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Research, part of a Special Feature on The Next Wave in Water Governance

Successful water governance pathways across problem contexts: a global qualitative comparative analysis

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ABSTRACT. It is widely acknowledged that the global water crisis is a governance crisis. To be effective, governance interventions must be designed to align with the specific context in which they are implemented. Our research aims to identify the types of water governance pathways that lead to successful sustainability performance, with a particular focus on the role of problem contexts. We use fuzzy set qualitative comparative analysis (fsQCA) to examine 41 water governance cases that address groundwater exploitation in agriculture and surface water pollution. The analysis reveals a clear link between the nature of the water problem and successful governance pathways, emphasizing the need for governance measures to align with the specific characteristics of the problems they aim to address. The results also underscore the importance of governance capacity, as evidenced in all three pathways that emerge as solutions in our QCA. Finally, the study shows that no single governance characteristics guarantees success; rather, it is the interplay of multiple, reinforcing governance characteristics that contributes to successful sustainability performance.

Key Words: *governance pathways; problem-specific pathways; QCA; sustainability performance; water governance*

INTRODUCTION

The global water crisis has been identified as a governance crisis (Taylor and Sonnenfeld 2019). With an increasing emphasis on governance as a means to address water problems, there has been a notable rise in the promotion and application of a multitude of approaches (Tropp 2007). Among these approaches, some have been promoted as universal remedies, or panaceas, receiving criticism from water governance scholars who argue that these approaches are proposed without a critical reflection on their appropriateness for the context in which they are applied (Meinzen-Dick 2007, Ingram 2011, Pahl-Wostl et al. 2012). Some examples of these approaches include privatization, integrated water resources management (IWRM), user-based management, or participatory models like water users associations (WUAs) and river basin management (Meinzen-Dick 2007, Moss 2012, Pahl-Wostl et al. 2012). Several studies have suggested that the implementation of these governance approaches varies significantly from one context to another, influenced by factors such as biophysical factors (Garrick et al. 2018), path dependency (Sehring 2009, Lukat et al. 2022), diverse understandings and interpretations (Biswas 2008, van Buuren et al. 2019), and their symbolic application to secure funding and gain greater acceptability (Biswas 2008).

Prior research on common-pool resources governance has also established that governance success depends on institutional and biophysical conditions (e.g., Baggio et al. 2016, Shin et al. 2020, Epstein et al. 2024). Although these studies have examined how social-ecological context influences governance effectiveness, less attention has been paid to whether different types of problems require distinct governance pathways. For instance, although we know that institutions must align with local contexts, it remains unclear whether those that effectively address issues such as point-source pollution from industrial discharge are equally effective in managing groundwater depletion caused by overextraction for agricultural use. Some studies have explored various aspects of problem context in water governance (e.g., Srinivasan et al. 2012, Kirschke et al. 2019, Bilalova et al. 2025) and explored appropriate governance approaches to address them (e.g., Varady et al. 2016, Wuijts et al. 2018). Building on this work, our study specifically examines how the nature of the water problem itself might influence which combinations of governance characteristics lead to successful sustainability performance.

In this study, we systematically assess various water governance cases to identify the governance pathways that contribute to successful water-related environmental sustainability performance (hereafter referred to as sustainability performance) in relation to the problems they address. For example, a governance pathway characterized by centralization and strong institutional capacity may effectively address point source water pollution, leading to measurable improvements in water quality. Specifically, we examine whether successful governance pathways vary depending on the problem context and, if so, explore their connection to the nature of the problem context. Building on Pahl-Wostl (2015), we define water governance as the processes regulating the development, management, and provision of water resources in response to diverse water-related issues or broader problem contexts. In this study, we use "problem contexts" to refer to recurring clusters of interconnected water problems related to the (un)sustainability of water resources and their use. Governance pathways, in turn, are constellations of characteristics that shape governance structure, decision-making processes, actor involvement and their interactions. These characteristics collectively determine governance performance. Here, performance is measured in terms of successful sustainability performance, meaning the extent to which governance pathways contribute to resolving targeted water-related problems, such as surface water pollution. Methodologically, the paper consists of a qualitative comparative analysis (QCA) of 41 water governance cases addressing groundwater exploitation in agriculture and surface water pollution. The cases were derived from a systematic literature review of 165 empirical water governance studies (Bilalova et al. 2024).

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THEORETICAL FRAMEWORK

The purpose here is to establish a theoretical foundation for understanding mechanisms through which a problem context and set of governance characteristics influence sustainability performance. Drawing from established governance theories, we specify main traits of problem contexts and identify a set of core governance characteristics that will serve as the basis for the empirical QCA analysis. By framing problem contexts and governance characteristics, we aim to establish clear, operationalizable conditions that enable a systematic assessment of sustainability performance across diverse governance pathways.

The key governance characteristics were derived from environmental governance theories and seminal works in the field (e.g., Duit and Galaz 2008, Larson and Soto 2008, Moss and Newig 2010, Moss 2012, Hegga et al. 2020, Jager et al. 2020). Although the governance characteristics presented here may not be exhaustive, they include those that are widely recognized as critical for effective governance performance, ensuring their relevance for the empirical QCA analysis.

Problem context

In designing effective governance measures, it is argued to be important to consider the attributes of the problem they aim to address (e.g., Peters 2005, Kirschke et al. 2019, Thomann et al. 2019). We understand water-related problem contexts, "problématiques," as "recurring clusters or ensembles of water-related issues (or problems) in relation to water resources and the (un)sustainability of these resources connected to their use" (Bilalova et al. 2025).

Peters (2005) identifies three core attributes of policy problems that influence the selection of measures. The first attribute determines whether a problem can have a finite and definable solution or if it tends to recur over time (Peters 2005). Problems with high solubility can be easily addressed with one-time interventions, whereas those with ongoing recurrence require sustained efforts (Hoornbeek and Peters 2017). Another crucial attribute is complexity, which encompasses factors such as the number of interests and actors involved, making negotiations challenging, the extent of technical expertise needed to understand the problem, and the existence of multiple and competing causal relations within it (Peters 2005). Complex problems demand a shared understanding and expertise/research (Hoornbeek and Peters 2017). Finally, scale refers to the magnitude of the problem and its range of effects (Peters 2005). Some problems can be broken down into smaller components, allowing for more targeted interventions, while others necessitate comprehensive solutions (Thomann et al. 2019)

From this description, we assume that the problem contexts that present clear management questions (e.g., which issues should be targeted to address the problem) can be addressed with straightforward solutions (e.g., optimizing the wastewater plant; DeFries and Nagendra 2017, Kirschke et al. 2017, Head 2022a). Such issues can be effectively managed through top-down regulatory measures (Ruhl 2005, Homsy et al. 2019). Contrarily, addressing complex problems with inherent goal conflicts, boundary-spanning nature, and non-linearity requires strategies such as multisector decision making, institutions enabling management across administrative boundaries, adaptive management, and stakeholder engagement (DeFries and Nagendra 2017).

Institutional fit and interplay

Following previous works (Young 2002, Moss and Newig 2010, Vatn and Vedeld 2012), we assume that a fit between the characteristics of governance and the biophysical system is essential for addressing environmental problems. Ensuring alignment between governance structure and the biophysical system is likely to result not only in better governance performance but also in resilient governance in relation to external shocks and disturbances (Vatn and Vedeld 2012). Conversely, a misfit between governance solutions and environmental problems has been argued to cause the failure of governance blueprints in effectively addressing problems (Young 2002, Epstein et al. 2015).

To capture the degree of fit, we rely on the literature, which mainly distinguishes between three types of fit: temporal (fit between the rate of environmental changes and the institutional capacity to respond), functional (fit between the functional linkages of the natural system), and spatial (fit between the geographic scopes of ecological issues and institutions; Vatn and Vedeld 2012, Epstein et al. 2015). We consider cases as misfit when institutional measures are either too localized or too broad to effectively address the problem (spatial misfit) or when governance results in a lag between biophysical processes and institutional responses, as well as a lag between the cause and symptoms of environmental problems (temporal misfit; Epstein et al. 2015). Misfit can also occur when parts of the ecological system are managed independently, irrespective of interconnectedness and feedback mechanisms (functional misfit; (Epstein et al. 2015).

In line with Young (1999), we assume that the success of institutions depends not only on their own features but also on their interactions with each other. Interplay is characterized by interactions among institutions within a single societal level (horizontal interplay) as well as interactions between levels (vertical interplay; Young 2002, Moss and Newig 2010). We assess the degree of interplay by examining both of these aspects. Institutional fit and interplay are not separate but rather interlinked. Because most resources have vertical links both upward and downward to systems of larger or smaller scales and horizontal effects on other resources at a similar spatial level (Brondizio et al. 2009), interplay becomes an important aspect of governing complex ecological systems. For example, it is argued that the effectiveness of institutions on a basin scale depends on good institutional interplay, coordination across levels and sectors (Moss 2012). To this end, we hypothesize that having institutional fit without proper interplay may result in poor sustainability performance.

Governance capacity, structure, and stakeholder involvement

Capacity is argued to be an important factor for effective policy making and implementation within a water governance context (e.g., Hegga et al. 2020, Li et al. 2021, Yousefi et al. 2024). It can be understood as the ability of individuals, groups, or organizations to fulfill their responsibilities, determined by both capabilities and resources within a given framework (Franks 1999). In this study, we assume a positive impact of capacity on the successful sustainability performance. We also expect capacity to play an important role in the effectiveness of the other characteristics, such as decentralization, participation, and adaptiveness, which will be explained below.

Decentralization has been heavily promoted as a blueprint by donor agencies, governments, and policy makers. For example, integrated water resources management (IWRM), integrated into the 2030 Agenda, highlights decentralization as one of its core principles. Decentralization refers to devolving power from higher levels to actors and institutions at lower levels within a political, administrative, and territorial hierarchy (Agrawal and Ribot 1999). Centralized decision making, which disregards local conditions, is argued to result in weak accountability and inadequate water resource management (Blomquist et al. 2005). In contrast, decentralization is theorized to enhance resource allocation, efficiency, accountability, and equity by aligning costs and benefits closely with local governments that understand local needs better than centralized governments (Larson and Soto 2008). We capture decentralization by assessing the degree of decision-making power devolution to the lower levels of government.

