



Identifying the Sensitivity of Complex Human-Water Systems Using a Qualitative Systems Approach

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As the complexity of human-water systems interactions is increasing, the need for an integrated view on water-related issues becomes more important. In this study we focus on the qualitative description of human-water interactions with the aim to identify sensitive system variables which may alter the established water resource system. Qualitative system analysis based on extensive expert elicitation regarding reservoir management was applied to disclose the politics behind water management visions and measures and to identify sensitive system variables where the different perspectives of stakeholders and decision-makers enter the human-water system in response to environmental change and societal processes. This highlights the interplay of the distribution of water and the distribution of power which is central within human-water systems. The results are 2-fold. First, we show, that such a qualitative approach is helpful in revealing sensitive system variables. Second, our analysis identifies (i) perception of change, (ii) risk to users, and (iii) discrepancy of actual and desired level of reservoir as the sensitive system variables deciding about thresholds in the specific setting of our case study. Hereby, the case study highlights also the applicability and usability of our approach. Aiming at sustainable water management, knowledge about the sensitive system variables is crucial to understand the effects of different visions and, hence, action within the human-water system to cover the whole range of societal responses. While we applied this approach on a reservoir management example, we are confident that this approach is transferable to other water management cases for identifying the complexity of interactions, sensitive system variables, and critical variables of change and transformation.

Keywords: qualitative system analysis, expert elicitation, influence diagrams, pluralistic water research (PWR), reservoir management, sustainable water management

INTRODUCTION

Sustainable water management systems aim at keeping the integrity of water-related ecosystems while at the same time meeting the needs and demands of the society over multiple generations (Wiek and Larson, 2012; Schneider et al., 2015; Poff et al., 2016). As the complexity of human-water systems interactions increases, an integrated view on water-related issues becomes more important (Troy et al., 2015; Ceola et al., 2016; Pande and Sivapalan, 2017; Xu et al., 2018), especially the recognition of the societal processes in form of norms and values (Sivapalan et al., 2012, 2014; Seidl et al., 2013; Lane, 2014).

Reservoir management is a particularly valuable example of such complex human-water interactions which needs to balance not only technical and natural perspectives, but also social and political ones. To understand current water resources management regulations, not only the distribution of water but also the distribution of power and the interplay between these two distributions are important dimensions requiring attention (Brisbois and de Loë, 2016; Wesseling et al., 2017; Zwartveen et al., 2017; Xu et al., 2018). Current water governance research, however, rather focuses on evaluating good practice examples than on analyzing the political and strategic decisions behind those practices (Zwartveen et al., 2017). Additionally, this strong focus on management solutions is masking the underlying political processes responsible for interventions and their outcomes (Wilson et al., 2019). There is the need to analyze the different stakeholders' perspectives and interests when interacting with the natural system (see e.g., Bakker and Morinville, 2013; Sayer et al., 2013; Evers et al., 2017; Xu et al., 2018), because the ability of this system to maintain its functions after a disturbance is influenced by human intervention (Liu et al., 2007). Hence, considering the plurality of framings and meanings is of utmost importance to understand the resilience or adaptive capacity of the human-water system when aiming at water sustainability under changing environmental and social conditions (Seidl et al., 2013; Xu et al., 2018).

In our study we particularly aim to address the sensitivity of the mutual feedback mechanisms between the human interaction, which is guided by norms, values and interests, and the physical properties of the water system. Addressing these sensitivities is an effective way to identify thresholds where a system changes its functionality (Evers et al., 2017) and therefore puts risks to other uses. We find that sensitive system variables are therefore starting points for possible future and alternative pathways in scenario analysis, because they indicate how different values and behavior may alter the human-water system (Swart et al., 2004; Lienert et al., 2006; Inayatullah, 2008). Here, we especially focus on the discursive power of the different stakeholders. Discursive power is the ability to control and influence norms and regulations (Ingram, 2013; Zwartveen et al., 2017) and to frame agendas (Brisbois and de Loë, 2016; Wilson et al., 2019). As the key strength of qualitative system modeling is to concisely describe problem narratives and to identify how different stakeholders may reason about a problem solution (Coyle, 2000; Halbe et al., 2013), we specifically make use of analyzing different water managers' perspectives. The multi-functionality of reservoir management is a valuable example of elucidating such differing viewpoints. While reservoirs are built to manage available water resources more independently from natural variability and to serve users' needs, there are trade-offs between increasing water storage for societal needs—such as compensation of water shortages—and at the same time maximizing the flood control zone to mitigate flooding. These trade-offs are aggravated by environmental concerns. In this study, we focus on the water managers' perception of environmental change and the impact of different perspectives and interests on their understanding of the human-water system.

Using a qualitative systems approach, this paper aims to understand the behavior of the system and to identify sensitive system variables which may alter the established water resource system and to discuss their impact on the distribution of water and power within sustainable water management. Hereby, the study also highlights the value of using a qualitative system approach to acknowledge norms, values, and alternative futures within societal processes.

MATERIALS AND METHODS

This study uses the pluralistic water research (PWR) approach (Evers et al., 2017) to visualize and contextualize the case study on reservoir management in its socio-hydrological or hydro-social complexity (section Case Study Reservoir Management Under Inter- and Intra-Annual Variability in Germany's Middlemountains). Based on this visualization and expert elicitation to highlight the perspective of different water experts (section Expert Elicitation—Identifying Objectives of Water Resources Decision-Making) a qualitative system analysis (section Qualitative System Analysis—Influence Diagrams and Cone of Influence Diagrams) is used to identify the sensitive system variables.

