qualitative status of waters is not assured. Such uncertainty can, in certain contexts, reduce the decisiveness of decision makers that is if they are interested in taking good decisions. In case of the European Water Framework Directive in Germany, for instance, some measures such as a further upgrade of wastewater treatment plants are not implemented due to high costs and unclear benefits, among others. This can have a negative impact on achieving the goal of a good qualitative status for water. The management strategy of decision making under uncertainty thus refers to the need to enhance the decisiveness of decision makers to approach specific goals. We assume that the governance dimensions of institutions and actors facilitate decisiveness:

First, low degrees of institutionalization in terms of obligation and precision may be both efficient and effective in terms of increasing decisiveness in situations of uncertainty. Low degrees of obligation enable actors to see and profit from rules without being obliged to comply with the agreement in case of unforeseen costs, ultimately enhancing certainty and thus decisiveness. Rules that are less obligatory in character also build a framework for future discussions, and thus decrease future decision-making costs. Finally, low degrees of precision are less cost-intensive and thus more efficient (at least if arrangements are legally binding) if future developments are unclear. Moreover, less precise rules can also foster learning processes in view of new developments [53].

Second, involving actors can facilitate decisiveness. To start with, classical studies have suggested that scientists influence the willingness of politicians to make decisions in uncertain situations [81]. Most importantly, scientists can provide information on the impact of decisions. Further, they can provide precise, quantified, but certainly not an "overdose" of information on uncertainty for such impacts, as has been suggested in the context of environmental management in the Netherlands [74]. Further, it has repeatedly been shown that involving veto players is likely to assure the acceptance and thus the implementation of decisions, thus building trust for decisions. However, increased actor involvement also hinders decision making, at least in cases of unanimous decision making. The reason for this is that higher numbers of actors, especially veto players, increase the number of veto points in a decision-making process.

3.6. Governance Strategies Facilitating Adaptation and Flexibility

Finally, the management strategy of adaptation and flexibility refers to the dimension of dynamics, interconnectedness and informational uncertainty, in particular. We assume that all governance dimensions are likely to facilitate this management strategy:

First, obligation and precision is likely to have a negative impact on adaptation and flexibility: If norms are both legally binding and precise, actors are not able to flexibly adapt to new changing conditions because transaction costs for renegotiating rules are high. By implication, norms that are legally binding but imprecise, or precise but non-binding, enable adaptation within a given framework, lowering the costs of transaction [53]. Thus: "While soft law is less credible than hard law, it provides needed flexibility under conditions of uncertainty" [60] (p. 551).

Second, the number and kind of actors is likely to impact adaptation and flexibility: To start with, a lower number of actors in the decision-making process is likely to be effective, since the amount of people increases the time needed for decisions [59,80,82], arguably leading to less flexible decision-making processes. To give some examples, 12-juror juries are at least slightly slower than six-juror juries [82]. Higher numbers of actors increasingly complicate decision making in international relations [77]. Admittedly, however, such time variations may be negligible, depending on the amount of saved time and the quality of the output. Picking up our example of jury deliberation, Saks and Marty [82] (p. 458) chose 12 person juries since the mean difference for deliberation time was not great, while the quality of deliberation was supposed to be enhanced; Ansell and Gash [59] emphasize that time-consuming collaboration can also facilitate the implementation of decisions. Further, involving experts in decision-making processes might negatively impact adaptive decision making. At first glance, experts are faster decision makers than novice problem solvers. However, there is evidence to suggest that experts tend to stick to previous decisions instead of adapting their judgments to changing conditions [47].

Third, deliberation seems to be negatively associated with flexible decision making, since deliberative fora are highly time consuming [69]. Thus, if a high degree of flexibility—in the sense of quick reaction times—is conducive to solutions, hierarchical modes of interaction might be preferable.

4. Linking Complexity, Management Strategies and Governance Strategies

The analyses in the last two sections have suggested several "fragment" strategies (management and governance strategies) to address complex sustainability problems. To be of use for analytical reasoning and empirical analyses, these strategies have to be connected. This section briefly recaps our ideas on how to connect these different strategies (see also Figure 2). In a first step, scientists and practitioners have to identify a specific problem structure. For instance, they can choose a highly complex problem (e.g., for an IWRM in general), a simple problem (e.g., for specific technical problems) or various complicated problems (e.g., different implementation problems of an IWRM). In a second step, users of the approach have to understand the management strategies for the solutions they are interested in. For instance, they can refer to all management strategies for solutions, or just to a subset of management strategies such as information gathering and modeling. As a result, there are various specific governance strategies to address these problems. Scientists can then choose if they are interested in all governance strategies, or just in those strategies related to a specific dimension on governance such as institutions or actors. This is helpful both for researchers who are interested in a specific research question, and practitioners who may just be able to use or change a small set of governance strategies (e.g., actors or rules) to better address a problem.

We admit that this connection is enormously challenging in both theory and practice. For instance, if you choose at least an ordinal scale for each dimension of complexity, we can differentiate 243 types of problems which can each be addressed with a different set of specific governance strategies. However, our work shows clearly that the variety of complex environmental problems in reality can impact the way that these problems are to be addressed. In fact, the approach demonstrates that institutions, actors, and interactions facilitate solutions depending on the complexity dimensions of goals, variables, dynamics, interconnectedness, and informational uncertainty. There is indeed a general tendency: The more complex the problem, the more dense governance facilitates solutions. However, this tendency differs in detail, and sometimes does not apply: Different occurrences of obligation and precision, different actor groups such as scientists and veto players, and different forms of interaction such as hierarchy and deliberation facilitate different management strategies for solutions. Sometimes, higher density governance is counterproductive for solutions.