Although it seems straightforward in theory, decentralization is a complex process that may not work as expected or may take longer than anticipated to yield benefits (Larson and Soto 2008, Meijerink and Huitema 2015). Once a decentralized system is in place, two major factors can significantly undermine its effectiveness. One of these factors is the lack of coordination, which can occur across levels and scales or among existing institutions (resulting from institutional bricolage and leading to the duplication of efforts; Meijerink and Huitema 2015). Another significant factor is poor capacity, which has been reported as a driving force behind the unsuccessful performance of decentralized governance. This occurs when roles and responsibilities are devolved to lower levels without providing them with adequate resources, such as financial and human resources, technical expertise, and knowledge (Meijerink and Huitema 2015, Hegga et al. 2020). Building on the arguments of Meijerink and Huitema (2015), we refrain from hypothesizing any positive or negative impact of decentralization on sustainability performance, as the interplay and capacity within the system determines its effectiveness.

Granting decision-making power to not only the local state actors but also the non-state actors has been argued as key to better environmental outcomes (e.g., Koontz and Thomas 2006, Dietz and Stern 2008, Newig and Fritsch 2009, Jager et al. 2020). As opposed to top-down decision making, participation allows for the integration of diverse values and sources of knowledge and is expected to result in more creative solutions, thus serving the common good rather than particular interests (Newig et al. 2023). Many scholars emphasize the importance of inclusivity in designing effective governance strategies for addressing complex problems, which enables enhanced knowledge, exploration of uncertainties, and accommodation of diverse values and perspectives (Head 2022b). However, having participation in place does not guarantee success because its design plays a decisive role. The recent study by Newig et al. (2023) concludes that the degree of power delegation, the extent to which participants can shape the decisions, strongly predicts better environmental outputs. To this end, we assume a positive impact of participation on sustainability performance and capture participation by assessing the degree of power delegation to non-state actors.

Adaptiveness/knowledge integration

Following the existing literature (Duit and Galaz 2008, Boyd and Folke 2012, Clarvis et al. 2014, Akamani 2016), we assume that addressing abrupt changes and uncertainties in complex water systems necessitates adaptive governance that is flexible and learning-based. Knowledge and learning play integral roles in adaptive governance (Karpouzoglou et al. 2016), which is essential for reorganization following changes and for designing strategies to navigate uncertainties and surprises (Folke et al. 2005). It is suggested that drawing from various knowledge sources, including local, traditional, scientific, and expert knowledge, relevant to the problem-solving process is important for managing and governance of complex adaptive systems (McLain and Lee 1996, Folke 2004, Armitage et al. 2009). In line with the arguments above, we capture adaptiveness/knowledge integration by assessing (1) the degree of flexibility in decision making, which is the ability of governing systems to adjust, revise, or change decisions in response to new information (i.e., monitoring of policy effects) and changing or unexpected conditions, (2) the use of the best available knowledge and evidence, and (3) the use of local or indigenous knowledge. We anticipate that adaptiveness/knowledge integration will positively impact sustainability performance, depending on the availability of the capacity required for adaptive management, as noted by DeFries and Nagendra (2017), who highlight the resource-intensive and time-consuming nature of monitoring systems.

In summary, this theoretical framework identifies key conditions —problem contexts, institutional fit, interplay, governance capacity, decentralization, participation, and adaptiveness/knowledge integration—that are hypothesized to influence sustainability performance (Table 1). These conditions will serve as the conceptual foundation for the QCA, allowing us to systematically analyze their impact across different governance pathways. By operationalizing these conditions, we aim to uncover the combinations of governance characteristics that lead to successful sustainability performance.

METHODS

Water governance problems are complex, typically arising from interactions among multiple factors rather than single causes. To systematically analyze successful governance pathways, we employ qualitative comparative analysis (QCA), a method widely used in previous governance studies (Knieper and Pahl-Wostl 2016, Villamayor-Tomas et al. 2020a, Vallury et al. 2022). QCA is a case-based comparative method that identifies causal patterns by analyzing configurations of conditions across multiple cases (Rihoux 2013).

QCA views causality as context-specific and rejects permanent causality, stressing equifinality (different paths can lead to the same outcome), complex combinations of conditions, and diversity (Ragin 1987, Berg-Schlosser et al. 2012). Unlike statistical techniques that seek a single best-fit causal model, QCA aims to identify multiple distinct causal models among comparable cases (Ragin 1987). We selected QCA specifically for its ability to identify multiple causal pathways because this study

Table 1. Overview of conditions included in the analysis.

Conditions	Definitions	Operationalization
Problem context	Recurring clusters or ensembles of water-related issues (or problems) in relation to water resources and the (un)sustainability of these resources connected to their use	The nature of water-related problem context (i.e., groundwater exploitation in agriculture or surface water pollution)
Institutional fit	Alignment between governance structures and ecological systems	Extent to which there is spatial (congruence between the geographical extents of an ecological problem and institutions), temporal (fit between institutional responses and the rate of biophysical processes), and functional fit (fit between institutional design and responses and the functional linkages of natural system) between the governance system and and the problem addressed
Institutional interplay	Coordination among institutions	Extent to which there is horizontal co-ordination (among institutions across sectors) and vertical co-ordination (among institutions across administrative levels)
Governance capacity	Governance system has its capacity (financial, human, technical, knowledge, etc.) to effectively implement policies	Extent to which the governance system has resources (financial, human, technical, knowledge, etc.) to effectively implement policies
Decentralization	Devolution of functions, responsibilities, and authorities to lower levels	Extent to which functions, responsibilities, and authorities is delegated to institutions at lower levels
Participation	Involvement of non-state actors in the decision making	Extent to which non-state actors are involved in the decision making
Adaptiveness/knowledge integration	Flexibility and the integration of various knowledge sources in the decision making	Extent to which the governance system is flexible (ability to adjust), use best available knowledge and experimentation, and integrates scientific, indigenous, or co-produced knowledge in the decision making

hypothesizes that diverse governance pathways lead to successful sustainability performance and that these pathways vary by problem contexts.

Data

This paper draws on cases identified in a systematic literature review of empirical water governance studies (Bilalova et al. 2024). From an original dataset of 223 cases, only 160 provided relevant information on the problem context, which is the central focus of this study. Initially, we conducted a case survey, coding cases with the problem contexts of groundwater exploitation in agriculture and surface water pollution (86 cases in total). The case survey method allows for identifying and analyzing patterns across cases by converting qualitative narratives into quantified variables (Jensen and Rodgers 2001). During the case survey, we coded each constellation of governance characteristics with sustainability performance as separate cases, following previous studies that used a similar approach (Villamayor-Tomas et al. 2020b), resulting in a total of 89 cases. Because of a significant share of missing data points (40%) across the coded variables and considering the limitations of QCA in handling missing data, we selected the 20 most data-complete cases from each problem context. To account for important within-case variation, we included one additional case. One of the selected cases had a counterpart that was coded separately during the case survey because it involved a distinct constellation of governance characteristics and resulted in a different sustainability performance. Although one of these was already included among the 20 selected cases, we added the second to ensure this variation was captured, resulting in a total of 41 cases. Although 10 of the selected cases had complete information, missing data for the remaining cases were filled in using expert surveys for 12 cases and additional case-based literature for the other 20, including one case that still had missing data after the expert survey. This process addressed missing data for 31 cases, resulting in a total of 41 cases, a number deemed sufficient for conducting QCA within our current capacity and resources. In total, our final dataset included 41 cases stemming from five different continents and a variety of settings (see Fig. 1 and Table A1.1 in Appendix 1 for more detail).

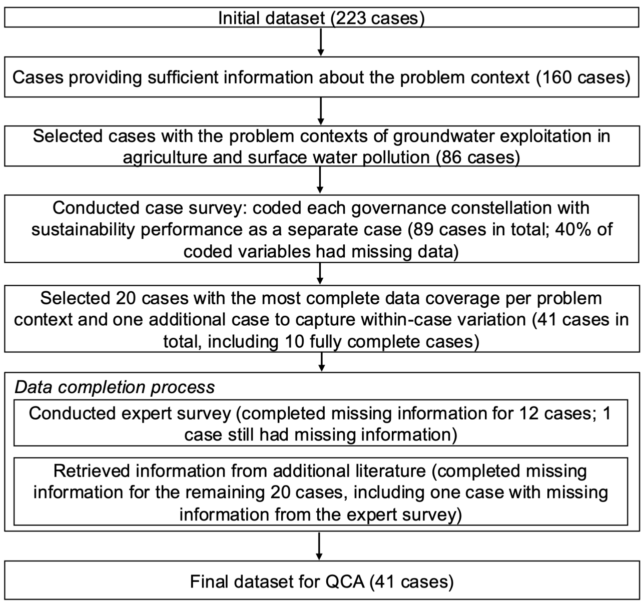
To ensure coding reliability and minimize potential bias, two coders conducted an initial test coding phase. The test coding demonstrated high average intercoder reliability (0.90), allowing the final coding to be conducted by a single coder. However, in cases of uncertainty, coding decisions were discussed and resolved collaboratively within the author team to enhance reliability.

Data analysis

This analysis was conducted using the QCA (Duşa 2019) and SetMethods (Oana and Schneider 2018) packages in R. Grounded in Boolean algebra and its fuzzy set extension, QCA is a set-theoretic method that proves highly instrumental in investigating cause-effect relationships (Goertz and Mahoney 2012, Oana et al. 2021). It enables the systematic comparison of cases, ranging from medium to large N (Greckhamer et al. 2013, Oana et al. 2021). QCA allows for exploring causal complexities between conditions and outcomes, including equifinal, conjunctural, and asymmetric causality, which can be interpreted in terms of necessity and sufficiency (Oana et al. 2021). Necessary conditions are those that are always present for the outcome to occur (a superset of the outcome), while sufficient conditions are those present when the outcome occurs, but the outcome can also occur without them (a subset of the outcome; Schneider and Wagemann 2010, 2012, Oana et al. 2021).