Case Study Reservoir Management Under Inter- and Intra-Annual Variability in Germany's Middlemountains

Reservoir management aims at both, flood protection and low flow mitigation. Due to the hydrological regime in the middle mountains in Germany, flood control with reservoirs is important during the winter term, while low flow support is needed during summer. Variability in precipitation or a change in precipitation patterns challenges the system as climate adaptation studies of several basins of the middle mountains in Germany show (Morgenschweis et al., 2006; Kufeld et al., 2013; Demny et al., 2014, 2018; Meon et al., 2018). Usually reservoirs have been filled up in March to collect water for the dryer period, however, the onset of these rainfalls starts later during the main growing season, reducing the discharge into the reservoir. Given this observed change, water managers drive two important questions. First, in a short-term perspective, how to cope with the deficit in water storage? For example, one could fill up the reservoir already in February, however, this means that the potential to decrease flooding is reduced. Second challenge, in a long-term perspective, is to understand the trade-offs between flood protection and low flow support under a changing climate. On the one hand water managers from water associations act on a catchment scale and try to understand the catchment processes under changing precipitation patterns to fulfill their task of providing flood protection, low flow support, and assuring ecological flow requirements, hydro-power generation, and recreation activities such as fishing or boating. On the other hand there are political actors such as the state agencies and district governments acting on different administrative scales and political levels. Their task is to balance trade-offs and enhance justice among the diversity of water users. They are also in control of the water associations

by permitting specific discharge rates and, hereby, setting the desirable reservoir level.

The pluralistic water research (PWR) concept (Evers et al., 2017) provides an analytical tool to understand the context around complex management issues, such as reservoir management, where neither the technical management part nor the political meanings get lost but rather complement each other. Core of the PWR concept are the two agents of human-water relations: sources and users/uses of water. With this categorization the concept tries to capture the natural and the social aspect of water, even though one should be aware that all kind of categorization are underlined by assumptions and highlight only particular aspects (Zwarteveen et al., 2017). Mapping (Furlong and Kooy, 2017; Kooy et al., 2018) and also unmapping in the sense of disclaiming (Mawani, 2019) distributions of water sheds also light upon involved stakeholders. The feedback and interlinkages between those agents are shaped by external influencing factors such as climate variability, cultural values, etc. (see e.g., Venot et al., 2007). PWR therefore helps integrating multiple framings and different sets of possible development paths and potentially desirable futures, hereby offering room for reflection on distributions of power. The human and physical boundary conditions provide the setting for analyzing water-related issues within the so called “human-hydro-scape” (Evers et al., 2017) which involves not only the physical space, but also the interaction of actors and authorities (Sayer et al., 2013) at different spatial and temporal scales. This especially highlights the diversity of actors who articulate their perspectives through societal processes and, hence, make political choice about water distribution (Zwarteveen et al., 2017) by their construction and contestation of the human-hydro-scape also in response to environmental changes (Evers et al., 2017). Hereby not only technical solutions but also the politics behind those discourses (Wilson et al., 2019) are important to understand the human-water interactions in response to environmental changes.

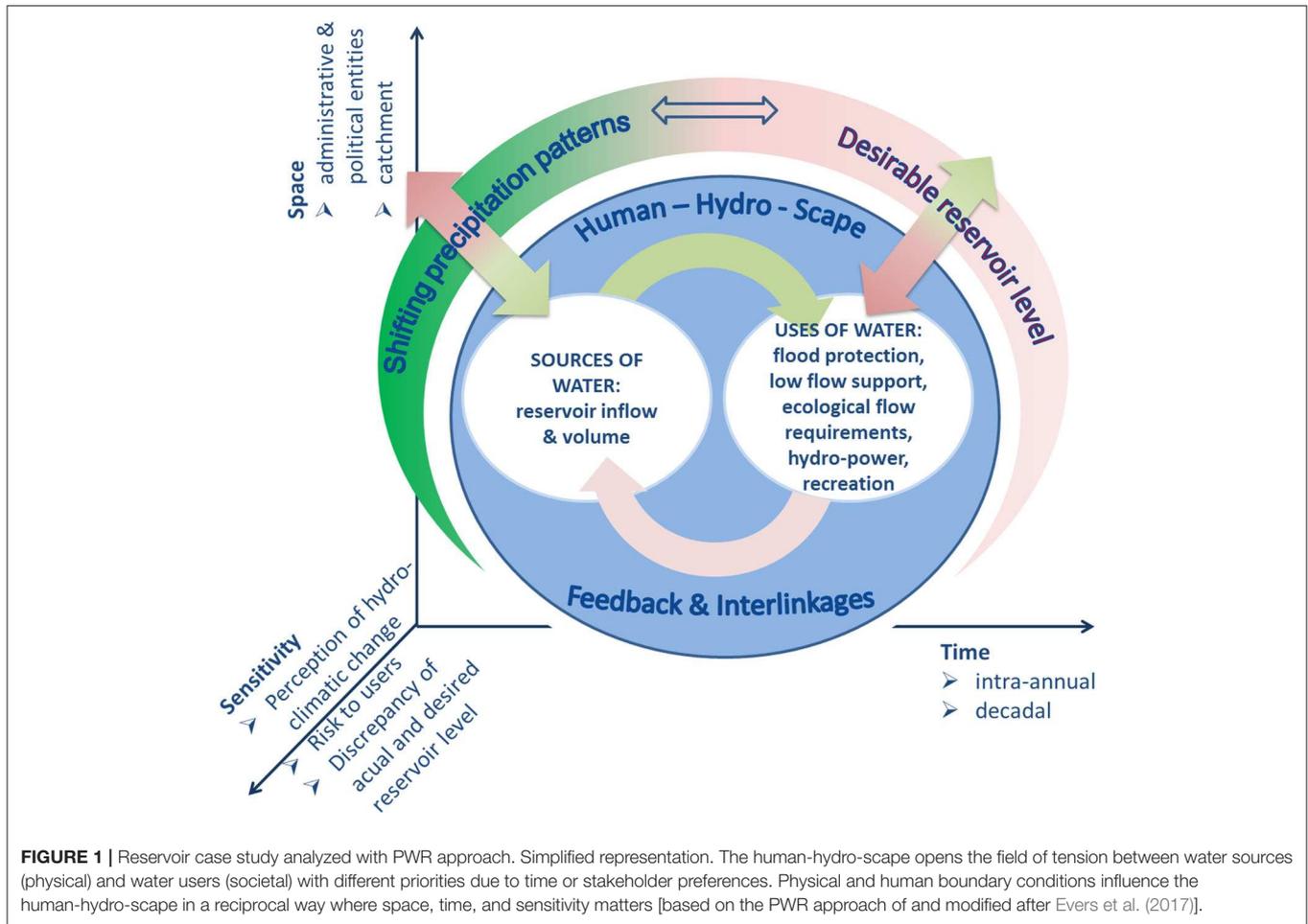
Our case study on reservoir discharge under changing precipitation patterns was therefore translated into the PWR approach to visualize and contextualize in a condensed way the complexity of the human-water interactions (**Figure 1**). Furthermore, by mapping the distribution of water ground is provided to identify the underlying political power behind the current distribution structure (Zwarteveen et al., 2017). In our case, the sources of water are reservoir inflow and reservoir volume. The users of water are stakeholders with different priorities in one or more of the following uses: flood protection, low flow support, ecological flow requirements, hydro-power generation, and recreation. Status quo of resources impacts most likely differently on the users and induces a reaction. This feedback process is the core of the human-hydro-scape which is influenced by the natural set boundary condition with its shifting precipitation pattern (Meon et al., 2018) and by the human set boundary condition with its pre-set desirable reservoir level (Kufeld et al., 2013). Therefore, the spatial reality of the human-hydro-scape is the catchment as well as the different administrative and political entities.

