Decision-making under uncertainty in model-based water management

The science-practice interface

Dissertation

zur

Erlangung des Doktorgrades (Dr. rer. nat.)

der

Mathematisch-Naturwissenschaftlichen Fakultät

der

Rheinischen Friedrich-Wilhelms-Universität Bonn

vorgelegt von

Britta Höllermann

aus

Plettenberg

Bonn, 2018

Angefertigt mit Genehmigung der Mathematisch-Naturwissenschaftlichen Fakultät der Rheinischen Friedrich-Wilhelms-Universität Bonn.

1. Gutachter: Prof. Dr. Mariele Evers

2. Gutachter: Prof. Dr. Bernd Diekkrüger

Tag der Promotion: 05.07.2018

Erscheinungsjahr: 2018

ACKNOWLEDGEMENTS

First, I would like to express my sincere gratitude to my advisor Prof. Dr. Mariele Evers for her continuous support of my research, her critical feedback and her encouragement to find my own way. Your guidance helped me in all the times of my research. Thank you for giving me the opportunity to engage in teaching and other research projects to cover my interests beyond my PhD project. I am grateful for the independent contributions I was allowed to make. Also, your counselling for my academic career is very much appreciated. I am glad I joined your working group.

I also wish to thank Prof. Dr. Bernd Diekkrüger for his constant encouragement and support over the years. You already supervised me as an undergraduate student and I got many chances to work with you during my diploma thesis, the IMPETUS project and as the coordinator of the focal research area water in our Department of Geography. I always cherished your guidance and advice. Even though I swapped working groups at one point, I appreciated the chance to stay close to you and your group with e.g. joint student courses or, lately, the summer school on wetlands in Uganda.

I owe many thanks to my interview partners. Thank you for your time, support, discussion contributions and valuable insights into your uncertainty management. The research has only been possible due to your willingness to share your current practice. I very much appreciate your dedication to my questions and I am very happy that I have the chance to meet at least some of you quite regularly at other occasions to catch up.

During my research I was surrounded by a great team of colleagues from my current and former working groups. I thank you all so much for sharing time, lunch, ideas, advice, laughs and also sometimes frustration. I learned a lot from all of you and appreciate that some of became good friends. My thanks go especially to Dr. Constanze Leemhuis, Dr. Simone Giertz, Dr. Thomas Cornelissen, Inken Rabbel, Dr. Linda Taft, Dr. Adrian Almoradie, Ivana Mirosavić, Miloš Mirosavić, and Mariana Madruga de Brito.

Many thanks to my closest friends! You are my cornerstone in life with your offer of distraction, your moral support, and especially your love and friendship. Märry, Dottie, Bettina, Clemens, Thomas, Mario, Constanze, and Nadine: you mean so much to me. This is especially true for my beloved parents who gave me roots to grow and wings to fly and help me on my way. I owe everything that I am to you.

Finally, most important and with all my heart I would like to thank my four incredible men at home! Philipp, for your love, patience and support. I couldn’t do without you. Finn, Matti and Lennard, for your unconditional love and for showing me what matters most in life. My dearest sons, you are my true superheroes and the most precious people in life! I couldn’t do without you, either.

TABLE OF CONTENTS

List of Tables

LIST OF FIGURES

SUMMARY

Balancing the different needs and demands of water users and managing the supply side under temporal and spatial variability and extremes has always been a challenging task for water managers. However, accelerated environmental and societal change aggravates water management as uncertainties increase even further. Decision-making in water management must integrate uncertainty information to base decisions on and be prepared for surprise and ambiguity. While it is often considered that decision-makers do not understand or – at least sometimes – ignore uncertainty analysis, this research shows that uncertainties do in fact matter for water managers and that they already cope with them and acknowledge them as an integral part of their planning. Therefore, this doctoral research aims at improving the understanding of how scientific uncertainties find better integration into planning and decision-making processes in model-based water management.

The thesis hereby follows the hypothesis that understanding and identifying the plurality of practitioners and the diversity of their approaches, perspectives, and reasoning are key aspects to close the science-practice gap. This understanding will enhance integration of uncertainties into planning and decision-making by closing the usability gap and, hereby, contributing to the robustness of decisions.

Extensive expert elicitation, a quantitative survey and qualitative system modelling present the applied methods to answer the research questions. The intensive engagement with practitioners plays a crucial role for the thesis to assess uncertainty perception and handling strategies of water managers. However, the group of practitioners is not regarded as a homogenous group as special attention has been paid to the heterogeneity of the water managers. In general, the findings draw from a broad range of water-related management objectives including surface water quantity management, climate change impacts and adaption, short- and medium-term flood forecasting and/or short- to long-term reservoir management. Even though the results are mainly demonstrated at the case of reservoir management under changing intra-annual and annual conditions, the findings can easily be transferred to other water-related management objectives.

The main finding of this research is that water managers acknowledge uncertainties. However, the degree of acknowledgement and handling capacity varies per level of

working experience, educational background, type of employer and affiliation to business unit. In close relation to their background, water managers have developed different strategies to handle uncertainties, approaches which may seem less obvious to scientists. For example, they reframe uncertainty into risk or focus on vulnerability, thereby emphasising a bottom-up approach. Additionally, tacit knowledge plays a major role in handling uncertainties as well as the implicit handling of process uncertainties. A lack of transparency, regulations and constraints in a highly politicized decision-making environment present limitations of uncertainty integration. Thus, the use of uncertainty strategies and routines applied by the practitioners differs regarding group membership and time-frame of the management objective.

In the course of this doctoral thesis, three major tools were developed to increase the transparency and integration of uncertainties:

1) a 2x2 uncertainty matrix,
2) an integration and analytical framework, and
3) a qualitative system model.

The uncertainty matrix highlights the different causes, level and location of uncertainties to transparently display limitations and emphasize interrelations of uncertainties. This matrix is embedded into the integration and analytical framework which pays special attention the practitioners' risk-based approach including the transfer of uncertainties into the judgement phase. The qualitative system model visualizes the application of user- and time-specific uncertainty routines in a causal loop diagram. The acknowledgment of heterogeneity of practitioners contributes by increasing the fit, interplay and interaction of uncertainty information.

The compilation of this research has identified criteria, described prerequisites and provided a practical strategy to improve the integration of scientific uncertainties into planning and decision-making processes in model-based water management. It gives implications for increasing usability of uncertainty information and enables second or third loop learning for adaptive or transformative water management by fostering cross-communication within practice and between science and practice. It also presents a theoretical construct to rethink uncertainty implications and their interrelations with respect to a plurality of perspectives, especially, regarding the diversity of practitioners.

Furthermore, this research contributed to the science-practice gap research by emphasising the plurality of practitioners' uncertainty perception and handling. Acknowledging this plurality overcomes the thinking of a linear causal chain of information and makes room for a plurality of knowing and, hence, different ways to cope with and to integrate uncertainties into final decisions.

ZUSAMMENFASSUNG

Eine zentrale Herausforderung für das Wassermanagement ist, den Ausgleich zwischen verschiedenen Wassernutzern und ihren Bedürfnissen herzustellen, bei gleichzeitiger Berücksichtigung zeitlicher und räumlicher Variabilität sowie Extreme des Wasserdargebots. Zunehmende Unsicherheiten aufgrund des Umweltwandels und sozialen Wandels erschweren das Management dieser Ressourcen zusätzlich. Die Integration von Unsicherheiten in Entscheidungsprozesse im Wassermanagement ist daher von besonderer Bedeutung, um auf unerwartete Ereignisse und eine große Bandbreite an möglichen Zukunftsszenarien vorbereitet zu sein. Während vielfach behauptet wird, dass Entscheidungsträgerinnen und Entscheidungsträger Informationen über Unsicherheiten entweder nicht verstehen oder sie, bisweilen auch aus taktischen Gründen, ignorieren, belegt diese Arbeit, dass Praxisakteurinnen und -akteure dem Thema Unsicherheiten eine hohe Relevanz zuschreiben und bereits verschiedene Strategien zum Umgang mit diesen Unsicherheiten entwickelt wurden. Ziel der Arbeit ist es zum Verständnis beizutragen, wie wissenschaftliche Unsicherheiten besser in Planungs- und Entscheidungsprozesse des modell-basierten Wassermanagements integriert werden und die Qualität des Wassermanagements damit verbessert werden kann.

Die Hypothese der Arbeit ist, dass das Verständnis und die Identifikation der Pluralität von Akteuren und ihrer unterschiedlichen Ansätze, Perspektiven und Entscheidungsmuster einen Schlüsselaspekt darstellen, um einen Beitrag zur Überbrückung der Lücke zwischen Forschung und Praxis zu leisten. Das Schließen der Lücke bedeutet ebenfalls, dass die wissenschaftlichen Erkenntnisse für die Praxis nutzbar gemacht werden. Gleichzeitig wird durch die Integration von Unsicherheiten in Entscheidungsprozesse ein Beitrag dazu geleistet, dass die Entscheidungen einen Großteil der Bandbreite an möglichen Zukunftsszenarien abdecken und die Robustheit der Entscheidungen erhöhen.

Hauptmethoden, um die Ziele dieser Arbeit zu erreichen, sind umfangreiche Experteninterviews, Umfragen und qualitative Systemmodellierung. Dabei ist die intensive Auseinandersetzung mit Praxisakteurinnen und -akteuren ein zentrales Element, um die Wahrnehmung und den Umgang mit Unsicherheiten von Wasserressourcenmanagerinnen und -managern einschätzen zu können. Die Akteurinnen und Akteure wurden dabei nicht als homogene Gruppe betrachtet, vielmehr wurde ein besonderes Augenmerk auf die Heterogenität der Expertinnen und Experten gelegt. Die Ergebnisse der Arbeit beziehen sich so auf ein weites Feld des Wassermanagements, u.a. wasserwirtschaftliches Mengenmanagement, Einfluss von Klimawandel und Adaptionsmöglichkeiten, kurz- und mittelfristige Hochwasservorhersagen sowie kurz- und langfristiges Management von Talsperren. Während die Ergebnisse hauptsächlich am Beispiel des Talsperrenmanagements unter sich ändernden intra-annuellen und annuellen Rahmenbedingungen erläutert werden, können sie auch auf alle anderen wasserbezogenen Bereiche übertragen werden.

Die zentrale Erkenntnis dieser Arbeit besteht darin, dass Wassermanagerinnen und -manager Unsicherheiten einen hohen Wert beimessen. Die Wahrnehmung und Berücksichtigung von Unsicherheiten und Handlungskapazitäten variieren jedoch in Abhängigkeit von der Erfahrungsstufe der Praxisakteurinnen und -akteure, ihres Bildungshintergrunds, ihres Arbeitgebers, sowie ihrer Zugehörigkeit zu bestimmten Geschäftsbereichen. In Anlehnung an ihr berufliches Umfeld haben diese Akteurinnen und Akteure verschiedene Strategien zum Umgang mit Unsicherheiten entwickelt, die auf den ersten Blick nur schwer von Wissenschaftlerinnen und Wissenschaftlern wahrgenommen werden. Beispielsweise übersetzen sie Unsicherheiten häufig in Risiko und fokussieren sich dabei auf die Vulnerabilität ihres zu managenden Systems. Zusätzlich spielt Erfahrungswissen im Umgang mit wissenschaftlichen Unsicherheiten und Prozessunsicherheiten eine große Rolle. Fehlende Transparenz, Normen und Regularien in einem hoch politisierten Umfeld erschweren die Integration von Unsicherheiten. Generell lässt sich sagen, dass die Wahl der Strategien zum Umgang mit Unsicherheit abhängig von Gruppenzugehörigkeit sowie vom Zeithorizont des zu managenden Objekts ist.

Im Rahmen der Arbeit wurden drei Werkzeuge zur Verbesserung der Transparenz und Integration von Unsicherheiten entwickelt:

1) eine 2x2 Unsicherheitsmatrix,
2) ein Integrations- und Analysekonzept, sowie
3) ein qualitatives Systemmodel.

Die Unsicherheitsmatrix zeigt transparent Art, Level und Quelle von Unsicherheiten und die damit einhergehenden Limitationen sowie Interrelationen der verschiedenen Unsicherheiten. Die Matrix ist in das Integrations- und Analysekonzept integriert, welches an die Bedürfnisse der Praxis anknüpft, einen risikobasierten Ansatz zu nutzen, und auch die Urteilsfindung mit einbezieht. Das qualitative Systemmodell visualisiert die Entscheidungsmuster von Wassermanagerinnen und -managern bezogen auf ihre Gruppenzugehörigkeit sowie den zu managenden Zeithorizont mittels eines „causal loop diagrams“. Durch die Visualisierung dieser Heterogenität wird ein Beitrag geleistet, die Nutzbarkeit wissenschaftlicher Erkenntnisse und ihrer Unsicherheiten für die Entscheidungsfindung zu erhöhen.