In this study, we use the fuzzy set version of QCA (fsQCA), which permits researchers to assign partial membership scores ranging from 0 (indicating non-membership) to 1 (representing full membership; Ragin 2008). These scores indicate the extent to which different cases belong to a set, with the crossover point (0.5) signifying maximum ambiguity or fuzziness in determining whether a case is more in or out of a set (Rihoux and Ragin 2009). Establishing these qualitative anchors requires a robust foundation of theoretical and empirical knowledge (Rihoux and

Fig. 1. Case selection process.



Ragin 2009, Schneider and Wagemann 2010). A critical analytical tool within QCA, the truth table, illustrates all logically possible configurations of conditions. Through minimization, the truth table facilitates identifying the shortest path sufficient for the outcome by eliminating irrelevant or redundant conditions (Oana et al. 2021).

Outcome and conditions

The outcome is measured as either success (1) or failure (0). A case is deemed successful if the governance intervention improves the sustainable use of water resources and the well-being of freshwater ecosystems. One successful case is illustrated in the study by Montero et al. (2006), which outlines how an inter-municipal initiative addressed pollution in the Ayuquila River in Mexico, reducing pollution levels from industries and urban areas. In failure cases, governance interventions either failed to address the problem or exacerbated water-related environmental issues. For instance, Rinaudo and Donoso (2019) describe how governance contributed to groundwater depletion in the Copiapó Valley in Chile. Our dataset comprises 18 success cases, accounting for 42% of all cases. Overall, the outcome has been defined based on whether the original study authors indicated a positive impact of governance on a sustainability issue (success) or a negative impact, reflecting a failure of governance to adequately address a sustainability issue (failure).

Our selection of conditions aligns with the theoretical framework outlined above. Regarding problem contexts, we rely on the previous study (Bilalova et al. 2025), which identified five water-related problem contexts: "groundwater exploitation in agriculture," "land and water systems sustainability," "surface water pollution," "industrial and household water security," and "hydropower vs. water ecology" based on the archetype analysis of water resources, their uses, and related sustainability issues. In this study, we only focus on groundwater exploitation in agriculture and surface water pollution, which encompass cases dealing with the water quantity aspects of agricultural groundwater withdrawal and cases addressing water quality issues resulting from the discharge of pollutants into surface water resources, respectively (Bilalova et al. 2025). These problem contexts are selected based on empirical and methodological considerations. Both groundwater exploitation in agriculture (n = 56) and surface water pollution (n = 30) include a substantial number of cases, providing a strong empirical foundation for analysis. In contrast, industrial and household water security (n = 23) and hydropower vs. water ecology (n = 13) involve fewer cases. Land and water systems sustainability was excluded because of its broader scope, encompassing a wider range of sustainability issues and water uses compared to other problem contexts. In contrast, groundwater exploitation in agriculture and surface water pollution are well-defined and distinct: they are not equally visible, vary in the urgency of response, and involve distinct actor dynamics, enabling a clear analysis of how governance pathways vary depending on the problem context.

Given that QCA suggests a range of three to seven conditions due to problems of theoretical interpretation and limited diversity (Oana et al. 2021), we constructed composite variables for fit, interplay, and adaptiveness/knowledge integration, respectively. Fit comprises three variables: spatial, temporal, and functional fit; interplay consists of two variables: vertical and horizontal interplay; and adaptiveness/knowledge integration includes three variables: flexibility in decision making, use of evidence, and knowledge integration. In line with Langhans et al. (2014), we aggregated the different components of these variables using an additive-minimum aggregation method, with equal weight from both the minimum and arithmetic aggregations. This method is useful because it combines the strengths of the two methods while ensuring that extreme values do not overly influence the aggregation. These conditions are measured on a scale from 0 to 1, where 0 indicates the absence of the condition, 1 signifies its complete presence, and values in between represent varying degrees of the condition (see Table A1.2 in Appendix 1). We primarily calibrated the raw data using direct calibration, employing a logistic function to align the raw data with three calibration anchors (Schneider and Wagemann 2012). We used indirect calibration for participation because the raw data corresponded to initial set-membership scores. Our anchor points were determined by examining the distribution of each variable to identify naturally occurring clusters and drawing on conceptual and empirical insights (Duşa 2019). As part of calibration diagnostics (Oana et al. 2021), we examined the calibrated sets for ambiguous cases (cases located at crossover points) and skewness of sets (as a rule of thumb, where less than 20% of the cases are either more "in" or more "out" than the calibrated set). For the analysis, we followed the standards of good practice suggested by Schneider and Wagemann (2010) and their protocol for the enhanced standard analysis (Schneider and Wagemann 2013).

Following the robustness test protocol by Oana and Schneider (2024), we conducted a series of tests, including sensitivity ranges, fit-oriented assessments, and case-oriented robustness tests. These results are detailed in Appendix 2, including the calibrated dataset.

RESULTS

The necessity analysis shows that capacity is the only condition that comes close to the conventional consistency threshold of 0.9 (Schneider and Wagemann 2012) with a value of 0.89 and a high RoN (0.852). None of the conditions are necessary for the negated outcome (i.e., absence of successful sustainability performance). More details can be found in Appendix 2.

Regarding the sufficiency analysis, we focus on presenting and discussing the intermediate solution. This solution includes only simplifying assumptions that represent easy counterfactuals, aligning with the researcher's directional expectations on how the conditions contribute to the outcome (Oana et al. 2021). Following the theoretical framework presented above, we set the anticipated impact for all governance-related conditions as positive, except for decentralization, which may have positive or negative effects on the outcome (Table A1.2 in Appendix 1). The results of the conservative and most parsimonious solutions, along with the truth tables for both the outcome and the negated outcome, can be found in Appendix 2.

Figure 2 presents the solutions, also referred to as successful governance pathways, leading to successful sustainability performance. The literature recommends 0.75–0.80 as the lower bound of consistency for sufficiency (Ragin 2008, Schneider and Wagemann 2012, Oana et al. 2021). Although the analysis primarily focuses on identifying configurations leading to successful sustainability performance, it also incorporates failure cases in calibrating conditions, constructing the truth table, and assessing the reliability of identified configuration. The findings reveal three solutions that result in successful sustainability performance, with an overall consistency of 0.98. The overall solution coverage is 0.67, suggesting that our solution explains the positive outcome for a large share of those cases that also display it. The solutions explain 14 out of the 17 cases with a positive outcome, while the remaining three did not meet the set threshold. This is not unusual, as some success cases may not align with the identified configurations, or other dynamics may be at play that are outside the focus of this study. Notably, we did not identify any fundamentally deviant cases, i.e., cases that contradict the sufficiency statement, being a member of the solution but not a member of the outcome (Nair and Gibbert 2016).

The analysis reveals two solutions specific to surface water pollution (~P1) and one generic solution covering both issues. None of the solutions are specific to groundwater exploitation in agriculture. One of the solutions specific to surface water pollution, solution 1, encompasses cases characterized by the absence of decentralization (~decentralization) and the presence of governance capacity, leading to successful sustainability performance in cases of surface water pollution (~P1). Compared to the other two solutions, this solution has a lower coverage (0.12) and is observed in only two cases. One of the two cases with this solution is the case of Tlaxcala in Mexico, where water treatment policy reforms within a hierarchical governance system with enough financing and low municipal participation have proven successful in terms of the percentage of treated water (Flores et al. 2016).

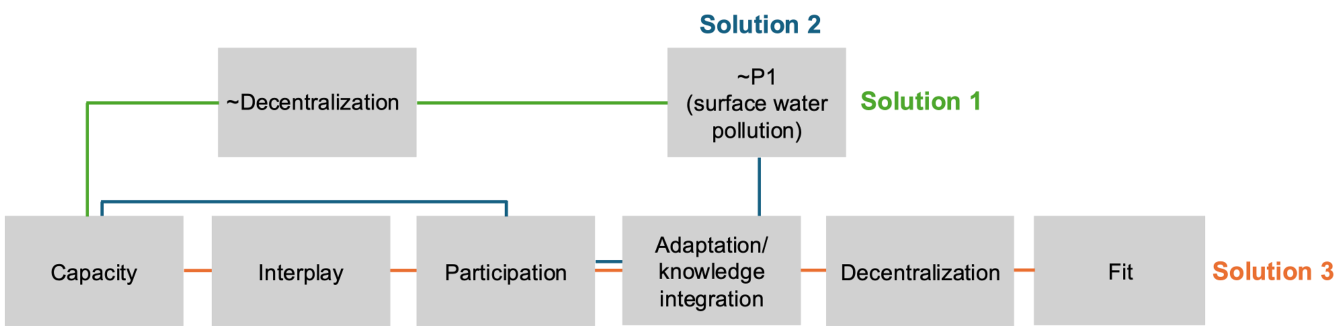
Another solution that leads to successful sustainability performance in the case of surface water pollution is solution 2. Similar to the previous path, the presence of capacity is one of the important conditions. In addition, cases in this solution are characterized by a high degree of participation and adaptation/knowledge integration. One example of a typical case with this solution is the St. Lawrence River Action Plan in Canada, which resulted in the cleanup of the river from pollutants and the protection of its ecosystem (Villeneuve et al. 2006). The case is characterized by a collaborative effort involving government actors as well as non-state actors, including communities (Villeneuve et al. 2006). The action plan had substantial financial and technical support, including for the community involved. Finally, in terms of adaptiveness, the decision making involved both scientific (more prominent in Phase II) and local knowledge (especially in Phase III) and was flexible as the planning of the phases was shaped by reflections (Villeneuve et al. 2006).

The third solution is independent of any problem context and encompasses cases of both groundwater exploitation in agriculture and surface water pollution. A closer examination of the cases within this solution reveals that those involving groundwater exploitation in agriculture and surface water pollution have almost an equal share, with a slight dominance of groundwater exploitation in agriculture (5 cases compared to 4). Successful sustainability performance within this solution results from the presence of governance capacity and a higher degree of fit, interplay, decentralization, and adaptation/knowledge integration. This solution has comparatively lower consistency (0.97) but the highest coverage (0.45).