The temporal scale covers an intra-annual as well as a decadal perspective.

The most crucial point of the PWR is the third axis, the sensitivity of the human-hydro-scape, which points out potential critical thresholds and tipping points, which challenge the resilience of the current human-water system (Liu et al., 2007; Xu et al., 2018). These sensitive variables cannot be derived from the case description but need to be ascertained from further analysis. We identified the sensitive variables by applying expert elicitation and qualitative system analysis (see sections Expert Elicitation—Identifying Objectives of Water Resources Decision-Making and Qualitative System Analysis—Influence Diagrams and Cone of Influence Diagrams for method and Results for results).

Expert Elicitation—Identifying Objectives of Water Resources Decision-Making

The empirical part of the study draws from extensive expert elicitation. We conducted 19 semi-structured interviews among experts from the German water resource management. Water resource management in Germany is regulated by national law and implemented by technical state agencies, district governments, and water associations. Water associations are a specific public corporation acting at the catchment scale and a particular form of organization in North-Rhine Westphalia. They are responsible to fulfill the public tasks for water regulation and quality. In contrast the district governments act on the administrative level and, besides other units, one unit is responsible for water regulation including e.g., flood risk management and reservoir governance and security. They supervise the communal level and are tied to the directives of the ministries represented by the state authorities. Some state authorities founded state-run company to fulfill the public task (similar to water associations), which still belong to their area of operation. We used these three different organizations to pre-select our interview partners. Hereby, we focused on experts predominantly but not exclusively concerned with reservoir management in Germany’s middlemountains. This first round was followed by snowball selection, where interview partners pointed out other experts within their field. In total we interviewed six experts from two different state agencies, four experts from two different district governments, and nine experts from four different water associations. The collection of data was on-going until saturation was reached. The interview partners have in common that they are concerned about reservoir management and balancing trade-offs regarding flood protection and low flow support. While we had previously grouped our experts according to their employer and a changing degree of enforcement power, during the interviews it became apparent that there are cross-organizational characteristics which have a greater influence on experts’ perspective and decision rationales on reservoir management. Within each organization different levels of discursive power could be identified which can be linked to three cross-organizational groups. The group with the least discursive power engages mainly with the operational management of the reservoir(s), another group focuses on risk management, and the third group having the highest level of