Insgesamt wurden Kriterien identifiziert, Voraussetzungen erläutert sowie eine praktische Strategie entwickelt, wie die Integration von wissenschaftlichen Unsicherheiten in wasserbezogene Planungs- und Entscheidungsprozesse verbessert werden kann. Es werden Ansätze aufgezeigt, mit denen die Nutzbarkeit von Unsicherheitsinformationen erhöht werden kann. Weiterhin können diese Ansätze dazu beitragen tiefere Lernprozesse anzustoßen und einen vertieften Diskurs zwischen Praxisakteurinnen und -akteuren untereinander sowie zwischen Wissenschaft und Praxis zu ermöglichen. Der theoretische Beitrag dieser Arbeit hebt die Bedeutung der Interrelationen von Unsicherheiten, der Pluralität an Perspektiven und Strategien hervor und induziert ein Umdenken bezüglich der Implikationen von Unsicherheiten. Indem die Vielfalt der Wahrnehmung und Handlungsstrategien hervorgehoben werden, wird die Forschung an der Schnittstelle Wissenschaft-Praxis bereichert, da sie alte Annahmen linear-kausaler Zusammenhänge von Informationen verwirft und Raum für eine Pluralität an Wissen sowie unterschiedliche Herangehensweisen hinsichtlich Unsicherheitsintegration in finale Entscheidungen eröffnet.

1 INTRODUCTION

1.1 PREFACE: UNCERTAINTY IN WATER MANAGEMENT

Balancing the different needs and demands of water users and managing the supply side under temporal and spatial variability and extremes has always been a challenging task for water managers. However, accelerated environmental and societal change aggravates water management as uncertainties increase even further (Ceola et al., 2016; Harremoës, 2003; Westerberg et al., 2017; Winkler, 2016). The assumption of stationarity, where the natural system varies within stable limits, has long been an underlying water resources management practice within the developed world. However, human disturbances in catchments - such as water infrastructure, channel modification or land use and land cover change - affect intensity and extent of e.g. flood risk and water supply beyond known limits. Furthermore, the changing natural variability shift limits as well (Milly et al., 2008). Decision-making in water management should therefore integrate uncertainty information to base decisions on and be prepared for surprise and ambiguity.

Since the well-recognized discussion by Funtowicz and Ravetz (1993) about science in post-normal age, research recognizing uncertainty has increased considerably. This is particularly true since the early 2000s, where the discussions about lacking uncertainty communication in the IPCC TAR (Intergovernmental Panel on Climate Change Third Assessment Report) increased the relevance of uncertainty acknowledgement. This general trend is also visible for water research where uncertainties get more prominent in publications (see Fig.1.1). Compared to normalized publication records within the research field water resources at Web of Science (WoS), papers with topics on ‘uncertainty’ and ‘uncertainty and risk’ have gained increasing importance since the early 2000s. From 2013

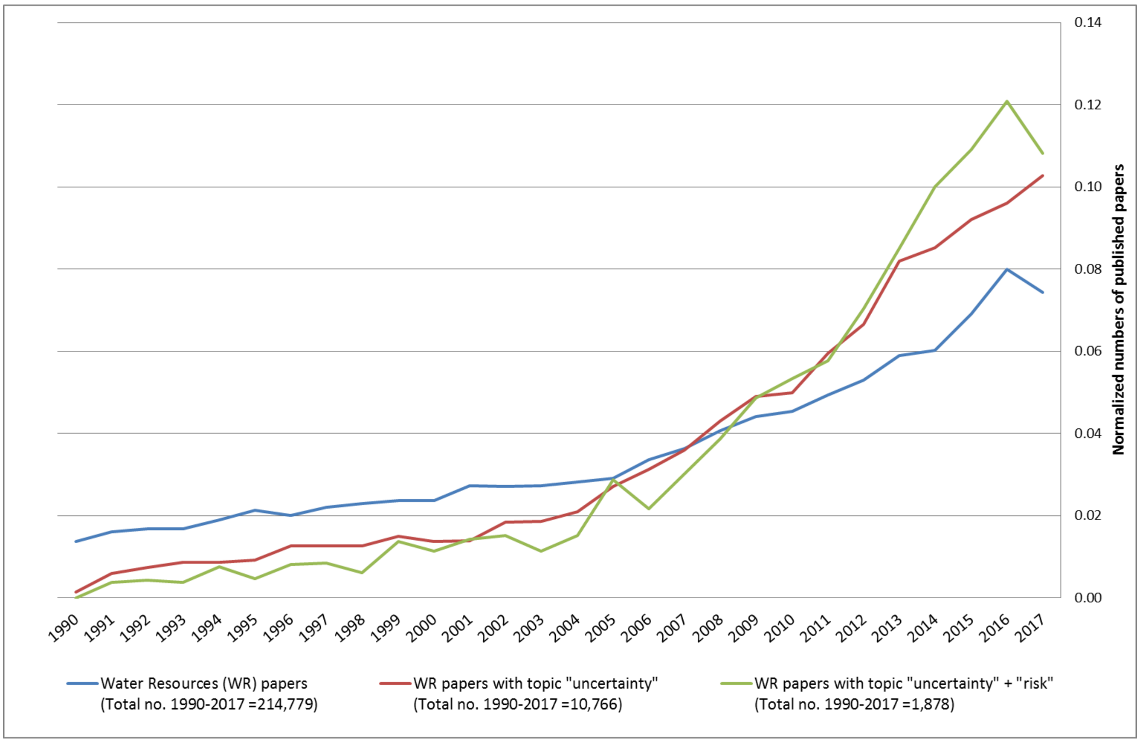

FIGURE 1.1 DEVELOPMENT OF PUBLICATIONS IN THE FIELD OF WATER RESOURCES WITH TOPIC 'UNCERTAINTY' AND 'UNCERTAINTY & RISK', NORMALIZED TO SHOW CHANGING DEGREE OF INCREASE FROM 1990 – 2017 (Source: Web of science analysis from Feb 2018)

on, also a risk perspective became more important and publications in this field increased. An important aspect pointed out by Willows et al. (2003), however, is that uncertainty acknowledgement and management is handled differently by practice and science. While science focusses mainly on the reduction of uncertainties (Maxim & van der Sluijs, 2011; Willows et al., 2003), literature indicates that decision-makers do not understand or ignore - sometimes due to tactical reasons - uncertainty analysis or only use it to foster delay or contradict decisions (e.g. Ballard & Lewandowsky, 2015; Kinzig et al., 2003; Rosenberg, 2007; Taylor et al., 2015; Winkler, 2016). Yet, practitioners apply a risk-based decision-making approach emphasizing the acceptance of uncertainty and recognition throughout the process (Willows et al., 2003) and weight uncertainty information in relation to other decision relevant factors. This presents a judgement process which is unique for each decision and its context (Aven, 2010). For example, reservoir management and its multi-functionality is embedded in a complex socio-hydrological system. The sensitivity of this system to environmental and societal change increases the challenging task of managing the often opposing objectives. Societal and ecological needs aiming at energy production or compensating water shortages must be balanced against flood prevention, where rather a large flood control zone is needed than a maximized reservoir volume. Due to the inherent uncertainties regarding the long-term climatic and socio-economic changes as well as the intra-annual variability of water inflow into reservoirs, problem solving needs active management of uncertainties.

Uncertainty is also a key criterion to choose among alternatives (Funtowicz & Ravetz, 1993), supports evaluation of reliability of findings (Kinzig et al., 2003), enhances transparency within the decision process (Reichert et al., 2007), and adds value to the findings by communication their limits (Pappenberger & Beven, 2006). It should therefore be integrated into any decision-making process. Harremoës (2003) argues that uncertainty will play a major role in water-related political decision-making, since neglecting information on complexity and uncertainty will lead to misinformed decisions (Stirling, 2010; Winkler, 2016; Zandvoort et al., 2017). Therefore, besides scientific problem solving, only an interactive dialogue between science and practice acknowledging unpredictability, uncontrollability, and a plurality of possible and legitimate perspectives will be suitable to develop sustainable solutions (Funtowicz & Ravetz, 1993; Smith & Stern, 2011) within the non-stationary socio-hydrological system (Milly et al., 2008). So far, however, best practice for decisions and assistance in uncertainty management in water resources management remains scarce (Beven, 2008; Bond et al., 2015; Leung et al., 2015).

1.2 UNCERTAINTY CHALLENGE AT THE SCIENCE-PRACTICE INTERFACE

Water resources managers are exposed to many forms of uncertainty while managing their resources. On the one hand, they must handle fundamental uncertainties. These are uncertainties which relate to variability of the phenomenon itself (aleatoric) or the limited knowledge about the phenomenon (epistemic) (e.g. Brugnach et al., 2008; Walker et al., 2003). While science is concerned with both forms of uncertainty, they emphasize fundamental uncertainties, especially the objective to increase precision and identify knowledge gaps as it supports the hypothesis that certain knowledge also means full trust (Maxim & van der Sluijs, 2011). On the other hand, practitioners are also exposed to uncertainties deriving from the planning process, so called process uncertainties (e.g. Abbott, 2005; Maxim & van der Sluijs, 2011; Sigel et al., 2010).[1] Dealing with this source of uncertainties is rather neglected by science and recognised only implicitly by practice

[1] More background information on uncertainties are found especially in chapter 2.3.2

(Höllermann & Evers, 2017). In general, the strong focus of science in reducing and emphasizing uncertainties - hereby sometimes obscuring information which is certain (Rosenberg, 2007) - and the risk-based approach of practitioners to implicitly handle uncertainties throughout the decision-making process, present two valuable yet contrasting approaches (e.g. Carter et al., 2007; Wilby & Dessai, 2010; Willows et al., 2003). This hinders effective knowledge transfer (e.g. Gabbert et al., 2010; Hulme, 2014; Roux et al., 2006; Toomey, 2016; Vogel et al., 2007; Wardekker et al., 2008; Weichselgartner & Kasperson, 2010).

In general, numerous factors hamper effective knowledge transfer at the science-practice interface. E.g. the transfer is not successful or complete if the aim of research is not in line with management objective (Kinzig et al., 2003) and practitioners context (Vogel et al., 2007), when ownership of knowledge production is not shared (Weichselgartner & Kasperson, 2010), actor have prejudice against each other (Kinzig et al., 2003), or translation issues regarding terminology arise. Regarding the latter, there is a pressing need to translate results into the professional jargon of the stakeholders. In case of flood management such a translation does not or only rarely occurs (Faulkner et al., 2007). Even though co-production of knowledge is regarded as supporting efficient knowledge transfer, Weichselgartner and Kasperson (2010) point out that functional, social, and structural factors present obstacles for such a co-production.

Where functional factors refer to differences in objectives and priorities, social factors refer to culture and mistrust, and structural factors address e.g. the institutional setting. Here, Lemos et al. (2012) propose to close the gap by increasing the usability of information and knowledge. This can be achieved through three factors: fit, interplay and interaction. Fit describes how well the information fits the users' need. Interplay addresses how the new knowledge and information interrelates with the users' current knowledge. Interaction, finally, describes the quality of exchange between users and producers of information and knowledge. This is why awareness regarding tacit knowledge (Ingram, 2013) and how this knowledge organizes new ideas around established concepts (Fazey et al., 2005; Weichselgartner & Pigeon, 2015) is required. Also, uncertainty as an integral part of information (Blöschl & Montanari, 2010) has to be transferred.

However, additionally to the hindrances mentioned above, uncertainty information poses additional challenges on this transfer. The fear of decision-makers to lose social and political trust when uncertainty implies to revise former decisions (Kasperson, 2010), the impact and influence of uncertainties on different stakeholders groups in potentially different ways (Irwin & Wynne, 1996; Olsson & Andersson, 2007), and the misuse of uncertainties as excuse for delay or inaction (Kinzig et al., 2003; Nilson & Krahe, 2012) are obstacles specifically related to transfer of uncertainty information. Hence, improved understanding of the user perspective of how differently uncertainty information is perceived, interpreted and reacted to supports effective uncertainty integration (Briley et al., 2015; Gabbert et al., 2010; Kundzewicz et al., 2018; Mauelshagen et al., 2014; Petr et al., 2014; Westerberg et al., 2017).

Practitioners are also exposed to decision uncertainty which guides their perception and decision-making processes. To cope with uncertainties, they use several behavioural patterns: availability, anchor, emotion, hypothesis and consistency (Eller et al., 2013; Renn, 2008). These psychological impacts may misguide information. For example, availability describes the presence of a topic due to medial presence, social discourse, personal experience, and memory which may not reflect the facts and figures. This is also true for using anchors, where existing information and experience from other fields is used for decision-making even though this information is not applicable for the specific context. Affect heuristic makes use of emotions rather than facts to decide about a topic (Renn, 2008). Further, people tend to prove hypothesis rather than dismiss them which might lead to overemphasizing information supporting a hypothesis and neglecting others. Finally, linking up to former decisions is thought to increase legitimacy and justification which makes the decision-maker tend to consistency (Kasperson, 2010). Even though decision uncertainty is off the scope of this thesis, the behavioural and psychological patterns are used as boundary conditions to connect to practitioners' decision reality and increase the value and integration of uncertainty information. For example, the developed tools (e.g. chapter 2) may positively influence availability and set specific anchors to support decision-making based on information and the limits of this information.