An example of a typical case within this solution is a pilot project in Tuppal Creek (an intermittent stream) in the Murray Darling Basin, Australia. The project was based on participatory decision making involving stakeholders from government bodies (across levels and sectors) and non-state actors. It was initiated by the Tuppal Creek Landholder Group (TCLG) and the former Murray Catchment Management Authority. The project aimed to be adaptive with flexible management objectives, monitoring, research informing the process, and learning through implementation (i.e., learning by doing). Decision making integrated both scientific and local knowledge. Finally, the project was designed in accordance with the ecological system of Tuppal Creek, aligning spatially, temporally, and functionally with its ecosystem (Conallin et al. 2018).

Finally, comparing the solutions for the outcome and the negated outcome also provides some insights that can be relevant (see Table A2.9 in Appendix 2). First, the role of capacity has been observed among the solutions to absence of successful sustainability performance, as its absence is noted in most solutions, except in the case where a poor fit with the decentralized system leads to groundwater depletion due to agricultural activities. Taken together with its high prevalence in the solutions for the positive outcome and its high scores in the necessity tests, an overall picture emerges in which capacity can be considered a necessary condition for achieving high sustainability performance. Second, looking at the generic solutions applicable to both problem contexts, we observe that capacity, fit, and interplay are important conditions. Their presence, together with other conditions, leads to successful sustainability performance, while their absence, coupled with decentralization being present or participation and adaptation/knowledge integration being absent, leads to unsuccessful sustainability performance.

Fig. 2. Intermediate solutions for successful water-related sustainability performance (consistency threshold 0.80). Note: ~ symbolizes the absence of the given condition.



Solutions	Consistency	PRI	Raw cov.	Unique cov.	No. of cases
Solution 1	1.000	1.000	0.118	0.098	2
Solution 2	1.000	1.000	0.315	0.099	7
Solution 3	0.967	0.967	0.452	0.255	9 (4 cases overlap with the second solution)

Overall solution consistency = 0.977
Overall solution coverage = 0.668
Overall PRI = 0.977

Conditions	Necessity	Sufficiency
Capacity	0.882	0.883
Interplay	0.752	0. 772
Participation	0.629	0.666
Adaptation/knowledge integration	0.879	0.608
Fit	0.748	0.791
Decentralization	0.882	0.500
~Decentralization	0.118	0.182
~P1 (surface water pollution)	0.588	0.476

DISCUSSION

This study aimed to explore the sustainability performance of water governance systems, focusing on the role of problem contexts. The results offer three key insights into the sustainability performance of water governance systems. First, we identified two successful governance pathways specific to surface water pollution, each with a distinct constellation. These pathways provide insight into the relationship between the nature of the problem context and the successful governance approaches. These findings empirically contribute to the literature linking the nature of the problem with governance measures (e.g., Peters 2005, DeFries and Nagendra 2017, Hoornbeek and Peters 2017). For example, in the case of the Tlaxcala Atoyac sub-basin, which corresponds to the first pathway (absence of decentralization and the presence of governance capacity), the main problem targeted was municipal wastewater, which was addressed by building wastewater treatment plants (Flores et al. 2016). Contrarily, in the case of second pathway (the presence of capacity, a high degree of participation and adaptation/knowledge integration), the pollution of the St. Lawrence River was linked to multiple sources (including industrial, municipal, and agricultural) concerning governments (Canada and Quebec) and impacted not only the river ecosystem but also wildlife and plant habitats, which required more nuanced and comprehensive intervention (Villeneuve et al. 2006). Other cases with solution two—Mersey Basin in the UK (Salthouse 2000), Laguna de Bay in the Philippines (Oledan 2001), Ayuquila River Basin in Mexico (Montero et al. 2006), and Tuppal Creek system in Australia (Conallin et al. 2018)—exhibit similar problem contexts related to surface water pollution spanning across administrative areas and involving complex stakeholder settings. This aligns with the prior research that governance measures should be designed in accordance with the attributes of the problem they aim to address, such as solubility, complexity, and scale (Peters 2005, DeFries and Nagendra 2017, Thomann et al. 2019).

Our study highlights the critical role of capacity in achieving sustainability performance, as evidenced by the consistent presence of governance capacity across all three successful governance pathways. Additionally, governance capacity stands out in the necessity analysis as a key factor for successful sustainability performance. These results are in line with the previous studies (Gill et al. 2017, Selig et al. 2017). Capacity also explains the varying performance of governance strategies, as its presence is noted in almost all solutions for successful sustainability performance, while its absence is observed in almost all cases of unsuccessful sustainability performance. Without adequate capacity, strategies effective in one context may not yield success in another (Hegga et al. 2020).

Finally, our findings confirm that there is no easy solution or panacea to ensuring water-related sustainability (see Meinzen-Dick 2007, Ostrom 2007). Most conditions included in our study have been prescribed by international organizations and policy makers for effective water governance (Gupta and Pahl-Wostl 2013, Meijerink and Huitema 2015, Huitema and Meijerink 2017, Woodhouse and Muller 2017). Despite success stories, a substantial body of literature reports a variety of failure stories in various contexts (e.g., Benson et al. 2014, Meijerink and Huitema 2017, Hegga et al. 2020). Our findings suggest that success is not solely reliant on a single condition or governance paradigm (e.g., decentralization vs. adaptive capacity), which is in line with the previous research (e.g., Gutiérrez et al. 2011, Baggio et al. 2016, Knieper and Pahl-Wostl 2016, Villamayor-Tomas et al. 2020a). As such, successful sustainability performance can be a result of the interplay of mutually reinforcing conditions. For instance, capacity influences adaptiveness (DeFries and Nagendra 2017), decentralization (Meijerink and Huitema 2015), and participation (Sabatier et al. 2005), while interplay is crucial for achieving a successful fit (Moss 2012). This emphasizes the need for a nuanced understanding of potential synergies and trade-offs among various governance characteristics.

Our study has some limitations that shall be addressed in future studies. One of the limitations is that we only look at two problem contexts, groundwater extraction in agriculture and surface water pollution. Future research can expand this analysis to other problem contexts, such as land and water systems, household and industrial water security, and hydropower vs. water ecology, to better understand the role of a problem context and to examine whether the results of this study are also observed in those problem contexts. Another limitation is that this study only presents the types of governance pathways for successful sustainability performance, without exploring their underlying causal interactions. More attention may be needed to the detailed causal interactions between conditions. Interactions within these successful governance pathways and between conditions and their causal link to successful performance could be further investigated in future studies by conducting in-depth analyses or process tracing. Such analyses would address a major limitation of this study: its reliance on data primarily drawn from the existing empirical literature on water governance. Specifically regarding sustainability performance, original studies may be biased, often favoring the publication of statistically significant results and a tendency to seek, interpret, and publish findings that confirm existing beliefs and hypotheses (Zvereva and Kozlov 2021). Furthermore, measuring the impact of water governance is generally difficult because of the complexity and diversity of contextual factors (Akhmouch et al. 2022), which may not be fully captured by the original studies. Thus, an in-depth analysis of governance pathways through a case study may help to provide a more nuanced understanding of the actual sustainability performance.

CONCLUSION

This study examined 41 water governance cases to identify governance pathways that lead to successful sustainability performance in relation to the problem contexts of groundwater exploitation in agriculture and surface water pollution. The analysis reveals three key findings, which contribute to enhancing our understanding of successful water governance for water-related sustainability, including the nexus between problem context, governance design, and successful water-related sustainability performance. First, our results confirm the linkage between the nature of a problem context and successful water governance pathways. Aligning problem context with the governance design can allow policy makers to enhance the effectiveness of their policies. Second, governance capacity emerges as a determining factor for the effectiveness of the governance pathways and, ultimately, successful sustainability performance, as evidenced in the necessity analysis and all three pathways to successful sustainability performance. The importance of capacity emphasizes the need for contextual considerations when transferring and implementing governance approaches. Finally, the findings substantiate that there is no easy solution to address water-related problems, as governance characteristics reinforce each other (as part of larger solution pathways) rather than being sufficient by themselves, necessitating a holistic approach to crafting institutions. Designing effective governance pathways would benefit from considering how different governance characteristics interact with each other rather than focusing on particular aspects in isolation.

Author Contributions:

Shahana Bilalova: conceptualization, data curation, methodology, formal analysis, investigation, visualization, writing – original draft, writing – reviewing and editing. Nicolas W. Jager: methodology, investigation, writing – review & editing. Jens Newig: conceptualization, writing–review & editing, supervision. Sergio Villamayor-Tomas: conceptualization, writing–review & editing, supervision.

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Data Availability:

The datasets generated and/or analyzed during the current study are available in the Leuphana University repository: https://doi.org/10.48548/pubdata-236.

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Appendix 1. Data and calibration

Information on the cases

The analysis encompasses 41 cases (Table A1.1). Among them, two cases are related to the Tlaxcala Atoyac Sub-Basin in Mexico (Flores et al. 2016), which were coded separately during the case survey as distinct constellations of governance characteristics that led to contrasting sustainability performance: one case successfully addressed surface water pollution, while the other failed. Among these cases, 20 address the problem context of groundwater exploitation in agriculture, while the remaining cases focus on surface water pollution. Overall, there are 17 cases of "success." Seven of these successful cases are related to groundwater exploitation in agriculture, while the rest pertain to surface water pollution. The cases cover a wide geographical distribution, covering Asia (China, India, Vietnam, Indonesia, Turkey), Europe (Estonia, Spain, UK), North America (USA, Canada), Latin America (Mexico, Chile), Africa (South Africa), Oceania (New Zealand, Australia), and the Middle East (Iran).

Table A1. 1 Overview of the cases.