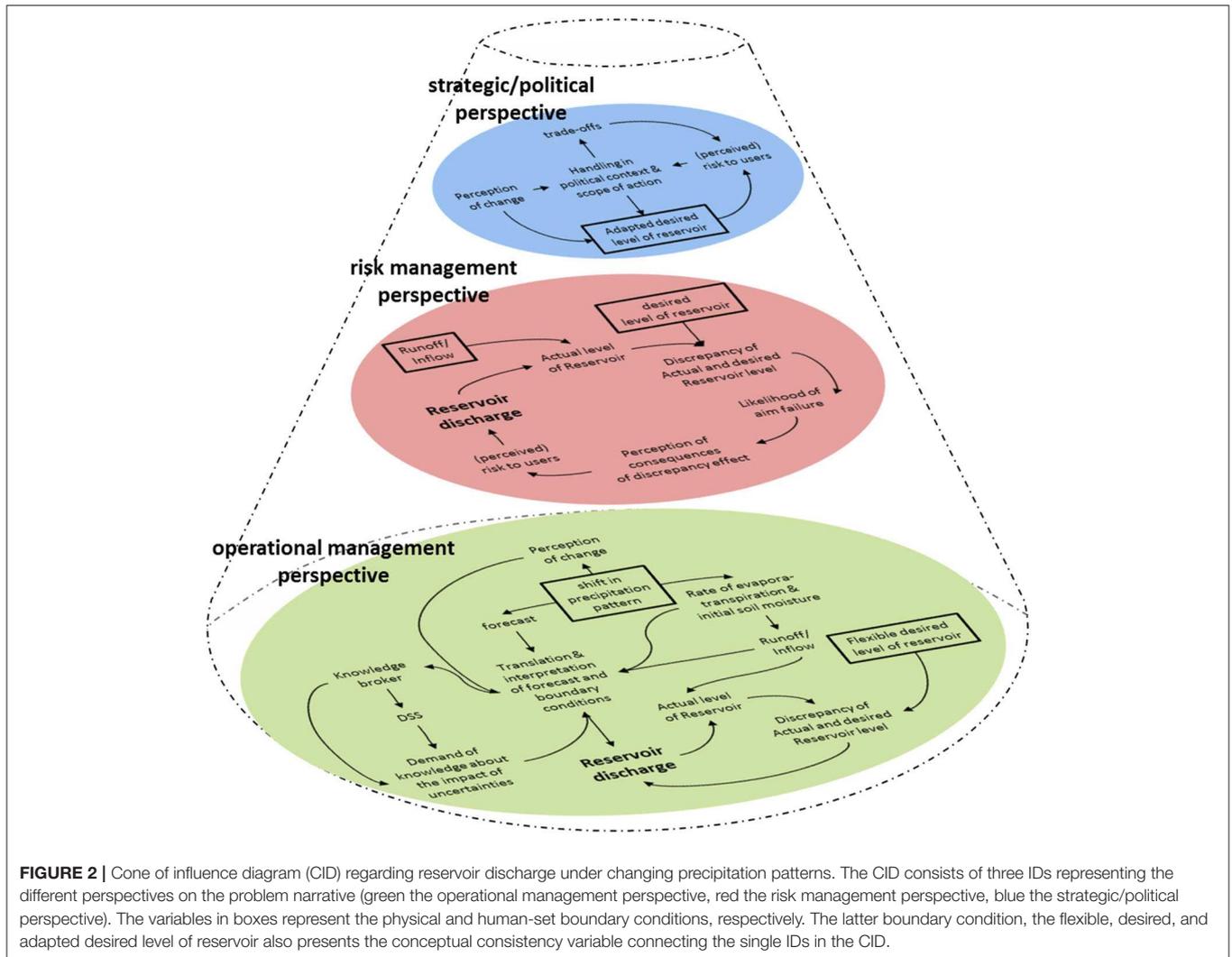
discursive power takes a strategic/political perspective regarding the development of their business/administrative unit. Hence, different levels of discursive power are found within each organization, which also correspond with the organizations' hierarchy. Legislative and executive power is held only by the elected parliaments who may consider the recommendations by the technical authorities.

According to Mayer (2012) the expert elicitation followed a semi-structured interview approach to focus on the experts' knowledge and information about rules, paradigms, frameworks, and logics of their planning and decision-making within their political, organizational, and institutional settings. All interviews, each about 60–90 min duration, were recorded and transcribed word for word but without notions of pausing, laughing, etc. according to the standard for expert interviews (Mayer, 2012). The analysis followed a multi-step and recursive approach in order to sustain validity of the analysis (Kuckartz, 2010) and was supported by using QDA software (MAXQDa). The code system evolved using the categories of the semi-structured interview questions as guiding topics, and additionally including topics and wordings raised by the experts. The final code system reflects these topics in overarching themes where the different codes describe the topics' dimension (Riger and

Sigurvinsdottir, 2016). For this study especially the practitioners' expertise and opinion on reservoir management and flood mitigation was analyzed to highlight their objectives and rationales for decision-making across all interviews and interview subgroups. The differentiation into the three cross-organizational sub-groups (operational management, risk management, and strategic/political perspective) emphasizes the differing rationales by sub-group membership which is e.g., reflected in **Figure 2**.

Qualitative System Analysis—Influence Diagrams and Cone of Influence Diagrams

The information drawn from the expert elicitation fed into a qualitative system analysis in form of an influence diagram (ID). An ID describes the relation of system variables to each other it consists of nodes (variables and/or points of decision-making) and their interrelation is shown by arrows. Closed structures of causality are represented by loops (Powell et al., 2016) and serve in our case to understand the different objectives and rationales for decision-making of the sub-groups. In general, thinking in systems allows exploring the elements of a system, their interconnections and the purpose or goal of the system (Meadows, 2008), hereby, laying focus on exploring how feedbacks govern the system's behavior (Coyle,



1996). A key strength of qualitative system modeling is to concisely describe problem narratives and to identify how different stakeholders may reason about a problem solution (Coyle, 2000; Halbe et al., 2013).

In this sense, the qualitative system model is the concretization of the PWR approach, which more generally describes the boundary conditions of the human-hydro-scape and identifies the different group of actors and the diversity of sources. According to Coyle (1996) we deployed a three step approach. Based on the results of the expert elicitation and the general PWR framework, we, firstly, identified the problem setting to develop a narrative which helps structuring the system (Dee et al., 2017) about the practitioners' water management objective regarding reservoir release under seasonal and long-term hydrological change (compare section Case Study Reservoir Management Under Inter- and Intra-Annual Variability in Germany's Middlemountains). Secondly, IDs were developed according to the interview information given by groups or sub-groups of the experts in a quasi-participatory manner (ElSawah

et al., 2013; Halbe et al., 2013; Inam et al., 2015). In total three different IDs were developed reflecting the experts' different views on the subject (see Figure 2). According to ElSawah et al. (2013) we understand the final IDs as our conceptualization of the interviewees' mental models reflected by the interview results. Thirdly, we analyzed the three diagrams by identifying causal loops in each ID and by connecting the different perspectives using the visualization of cone of influence diagram (CID) (Coyle, 1996). The CID allows to study the same problem but at different levels of detail and, what we argue here, at different stakeholders' perspectives. Within the CID the different levels are not disconnected via a conceptual consistency variable. By applying the CID, we identify the conceptual consistency between the different levels in order to find bridging elements between the perspectives. By analyzing how these bridging elements are integrated in causal loops for each ID, we are able to identify variables which are sensitive to change across all levels. By highlighting the plurality of approaches the CID can act as an interface to facilitate dialogue among the

diversity of involved stakeholders (Halbe et al., 2013) and critical decision rationales can be identified. By laying focus on the connectivity and bridging elements of the different IDs we used simplified conventions for drawing influence diagrams (Coyle, 1996; Sterman, 2000) by using solid lines to represent both, flows and influences, and by leaving out the polarity of the feedback.