The challenge of uncertainty integration at the science-practice interface is mostly presented by how to communicate information about uncertainty in a way that practitioners can make use of and support in robust decision-making. Here, Winkler (2016) points out that openness to a plurality of approaches is important to highlight uncertainties and address the practitioners. She particularly regards geographers as responsible to assist planners with their decision-making under uncertainty by "developing novel ways to characterize and communicate uncertainty […]" and by "adopting a proactive attitude toward the inclusion of uncertainty and complexity in decision making (which) will benefit everyone in the long term" (Winkler, 2016, p. 1428f.).

Challenged by her call, this doctoral thesis contributes to closing the science-practice gap by improving the understanding of how scientific uncertainties may find better integration into decision-making in the face of plurality of approaches and understandings. Further, it contributes by proposing new ways of understanding uncertainty and by providing demand-orientated tools to increase transparency about uncertainty, uncertainty perception and decision-making rationales.

The following sections describe the aim and objectives of this thesis in more detail (chapter 1.3) and highlight the scientific approaches applied to solve the issue (chapter 1.4).

1.3 AIM AND OBJECTIVES

The aim of this doctoral research is to improve the understanding of how scientific uncertainties find better integration into planning and decision-making processes in model-based water management. Due to climate variability and change as well as societal change water management decisions will be particularly under uncertainty. To improve the quality and robustness of decisions it is a prerequisite to take the underlying uncertainties into account. However, science and practice approach uncertainties differently. While science focusses more on reducing uncertainties in e.g. their models, practice makes use of risk-based approaches to acknowledge uncertainties throughout the whole planning and decision-making process (Willows et al., 2003) as strategic planning and policy making closely relate to risk management (Smith & Stern, 2011). This allows assessing the risk in relation to the impact of scientific uncertainties (UNESCO-IHP, 2011). Another advantage of a risk-based approach is the integration of physical as well as societal variables and actors on different scales to weight for example water-related trade-offs (Bakker & Morinville, 2013). Additionally, uncertainty is only one of many decision criteria and balancing these criteria is always a judgement process which highly depends on context (Aven, 2010). In order to keep research findings connected to a multitude of risk concepts, this study draws on a more general concept, the Risk Governance

Framework of the International Risk Governance Council (IRGC) (IRGC, 2005, 2008). Within this framework five main elements are addressed:

1) Pre-Assessment with transdisciplinary risk and problem definition,
2) Risk appraisal drawing knowledge from scientific risk assessment and public concern,
3) Characterization and evaluation as a judgement process considering scientific knowledge and societal norms and values,
4) Risk management as an implementation of measures to cope with risk, and
5) Communication as a linking and integrating element.

Figure 1.2 presents the risk governance framework and displays one further key issue regarding the risk perspective. The risk cycle consists of two main systems, the knowledge system (where we understand a problem) and the decision system (where we make choices). While the second phase (risk assessment) and the fourth phase (risk management) belong to the understanding or decision part of the risk cycle, the third phase - the judgement phase which characterises and evaluates the risk - is situated at the interface of understanding and deciding.

Bearing this in mind it is crucial for this research to:

a) focus on what happens with uncertainty assessment going from phase two to three,
b) how this knowledge is used or usable and may transform in phase three, and
c) what impact it still has during the implementation of measures (phase four).

The risk-based approach is therefore regarded as particularly useful not only as it represents practitioners' background, but also because it recognizes the different stages of uncertainty handling.

The particular focus of this study is on perception and handling of uncertainties from science and practice. Their differences as well as their commonalities are investigated to find a bridging concept and to increase the integration of uncertainties into final water management decisions. This goal is achieved by following three key objectives and related questions (which are also located in the risk governance framework in Fig. 1.2):

1) Develop a risk-based integration and analytical framework for uncertainty acknowledgement:

- Which uncertainty characteristics fit the need and demand of science and practice?
- How can these uncertainties and the knowledge about them be communicated in a structured way benefiting decision-making?
- How does this fit a risk-based planning and decision-making approach?

2) Identify key characteristics of uncertainty handling and perception at the science - practice and knowledge - decision interface:

- What happens at the interface of knowing and deciding with uncertainty information?
- On what does uncertainty integration depend on?
- Which uncertainty routines are used by practitioners?

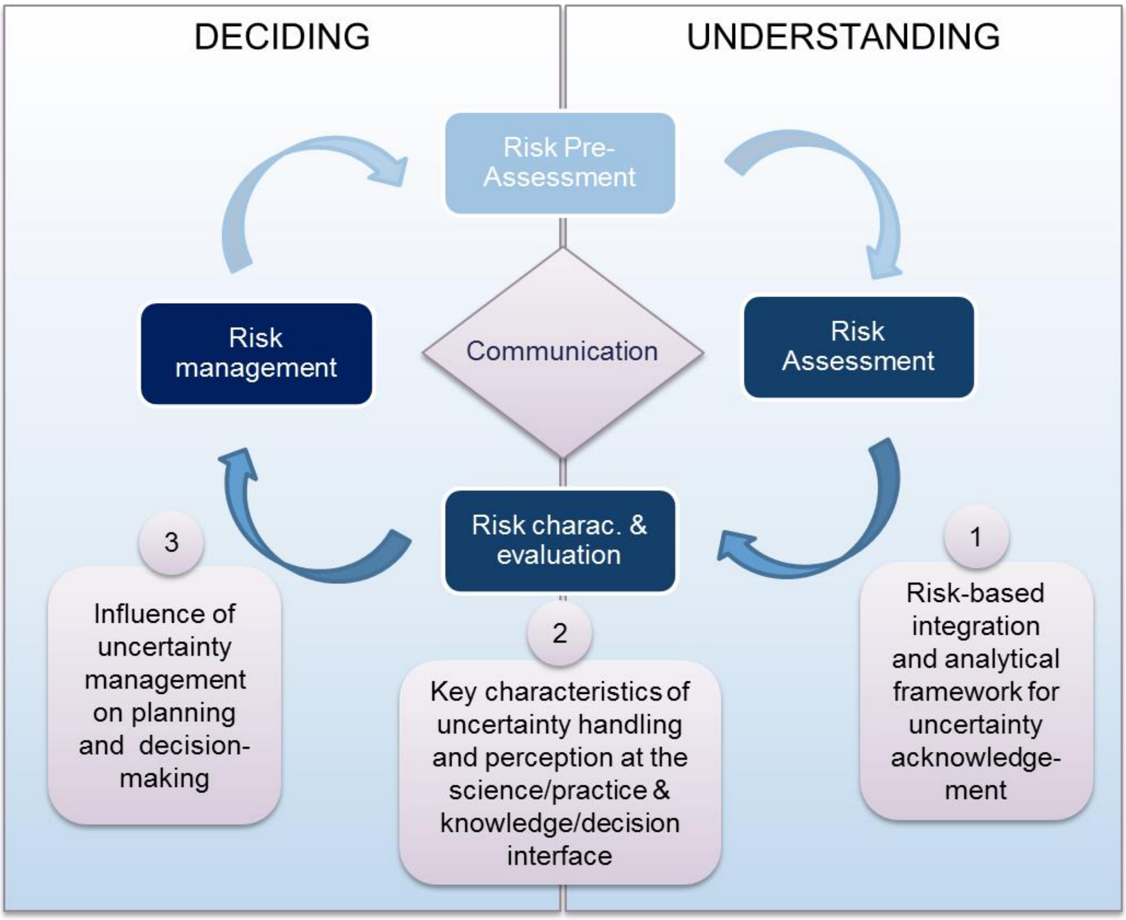

FIGURE 1.2 RESEARCH OBJECTIVES STRUCTURED WITHIN THE RISK GOVERNANCE FRAMEWORK, NUMBERS REFER TO NUMBER OF RESEARCH OBJECTIVE (own figure, modified and based on risk governance framework (IRGC, 2005, 2008))

3) Visualize the influence of uncertainty management on planning and decision-making due to the plurality of practitioners:

- How do different actors behave when dealing with uncertainty?
- How to deal with the plurality of perspectives on uncertainty management?

The doctoral thesis investigating the above aim and objectives comprises three research articles presented in chapters 2 - 4. The underlying scientific approach and methods to these articles is presented in the following section.

1.4 SCIENTIFIC APPROACH AND METHODS

The research questions presented above require a scientific approach which simultaneously creates an understanding of how users and producers of uncertainty alike deal with, communicate and appreciate uncertainty information, and which is open for findings that may go beyond the simple user and producer or practice and science categorisation. As elucidated in chapter 1.3, a risk-based approach allows monitoring uncertainty throughout the management process from understanding to deciding (also compare Fig. 1.2). Hereby, examining the plurality of facets of uncertainty and their potential transformation regarding the impact, importance, and value for the different actors and stakeholders involved in the process. These actors may be scientists, water managers, government employees or (political) decision-makers.

For this research, the case of reservoir management was used to exemplify the diverse challenges water manager experience when steering reservoir discharge under change and uncertainty. Reservoir management optimally presents uncertainty impact on different temporal and spatial scales with its partially diverging tasks due to intra-annual climatic variability such as securing water supply during low flows and preventing floods. On a long-term perspective, socio-economic change directly feedbacks into reservoir management responsible for water supply, hydropower generation and flood protection. Land use and land cover change (LUCC) as well as climate change (CC) indirectly feedback to trade-off management. Examples are accelerated climate extremes which aggravate managing the diverse tasks and increase the underlying risk of management failure. Against this backdrop, active handling of uncertainties - especially if they are sensitive to spatial and temporal scales - is of utmost importance to derive robust decisions. Hence, reservoir management is regarded as a fruitful case study to investigate the opportunities and benefits of uncertainty integration.

The research is based on a mixed methods approach. Besides conducting relevant literature review, quantitative and qualitative methods were applied, including survey, expert elicitation and qualitative system analysis. This mix allowed triangulation among different data, sources and perspectives to examine the research topic from different angles and contribute to a comprehensive understanding of science's and practice's specific viewpoints. Each method contributes to the following chapters with different intensity. Chapter 2 focuses on the theoretical conceptualisation and therefore relevant literature review supported by first analysis of expert elicitation is the dominating method. Chapter 3 draws on findings gained from intensive expert elicitation in combination with survey results, where the latter support and complement the findings of the expert interviews. Chapter 4 builds on the results of the former methods and synthesises these insights into a qualitative system analysis in form of an influence / causal loop diagram (chapter 4.2).

The research methods are described at length within the respective chapters. This is particularly true for chapter 3.2 where the expert elicitation as well as the questionnaire setting and participants are explained in detail (see also Tab. 3.1), and for the qualitative system analysis in chapter 4.2.3. However, the following sections will summarize the chosen research methods and review the impact of this method in achieving the goal of this doctoral thesis.

1.4.1 LITERATURE REVIEW

The literature review focussed on influential approaches concerned with the development of frameworks, typologies and characterizations of uncertainties within the field of water resources and the closely related field of environmental planning and management[2]. The aim of this review was to identify the differences and commonalities of these approaches and to develop a condensed uncertainty matrix where the further investigation is based on (compare Tab. 1.1).

---

[2] A description of these approaches can be found in chapter 2.3.2.

It could be shown that while the reviewed approaches differ regarding their foci, perspectives and objectives, they rather overlap and complement than exclude each other. Two key criteria are level and location of uncertainty, where the level describes the degree of uncertainty (from e.g. certain to uncertain) and the location the source of uncertainty (e.g. model algorithm) (Brugnach et al., 2007; Janssen et al., 2005; Refsgaard et al., 2007; Walker et al., 2003). When it comes to causes of uncertainty, the broad review suggests two main foci depending on research background. Besides the focus on fundamental or environmental uncertainties describing the uncertainty due to the phenomenon itself (aleatoric) or to the knowledge about the phenomenon (epistemic) (Walker et al., 2003), others highlight the importance of uncertainties deriving from planning, called process (Abbott, 2005), procedural (Maxim & van der Sluijs, 2011) or practical uncertainty (Sigel et al., 2010). These key characteristics (2 causes, level, and location of uncertainty) were implemented into the newly developed 2x2 uncertainty matrix as the basis for further research on this subject. Table 1.1 provides an overview of this matrix with exemplary questions and the underlying concept. Studies from Brugnach et al. (2008) and van den Hoek et al. (2014) showed that knowledge relationships and cascading uncertainties closely connect different sources of uncertainty. This doctoral research shows that this interrelation is also between the causes of uncertainty (e.g. Fig. 2.2 and chapter 2.4.3).

TABLE 1.1 2x2 UNCERTAINTY MATRIX WITH EXPLANATORY QUESTIONS WHICH ARE DRAWN FROM THE EXPERT INTERVIEWS AND VISUALIZE THE MANY FACETS OF UNCERTAINTY (table modified and translated from Höllermann & Evers, 2015a)

Cause of uncertainty	Level/degree of uncertainty	Location of uncertainty
Fundamental uncertainties (aleatoric or epistemic)	To what extent is the probability of occurrence of an event or consequences of actions known? → *Description of available knowledge from certain to uncertain and ignorant*	How is the reflection process about the limitations regarding boundary conditions, data, parameter, choice of model and model results? → *For example the knowledge about the sensitivity of the managed system*
Procedural uncertainties (planning process)	How does risk perception decides about uncertainty acknowledgement? → *Reflection about practitioners decision patterns and anchors* How do strategic liabilities and responsibilities influence uncertainty recognition? → *Reflection about trade-offs*	Which financial, political, or personal limitations and boundary conditions apply? → *Degree of availability of resources* Whose or what interests should be defended or represented? → *Question of responsibility*

In conclusion, the results of the review provided the ground for a condensed yet comprehensive uncertainty matrix and built the basis for developing questions for expert elicitation and the survey. Especially, the integration of the procedural or process uncertainties proofed to be a strong connecting element with respect to the practitioners' perspectives on uncertainties (compare chapter 2.5, 3.3.2, and Fig. 3.2).