Case name	Country	Problem context	Water sustainability performance	Original source
Transjurisdictional Water Pollution Management in China	China	Surface water pollution	Failure	Ongley, E. D., and X. Wang. 2004. Transjurisdictional water pollution management in china: The legal and institutional framework. *Water International* 29(3):270–281.
Zhangweinan River Basin	China	Surface water pollution	Failure	Zhang, Y., G. Fu, T. Yu, M. Shen, W. Meng, and E. D. Ongley. 2011. Trans-jurisdictional pollution control options within an integrated water resources management framework in water-scarce north-eastern China. *Water Policy* 13(5):624–644.
Water Pollution Control in Guangzhou, Pearl River	China	Surface water pollution	Failure	Yu, Y., D. G. Ohandja, and J. N. B. Bell. 2012. Institutional Capacity on Water Pollution Control of the Pearl River in Guangzhou, China. *International Journal of Water Resources Development* 28(2):313–324.
The Matsalu Bay	Estonia	Surface water pollution	Failure	Eckerberg, K. 1997. Comparing the local use of environmental policy instruments in nordic and baltic countries - The issue of diffuse water pollution. *Environmental Politics* 6(2):24–47.
Water Governance in Indonesia	Indonesia	Surface water pollution	Failure	Chattopadhyay, S., and K. Thiruvananthapuram. 2018. Challenges of water governance in the context of water quality problem: Comparative study of India, Indonesia and Germany. Transactions of the Institute of Indian Geographers 40(2):171–183.
Tlaxcala Atoyac Sub-Basin	Mexico	Surface water pollution	Success	Flores, C. C., V. Vikolainen, and H. Bressers. 2016. Water governance decentralisation and river basin management reforms in hierarchical systems: Do they work for water treatment policy in Mexico's Tlaxcala Atoyac sub-basin? *Water (Switzerland)* 8(5).
Tlaxcala Atoyac Sub-Basin	Mexico	Surface water pollution	Failure	Flores, C. C., V. Vikolainen, and H. Bressers. 2016. Water governance decentralisation and river basin management reforms in hierarchical

				systems: Do they work for water treatment policy in Mexico's Tlaxcala Atoyac sub-basin? *Water (Switzerland)* 8(5).
Olifants River (mid-1990s-2005/2006)	South Africa	Surface water pollution	Failure	Biggs, H. C., J. K. Clifford-Holmes, S. Freitag, F. J. Venter, and J. Venter. 2017. Cross-scale governance and ecosystem service delivery: A case narrative from the Olifants River in north-eastern South Africa. *Ecosystem Services* 28:173–184.
Institutional Design in Managing Water Pollution from Vietnam's Craft Villages in the Red River Delta Region of Vietnam	Vietnam	Surface water pollution	Failure	Mahanty, S., and T. D. Dang. 2013. Crafting Sustainability? The Potential and Limits of Institutional Design in Managing Water Pollution from Vietnam's Craft Villages. *Society and Natural Resources* 26(6):717–732.
Water Quality Management in Singapore	Singapore	Surface water pollution	Success	Tortajada, C., and Y. K. Joshi. 2014. Water quality management in Singapore: the role of institutions, laws and regulations. *Hydrological Sciences Journal* 59(9):1763–1774.
Cases of the Chilika, Kolleru and Vembanad Lakes	India	Surface water pollution	Failure	Narayanan, N. C., and J. P. Venot. 2009. Drivers of change in fragile environments: Challenges to governance in Indian wetlands. *Natural Resources Forum* 33(4):320–333.
Tuppal Creek system	Australia	Surface water pollution	Success	Conallin, J., E. Wilson, and J. Campbell. 2018. Implementation of Environmental Flows for Intermittent River Systems: Adaptive Management and Stakeholder Participation Facilitate Implementation. *Environmental Management* 61(3):497–505.
Government and Community Intervention on the St. Lawrence River	Canada	Surface water pollution	Success	Villeneuve, S., J. Painchaud, and C. Dugas. 2006. Targeted sustainable development: 15 years of government and community intervention on the St. Lawrence River. *Environmental Monitoring and Assessment* 113(1–3):285–301.
Environmental Planning in the Great Lakes (RAP)	Canada/United States	Surface water pollution	Failure	Beierle, T. C., and D. M. Konisky. 2001. What are we gaining from stakeholder involvement? Observations from environmental planning in the Great Lakes. *Environment and Planning C: Government and Policy* 19(4):515–527.

Trans-boundary Water Governance in the Great Lakes Basin	Canada/United States	Surface water pollution	Success	Talukder, B., and K. W. Hipel. 2020. Diagnosis of sustainability of trans-boundary water governance in the Great Lakes basin. *World Development* 129.
Inter-municipal Initiative for the Integrated Management	Mexico	Surface water pollution	Success	Montero, S. G., E. S. Castellón, L. M. M. Rivera, S. G. Ruvalcaba, and J. J. Llamas. 2006. Collaborative governance for sustainable water resources management: The experience of the Inter-municipal Initiative for the Integrated Management of the Ayuquila River Basin, Mexico. *Environment and Urbanization* 18(2):297–313.
Freshwater Management Regime in Manawatu River Catchment	New Zealand	Surface water pollution	Success	McNeill, J. 2016. Scale Implications of Integrated Water Resource Management Politics: Lessons from New Zealand. *Environmental Policy and Governance* 26(4):306–319.
Watershed Management in Laguna de Bay	Philippines	Surface water pollution	Success	Oledn, M. T. T. 2001. Challenges and opportunities in watershed management for Laguna de Bay (Philippines). *Lakes and Reservoirs: Research and Management* 6(3):243–246.
River Restoration Project in Incheon	South Korea	Surface water pollution	Success	Lee, S., and G. W. Choi. 2012. Governance in a River Restoration Project in South Korea: The Case of Incheon. *Water Resources Management* 26(5):1165–1182.
Water Management and Governance in l'Albufera de València Wetland	Spain	Surface water pollution	Failure	Jégou, A., and C. Sanchis-Ibor. 2019. The opaque lagoon. Water management and governance in L'albufera de València Wetland (Spain). *Limnetica* 38(1):503–515.
The Mersey Basin Campaign	United Kingdom	Surface water pollution	Success	Salthouse, C. 2000. Making the most of the Mersey estuary: A partnership approach to catchment management. *International Journal of Urban Sciences* 4(2):129–138.
Copiapó Valley	Chile	Groundwater exploitation in agriculture	Failure	Rinaudo, J. D., and G. Donoso. 2019. State, market or community failure? Untangling the determinants of groundwater depletion in Copiapó (Chile). *International Journal of Water Resources Development* 35(2):283–304.

The Minqin Oasis of Northwest China	China	Groundwater exploitation in agriculture	Failure	Hu, X. J., Y. C. Xiong, Y. J. Li, J. X. Wang, F. M. Li, H. Y. Wang, and L. L. Li. 2014. Integrated water resources management and water users' associations in the arid region of northwest China: A case study of farmers' perceptions. *Journal of Environmental Management* 145:162–169.
The Case of the Shiyang River Basin	China	Groundwater exploitation in agriculture	Success	Hu, X. J., Y. C. Xiong, Y. J. Li, J. X. Wang, F. M. Li, H. Y. Wang, and L. L. Li. 2014. Integrated water resources management and water users' associations in the arid region of northwest China: A case study of farmers' perceptions. *Journal of Environmental Management* 145:162–169.
The Groundwater System in the Rafsanjan Plain	Iran	Groundwater exploitation in agriculture	Failure	Mirnezami, S. J., C. de Boer, and A. Bagheri. 2020. Groundwater governance and implementing the conservation policy: the case study of Rafsanjan Plain in Iran. *Environment, Development and Sustainability* 22(8):8183–8210.
Water Governance in Dryland System in the Rio Del Carmen Wastershed	Conchos	Groundwater exploitation in agriculture	Failure	Lopez Porras, G., L. C. Stringer, and C. H. Quinn. 2019. Corruption and conflicts as barriers to adaptive governance: Water governance in dryland systems in the Rio del Carmen watershed. *Science of the Total Environment* 660:519–530.
Groundwater Governance in Pakistan	Pakistan	Groundwater exploitation in agriculture	Failure	Qureshi, A. S. 2020. Groundwater governance in pakistan: From colossal development to neglected management. *Water (Switzerland)* 12(11):1–20.
Upper Guadiana Basin, Castilla-La Mancha	Spain	Groundwater exploitation in agriculture	Failure	Knüppe, K., and C. Pahl-Wostl. 2013. Requirements for adaptive governance of groundwater ecosystem services: Insights from Sandveld (South Africa), Upper Guadiana (Spain) and Spree (Germany). *Regional Environmental Change* 13(1):53–66.
Irrigated Agriculture in Turkey	Turkey	Groundwater exploitation in agriculture	Failure	Özerol, G., and H. Bressers. 2015. Scalar alignment and sustainable water governance: The case of irrigated agriculture in Turkey. Environmental Science and Policy 45:1–10.
Farmer Participation and Irrigation Practices in Harran Plain	Turkey	Groundwater exploitation in agriculture	Failure	Özerol, G. 2013. Institutions of farmer participation and environmental sustainability: A multi-level analysis from irrigation management in

				Harran Plain, Turkey. *International Journal of the Commons* 7(1):73–91.
Tampa Bay Water	United States	Groundwater exploitation in agriculture	Success	Asefa, T., A. Adams, and I. Kajtezovic-Blankenship. 2014. A tale of integrated regional water supply planning: Meshing socio-economic, policy, governance, and sustainability desires together. *Journal of Hydrology* 519(PC):2632–2641.
Agricultural User Groups Created Across France	France	Groundwater exploitation in agriculture	Failure	Rouillard, J., and J. D. Rinaudo. 2020. From State to user-based water allocations: An empirical analysis of institutions developed by agricultural user associations in France. *Agricultural Water Management* 239.
WDP in Rajasthan, India	India	Groundwater exploitation in agriculture	Failure	Singh, C. 2018. Is participatory watershed development building local adaptive capacity? Findings from a case study in Rajasthan, India. *Environmental Development* 25:43–58.
Integrated River Basin Management (IRBM) Programme in the Conchos River	Mexico	Groundwater exploitation in agriculture	Failure	Barrios, J. E., J. A. RodríGuez-Pineda, and M. De La Maza Benignos. 2009. Integrated river basin management in the Conchos river basin, Mexico: A case study of freshwater climate change adaptation. *Climate and Development* 1(3):249–260.
The Period 1999-2010: New Public Management and Collaboration in Canterbury	New Zealand	Groundwater exploitation in agriculture	Failure	Kirk, N., A. Brower, and R. Duncan. 2017. New public management and collaboration in canterbury, New Zealand's freshwater management. *Land Use Policy* 65:53–61.
Sandveld, Western Cape Province	South Africa	Groundwater exploitation in agriculture	Failure	Knüppe, K., and C. Pahl-Wostl. 2013. Requirements for adaptive governance of groundwater ecosystem services: Insights from Sandveld (South Africa), Upper Guadiana (Spain) and Spree (Germany). *Regional Environmental Change* 13(1):53–66.
Olifants River (2007-2016)	South Africa	Groundwater exploitation in agriculture	Success	Biggs, H. C., J. K. Clifford-Holmes, S. Freitag, F. J. Venter, and J. Venter. 2017. Cross-scale governance and ecosystem service delivery: A case narrative from the Olifants River in north-eastern South Africa. *Ecosystem Services* 28:173–184.