RESULTS

Our results are based on the assumption that the human-water system is a co-produced system, where the feedback and interlinkages between water users and water sources decide about the state of the human-hydro scape. The intensity of the feedback loops give hint about the sensitivity of the system (Evers et al., 2017) and are key variables to change the current system. Although we could identify sensitivity both from the natural system and the societal and managerial processes, the results focus especially on the latter as we find that the combination of PWR approach and qualitative system analysis is the method of choice to identify the systems sensitivities from the human perspective and their perception of the natural system.

Influence Diagrams and Cone of Influence Diagram—Analyzing Rationales for Water Resources Management Decisions

Based on the cross-organizational characteristics of the interviewed experts (section Expert Elicitation—Identifying Objectives of Water Resources Decision-Making) who are either engaged in operational management, risk management or strategic/political development of their business unit, we developed three influence diagrams (ID) to cover the different objectives and decision rationales of these sub-groups.

The first ID is drawn from the operational management perspective (Figure 2, green ID). The focus of the ID is on reservoir discharge, where the actual level of reservoir and the discrepancy of actual and desired reservoir level decide about the amount of discharge within a causal loop. However, this decision rational is influenced in two ways. First, precipitation forecast and boundary conditions of the catchments such as soil moisture, evapotranspiration rate, etc. are used to estimate potential inflow into the reservoir within the next days and week. Underlying uncertainties maybe managed trough e.g., knowledge brokers and/or decision-support tools. Second, the desirable reservoir level presents the human set boundary condition of the system decreasing the scope of action. Both criteria are important to decide about a change in reservoir discharge. With their perception of change in precipitation patterns water managers see a need to be more flexible with the desired level of reservoir and adapt it to the current situation:

“We have just begun to discuss about a dynamic flood control zone. Instead of having a control zone of x Mio m^3 constantly during the winter term, we decide on the amount based on the current hydro-climatic condition of the whole catchment. [...] This will help to back up in both directions, where a static value cannot acknowledge the forecast of the inflow, if it will reduce

or increase, with completely different implications on discharge decisions.” (IP 3.1¹)

Finally, it is necessary to produce a resilient and elastic system. And that is the solution. Not a static construction of flood protection measures, but an elastic system, which deals with the variability of nature as elastic and resilient as possible. (IP 3.9)

Putting the environmental changes upfront, this level tries to argue on basis of the physical boundary conditions and to influence the discourse on desired level of reservoir. However, this level is well aware about their limited enforcement power and the problem, that

“if there is flexibility, the regulatory authority has less power but is still responsible.” (IP 3.1)

The second ID is drawn from a risk management perspective (Figure 2, red ID). External drivers influencing the decision are the reservoir inflow and the human set boundary condition regarding the desired reservoir level. The likelihood of aim failure due to the discrepancy between actual and desired reservoir level is a key criterion to decide about potential consequences and the (perceived) risk to users of this discrepancy effect. The causal loop highlights that the decision to change reservoir discharge is based on this risk assessment:

“We need to increase our reservoir release to $12m^3$, but there is a hydro-power generator downstream who can only use maximum of $11 m^3$, with $12m^3$ one is lost for his production. Then we have to decide if we can be flexible in our increase to satisfy our flood protection duty and the revenue of our customer.” (IP 3.4)

Within limited ranges this level has the opportunity and power to balance out different needs and demands. Especially, the perception and assessment of the environmental systems, e.g., the current weather conditions, interplays with the tendency to balance the trade-offs:

“If there is the situation where according to the operation plan the discharge needs to be changed and this change, we know, will induce conflicts downstream, especially if we increase the discharge, we will get corresponding feedback [from downstream users/affected stakeholders]. During such a situation I intensify my weather observations and (...) assess the likelihood of the projected inflow to the reservoir to estimate the consequences. If we have a dry period, than it is easy, that the projected precipitation won't harm (...) but in winter, when you have snow layers, increasing temperatures, more precipitation, than this situation becomes more critical.” (IP 3.8)

The third ID is developed from a strategic/political perspective (Figure 2, blue ID). Central to this perspective is the political context in which the scope of action and the perceived risk to

¹All quotes have been translated from German into English. IP stands for interview partner. The first number indicates the affiliation to employer, where 1 is state agency, 2 is district government, and 3 is water association. The second number randomly indicates the single experts.

users is defined. Here, two important causal loops are intersecting where (1) is concerned about trade-offs and (2) about the desired level of reservoir. The perception of hydro-climatic change influences the scope of action and may force to decide about an adapted desired level of reservoir, hereby balancing trade-offs and risk to users in different ways:

“We have the responsibility to inform citizens and municipalities potentially affected by floods. Here, I cannot take the minimum, just to leave more space of action/planning, because this would lead to an accumulation of values within the floodplains, so the damage would be higher when it comes to a flood.” (IP 2.1)

or

“You are aware of potential loss events and accept that there could be a failure, if there is not a significant security risk that comes with this failure. Then it is sometimes more efficient to live with the damage.” (IP 3.3)

This level has the highest agency regarding discursive power and influence of the discourse about the distribution of water because with their recommendations there are able to direct the legal discretion:

“We, as the highest technical state authority, prepare the basis for decision-making processes and provide recommendations (...) where we also guide and focus the legal discretion” (IP 1.3)

A closer look at the single IDs shows that the way of reasoning differs, however, the focus on the human set boundary condition, in detail the flexible, desired, and adapted desired level of reservoir could be identified as a conceptual consistency variable (Coyle, 1996) connecting the different views (Figure 2). The desired level of reservoir presents a guiding criterion to decide about potential risks to users during risk assessment or is experienced by the operational management as rigid regulations which stall a flexible approach in reacting to variabilities and underlying uncertainties (Höllermann and Evers, 2017). On a higher level, this desired level of reservoir maybe challenged by perception of change and future needs leading to an adapted desired reservoir level.