1.4.2 EXPERT ELICITATION AND SURVEY

The expert elicitation (chapter 3.2.1) was conducted to identify practitioners' perception, understanding, and handling of uncertainty within their working environment and the survey (chapter 3.2.2) adds also the scientists' perspective to this issue.

Semi-structured interviews were conducted with 20 experts from state agencies, district governments, water associations and private business in Germany. Their educational background covers geosciences and engineering. In general, the topical focus of these experts is on surface water quantity management with some experts paying special attention to climate change impacts and adaptation. The choice of interview format, experts and analysis followed recommendations by Mayer (2012), Meuser and Nagel (2009), and Kuckartz (2010) for qualitative expert elicitation and analysis. The interview format targeted at the expertise of the interviewees. The choice of experts has been twofold. First, they should have at least 10 years of experience in their field and institutional setting. Second, the expert choice should take properties of the expert population into account and therefore cover different levels of decision competency and work settings (compare Tab. 3.1). The semi-structured interviews followed an open guideline to increase comparability and leave space for topics raised by the interview partners. The questions of the guideline were based on topics assessed essential during literature review: 1) Professional background, 2) Definition, perception and evaluation of uncertainties, 3) Handling of uncertainties, 4) Knowledge transfer for knowledge-based decisions, 5) Role of uncertainties in the decision-making process, and 6) Conflict potential, risk management and uncertainty. The concrete questions can be found in Annex 7.1. The recorded and transcribed interviews were then analysed by using a qualitative data analysis (QDA) software (MaxQDa). A multi-step and recursive approach to identify key issues and topics raised by the experts was applied to sustain the validity of the analysis (Kuckartz, 2010) and derive general or common viewpoints across all interviewees or groups of experts.

In addition, the survey addressed practitioners as well as scientists. The questionnaire (Annex 7.2) covers likewise the topics assessed important during literature review, however, included a quantitative component and was descriptively analysed with a statistical program (SPSS) according to code of practice (Akremi et al., 2011; Kuckartz et al., 2013). Participants of the survey were conference attendees of the German Day of Hydrology in 2015 in Bonn. In general, this conference serves as a get together of the German-speaking water community from science and practice. The questionnaire was distributed among the conference attendees and 19 % of them replied. Given this rate of feedback the analysis does not claim to be comprehensive or representative. However, the results provide some valuable insights which complement and support the interview results.

The triangulation of the qualitative and quantitative approach with its different participants proofed valuable as it enabled to also pay attention to intra-group variabilities with different levels of work experience, educational background and affiliation to employer and business unit (chapter 3 and 4). So far, science and practice have been treated as two major groups, but this research suggests that - beyond the science and practice divide - other criteria play an important role in dealing with uncertainty.

In conclusion, the expert elicitation and survey substantially contributed to discover the plurality of practitioners' perspectives on uncertainty perception and handling as it is shown especially in chapter 4. While chapter 3 stresses the level of working experience as a cross-cutting property of science and practice, hereby contributing a new perspective to the science - practice gap research.

1.4.3 QUALITATIVE SYSTEMS ANALYSIS

Aim of the qualitative system analysis (for more details see chapter 4.2.3) was to reflect the interrelations of the different system elements using reservoir management under short- and long-term variability and change as an example. This approach enabled the identification of uncertainty perceptions and uncertainty management strategies at specific points in the decision-making process as it is a key strength of qualitative system modelling to concisely describe problem narratives and identify feedback loops and different stakeholder perceptions (Coyle, 2000; Halbe et al., 2013). To grasp the latter, the content of the expert interviews served as a quasi-participatory input and reproduced the different perceptions in one common influence diagram (ID) (ElSawah et al., 2013; Halbe et al., 2013; Inam et al., 2015). In a next step, causal loops within the ID were identified (Powell et al., 2016) and uncertainty routines, which were developed from the synthesis of expert elicitation and survey (compare chapter 4.2.1 with Tab. 4.1), could be attributed to the different loops, hereby reflecting the plurality of practitioners' strategies to cope with uncertainty.

In conclusion, by applying qualitative system analysis the plurality of approaches regarding uncertainty perception and handling were uncovered, transparently localised and interrelations stressed. This research method, therefore, benefited this study by allowing to visualize the synthesis of the findings of the expert elicitation and survey. Furthermore, it added value to this research by identifying the interaction of loops and flows of uncertainty information and routines.

1.5 OVERVIEW OF MANUSCRIPTS

This doctoral thesis is a cumulative dissertation and consists of three individual manuscripts (chapters 2 – 4) prepared for publication in international peer-reviewed journals. The first two manuscripts are published in *PHIAS* and *Environmental Sciences and Policy*. The third manuscript is submitted to *Water Resources Research* and is currently under review.

Britta Höllermann wrote all manuscripts and reviewed the relevant literature for the theoretical background. She designed the research framework, chose the research methods, carried out the empirical and analytical working steps, interpreted the results and put the research findings into a larger context. Prof. Dr. Mariele Evers is co-author of all manuscripts as she supported the research, its design, and critically reviewed the research and writing process.

An overview of all manuscripts with related research foci, key points and general contribution is given in table 1.2. As the table shows, the three manuscripts are consecutively structured, beginning with the analysis of science and practice based approaches to uncertainty handling by using a risk-based and theoretical approach. In a second step, further investigation at the science - practice interface helped understanding potential gaps and misfits regarding transfer, interpretation and usability of uncertainty

Table 1.2 Summary of manuscripts with foci, key points and main contribution

Chapter	Publication	Focus on...	Key points	Main contribution
2	Höllermann, B., & Evers, M. (2015). Integration of uncertainties in water and flood risk management. Proc. IAHS, 370, 193-199. doi: 10.5194/piahs-370-193-2015	...science and practice based approaches to uncertainty	• Integration and analytical framework provides a. shortcut for structured transfer and exchange of uncertainty information b. overview of neuralgic points c. a tool to positively influence practitioners' anchors • 2x2 uncertainty matrix grasps different dimensions of uncertainty in a condensed way by visualizing the interrelation of fundamental and process uncertainties • Risk-based approach allows assessing the scope of action within wider political and societal context	Development of a risk-based integration and analytical framework for uncertainty acknowledgement
3	Höllermann, B., & Evers, M. (2017). Perception and handling of uncertainties in water management—A study of practitioners' and scientists' perspectives on uncertainty in their daily decision-making. Environmental Science & Policy, 71, 9-18. doi: http://dx.doi.org/ 10.1016/j.envsci.2017.02.003	...science - practice and knowledge - decision interface	• Uncertainties are central aspects of any decision in water management • Level of uncertainty acknowledgement varies among and within professions • Level of work experience is a cross-cutting uncertainty handling property • Practitioners reframe uncertainty into risk/consequences to cope with uncertainty • Uncertainty handling is challenged by science vs. policy/practice-based approaches	Analysis of differences and commonalities of scientists' and practitioners' uncertainty perspective
4	Höllermann, B., & Evers, M. (2018). Decision-making under uncertainty: Acknowledging plurality of water managers' uncertainty handling routines through qualitative system analysis. Water Resources Research (under review)	... plurality of practitioners' perspectives on uncertainty	• Elicitation of user and time specific uncertainty routines to understand the plurality of perspectives and to close the science-practice gap • Qualitative system modelling as a vehicle to foster cross-communication and (social / organizational) learning • Practical strategy to increase fit and interplay and consequently integration of uncertainties in water-related decision-making processes	Visualization of plurality of practitioners' uncertainty routines during decision-making process to foster cross-communication, transparency and integration of uncertainties in final decisions

information. Finally, the third manuscript focusses on the plurality of practitioners' perspectives to give hints of how to close gaps and redirect misfits to improve uncertainty integration for robust decision-making. Hereby, the research pays unique attention to the different needs and demands of specific groups of practitioners.

In the following, all three manuscripts are presented as chapters 2 to 4 before presenting an overall conclusion of this doctoral research.

2 INTEGRATION OF UNCERTAINTIES IN WATER AND FLOOD RISK MANAGEMENT[3]

ABSTRACT

Water management is challenged by hydrological and socio-economic change and hence often forced to make costly and enduring decisions under uncertainty. Thus, thinking beyond current acknowledged and known limits is important to consider these changes and the dynamic of socio-hydrological interactions. For example, reservoir management aiming at flood reduction and mitigation has to cope with many different aspects of uncertainty. The question is to what extent can, do and should these uncertainties have implications on planning and decision-making?

If practice recognises uncertainties they frequently use risk-based decision approaches to acknowledge and handle them by e.g. relating them to other decision relevant factors, while science is mostly preoccupied in reducing these uncertainties. Both views are of relevance and a risk focused approach is needed to bridge the different perspectives covering all significant aspects of uncertainty. Based on a review of various characteristics and perceptions of uncertainty, this paper proposes a new analytical framework where the various aspects of uncertainty are condensed and a risk perspective is added. It thus goes beyond a pure typology and provides an overview of neuralgic points and their location and appearance during the decision-making process. More over this paper supports a

[3] A version of this chapter has been published as: Höllermann, B., & Evers, M. (2015). Integration of uncertainties in water and flood risk management. *Proc. IAHS*, 370, 193-199. doi: 10.5194/piahs-370-193-2015

structured and evaluated knowledge assessment and knowledge transfer for informed decision-making and points out potential fields of action and uncertainty reduction. Reservoir management targeting at flood prevention is used as an illustration to present the analytical framework, which is also amended by the needs and demands of practitioners, using first results of expert interviews.

2.1 INTRODUCTION

Reservoir management is embedded into a complex socio-hydrological system sensitive to socio-economic, climate, land use and land cover changes. The multi-functionality of many reservoirs is a challenging task regarding the often opposing objectives. On the one hand water management aims at storing water for societal and ecological needs concerning energy production and compensating water shortages, while on the other hand targeting at maximizing the flood control zone for flood mitigation. Decisions are therefore made under risk and uncertainty. E.g. even though measures of mitigation have been put in place flooding may occur as precipitation turned out to be higher than anticipated from uncertain weather forecasts. Or the other way, that preventive reservoir relief in expectation of a large rain event turned out to be an overestimation increasing the risk of future supply failures and economic losses. The question is to what extent can, do and should these uncertainties have implications on planning? Actors facing uncertainties also tend to compensate the uncertainty by e.g. making use of anchors (Renn, 2008). Anchors are readily available information which is sometimes put in the current context even though it may not be applicable for the exact situation. This psychological factor also stresses the need for structured uncertainty information and further poses the question: How can uncertainties be effectively integrated into decision-making in order to reduce risks or to take appropriate measures for risk mitigation?

This paper provides the basis for answering these questions by proposing a new analytical framework where various aspects of uncertainty are condensed and a risk perspective is added. Furthermore, the needs and demands of practitioners are acknowledged by using first results of expert interviews amending the framework and ensuring the compatibility and operability of the framework for practitioners.

2.2 RISK, UNCERTAINTY AND THE NEED FOR KNOWLEDGE TRANSFER

How to distinguish between risk and uncertainty? According to the flood risk definition of the EU floods directive 2007/60/EC, risk is defined as a product of the probability of occurrence of an event and its consequences, while it is not exactly known when or where the event happens. Uncertainty hereof describes the situation when occurrence probability and/or the extent of consequences are not assessable (Willows et al., 2003). With this definition risk can be regarded as an optimal state, because we command of sufficient and approved management strategies to cope with, e.g. by applying quantitative cost-benefit analysis or qualitative optimizing models. In his uncertainty matrix Stirling (2010) points out this argument by describing risk as a state of high knowledge regarding probabilities and possibilities. However, due to the unpredictability of future boundary conditions such as hydrological and ecological change, social and economic developments and especially the public awareness of e.g. flood protection measures or security needs (Hooijer et al., 2004), more and more decisions must be taken beyond the assessable risk. Decisions under complexity and uncertainty become more frequent (cf. Funtowicz & Ravetz, 1993). Stirling (2010) denotes the reduced knowledge regarding probabilities and/or possibilities as uncertainty, ambiguity, and ignorance, respectively (cf. Fig. 2.1). He demands that practitioners must therefore take a broader view on their degree of knowledge and their pool of decision-making methods for planning. Given this challenge an intensified information and knowledge exchange between science and policy/practice is important for key decisions. As uncertainty is part of information and not a lack of knowledge (Blöschl & Montanari, 2010) it has to be communicated and transferred as well. Therefore, integration of uncertainty information is a key criteria to choose between alternatives during a decision process (Funtowicz & Ravetz, 1993) and supports evaluation of reliability of the findings (Kinzig et al., 2003). Furthermore, it enhances transparency within the decision process (Reichert et al., 2007) and puts value on the findings by communicating their limits (Pappenberger & Beven, 2006). Given the many factors of hindrance of the science - practice dialogue (Weichselgartner & Kasperson, 2010) the question is how and what kind of uncertainty information is best presented and communicated to be effectively integrated into the decision-making process.