PIM activities at the Kra-siew Reservoir	Thailand	Groundwater exploitation in agriculture	Success	Sinclair, A. J., W. Kumnerdpet, and J. M. Moyer. 2013. Learning sustainable water practices through participatory irrigation management in Thailand. *Natural Resources Forum* 37(1):55–66.
The SAGEs	France	Groundwater exploitation in agriculture	Success	Piégay, H., P. Dupont, and J. A. Faby. 2002. Questions of water resources management. Feedback on the implementation of the french SAGE and SDAGE plans (1992-2001). *Water Policy* 4(3):239–262.
The Ashburton Water User Group and Opuha Community Water Storage Dam	New Zealand	Groundwater exploitation in agriculture	Success	Marquardt, M., and S. Russell. 2007. Community governance for sustainability: Exploring benefits of community water schemes? *Local Environment* 12(4):437–445.
The Twyford Cooperative Company Ltd in Hawke's Bay and Central Plains Water Ltd	New Zealand	Groundwater exploitation in agriculture	Success	Boone, S., and S. Fragaszy. 2018. Emerging scarcity and emerging commons: Water management groups and groundwater governance in Aotearoa New Zealand. *Water Alternatives* 11(3):795–823.

Table A1.2 Conditions, outcome, and calibration decisions.

Condition	Description	Original scale	Calibration			Expected impact on the outcome
			0	**0.5**	**1**	
Capacity (CAP)	Governance system has its capacity (financial, human, technical, knowledge, etc.)	No (0); To some extent (0.5); Yes (1)	0	0.75	1	+
Fit (FIT)	Does the institutional arrangement match with a problem scale? (Additive-minimum aggregation - *Following Langhans et al. (2014), we added the arithmetic mean and the minimum of related conditions and divided the sum by two).*	No (0); To some extent (0.5); Yes (1)	0.1	0.45	0.7	+

	Spatial: congruence between the geographical extents of an ecological problem and institutions *Temporal*: fit between institutional responses and the rate of biophysical processes *Functional*: fit between institutional design and responses and the functional linkages of natural system					
Interplay (INTER)	Interplay (Additive-minimum aggregation) *Vertical*: There is a strong coordination among government bodies across administrative levels *Horizontal*: There is a strong cooperation among governance bodies across sectors	No (0); To some extent (0.5); Yes (1)	0.1	0.55	1	+
Decentralization (DEC)	Functions, responsibilities, and authority are delegated to very local levels of decision-making	No (0); To some extent (0.5); Yes (1)	0	0.4	1	-/+
Participation (PART)	Degree of engaging non-state actors into the decision-making	Not involving (0); consultation (0.33); collaborative decision-making (0.67); full decision-making power (1);	0	0.5	1	+
Adaptiveness/knowledge integration (ADAPT/KNOW)	Degree of adaptiveness and knowledge integration (Additive-minimum aggregation) *Flexibility*: Governance is flexible and allows for adjustments when new information becomes available, especially in presence of high uncertainty *Use of evidence*: Using the best available knowledge and experimentation (i.e., policy and management as experiments and learning-by-doing) *Knowledge integration*: Scientific, indigenous as well as co-produced knowledge integration into decision-making	No (0); To some extent (0.5); Yes (1)	0.1	0.25	0.7	+

Problem context 1: Groundwater exploitation in agriculture (P1)	Problem context (i.e., problématique) of groundwater exploitation in agriculture	Absent (0); Present (1) Presence of the condition denotes to groundwater exploitation in agriculture, while the absence refers to surface water pollution	0	0.5	1	
Successful water-related sustainability performance (OUT)	Water governance system/intervention resulted in positive changes in water-related environmental sustainability issue/water resources in terms of improvements	Failure (0); Success (1)	0	0.5	1	

Table A1. 3 Data description.

Variable	**n**	**min**	**max**	**mean**	**sd**
Capacity	41	0	1	0.5	0.5
Fit	41	0	1	0.4	0.4
Interplay	41	0	1	0.4	0.4
Decentralization	41	0	1	0.6	0.4
Participation	41	0	1	0.4	0.4
Adaptiveness/knowledge integration	41	0	1	0.4	0.4
Problem context 1: Groundwater exploitation in agriculture	41	0	1	0.4	0.4
Water-related sustainability performance	41	0	1	0.4	0.5

Table A1. 4 Calibrated dataset.

CASE	CAP	FIT	INTER	DECEN	PART	ADAPT/KNOW	P1	OUT
1	0	0.1	0	0	0	0	0	0
2	0	0	0	1	0	0	0	0
3	0	0	0	1	0	0	0	0
4	0	0	0	0	0	0.3	0	0
5	0	0.3	0	1	0	0.3	0	0
6	1	0.1	0.4	0	0	0	0	1
7	0	0.1	0.4	1	0	0	0	0
8	0	0	0	1	0	0.3	0	0
9	0	0	0	0	0	0	0	0
10	1	0.3	1	0	0.33	1	0	1
11	0	0	0	1	0.33	0	0	0
12	1	1	1	1	0.67	1	0	1
13	1	0.3	1	1	0.67	1	0	1
14	0	1	1	1	0.67	1	0	0
15	1	0.1	0.4	1	0.67	0.6	0	1
16	1	1	1	1	0.67	0.6	0	1
17	1	0.1	0	1	0.67	0.9	0	1
18	1	1	1	1	0.67	1	0	1
19	0	1	0.6	1	0.67	0.6	0	1
20	0	0	0	1	0.67	0.8	0	0
21	1	1	1	1	1	1	0	1

22	0	0	0	0	0	0.6	1	0
23	0	0.3	0	0	0	0.3	1	0
24	1	1	0	1	0	0.3	1	1
25	0	0	0	0	0	0	1	0
26	0	0	0	0	0	0	1	0
27	0	0	0	1	0	0	1	0
28	1	0.3	0.4	1	0	0.6	1	0
29	0	0.1	0	0	0	0	1	0
30	0	0	0	1	0.33	0	1	0
31	0	1	0.6	1	0.33	0.6	1	1
32	0	0.8	1	1	0.67	1	1	0
33	0	0.1	0	1	0.67	0.3	1	0
34	1	0.3	1	1	0.67	1	1	0
35	1	0	0	1	0.67	1	1	0
36	0	0.1	0	0	0.67	0	1	0
37	1	1	1	1	0.67	0.9	1	1
38	1	1	1	1	0.67	1	1	1
39	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1
41	1	1	1	1	1	1	1	1

Table A1. 5 Results of the skewness analysis for the outcome and conditions after calibration.

Variable	Cases > 0.5 / Total number of cases
CAP	18 / 41 = 43.90 %
FIT	14 / 41 = 34.15 %
INTER	16 / 41 = 39.02 %
DECEN	30 / 41 = 73.17%
PART	20 / 41 = 48.78 %
ADAPT/KNOW	22 / 41 = 53.66 %
P1	20 / 41 = 48.78 %
OUT	17 / 41 = 41.46 %

Appendix 2. Fuzzy-set Qualitative Comparative Analysis (fsQCA)

Table A2. 1 Analysis of necessity for the successful and unsuccessful water-related sustainability performance.

Conditions	Successful water-related sustainability performance (OUT)		Absence of successful water-related sustainability performance (~OUT)	
	Cons.Nec	RoN	Cons.Nec	RoN
CAP	0.882	0.885	0.118	0.462
FIT	0.765	0.869	0.235	0.450
INTER	0.765	0.861	0.235	0.456
DECEN	0.882	0.423	0.118	0.769
PART	0.629	0.823	0.371	0.462
ADAPT/KNOW	0.784	0.727	0.216	0.560
P1	0.412	0.618	0.588	0.645

For a condition to be deemed necessary, the recommended consistency threshold is 0.9, indicating that the condition should be observed in at least 90% of the cases where the outcome is present (Schneider and Wagemann 2012). Upon examining our conditions, we observe that the consistency value is below this threshold for all seven conditions, for the negated outcome (absence of successful sustainability performance) (~OUT) (Table A2.1). In the case of the outcome (successful water-related sustainability performance) (OUT), there are two conditions with a very close consistency value, which are capacity (CAP) and decentralization (DECEN). However, having a closer look at the RoN (Relevance of Necessity), we observe that only capacity has RoN above the recommended value of 0.6 (see Oana et al. 2021). The RoN, or Relevance of Necessity, assesses whether a condition is non-trivial by comparing the sizes of the condition set to the outcome sets (Schneider and Wagemann 2012). When the outcome set and the condition set diverge significantly in size—either because the outcome is very small (very few cases are members) or because the condition set is very large (almost all cases are members)—a necessity claim becomes trivial (Oana et al. 2021).