Referring to the distribution of power as one important aspect of human water interaction (Ingram, 2013; Brisbois and de Loë, 2016; Zwarteven et al., 2017; Wilson et al., 2019) the CID highlights the power of the strategic and political level to change the desired reservoir level and the quality and terms of interaction (reflected by the two arrows pointing to this boundary condition) in comparison to the other levels who have to obey the regulation and have to meet the desired reservoir level (reflected by the arrow pointing from this variable).

Sensitive System Variables of the Human-Hydro-Scape—Analyzing the Connectivity of the Different Decision Rationales

The three IDs (section Influence Diagrams and Cone of Influence Diagram—Analyzing Rationales for Water Resources

Management Decisions) highlight the different rationales behind the conceptual consistency variable. Figure 3 shows how this variable connects all levels and highlights those variables which have at least entry points for decision-making from two levels. These variables are (i) Perception of change, (ii) Risk to users, and (iii) Discrepancy of actual and desired level of reservoir. At these variables different decision pathways are possible, affecting the whole system, and hence, are able to shape and alter the human-hydro-scape. We therefore understand these variables as the sensitive system variables as they explain how and when the system changes. However, this might be different regarding the three perspectives.

Perception of Change

From the operational management perspective, the desired reservoir level needs more flexibility to respond to variabilities in especially intra-annual precipitation patterns. Here, the operational level makes use of selected data presentation to make their case for a more flexible approach:

“The yearly amount of precipitation has not changed. (...) then the board [equals strategic/political level] scrutinizes the low reservoir level as there has been 1,400 mm of annual precipitation. But we observe that it has rained at the ‘wrong’ time (...). The question arises which key figures we present (...).” (IP 3.1)

The interview partner highlights that an intra-annual change in precipitation pattern without a change in annual amount has an important effect on the water budget of the reservoir as precipitation falls now during the growing period and instead of contributing to surface and reservoir inflow most of the water is used for transpiration (Meon et al., 2018; Höllermann and Evers, 2019). From his point of view it is a matter of different presentation of hydrological data to represent the current natural system explaining the shortfalls during the summer season. This view implies that the selection of data presentation and format is also informed by particular views, experiences and visions of futures from the “data provider” (Zwarteven et al., 2017) which can unintentionally or intentionally impact the perception of hydro-climatic change of other groups such as the strategic level (compare ID 3, red). For example, in response to a potential increase of flood extent the strategic level needs to

“balance and consider, how much [they] (we) have to invest to protect an area against the costs of restricted building development.” (IP 2.1)

Risk to Users

The assessment of the risk to users about who benefits or who loses (Wilson et al., 2019) is also informed by particular views, experiences and visions of the stakeholders regarding the rate of change. For one interviewee

“Risk is defined by e.g. probability of event times the damage as one simple risk definition. One could definitely describe risk more holistic. (...) regarding flood risk, I have many areas where we find hazard due to the flood event, but it is only risk, when this hazard affects goods we regard as deserving protection.” (IP 1.2)

In this regard another interviewee points out that:

“it is the tasks of the society and their democratic legitimized elected parliaments to decide [about a threshold] and to create binding regulation which ensure legal certainty. (...) It is up to the society to decide about the rules and limitations. We [the water management] can add expert advice and inform about the consequences, costs, etc., but it is not within our responsibility to vote yes or no.” (IP 3.3)

The interviewee highlights the responsibilities and hence the political decisions behind the water management. He admits that the decided threshold/regulation is a function of negotiation of acceptable risks to users, which will eventually alter the desired reservoir level. Even the perception of risk is part of the negotiation process:

“When we determined floodplains for 100-year flood event, we had many complaints from landowners who didn't want to accept that their site should be exposed to flooding, because their family never experienced floods.” (IP 2.2)

Discrepancy of Actual and Desired Level of Reservoir

The sound understanding of the hydrological system and its behavior under change is important information to base decisions (Zwarteveen et al., 2017) when assessing the discrepancy of the actual and desired reservoir level. Regarding the changing climate signal, they propose a

“flood change factor (...) representing a scenario of change which is based on evidence and covering no-regret and win-win measures. This is a consensus based protection factor, however, residual uncertainty and risk exist and we have to live with it. But with this factor we were able to give a recommendation.” (IP 1.5)

However, as the following quote from the operational management shows, different interest groups approach the assessment of the discrepancy differently and such a flood change factor could potentially put at risk specific needs and demands:

“One expert report [written by ecologists aiming at biodiversity] claims minimum flow requirements exceeding the medium discharge. We ask him how to handle this. These are the hard ecologists. To follow this claim we would need to increase the minimum discharge, on a regular basis, this is beyond our available resources.” (IP 1.1)

While both groups, the ecologists aiming at increasing biodiversity and the water manager aiming at balancing societal water demand, see a need to react on the discrepancy of actual and desired reservoir level, the consequences of the discrepancy are perceived differently. While the ecologists in this quoted example put a stronger emphasis on the failure regarding minimum flow requirements, the water manager obeys his duty to fulfill societal needs during drier periods. The quote shows that in balancing trade-offs some uses are compromised over others and the priorities are a matter of the reciprocal interaction of negotiations and actual water availability. The interplay with the projected future water availability becomes obvious here

as the projections about the future will most probably change current negotiations.