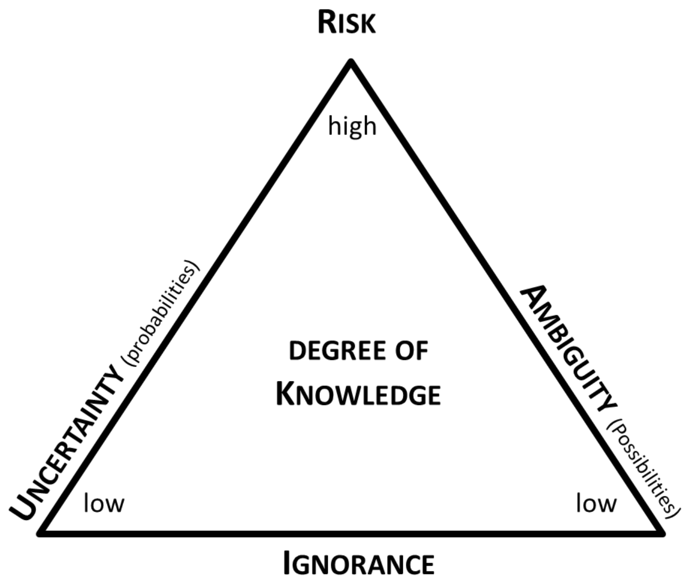

FIGURE 2.1 UNCERTAINTY RISK TRIANGLE (modified after Stirling (2010))

2.3 CONCEPTUALISATION OF THE FRAMEWORK

Raising trust of stakeholders and public in findings is another important reason for uncertainty assessment, however, seldom acknowledged (Maxim & van der Sluijs, 2011). While science is mostly preoccupied in reducing uncertainties, practice developed risk-based approaches recognise, acknowledge and handle uncertainties by e.g. balancing them against other decision-relevant factors (Aven, 2010; Willows et al., 2003). The following sections therefore consider both perspectives: the scientific approach in uncertainty reduction and the practitioners' risk-based approach in acknowledging and handling uncertainties. By proposing an analytical framework bridging these valuable different perspectives the chapter concludes.

2.3.1 RISK PERSPECTIVE

Planning often relates to risk management (Smith & Stern, 2011) as it requires integrating physical and social variables as well as a variety of stakeholder interests in order to better reflect and resolve water-related trade-offs (Bakker, 2012) and/or the dynamics of the co-evolution of the socio-hydrological system (Di Baldassarre et al., 2013). Here, considering uncertainties and balancing them against other concerns during the risk assessment process is important for the contextualised judgement process (Aven, 2010). Therefore, the distinction between understanding and deciding is a key concept in the risk governance framework of the international risk governance council (IRGC) reflecting the importance of first analysing all facts about the risk and then make a judgement in order to be as objective and transparent as possible (IRGC, 2005, 2008). Risk governance covers the four main steps i) Pre-Assessment, where the risk is framed and defined considering also divers and opposing perspectives of varied stakeholder, ii) Appraisal, where the risk is assessed using both scientific risk assessment and public perception of the risk, iii) Characterisation and evaluation, where the risk is ranked and judged considering the scientific findings and social values, and iv) Management, where the measure facing the risk are implemented. Communication is a central part of the risk governance framework in order to share and co-produce knowledge among the knowledge providers, actors and stakeholders along the risk governance process.

2.3.2 UNCERTAINTY PERSPECTIVE

During the last 15 years multiple frameworks, typologies and characterisations of uncertainties were developed to better describe and identify uncertainty. While the approaches differ concerning their foci, perspectives and objectives, they very seldom exclude but rather overlap each other. In this chapter a selection of influential approaches, mainly in the field of water resources and related fields are presented.

Walker et al. (2003) distinguish uncertainty into level, nature and location, where level describes the degree of uncertainty, nature the causes of uncertainty and location the sources of uncertainty. Others followed this characterisation (e.g. Brugnach et al., 2007; Janssen et al., 2005; Refsgaard et al., 2007) and extended it by introducing knowledge relationships and objects (Brugnach et al., 2008) as well as the idea of cascading uncertainties (van den Hoek et al., 2014). Sigel et al. (2010) differentiate fundamental and practical causes of uncertainty as well as norm-related uncertainty, hereby adding a new uncertainty dimension. Similar, the classification of Maxim and van der Sluijs (2011) looks at three dimensions of uncertainty: substantive, contextual and procedural. Abbott (2005) acknowledges the importance of managing both environmental and planning process uncertainties. Finally, Gabbert et al. (2010) highlight the user-driven perspective on uncertainty information needs.

How to condense and integrate the various foci, perspectives and objectives of uncertainty? First, all characterisations have an uncertainty range in common often described as the level of uncertainty. The scale ranges e.g. from “certainty” to “uncertainty” to “lack of knowledge” (Sigel et al., 2010), or from “determinism” to “statistical uncertainty, scenario uncertainty and recognised uncertainty, indeterminacy” to “total ignorance” (Walker et al., 2003). Brugnach et al. (2008) complement this “not knowing enough”-range by pointing out ambiguity as “knowing differently”. van Asselt and Rotmans (2002) approach is similar with scales ranging from “inexactness” to “conflicting evidence” to “irreducible ignorance”. This high overlap in the level of uncertainty can be summed up with the adapted uncertainty matrix from Stirling (2010) (Fig. 2.1). Second, there is broad acceptance in identifying the source or location of uncertainty, like model, input data, etc. even though some differences about the term exist (cf. Sigel et al., 2010). Third, causes of uncertainty are described by many of the authors, however, to a different extent. Walker et al. (2003) refer to the nature of uncertainty of the phenomenon, hereby distinguishing the uncertainty due to the phenomenon itself, the variability uncertainty (sometimes also called aleatoric or objective uncertainty), and the uncertainty due to the knowledge about the phenomenon (epistemic uncertainty). Notably, they focus on the causes of uncertainty of the phenomenon or - as other authors call it - the environmental, substantive or fundamental uncertainty (e.g. Abbott, 2005; Maxim & van der Sluijs, 2011; Sigel et al., 2010). In addition, uncertainty caused by planning is called process uncertainty (Abbott, 2005), procedural uncertainty (Maxim & van der Sluijs, 2011), or practical uncertainty (Sigel et al., 2010).

Conclusively, key criteria to evaluate the characteristics of uncertainty are the level and the location of uncertainty complemented by the two causes of uncertainty (Fig. 2.2). The level is described by using the interrelations of risk, uncertainty, ambiguity and ignorance as a degree of knowledge. This is also the case for the procedural uncertainties which occupy a central role in this matrix. While one can distinguish these two causes of uncertainty quite well, they also mutually influence each other. Improving or reducing either one may have a positive effect on the other. This effect is described by van den Hoek et al. (2014) cascades of interrelated uncertainties regarding the three knowledge objects nature, technology and society. The 2x2 matrix shows this in a clear and concise format, hereby providing a condensed yet comprehensive analytical tool to structure uncertainty information (Fig. 2.2). For further comprehension the completed matrix provides explanation of localisations of potential causes of uncertainty.

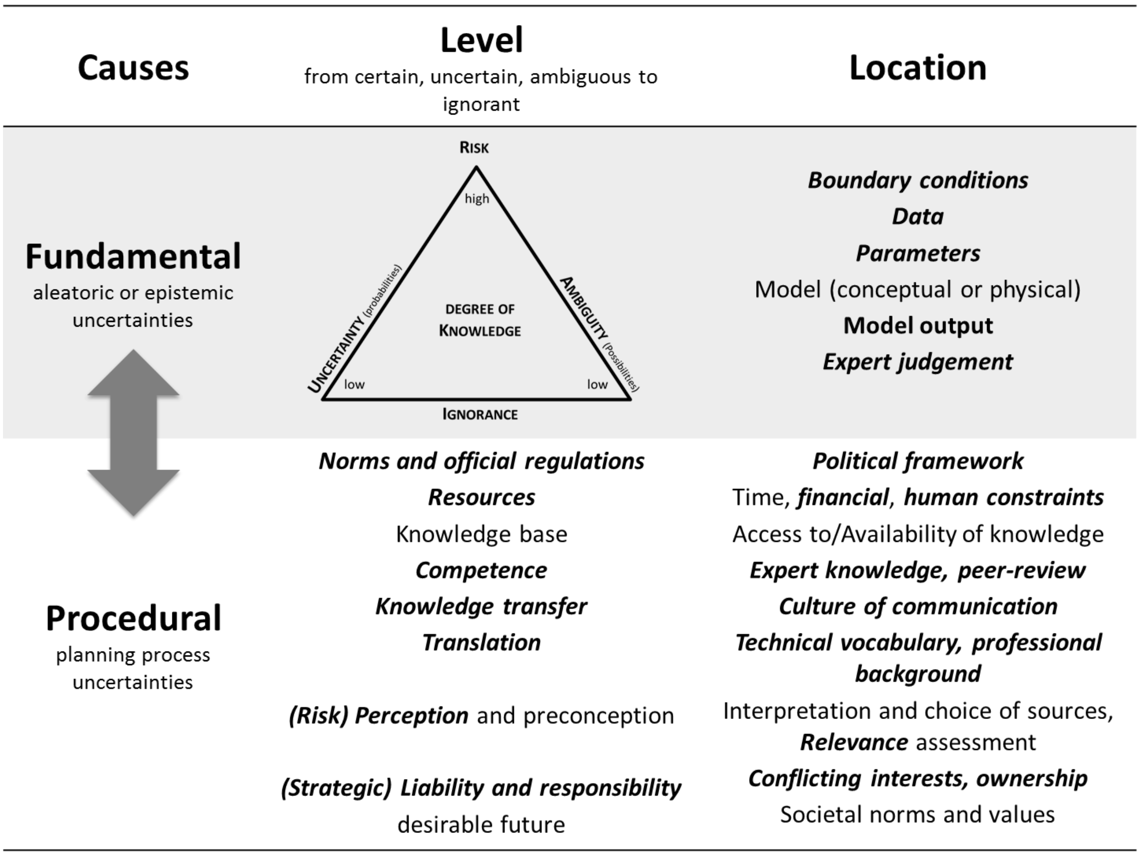

FIGURE 2.2 CONDENSED 2X2 UNCERTAINTY MATRIX (terms formatted italic bold reflect experts' uncertainty perception and experience, section 2.4)

2.3.3 BRIDGING THE TWO PERSPECTIVES

The brief literature review on uncertainties shows that a vast understanding of uncertainties exists, however, so far an explicit link to risk-based planning and decision-making is missing. It is important to notice that during the risk governance phase the extent and emphasis of uncertainties differ, the 2x2 uncertainty matrix is therefore relevant for each step. Additionally, recognising the three knowledge objects is important to precisely identify neuralgic points, potential fields of action and interrelations (Fig. 2.3). Communication, illustrated by the arrow linking the different risk governance steps, is the connecting element. While the last step “risk management” is missing in this figure - as the implementation uncertainties are out of scope of this paper - the analytical framework can integrate this aspect if needed.

The challenge during the judgement process is to relate the condensed uncertainty characteristics from the two preceding phases to the evaluation of the acceptable and tolerable risk. The detail in figure 2.3 shows this reciprocal process. The traffic light model, defining limits between acceptable risk (green), necessary risk reduction measures (yellow) and intolerable risk (red) (cf. IRGC, 2005), is adjusted to a triangle, resembling the uncertainty risk triangle. Even though the two axis probabilities/possibilities and occurrence probability/extent of consequences are not of equal value and a direct comparison is not possible, the triangle illustration supports the judgement process by providing a simple tool of acknowledging and integrating uncertainty information into the evaluation process. The integration of procedural uncertainty also reflects the significance of recognising these uncertainties as they are crucial in defining and negotiating the acceptable risk level.

Thus, the framework goes beyond a pure uncertainty characterisation by identifying information needs during the decision-making process. Moreover it points out fields of action and uncertainty reduction in respect to causes, locations and knowledge objects, hereby supporting risk evaluation under uncertainty and enhancing informed decision-making.