Table A2. 2 Truth table for the presence of the outcome

	CAP	FIT	INTER	DECEN	PART	ADAPT /KNOW	P1	OUT	n	incl	PRI	cases
65	1	0	0	0	0	0	0	1	1	1	1	104
79	1	0	0	1	1	1	0	1	2	1	1	7,47
83	1	0	1	0	0	1	0	1	1	1	1	105
95	1	0	1	1	1	1	0	1	1	1	1	37
127	1	1	1	1	1	1	0	1	4	1	1	29,117, 110,140
128	1	1	1	1	1	1	1	1	5	0.94	0.94	66,71,60, 118,130
106	1	1	0	1	0	0	1	0	1	0.70	0.70	113
60	0	1	1	1	0	1	1	0	1	0.63	0.63	1
63	0	1	1	1	1	1	0	0	2	0.45	0.45	101,14
64	0	1	1	1	1	1	1	0	1	0.33	0.33	126
1	0	0	0	0	0	0	0	0	3	0	0	12,120,12 2
2	0	0	0	0	0	0	1	0	4	0	0	75,16,121, 48
4	0	0	0	0	0	1	1	0	1	0	0	41
6	0	0	0	0	1	0	1	0	1	0	0	50
9	0	0	0	1	0	0	0	0	6	0	0	17,31,115, 104_1,67, 131
10	0	0	0	1	0	0	1	0	2	0	0	28,46
14	0	0	0	1	1	0	1	0	1	0	0	77
15	0	0	0	1	1	1	0	0	1	0	0	22
76	1	0	0	1	0	1	1	0	1	0	0	52
80	1	0	0	1	1	1	1	0	1	0	0	64
96	1	0	1	1	1	1	1	0	1	0	0	58

Note: If the row is sufficient for the outcome set, it is shown in the "OUT" column. The "n" column refers to the number of cases with each path. The "inclusion score," or consistency for path sufficiency, is displayed in the "incl" column. We set the consistency threshold at 0.8, and the paths that meet these criteria have been shown in light grey. These paths are included in the minimization.

Table A2. 3 Truth table for the negated outcome.

	CAP	FIT	INTER	DECEN	PART	ADAPT /KNOW	P1	~OUT	n	incl	PRI	cases
1	0	0	0	0	0	0	0	1	3	1	1	12,120,122
2	0	0	0	0	0	0	1	1	4	1	1	75,16,121,48
4	0	0	0	0	0	1	1	1	1	1	1	41
6	0	0	0	0	1	0	1	1	1	1	1	50
9	0	0	0	1	0	0	0	1	6	1	1	17,31,115,104_1,67,131
10	0	0	0	1	0	0	1	1	2	1	1	28,46
14	0	0	0	1	1	0	1	1	1	1	1	77
15	0	0	0	1	1	1	0	1	1	1	1	22
76	1	0	0	1	0	1	1	1	1	1	1	52
80	1	0	0	1	1	1	1	1	1	1	1	64
96	1	0	1	1	1	1	1	1	1	1	1	58
64	0	1	1	1	1	1	1	0	1	0.67	0.67	126
63	0	1	1	1	1	1	0	0	2	0.55	0.55	101,14
60	0	1	1	1	0	1	1	0	1	0.37	0.37	1
106	1	1	0	1	0	0	1	0	1	0.30	0.30	113
128	1	1	1	1	1	1	1	0	5	0.06	0.06	66,71,60,118,130
65	1	0	0	0	0	0	0	0	1	0	0	104
79	1	0	0	1	1	1	0	0	2	0	0	7,47
83	1	0	1	0	0	1	0	0	1	0	0	105
95	1	0	1	1	1	1	0	0	1	0	0	37
127	1	1	1	1	1	1	0	0	4	0	0	29, 117,110,140

Prior to minimization, we checked the truth table to determine whether rows contain enough empirical evidence and for any contradictory truth table rows (Table A2.2 and Table A2.3). Contradictory truth table rows are the rows that are sufficient for both the occurrence and non-occurrence of the outcome (Oana and Schneider 2024). Our truth table did not contain such rows.

Table A2. 4 Conservative solution for the outcome (OUT).

	inclS	**PRI**	**covS**	**covU**	**Cases**
CAP*~FIT*DECEN*PART*ADAPT/KNOW*~P1	1	1	0.112	0.086	7,47; 37
CAP*FIT*INTER*DECEN*PART*ADAPT/KNOW	0.964	0.964	0.451	0.426	29,117,110, 140; 66,71,60, 118,130
CAP*~FIT*~INTER*~DECEN*~PART*~ADAPT/KNOW*~P1	1	1	0.033	0.033	104
CAP*~FIT*INTER*~DECEN*~PART*ADAPT/KNOW*~P1	1	1	0.039	0.039	105
M1	0.973	0.973	0.609		

Table A2. 5 Prime implicant chart for the conservative solution.

	65	**79**	**83**	**95**	**127**	**128**
CAP*~FIT*DECEN*PART*ADAPT/KNOW*~P1	-	X	-	X	-	-
CAP*FIT*INTER*DECEN*PART*ADAPT/KNOW	-	-	-	-	X	X
CAP*INTER*DECEN*PART*ADAPT/KNOW*~P1	-	-	-	X	X	-
CACAP*~FIT*~INTER*~DE-CEN*~PART*~ADAPT/KNOW*~P1	X	-	-	-	-	-
CAP*~FIT*INTER*~DECEN*~PART*ADAPT/KNOW*~P1	-	-	X	-	-	-

Minimization in QCA is used to find the simplest solution and involves two steps using the Quine-McCluskey Algorithm: 1. Identifying prime implicants, and 2. Minimizing prime implicants by identifying and dropping logically redundant prime implicants. The Prime Implicant Chart (Table A2.5) shows the link between prime implicants and primitive expressions, helping to distinguish between logically essential and redundant ones (i.e., primitive expressions are still covered after the prime implicant is dropped) (Oana and Schneider 2024).

Table A2. 6 Conservative solution for the negated outcome (~OUT).

	inclS	PRI	covS	covU	cases
~CAP*~FIT*~INTER*~PART*~ADAPT/KNOW	1	1	0.567	0.295	12,120,122; 75,16,121,48; 17,31,115, 104_1,67,131; 28,46
~CAP*~FIT*~INTER*~ADAPT/KNOW*P1	1	1	0.312	0.050	75,16,121,48; 50; 28,46; 77
~CAP*~FIT*~INTER*~DECEN*~PART*P1	1	1	0.204	0.025	75,16,121,48; 41
CAP*~FIT*~INTER*DECEN*ADAPT/KNOW*P1	1	1	0.065	0.037	52; 64
CAP*~FIT*DECEN*PART*ADAPT/KNOW*P1	1	1	0.056	0.028	64; 58
~CAP*~FIT*~INTER*DECEN*PART*ADAPT/ KNOW*~P1	1	1	0.028	0.019	22
M1	1	1	0.753		

Table A2. 7 Prime implicants chart for the negated outcome (~OUT).

	1	2	4	6	9	10	14	15	76	80	96
~CAP*~FIT*~INTER*~PART*~ADAPT/KNOW	X	X	-	-	X	X	-	-	-	-	-
~CAP*~FIT*~INTER*~ADAPT/KNOW*P1	-	X	-	X	-	X	X	-	-	-	-
~CAP*~FIT*~INTER*~DECEN*~PART*P1	-	X	X	-	-	-	-	-	-	-	-
CAP*~FIT*~INTER*DECEN*ADAPT/KNOW*P1	-	-	-	-	-	-	-	-	X	X	-
CAP*~FIT*DECEN*PART*ADAPT/KNOW*P1	-	-	-	-	-	-	-	-	-	X	X
~CAP*~FIT*~INTER*DECEN*PART* ADAPT/KNOW*~P1	-	-	-	-	-	-	-	X	-	-	-

```
M1: CAP*~P1 + (CAP*FIT*INTER) -> OUT
M2: CAP*~P1 + (CAP*FIT*PART) -> OUT
M3: CAP*~P1 + (CAP*FIT*ADAPT/KNOW) -> OUT

                                                ---------------------------
                           inclS   PRI    covS   covU   (M1)   (M2)   (M3)
--------------------------------------------------------------------------
1              CAP*~P1   1.000  1.000  0.529  0.235  0.244  0.302  0.270
--------------------------------------------------------------------------
2        CAP*FIT*INTER   0.945  0.945  0.580  0.007  0.294
3         CAP*FIT*PART   0.966  0.966  0.483  0.000         0.255
4   CAP*FIT*ADAPT/KNOW   0.944  0.944  0.567  0.020                0.307
--------------------------------------------------------------------------
                    M1   0.961  0.961  0.824
                    M2   0.979  0.979  0.785
                    M3   0.961  0.961  0.837

                         cases
---------------------------
1              CAP*~P1   104; 7,47; 105; 37; 29,117,110,140
---------------------------
2        CAP*FIT*INTER   29,117,110,140; 66,71,60,118,130
3         CAP*FIT*PART   29,117,110,140; 66,71,60,118,130
4   CAP*FIT*ADAPT/KNOW   29,117,110,140; 66,71,60,118,130
---------------------------
```

Figure A2. 1 Most parsimonious solution for the outcome (OUT)

```
M1: ~FIT*P1 + (~CAP*~FIT) -> ~OUT
M2: ~FIT*P1 + (~CAP*~INTER) -> ~OUT

                                         -------------------
               inclS   PRI   covS   covU   (M1)   (M2)
-----------------------------------------------------------
1     ~FIT*P1  1.000  1.000  0.455  0.101  0.101  0.110
-----------------------------------------------------------
2    ~CAP*~FIT  1.000  1.000  0.746  0.013  0.393
3  ~CAP*~INTER  0.954  0.954  0.773  0.048         0.428
-----------------------------------------------------------
            M1  1.000  1.000  0.848
            M2  0.960  0.960  0.883

               cases
--------------------
1      ~FIT*P1  75,16,121,48; 41; 50; 28,46; 77; 52; 64; 58
--------------------
2    ~CAP*~FIT  12,120,122; 75,16,121,48; 41; 50; 17,31,115,104_1,67,131; 28,46; 77; 22
3  ~CAP*~INTER  12,120,122; 75,16,121,48; 41; 50; 17,31,115,104_1,67,131; 28,46; 77; 22
--------------------
```

Figure A2. 2 Most parsimonious solution for the negation of the outcome (~OUT)

We also checked for the contradictory simplifying assumptions. When the same logical remainder row is included in the logical minimization for both the outcome's occurrence (Y) and non-occurrence (~Y), this is known as a contradictory simplifying assumption (CSA) (Oana and Schneider 2024). We did not identify any.