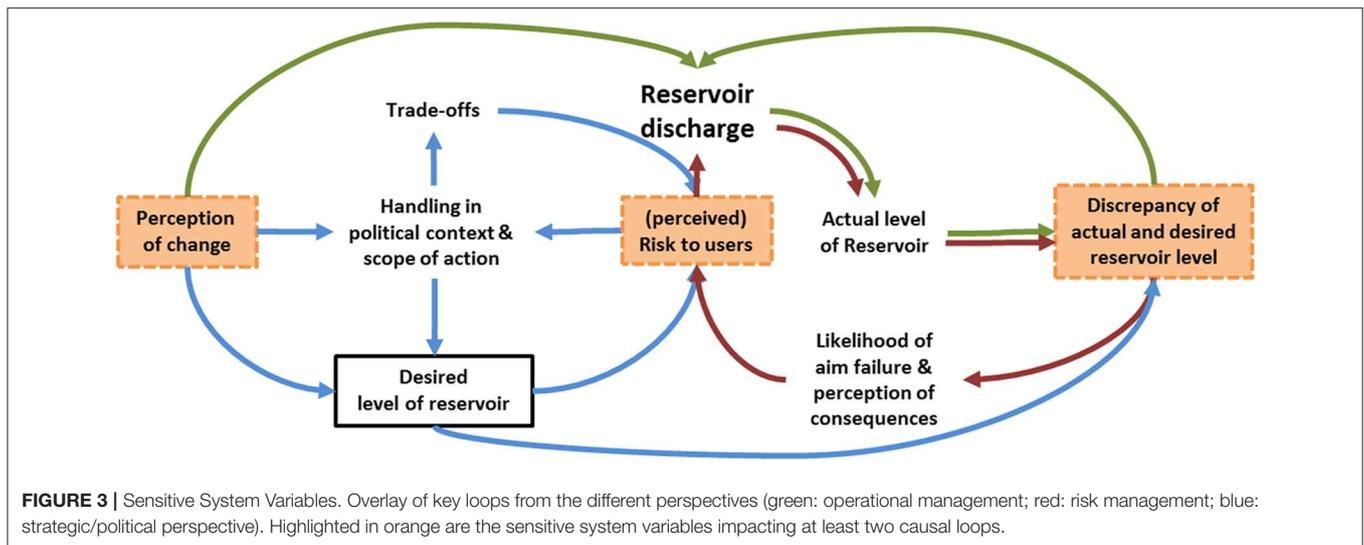
Using the PWR concept in combination with qualitative system dynamics approach in form of CID helped disclosing three important aspects regarding human-water interactions for the reservoir management case study: (1) it reveals and analyses the political dimension behind water management decisions, (2) it highlights the impact of hydro-climatic variability and change on natural and man-made water systems, and (3) unfolds the interaction of 1 and 2 through the sensitive system variables, which act as the interface between the human and the environmental system, namely: perception of change, perceived risk to users, and the discrepancy of desired and actual reservoir level (see **Figure 3**). The third point is of crucial importance as this interaction is at the heart of complex human-water systems and presents sensitive control variables deciding about retaining or altering a system (Liu et al., 2007). At this point is also becomes clear, that negotiating boundary conditions is a result of the contestation of human-hydro-scape by the diversity of actors with distinct responses to environmental changes (Evers et al., 2017) and political power over water distribution (Zwarteveen et al., 2017).

DISCUSSION AND CONCLUSION

Our analysis and in accordance with studies from water governance and management (Brisbois and de Loë, 2016; Wesselink et al., 2017; Zwarteveen et al., 2017; Xu et al., 2018) we showed that there are in general two dimensions which need acknowledgment in order to understand current regulations of water management. These two are (1) the physical distribution of water, and (2) the distribution of power. Where the former engages with the materiality of water and the human interactions to describe patterns [e.g., Westerberg et al., 2017; Zwarteveen et al., 2017], the latter elaborates on how power relations shape those patterns [e.g., Brisbois and de Loë, 2016; Wilson et al., 2019]. Both dimensions are interlinked and mutually influence each other. In our case study we could identify the sensitive system variables which connect both spheres and are entry points for system change. The capacity to adapt or to buffer changes strongly decides about the systems' sustainability (Xu et al., 2018). Thus, sustainable water management needs acknowledgment of the environmental as well as social system interplaying in our so called “human-hydro-scape”. Within this human-hydro-scape sensitive system variables help explaining how the distribution of water and power constitute each other and how future interactions may re-construct the human-hydro-scape.

Distribution of Water and Power

In our reservoir example water is distributed to serve as water supply for settlements, flood protection for riparian households, minimum flow support for conservation, and input for hydro-power generation, just to name a few. Those distributions follow a priority based agenda (Morgenschweis et al., 2006), e.g., flood protection is more important vs. hydro-power generation. Hence, the distribution of water follows a pattern which justifies access to water and also decides about



the exposure to water-related risks (Zwarteveen et al., 2017). Mapping (Furlong and Kooy, 2017; Kooy et al., 2018) and also unmapping or disclaiming (Mawani, 2019) those distributions of water sheds light upon which actors are involved and to what extent. This contextualization helps identifying current patterns of distribution, of who gets provision and/or protection and who is left out (Ingram, 2013; Patt and Weber, 2014; Chong et al., 2018). It highlights the interlacing of power of institutions and infrastructure (Wilson et al., 2019) by disclosing the flow of resources as well as the flow of power (Wesselink et al., 2017; Rodríguez-de-Francisco et al., 2019). The flow of power is for example visualized by drawing influence diagrams (see sections Influence Diagrams and Cone of Influence Diagram—Analyzing Rationales for Water Resources Management Decisions and Sensitive System Variables of the Human-Hydro-Scape—Analyzing the Connectivity of the Different Decision Rationales; **Figures 2, 3**). Even though all levels regard the desired level of reservoir as a boundary condition, the power to challenge the condition differs. While the operational level may argue using specific forms of data presentation to challenge the current boundary condition and to influence the strategic/political level's perception of hydro-climatic change its discursive power is limited. In contrast, the political level has the only discursive power to challenge current rules and regulations regarding the desired reservoir level. In this regard our analysis of the sensitive system variables shows that the perception of change and the risk to users are critical in evaluating the current human-water system. For example,