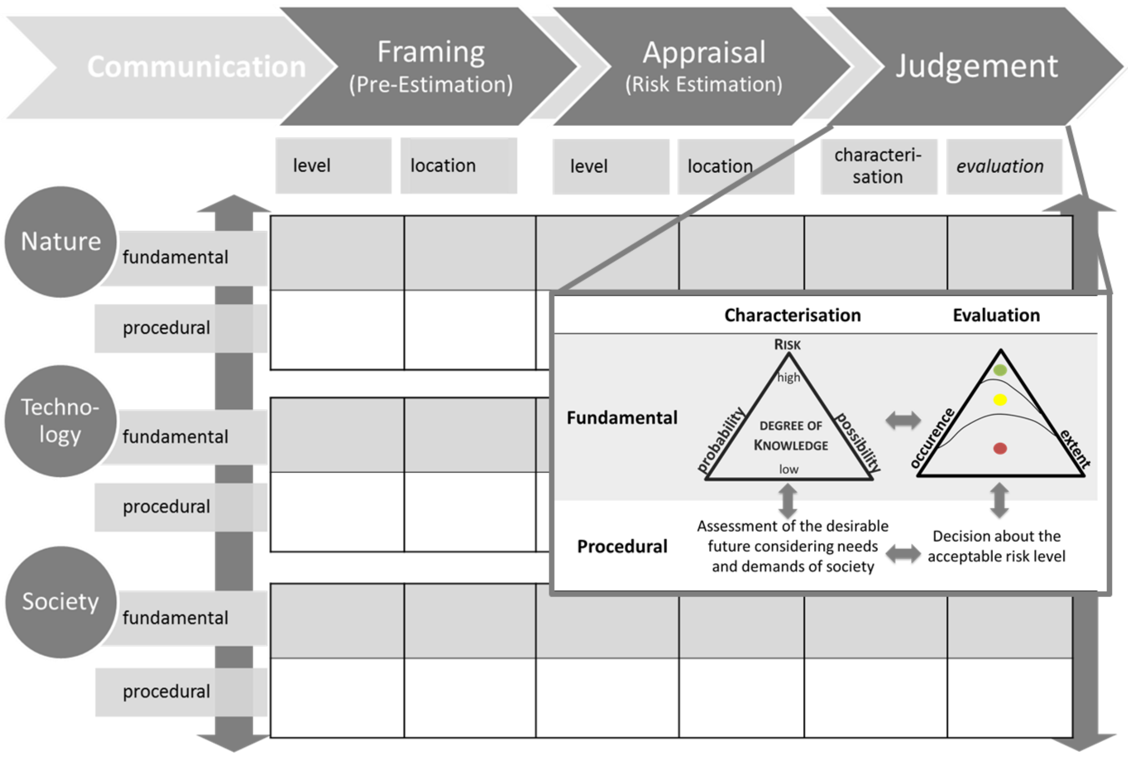

FIGURE 2.3 ANALYTICAL FRAMEWORK HIGHLIGHTING THE INTERRELATIONS AND MUTUAL INFLUENCE BETWEEN KNOWLEDGE OBJECTS AND CAUSES OF UNCERTAINTY INTEGRATED INTO THREE RISK GOVERNANCE STEPS. THE DETAIL BOX SHOWS THE SPECIAL LINK OF THE UNCERTAINTY RISK TRIANGLE, PROCEDURAL UNCERTAINTIES AND THE EVALUATION OF ACCEPTABLE RISK LEVELS DURING THE JUDGMENT PHASE.

2.4 CONCEPT VALIDATION WITH EXPERT INTERVIEWS

Aiming at understanding the needs of practitioners concerning their uncertainty management 9 experts were consulted and interviewed so far. The experts are working in German scientific state authorities and water associations with a background and profession in geoscience or engineering in water and flood risk management. The interview partners were either directly engaged in planning and decision-making processes or provided fundamentals for decision-makers. The interviews followed a semi-structured guideline covering the topics awareness and handling of uncertainty, knowledge transfer, role of uncertainties in decision and planning processes, and risk management. More interviews are envisaged and will also address experts from business focussing on e.g. hydro-power generation. The findings are first results of this ongoing research.

2.4.1 INTEGRATING THE RISK PERSPECTIVE

All practitioners regard uncertainties as part of their daily business and have developed strategies to cope - sometimes unwittingly - with many facets of uncertainty (Fig. 2.4). They see uncertainty information as an important part of the information from which to assess the risk or the consequences of decisions. Hereby the interrelation of uncertainty, risk and risk perception is highlighted. Yet, few of the interviewees apply classical risk assessment explicitly. Even though at the moment, there is no explicit risk assessment, the proposed structure supports the planning process by visualising the interrelation and dependency of uncertainty and risk, hereby, providing scientifically sound and situation-adapted anchors for decision-making. Hence, the integration of a risk perspective is of high value regarding the experts' implicit risk assessment and the impact of risk perception.

2.4.2 UNCERTAINTY FOCUS

Regarding the experts' uncertainty awareness, the focus on uncertainties related to operational flood management is more prominent than long-term adaptation management (Fig. 2.4). Analysis suggests that risks from long-term changes are perceived minor to short-term flood risk, partially as the adaptation capacity of water management is assessed high by the experts. Besides, some interviewees argued that the impact compared to the assessed long-term risk and large range of uncertainty is not high enough to account for investing in adaptation measures now. Proportionality is a key decision criterion for them.

2.4.3 INTERRELATIONS OF CAUSAL UNCERTAINTIES

Water managers experience trade-off situations concerning their reservoir operation in order to minimize potential flood risk damage while at once assessing the economic loss for e.g. hydro-power generation. Figure 2.4 highlights two examples where uncertainties influence the scope of action.

	Level		Location	
Fundamental	*Uncertainty*	**ensemble ranges (A,C)** **sensitivity (A,B,C)**	*Boundary conditions*	**actual reservoir storage volume (A,B)**
	Ambiguity	quality of model (C)	*Data*	**short-term weather forecast (A)** continous time-series data (A,C,B) climate scenarios (C) socio-demographic development(C)
	(Recognised) Ignorance	chaotic flood behavior (A) change to risk society (B,C)	*Model output*	robustness (A,B,C)
			Parameter	**sensitivity (A,B)**
			Expert judgement	about **robustness** of data, **model output** and parameter (A)
Procedural	*Norms and regulations*	permanent water retention currently not approvable (C)	*Political framework*	risk perception and experiences (A,C)
	Resources	maintenance of sufficient gauging stations (A,B,C)	*Financial and human contraints*	basis for better equipments with resources: gauging stations and maintenance staff (B)
	Competence	**broaden team (A)**	*Peer-review*	**consult authority (A,B)**
	Knowledge transfer	regular team meetings, personal contact, public communication (A,B)	*Culture of communi-cation*	media integration (A) paradigm change to risk society (A,C)
	Risk perception	**depends on boundary condition**, e.g. reservoir volume (A,B)	*Relevance*	over sensitization against flood risk (A) experiences (A,C)
	Strategic liability and responsibility	operation needs decision on one value, not a range (A) security factors and **economic viability (B,C)**	***Conflicting interests and ownership***	**potential flood mitigation versus actual economic losses of stakeholders (A)**

FIGURE 2.4 FLOOD RISK MANAGEMENT EXEMPLIFIED IN THE 2X2 UNCERTAINTY MATRIX (A: operational flood management / B: medium-term operation / C: long-term adaptation management; accentuations in black and red bold refer to examples explained in text)

In the first example (black bold), the fundamental cause of uncertainty regarding the level of sensitivity is located in parameter sensitivity and/or actual reservoir storage volume. This boundary condition and its sensitivity may decide about the risk perception. The scope of action is then assessed by also considering the strategic responsibility for the stakeholders or customers and their economic viability. E.g. experts have to evaluate if the flood control zone is still large enough to mitigate the expected flood event without increase reservoir discharge higher than exploitable by hydro-power. The knowledge about the level of uncertainty regarding sensitivity is focal for this decision.

The second example (red bold) starts with level of uncertainty due to ensemble ranges in short-term weather forecasts. Here procedural uncertainty arises concerning competence. By e.g. improving the understanding of the climate model output robustness due to integration of peer review the level of competence increases. Some experts stressed the importance of having local, good and personal contact to climate experts. The scope of action regarding the level of preventive - potentially harmful - reservoir relief is, hence, supported by the experts' judgement of model output robustness.

2.4.4 RESOURCES AND TRANSPARENCY

Reflection on uncertainty handling the experts often referred to lacking resources. For flood risk management they point out the importance of monitoring data for reducing uncertainties, however, a lack of financial and human resources do not allow maintaining a large net of gauging stations. Simultaneously existing measurement nets are under pressure due to cutbacks. From the interviewees' perspective, highlighting the locations of uncertainties provides a sound base when discussing with sponsors.

Being transparent how recommendations or decisions are concluded (e.g. choice of model) is one strategy of the experts to cope with uncertainties. However, the transparency pointed out by the experts only focusses on the fundamental causes of uncertainty and neglected the process uncertainty with which they dealt unwittingly or only implicitly.

Hence, the proposed structure adds transparency to the planning process by raising awareness of the many sources of process uncertainties, the interrelations and fields of action.

2.5 CONCLUSIONS AND OUTLOOK

Uncertainty matters for practitioners. They show high interest and engagement in this topic and regard uncertainty information as a complementary yet essential part in planning and decision-making. The interviewees have developed strategies to cope with and compensate uncertainties either indirectly by considering fundamental uncertainties (e.g. application of sensitivity analysis) or planning process uncertainties (e.g. increasing competence). To adequately consider the efforts and costs of assessing or reducing uncertainty and the potential impact of uncertainty with limited resources, most experts implicitly apply a - more or less unstructured – risk-based planning or decision-making approach.

In addition, as Faulkner et al. (2007) propose, there is a need for translation to overcome linguistic uncertainty. During the interviews it became apparent that experts dispose of differentiated knowledge about uncertainties, however, the terms used differed from scientific terms. Participatory processes acting as knowledge brokers between science and practice are a potential solution to bridge different perceptions and conceptions in order to cope with uncertainties in flood risk management (cf. Brugnach et al., 2007). Due to limited financial, human and time resources participatory processes are not always feasible. The proposed analytical framework provides a shortcut for transferring and exchanging uncertainty information. Furthermore, the framework can also be used to support and structure participatory processes.

The consistent integration of uncertainties in flood risk management is in need of structured and condensed information. Such a structured framework will positively influence the practitioners' anchors by providing sound uncertainty information and/or making missing information visible. Moreover, it can support the practitioners in assessing the risk and potential scope of action. The presented results validated the general applicability of the framework. Ongoing expert interviews and analysis will assess the user-driven information needs more comprehensively. Nevertheless, the proposed analytical framework already bridges the two perspectives of science and practice and can therefore provide an overview of neuralgic points of uncertainty during the risk-based decision-making process. It is assumed that this positively supports the choice of risk management strategies and decision.

3 PERCEPTION AND HANDLING OF UNCERTAINTIES IN WATER MANAGEMENT - A STUDY OF PRACTITIONERS' AND SCIENTISTS' PERSPECTIVES ON UNCERTAINTY IN THEIR DAILY DECISION-MAKING[4]

ABSTRACT

Uncertainties are central in any decision-making in water resource management. However, science and practice approach uncertainty handling and management in different ways. Science, for example, focuses on reducing uncertainties and / or places a good deal of emphasis on uncertainty quantification, while policy and practice apply risk-based decision approaches in order to cope with uncertainties throughout the entire management process. This study analyses how practitioners perceive and handle uncertainties in their daily decision-making routines at the knowledge/decision interface and how they evaluate and integrate uncertainty information into their decision-making. Expert interviews and questionnaires were used to examine and compare the practitioners' and scientists' perspectives on uncertainty management. Our results show that uncertainties matter for practitioners and that uncertainty information is regarded as highly relevant. However, scientists place more emphasis on uncertainties than practitioners. We further assert that there is a science-practice gap, where e.g. practitioners apply a bottom-up approach, thinking from potential measures upwards instead of impacts downwards. Scientists focus

[4] A version of this chapter has been published as: Höllermann, B., & Evers, M. (2017). Perception and handling of uncertainties in water management—A study of practitioners' and scientists' perspectives on uncertainty in their daily decision-making. Environmental Science & Policy, 71, 9-18. doi: http://dx.doi.org/10.1016/ j.envsci.2017.02.003

strongly on environmental uncertainties, while practitioners acknowledge and are guided by process uncertainties. Furthermore, rigid regulations in a predict-and-control manner hinder the implementation of flexible and adaptive management which acknowledge uncertainties. We also found that practitioners' belonging to type of employer and business unit influences their level of uncertainty recognition and, hence, both affects the size of the science-practice gap and causes tension among practitioners from different business units and employers. Beside this gap, we show that the level of work experience is a cross-cutting property of scientist and practitioners, where uncertainty awareness and handling increases with work experience. This insight provides a basis on which to build routines for uncertainty integration into planning and decision-making and to bridge the science-practice gap.