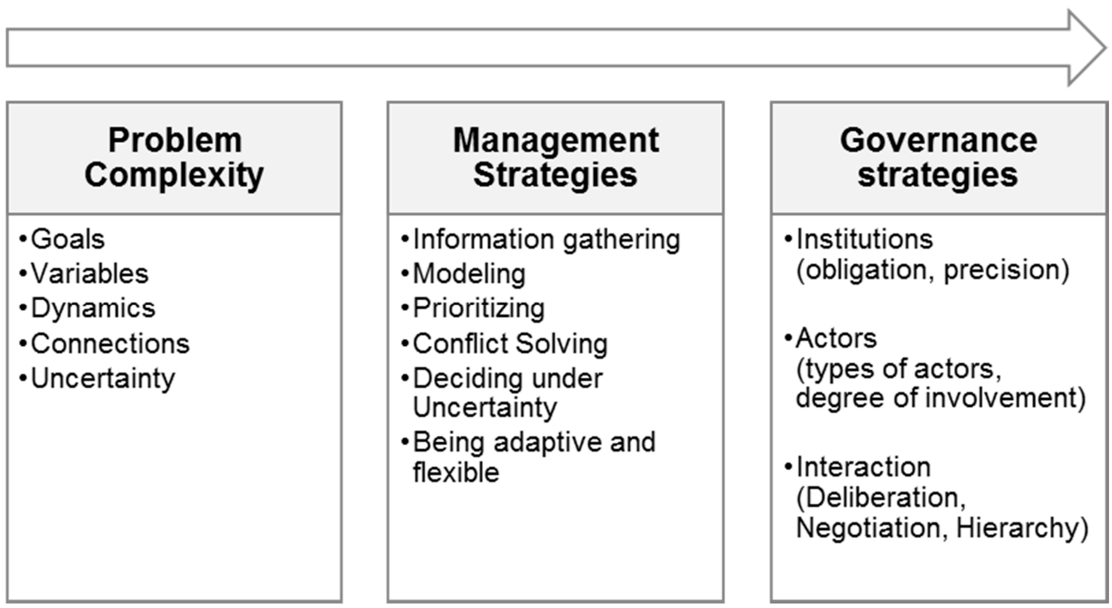

Figure 2. Linking Complexity, Management Strategies, and Governance Strategies.

5. Conclusions

The main goal of this article was to provide a multi-dimensional approach to governance and complex environmental problem solving. In order to achieve this goal, we suggested a functional "how-to"-approach consisting of two steps. First, we operationalized complexity and defined management strategies to address different complexity dimensions, drawing mainly on psychology research. Second, we identified governance strategies that enabled and facilitated these management strategies. Linking the different strategies demonstrates that institutions, the involvement of actors, and specific forms of interactions facilitate solutions, depending on the complexity dimensions of goals, variables, dynamics, interconnectedness, and informational uncertainty.

These insights expand our knowledge of governance for complex problem solving considerably. Most importantly, institutions may be much more relevant for addressing complex environmental problems than has been assumed so far. Moreover, the popular hypothesis of "diversity" [23] (p. 365) for addressing complex problems has been specified in terms of the type and quantity of actors, as well as the form of their interaction. Further, we have demonstrated that the concept of complexity is useful for a systematic approach to addressing policy problems, as different complexity dimensions influence which kind of governance strategies facilitate solutions. We thus advise researchers and practitioners to focus on the specific complexity degree of environmental problems when searching for useful governance strategies to address these problems.

This has implications for discussions related to the solution of environmental resource problems in general, and problems related to water and the WFD in particular. Researchers in these fields have continuously raised the role of participation, social learning and multi-stakeholder platforms, in order to address these complex problems [15,83–87]. They have also struggled continuously with finding the 'right' levels of participation, e.g., related to which types of actors should be involved, and to which degree [29,65,68]. Adding to this research, our work suggests how participatory modes of governance can be applied more effectively, depending on the nature of complexity of the problem at hand.

To further refine the framework, researchers can draw on more specific findings from psychology research. Most importantly, research can analyze the way in which the five dimensions of complexity contribute specifically to the degree of problem complexity. For example, dynamics seem more important for defining the degree of complexity than the dimension of variables [31]. Further possibilities to refine the approach relate to our governance strategies. First and foremost, governance researchers might discuss the relative importance of the suggested strategies with a view to effective problem solving. For instance, researchers could compare the relative impact of obligatory and precise rules on the one hand, and deliberation of stakeholder groups on the other hand. Future research could also systematically integrate the role of various boundary conditions for governance strategies. Cases in point are numerous rules for designing effective participatory processes and deliberation [28,70].

Next to further refinements based on literature reviews, we suggest an evidence-based approach to (a) determine the relevance of the general approach; (b) identify varying degrees of relevance of several dimensions (weighting of dimensions); and (c) solve theoretical controversies, for example by clarifying the specific conditions for the applications of hypotheses. We particularly suggest here to apply the approach to a specific case study, in order to illustrate and test its use in more detail. If the approach appears useful, research still has to clarify how it can be implemented into the practice of environmental problem solving. This is especially important, given the various issues this task entails, such as transaction costs for governance design.

To conclude, we hope that our approach contributes to more differentiated discussions on the governance of complex problem solving. We do not claim, however, that our approach is comprehensive in the sense that it includes all relevant aspects to address complex environmental problems. We rather understand it as a flexible organizing framework that is to be adapted based on the current state of research. We thus invite researchers to problematize our strategies, as referred to in this article, e.g., by suggesting counterevidence for specific governance strategies. If this demanding path is followed, the buzzword of complexity has the potential to be transformed into a useful concept for more systematic analyses of environmental sustainability problems in both theory and practice.

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