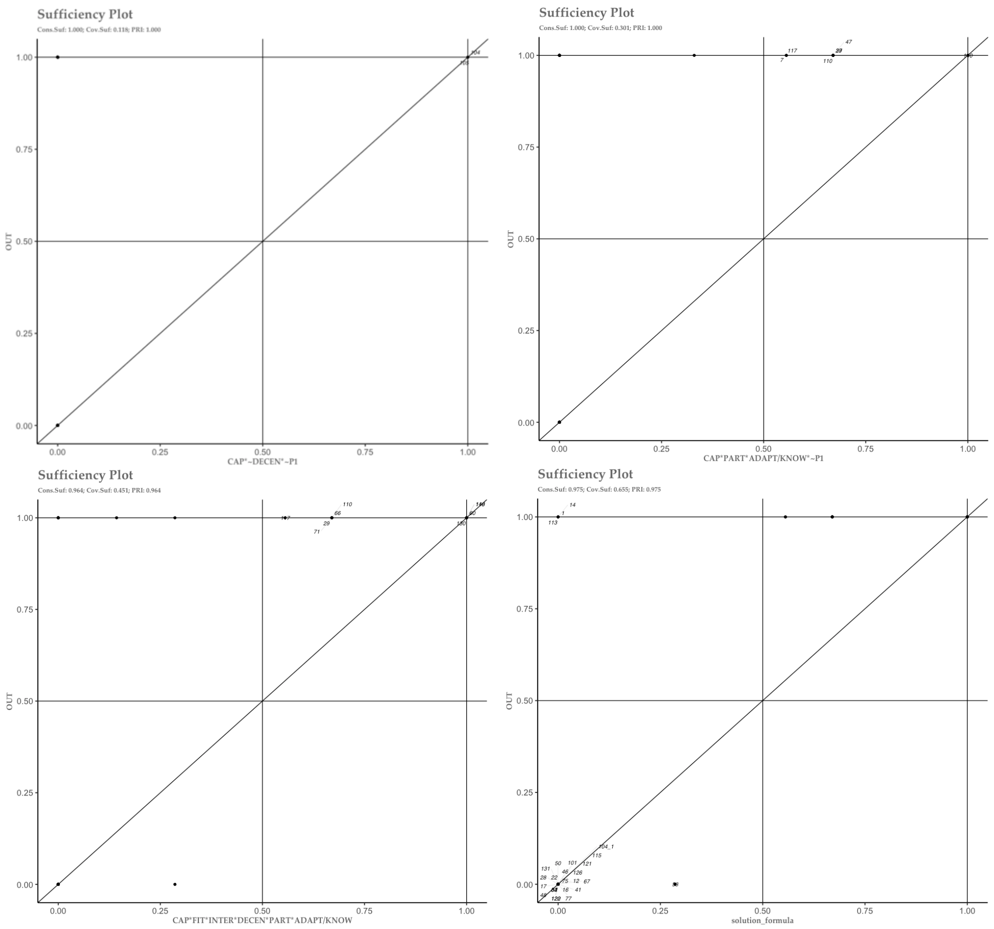

Figure A2. 4 Plot for the intermediate solution paths and the formula.

Plotting the solution paths and formula for the outcome (Figures A2. 4), we observe no deviant case consistency in kind for any of the solution paths (lower right quadrant).

Table A2. 8 Easy counterfactuals, which are based on the researcher's directional expectations on the ways in which the conditions influence the result, used for the intermediate solution.

	CAP	FIT	INTER	DECEN	PART	ADAPT/KNOW	P1
7	1	0	0	0	0	1	0
69	1	0	0	0	1	0	0
71	1	0	0	0	1	1	0
81	1	0	1	0	0	0	0
85	1	0	1	0	1	0	0
87	1	0	1	0	1	1	0
97	1	1	0	0	0	0	0
99	1	1	0	0	0	1	0
101	1	1	0	0	1	0	0
103	1	1	0	0	1	1	0
111	1	1	0	1	1	1	0
113	1	1	1	0	0	0	0
115	1	1	1	0	0	1	0
117	1	1	1	0	1	0	0
119	1	1	1	0	1	1	0

Table A2. 9 Intermediate solution for the negation of the outcome.

	inclS	PRI	covS	covU	cases
~FIT*DECEN*P1	1	1	0.229	0.110	28,46; 77; 52; 64; 58
~CAP*~FIT*~INTER*DECEN	1	1	0.380	0.062	17,31,115,104_1,67,131; 28,46; 77; 22
~CAP*~FIT*~IN-TER*~PART*~ADAPT/KNOW	1	1	0.567	0.105	12,120,122; 75,16,121,48; 17,31,115,104_1,67,131; 28,46
~CAP*~FIT*~INTER*~PART*P1	1	1	0.288	0.025	75,16,121,48; 41; 28,46
~CAP*~FIT*~IN-TER*~ADAPT/KNOW*P1	1	1	0.312	0.022	75,16,121,48; 50; 28,46; 77
M1	1	1	0.821		

We checked contradictory simplifying assumptions also for the intermediate solution and found none.

Robustness analysis for the intermediate solution for the outcome (OUT)

Following Oana et al. (2021), we conducted a three-step approach that includes sensitivity range (i.e., ranges that allow adjustments to be made to the frequency cutoff, raw consistency threshold, and calibration anchors, respectively, without changing the solution's Boolean expression), fit-oriented robustness (i.e., robustness of the solution to multiple and simultaneous changes), and case-oriented robustness (i.e., identifying various types of cases (robust cases, shaky cases, and possible cases) in the intersection between various alternative solutions created) evaluation (Table A2.10, Table A2.11, Table A2.12, and Figure A2.5).

Table A2. 10 Sensitivity ranges for calibration anchors for the conditions.

		FIT	**INTER**	**ADAPT/KNOW**
	Lower bound	NA	NA	NA
Exclusion	Threshold	0.1	0.1	0.1
	Upper bound	NA	NA	NA
	Lower bound	NA	NA	0.25
Crossover	Threshold	0.45	0.55	0.25
	Upper bound	NA	NA	NA
	Lower bound	NA	NA	NA
Inclusion	Threshold	0.7	1	0.7
	Upper bound	NA	NA	NA

Note. We only ran the analysis for the conditions that underwent indirect calibration.

Table A2. 11 Sensitvity ranges for raw consistency threshold and n.cut.

	Raw consistency threshold	N.cut
Lower bound	NA	2
Threshold	0.8	2
Upper bound	0.93	2

For the fit-oriented robustness, we made the following changes to the test solution:

1. Adjusted the consistency to 0.75.
2. Modified the calibration for "FIT" by assigning anchor points of 0, 0.4, and 1.
3. Set the n.cut to 1.

Table A2. 12 Robustness parameters for the fit-oriented robustness analysis.

	RF_cov	RF_cons	RF_SC
Robust-ness_Fit	0.934	0.867	0.81

We observe that RF_cov and RF_cons are both smaller than 1, indicating that the solution and the test solution do not perfectly overlap (Table A2.12). However, the numbers are quite high, suggesting that the overlap is substantial.

```
$CaseParameters
                      RCR_typ RCR_dev RCC_Rank
Robustness_Case_Ratio   0.933       0        3

$CaseTypes
Robust Typical Cases (IS*MIN_TS and Y > 0.5) :
-------------------

Boolean Expression: CAP*~P1 + CAP*FIT*INTER

Cases in the intersection/Total number of cases: 14 / 41 = 34.15 %
Cases in the intersection/Total number of cases Y > 0.5:  14 / 17 = 82.35 %

Case Names:
104 105 29 37 7 117 47 110 140 66 71 60 118 130
-------------------

Robust Deviant Cases (IS*MIN_TS and Y < 0.5) :
-------------------

Boolean Expression: CAP*~P1 + CAP*FIT*INTER

Cases in the intersection/Total number of cases: 0 / 41 = 0 %
Cases in the intersection/Total number of cases Y < 0.5:  0 / 24 = 0 %

Case Names:
No cases in this intersection
-------------------
```

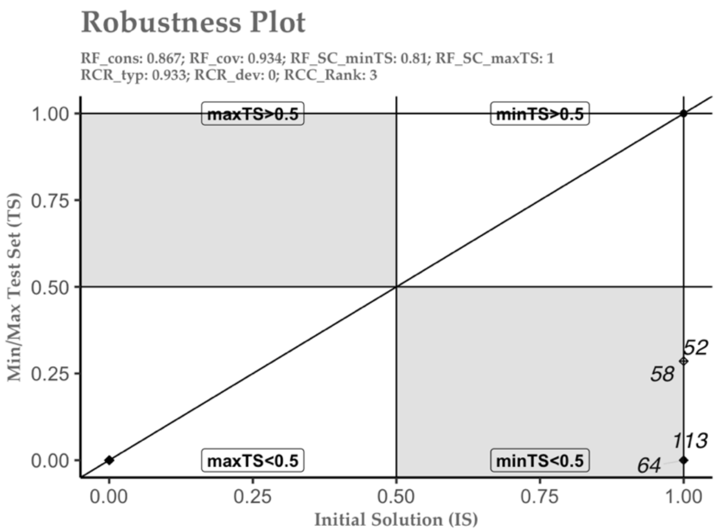

Figure A2. 5 Case-oriented robustness results.

The case-oriented robustness analysis reveals that 93% of the typical cases are member of both initial solution and test solution (Figure A2.5). The plot does not show any case in the problematic upper-left quadrant.