3.1 INTRODUCTION

Decision-makers are exposed to many forms of uncertainty when managing water resources. Firstly, they must handle fundamental uncertainties, which relate to the phenomenon itself (e.g., Brugnach et al., 2008; Walker et al., 2003). Secondly, they are exposed to process and planning uncertainties (e.g., Abbott, 2005; Maxim & van der Sluijs, 2011; Sigel et al., 2010), which are not often explicitly recognised by practitioners, yet strongly influence fundamental uncertainty handling (Höllermann & Evers, 2015a). For example, in the light of ensemble ranges in short-term weather forecasts (fundamental uncertainties) and, hence, uncertainty with regard to flooding potential, water managers have to decide on the impact of preventive reservoir release. This may also include their obligations and responsibilities towards stakeholders (process uncertainties) when balancing the costs of potential flooding against economic losses of e.g. reduced hydropower generation. While science focuses on reducing (Maxim & van der Sluijs, 2011) and emphasising uncertainties, and hereby at times obscuring information which is certain (Rosenberg, 2007), policy makers and practitioners apply risk-based decision approaches in order to cope with the inherent uncertainties throughout the management process (Willows et al., 2003). This is especially true when water managers must handle trade-offs such as managing reservoirs with two conflicting objectives. On the one hand, they have to serve a flood retention purpose but on the other hand they have to guarantee supply during the dry season/months. This gap between science and practice limits effective knowledge transfer (e.g., Gabbert et al., 2010; Hulme, 2014; Roux et al., 2006; Toomey, 2016; Vogel et al., 2007; Wardekker et al., 2008; Weichselgartner & Kasperson, 2010) due to the different assessment approaches: science-based versus practice/policy-based (e.g., Carter et al., 2007; Wilby & Dessai, 2010). For example, when faced with climate change projections with a large range of uncertainties, practitioners tend to focus on vulnerabilities due to flooding or drought and on interventions which will reduce this vulnerability (Höllermann & Evers, 2015b). It is important to integrate uncertainties into the process of risk assessment and problem understanding so as to be able to choose among alternatives (Funtowicz & Ravetz, 1993) and to assess the reliability of findings (Kinzig et al., 2003). In the course of risk judgement at the interface of understanding and deciding (Renn, 2008) the influence of uncertainties on the decision outcome is evaluated in relation to other decision-relevant factors (Aven, 2010). At this stage, uncertainties may delay or contradict decisions (e.g., Ballard & Lewandowsky, 2015; Kinzig et al., 2003; Rosenberg, 2007; Taylor et al., 2015) rather than contribute to high quality decisions. To overcome this challenge, it has been proposed that uncertainty should be reframed into risk (e.g., Corner et al., 2015; Painter, 2015; Pidgeon & Fischhoff, 2011). A structured presentation of all forms of uncertainties, such as the risk-based integration and analytical concept of Höllermann and Evers (2015a, 2015b) may support this step, foster communication and add transparency by serving as a broker in three ways: 1) structuring information, 2) framing uncertainty as risk and 3) negotiating the level of complexity in relation to management options. The concept draws hereby on the idea that uncertainty and risk are closely connected (see section 3.2) and that the identification of fundamental and procedural uncertainties help assess suitable risk management strategies, thus facilitating decision-making at the knowledge/decision interface. For example, risk perception regarding potential flooding may vary depending on the assessment of the current discharge situation, soil moisture preconditions and precipitation event. If soil moisture and/or general discharge are perceived as uncritical, water managers prefer not to implement flood prevention measures, even though the probability and the extent of precipitation are uncertain.

The scope of this paper is to identify how uncertainties are handled at the knowledge/decision interface described above. We further investigate how reframing may support the integration of uncertainty into water management decisions. In addition to profession (scientist or practitioner) we also explore other criteria which influence uncertainty handling and perception.

3.2 MATERIALS AND METHODS

Method triangulation was applied to explore the research question. This mixed methods approach includes qualitative and quantitative data derived from expert interviews and questionnaires. The questions guiding the interview and questionnaire were developed after reviewing key literature on uncertainty handling in order to substantiate and fill the information gap.

3.2.1 QUALITATIVE ANALYSIS – EXPERT INTERVIEWS

A semi-structured interview approach was chosen in order to focus on the experts' knowledge and to provide information about rules, paradigms, frameworks and logics of their planning and decision-making within their respective organisational or institutional settings (Mayer, 2012). Topics included definition, perception, evaluation and handling of uncertainty, knowledge transfer, role of uncertainties in planning and decision-making processes, risk management and biographical data. The selection of the experts followed an ex ante predefinition according to Meuser and Nagel (2009) using specific criteria and characteristics. An expert in this sense is somebody who is responsible for and takes control of problem solving or has privileged access to information about decision-making processes (Meuser & Nagel, 2009:470). However, to make more general conclusions about the population from which the sample is obtained, the ex ante predefinition takes properties of its parent population into account (Mayer, 2012). In this study, 20 experts from the water management field in Germany were interviewed, representing state agencies (6), district governments (4), water associations (9) and private water business (1). Thus, they represent four areas of work and foci in terms of their tasks and responsibilities. Their educational background is, in most cases, engineering (14); some also have further training in administration. They are engaged either in the strategic development of their business/administrative unit, in operative management, especially in flood forecasting and reservoir management, and/or in basic research. Hence, their involvement in planning and decision-making is either direct, or, by providing scientifically sound decision-making material, indirect. The topical focus of most interviewed experts is on surface water quantity management, with some experts paying special attention to climate change impacts and adaption. Some of them are particularly engaged in short- and medium-term flood forecasting and/or short- to long-term reservoir management. Only two interviewees are involved in groundwater monitoring. As a prerequisite for classification as an expert, the majority of interview partners (18) have more than 10 years of work experience, only two have less than 10 years, but are very close to 10 years' experience (more details Tab. 3.1). The interviews, each of about 60-90 minutes duration, were recorded and transcribed according to the standard for expert interviews (Mayer, 2012). They were analysed using QDA software (MaxQDa) and by applying a multi-step and recursive approach in order to sustain the validity of the analysis (Kuckartz, 2010). The code system evolved using the categories of the semi-structured interview questions and including topics and wordings raised by the experts. Where applicable, a concept specification was used to indicate to what extent the experts agreed or disagreed with an assumption or statement. The coding tree enabled us to analyse the experts‘ views on uncertainty from different perspectives. The aim of the analysis is to highlight the general or common opinions on a topic across all interviews or interview groups.

TABLE 3.1 SUMMARY OF INTERVIEW AND QUESTIONNAIRE PARTICIPANTS

		Expert interview				**Questionnaire**		
		State Agency	***District Government***	***Water Association***	***Private Business***	***Scientists***	***Practitioners***	***Scientist & Practitioner***
Work Experience	***< 10 years***	1	1	0	0	13	7	0
	> 10years	5	3	9	1	9	6	1
Educational Background	***Geosciences***	4	1	1	0	15	7	0
	Engineering	2	3	8	1	1	5	1
	Geosciences & Engineering	0	0	0	0	6	1	0
	Geo- & Social Sciences	0	0	0	0	0	1	0
Business Unit	***Strategy***	3	4	8	1	*no information*		
	Operations	1	0	7	0			
	Fundamentals	4	0	3	0			
Total participants		***6***	***4***	***9***	***1***	***22***	***13***	***1***

3.2.2 QUANTITATIVE ANALYSIS – QUESTIONNAIRE

While the expert interviews focused on the practitioners‘ perspective on uncertainty, the questionnaire addressed practitioners and scientists. The questionnaire covered the topics from the semi-structured interviews and focused on the relevance of uncertainty for the participants’ daily working environment and their uncertainty perception, handling and communication. Most of the questions asked the participants to agree or disagree on specific statements using a five point Likert scale. The setup also used item batteries to build indices about attitudes towards e.g. uncertainty communication. Statistical background data on education, job description, experience, etc. were prerequisites for forming groups regarding i.e. level of work experience, educational background, etc. After preliminary tests and adjustments, the questionnaire was distributed among conference participants at the German “Day of Hydrology” in Bonn in March 2015. This annual conference is hosted by different scientific institutions and invites the whole German-speaking water community from science and practice. Of 193 conference participants (students and exhibitors were excluded) 37 experts (22 scientists, 14 practitioners, 1 scientist & practitioner) filled out the questionnaire. The analysis of the questionnaire was supported by a statistical program (SPSS) for all numerical answers and by a QDA program (MaxQDa) for the open questions. The descriptive statistical analysis included a comparison of average, medians, modes, minimum, maximum and quantiles e.g. in the form of boxplots. Cross tables and relations of statements and indices were produced either for the whole group of participants or for sub-groups. With this relatively small number of samples the analysis does not claim to be comprehensive and representative for all scientists and practitioners in the water field; thus, only descriptive statistical analysis has been applied to gain an insight into the characteristics of the sample but not of the parent population. However, the results provide some valuable insights which complement and support the interview results.

3.3 RESULTS

We are especially interested in uncertainty handling during the assessment process, which involves the knowledge and understanding of a problem, and during the judgement process, which takes place at the interface of understanding and deciding. Hence, the presentation of the results follows a thematic structure: 1) general perception of uncertainty, 2) definition and sources of uncertainty, 3) handling of uncertainties during the assessment process, 4) integration of uncertainties in decision-making at the knowledge/decision interface, and 5) communication. The findings of both the qualitative and quantitative study are presented and compared with arguments and conclusions from the literature. Although the focus of our research is on the different perspectives of science and practice, we also look beyond professions and reflect the experience of a person and their educational background. In the case of the interviewed practitioners we also take the organisation and business unit in which the interviewee is employed into account (Tab. 3.1).

3.3.1 PERCEPTION OF UNCERTAINTY

The participants in the questionnaire assessed the relevance of uncertainties for their daily working environment to be quite high. The analysis shows that the scientists perceive uncertainties as more relevant than practitioners (Fig. 3.1a). However, the difference between these groups is less striking than between groups of different lengths of working experience (> 10 years and < 10 years). The results show that the more work experience a participant has, the more sensitive he or she is to uncertainties (Fig. 3.1b). The recognition of experience as a relevant factor is confirmed by the interviewed experts, who differentiate expert knowledge into expertise and experience, pointing out the importance of experience for e.g. understanding and evaluating model results (e.g. IPs 2.2, 3.2, 3.5, 3.7). In contrast, scholars focus on the challenges of knowledge transfer/implementation at the science – practice/policy interface or divide (e.g., Gabbert et al., 2010; Hulme, 2014; Roux et al., 2006; Toomey, 2016; Vogel et al., 2007; Wardekker et al., 2008; Weichselgartner & Kasperson, 2010) and do not refer to or take into account the needs or demands deriving from the different levels of experience. Consequently, we recognise that differences in both profession and experience affect perceptions of uncertainty.

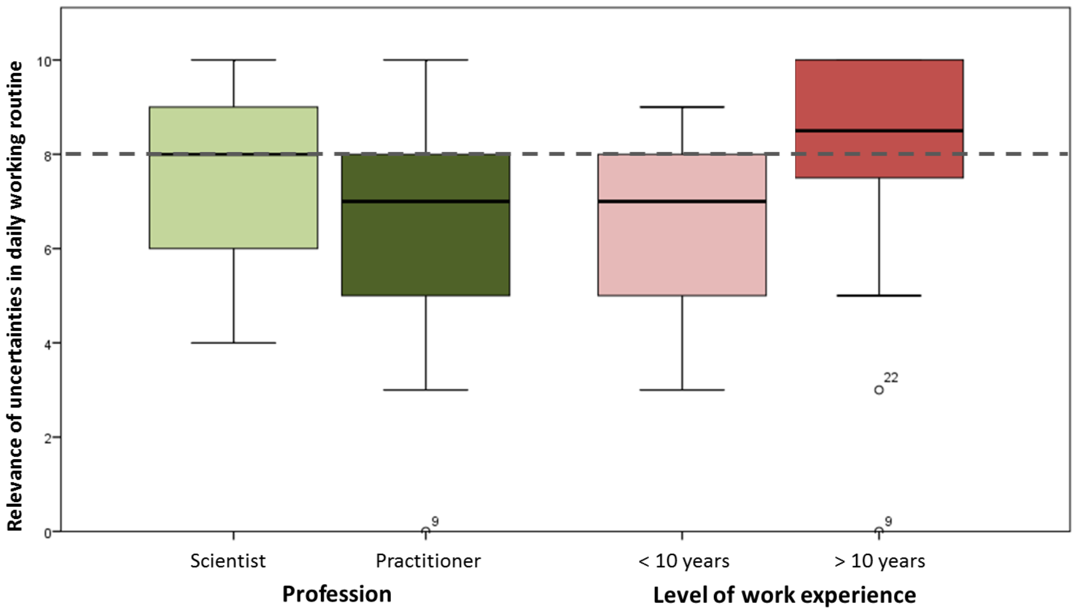

FIGURE 3.1 THE RELEVANCE OF UNCERTAINTIES FOR THE PARTICIPANTS IN THE QUESTIONNAIRE BY THE SUB-GROUPS A) PROFESSION AND B) YEARS OF WORK EXPERIENCE. THE DASHED LINE PRESENTS THE MEDIAN OF THE TOTAL GROUP

3.3.2 DEFINITION AND SOURCES OF UNCERTAINTIES

With respect to climate change communication of scientific incertitude, scholars (e.g., Corner et al., 2015; Painter, 2015; Pidgeon & Fischhoff, 2011) stress the importance of shifting from uncertainty to risk framing to serve decision-making. In our understanding, risk and uncertainty are closely connected. We use the definition of the EU floods directive 2007/60/EC to define risk as a product of the probability of occurrence of an event and its consequences. We follow Stirling (2010) in his argument that risk is a state of high knowledge regarding probabilities and possibilities, where risk assessors possess sufficient and approved management strategies to cope with the risk, e.g. cost-benefit analysis. Due to unpredictable future boundary conditions e.g. hydrological change or social development the assessment of probability and consequences is limited and, hence, uncertain (Höllermann & Evers, 2015b; Willows et al., 2003). We believe that by highlighting this link, the integration of uncertainty information into planning and decision-making processes can be more effective e.g. by choosing appropriate management strategies which acknowledge uncertainties. For this reason, we studied how our study participants defined risk and uncertainty.