"[...] one community doubted the delineation of a flooding area because of uncertainties in the applied model and this is why the community does not want to agree to the flooding area within their city district. As a consequence, they have no constraints and limitations regarding their actions." (IP 2.1)

This quote highlights that the model results as a representation of the natural processes are challenged by strategic interests or

balanced against the potential risk to users. From this point one can argue that all changes in infrastructure and infrastructure management is based on how power is balanced and, by mapping these distributions of water, underlying political power imbalances can be identified (Wesselink et al., 2017). Discursive power, as highlighted in the interviewee's quote above, is the power to control and influence norms and regulations (Ingram, 2013; Zwarteveen et al., 2017) and to frame agendas (Brisbois and de Loë, 2016; Wilson et al., 2019). Hence, when focusing solely on the water-related issue there is the risk of decoupling of broader political and social power relations (Brisbois and de Loë, 2016). In our study these broader power relations focus on trade-offs among different users and less about intra-annual hydro-climatic changes potentially adversely affecting the negotiated distribution of water. From our viewpoint the sensitive system variables are key linking variables which couple both dimensions. The identification of those variables contributes to a better understanding of complex human-water systems. For example, in our case study the perception of change which differed between the stakeholders is the driver for different decision rationales and hence different preferred reactions to and of the water system.

Sensitive System Variables and Sustainable Water Management

Sustainable water management aims at balancing ecological and social needs to ensure maintaining ecosystem functions over generations (Wiek and Larson, 2012; Schneider et al., 2015; Poff et al., 2016). However, desirable future(s) need to be negotiated among the different stakeholder needs and aspirations, which means there is no single best answer (Evers et al., 2017; Xu et al., 2018) and the search for a single optimized solutions (Sivapalan et al., 2012; Di Baldassarre et al., 2013) only leads to a decoupling of the water and broader societal system (Brisbois and de Loë, 2016). But, sustainability requires this coupling to understand the systems' resilience and adaptability (Xu et al., 2018). Hereby, the identification of power relations underlying informal or formal regulations of water distribution plays an

important role (Zwarteveen et al., 2017). Furthermore, the sound understanding of the dynamics of the hydrological system builds the basis to develop target-oriented responses to meet the negotiated human set boundary condition. However, climate variability and global change may challenge the human-water system by reaching thresholds (Liu et al., 2007), which are in our study the sensitive system variables perception of change, risk to users, and discrepancy of actual and desired reservoir level. Additionally, to acting as key linking elements between the political dimension of water management decisions and the natural and man-made water system (see sections Results and Distribution of Water and Power), these sensitive system variables are the starting point of the plurality of perspectives (Evers et al., 2017) negotiating about desirable and alternative futures (Inayatullah, 2008). However, aiming at a sustainable water future guidance is needed. Here, scenario analysis provides a tool for systematic thinking about the future (Lienert et al., 2006) as scenarios act as coherent and plausible stories about possible and alternative pathways of socio-ecological systems (Swart et al., 2004; Inayatullah, 2008). Swart et al. (2004) point out that especially in complex socio-ecological systems, such as our discussed human-water system, qualitative scenario exploration, capable of integrating values, and personal or institutional behavior impacting the system, complements the quantitative scenario analysis of the natural system (e.g., climate scenarios). Our study contributes to this scenario building by identifying sensitive system variables, which can be used to develop a set of scenarios covering the different perceptions of risk to users in response to the perception of change and the physical distribution of water.

Concluding Remarks on Analyzing Complex Human-Water Systems From a Qualitative Systems Perspective

The complexity of human-water systems needs a profound understanding of the interaction of the water and the social system. Using the PWR concept to contextualize our reservoir case study and applying a qualitative systems approach disclosed the politics behind water management visions and measures and identified at which points these potentially different perspectives enter the socio-ecological system in form of sensitive system variables. Sustainable water resource system management must address the social as well as the natural nature in order to reach social and environmental justice (Perreault, 2014). The qualitative system analysis using IDs and CID proved to be helpful in understanding—from different stakeholder perspectives—the complexity of human-water interactions under changing environmental conditions (Ingram, 2013; Ceola et al., 2016; Wesselink et al., 2017; Westerberg et al., 2017; Xu et al.,

2018) and in identifying the sensitive system variables. These variables not only linked water management decision rationales with the water system, but also highlighted the plurality of possible responses to change providing a starting point for scenario development including the whole range of societal response. We are aware that the results of our case study of reservoir management in the German middlemountains are case specific regarding the identified stakeholders, perspectives and sensitive variables, and that they are not directly transferable to other regions and cases. However, we are confident that our methodological approach is transferable to other water management cases for identifying the complexity of interactions and sensitive system variables. Hence, the qualitative system analysis approach proved to be successful in acknowledging the environmental and social system and their interactions and in identifying critical variables of change and transformation leading to a broader perspective on alternative futures. This research focused on the qualitative description of human-water interactions and highlighted the value of using qualitative system analysis as an important complementary part to quantitative water resources assessment to cover the whole range of societal responses.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article can be made available by the authors, hereby guaranteeing the anonymity of the interview partners.

ETHICS STATEMENT

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

BH: conceptualization, formal analysis, visualization, and writing—original draft. BH and ME: methodology and writing—review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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