While the majority of experts clearly distinguish between uncertainty and risk, few of them use exclusively the term risk or hazard. They either fail to account for uncertainty or they use the term ‘risk’ to imply uncertainty. Many use ‘classical’ risk definitions such as ‘probability of occurrence * vulnerability’, ‘*event’ or ‘*damage’, with the experts from the water associations placing particular emphasis on ‘probability of occurrence * damage’. Additionally, the experts connect risk to consequences. Decisions and actions follow consequences and the evaluation of these consequences determines the risk attitude, e.g. risk averse. The results of the questionnaire support this finding, as the majority of the participants (70%) use a classic risk definition. This is especially true for the group of scientists (79%, compared to 57% of the group of practitioners). The group of practitioners further emphasize trade-offs and consequences as a definition of risk. Furthermore, the more experienced participants focus strongly on the ‘classical’ risk definition which is concerned with the consequence e.g. damage or vulnerability rather than ‘simple’ event probability.

While there is more or less cohesion with respect to the risk definition, the picture concerning uncertainty definition is more diverse. Imprecision or inaccuracy account for

57% of the scientists' and 41% of the practitioners' definitions; however, the practitioners are less concrete about the nature of imprecision than the scientists, who emphasise e.g. model input. Furthermore, the more experienced participants also account for the ‘unknown unknowns’ which result in either shock or surprise and they highlight the importance of looking at consequences and trade-offs. This experience is shared by the interviewed experts. The last finding in particular supports the view that by offering constructive discourse, reframing can be more effective in integrating uncertainties into decisions (Painter, 2015), thus allowing evaluation of options (Pidgeon & Fischhoff, 2011) and reflecting the current practice among water managers and more experienced scientists and practitioners.

During the last decade multiple frameworks and typologies have been developed to characterise and identify level, sources and nature of uncertainty (e.g., Brugnach et al., 2008; Refsgaard et al., 2007; Walker et al., 2003). The focus of characterisation is laid on fundamental or environmental uncertainties. These are uncertainties which are related to the variability of and the current state of knowledge on the phenomenon. However, others (Abbott, 2005; Maxim & van der Sluijs, 2011; Sigel et al., 2010) add and highlight uncertainties caused by planning, so-called process or procedural uncertainties, as another important nature or cause of uncertainty in decision-making. In a previous study on flood risk management (Höllermann & Evers, 2015b) we showed that fundamental and process uncertainties are interrelated and affect each other. For example, the assessment of reservoir sensitivity (fundamental uncertainty) during a flood situation decides risk perception and hence the degree of acknowledgement of the strategic responsibility for stakeholders and economic viability (process uncertainty). We found that our study participants are more aware of fundamental uncertainties, and only two of the interviewees described process uncertainties when defining uncertainty. However, during the interview 14 of the experts implicitly point out uncertainties related to planning and decision-making processes: 1) evaluation and interpretation of information may vary according to the person in charge or the interests involved, especially of qualitative data, 2) competence of employees and human behaviour is closely related to understanding, and 3) the broad scope of action in political guidelines may force other uncertainties, even though these guidelines provide a framework for orientation. The survey shows a striking difference among sub-groups, when assessing the uncertainty relevance of norms (social and legal). 71% of practitioners but only 23% of scientists assess norms as relevant;

similarly, 63% of practitioners and 27% of scientists view regulations as having uncertainty relevance. The same picture holds true regarding the differences in experience, where the more experienced researchers and practitioners place a stronger emphasis on process uncertainties (Fig. 3.2).

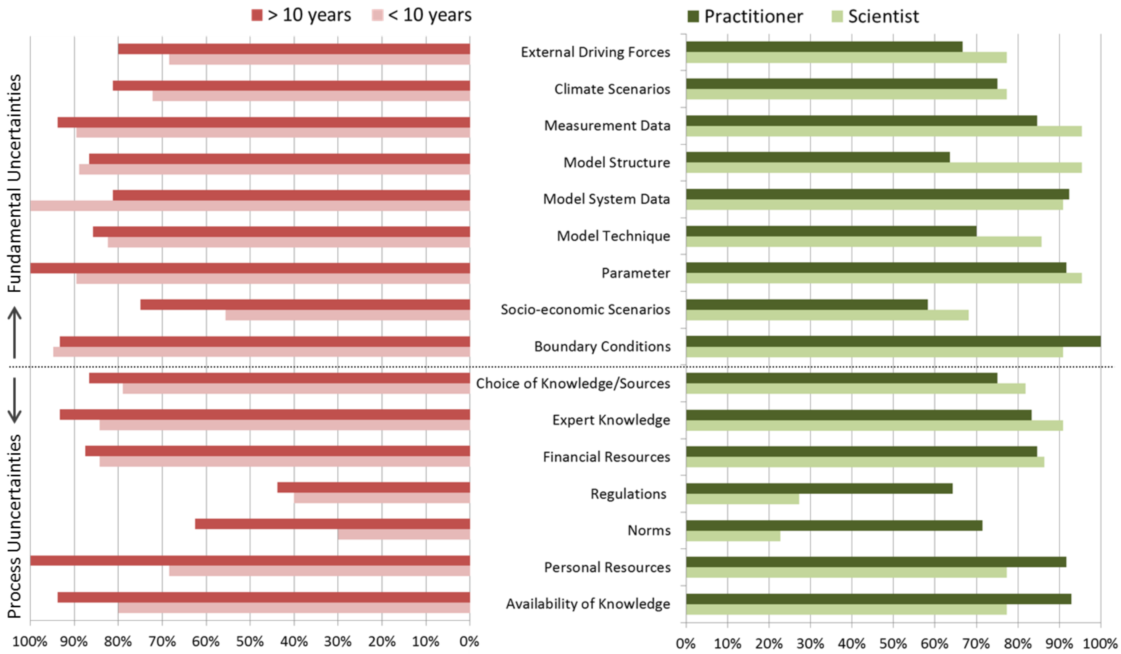

FIGURE 3.2 ASSESSMENT OF RELEVANCE OF UNCERTAINTY SOURCES FOR DAILY WORKING ENVIRONMENT COMPARING THE SUB-GROUPS LEVEL OF WORK EXPERIENCE AND PROFESSION

3.3.3 HANDLING OF UNCERTAINTIES DURING ASSESSMENT - THE PROCESS OF UNDERSTANDING

In general, the interviewed practitioners describe two approaches to handling uncertainty within their working environment. Firstly, they make use of specific tools to estimate fundamental uncertainties. Secondly, they adapt specific behaviour beyond these tools and approaches in order to acknowledge the inherent uncertainties.

The experts make use of e.g. uncertainty bounds, sensitivities, scenarios, and vulnerability analysis to handle uncertainties. Even though uncertainty bounds are widely used, the usability is regarded as rather poor by many of the experts, especially regarding climate change projections, as it is difficult to derive decisions. Wilby and Dessai (2010) confirm that uncertainty bounds, common in impact analysis, tend to provide an impracticable range of potential measures. Additionally, the effort involved in obtaining this information is regarded as too high compared to the usability of the outcome. Hence, from the experts' perspective the usage of sensitivities together with scenarios is regarded as more effective and practicable for an understanding of models and critical parameters. Furthermore, no-regret measures can be deduced from sensitivities.

The integration of uncertainty information is a key criterion when choosing among alternatives (Funtowicz & Ravetz, 1993) and helps evaluate the reliability (Kinzig et al., 2003) and the limits of findings (Pappenberger & Beven, 2006). Willows et al. (2003) assert that practitioners developed a risk-based approach to recognise, acknowledge and handle uncertainty during planning. In our study, the experts developed distinct behaviour to acknowledge and handle uncertainties underlying the risk approach. They regard uncertainty information as important for assessing the risks or consequences of their decisions, hereby strongly relating uncertainty, risk and risk perception. Most of the interviewed experts apply a more implicit and/or less structured risk-based planning or decision-making approach (see also Höllermann & Evers, 2015b). For example, the experts highlight the importance of transparency throughout the working steps in the form of documenting key decision pathways, stipulations, and different forms of presentation, even though the implementation of this transparency is partly in its infancy and more wishful thinking than reality. Frequent consultation of experts within the relevant field of expertise (e.g. staff from universities or engineering offices with specific knowledge and new ideas) and sharing of experiences (e.g. involving stakeholders with regard to local conditions) helps evaluate the impact of uncertainties. Expert opinions are valued particularly by the more experienced questionnaire participants. This group is also the most active group in handling uncertainties when looking at the index for uncertainty handling, with 75% of this group being above the median of the less experienced.

Pappenberger and Beven (2006) point out seven reasons why parts of the water resources research community still do not honour uncertainty analysis, e.g. they feel it is not necessary, cannot be understood by policy makers and public, is too difficult to integrate into decision-making, is too difficult to perform, etc. Pappenberger and Beven (2006) conclude that these reasons are not valid arguments for avoiding uncertainty analysis. In general, the participants in our survey agree with Pappenberger and Bevens' (2006) conclusion. However, a closer look at individual answers reveals that participants tend to see that uncertainty analysis cannot be understood by decision-makers and the public. This is especially true for the practitioners, the majority of whom (about 62%) agree with this statement, with only 8% disagreeing (Fig. 3.3). While the majority of scientists (68%)

reject the statement that uncertainty analysis cannot be integrated into decision-making processes, the practitioners are two-minded in their replies, with 43% disagreeing and 36% agreeing. The same applies to the more experienced participants, with 73% rejecting this hypothesis; of the less experienced 33% agree and 44% disagree. In contrast, there is agreement in both groups that uncertainty analysis is relevant for the quality of decisions and increases trust in the robustness of the decision basis. In conclusion, information on uncertainty analysis is regarded as valuable. It is not clear, however, how this is best integrated into the decision-making process as handling and communication routines may be lacking.

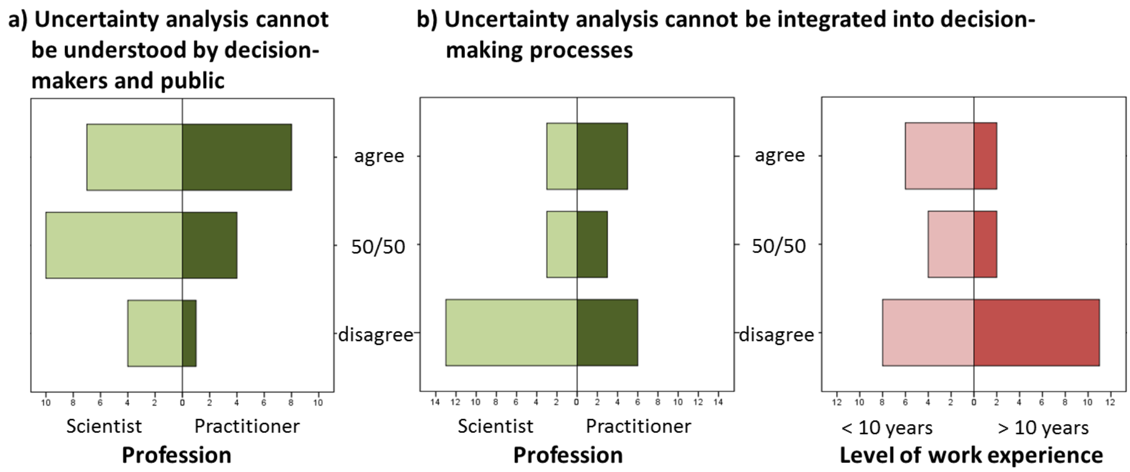

FIGURE 3.3 A) ASSESSMENT OF WHETHER DECISION-MAKERS AND THE PUBLIC ARE ABLE TO UNDERSTAND UNCERTAINTY ANALYSIS, AND B) ASSESSMENT OF WHETHER UNCERTAINTY ANALYSIS CAN BE INTEGRATED INTO PLANNING AND DECISION-MAKING PROCESSES

3.3.4 INTEGRATION OF UNCERTAINTIES IN DECISION-MAKING AT THE INTERFACE OF UNDERSTANDING AND DECIDING

Scholars have stated that uncertainties may delay decisions and may be used tactically (Kinzig et al., 2003) and that the political will to take action on specific environmental issues may be jeopardized by stressing information regarding uncertainties (Ballard & Lewandowsky, 2015; Rosenberg, 2007) and, hence, decision-makers are more inclined to disregard this information (Taylor et al., 2015). However, depending on the business focus of the practitioners, our results show that the value of uncertainties and the consequences regarding their acknowledgement is experienced differently. Here, the experts with more strategic focus confirm a delay or tactical misuse because of political or personal power and interests. For example, as one interviewee states (IP2.1):

> *"Yes, of course, not in our unit. But I know that 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."*

However, the experts, especially those with a business focus on evidence-based information provision, also take into account that the delay may be caused by improving the decision-making basis, which takes time. Practitioners working in operative business experience no delay as they are under pressure with their decisions, e.g. in the case of flooding they have to decide about adjusting discharge levels from reservoirs or on the possible implementation of further precautions such as evacuations.

The varied reactions to the above hypotheses of delay and tactics show that decision-making is a highly complex process where the evidence-based knowledge and information enters an arena of power relations, budget restrictions and social values (Larson et al., 2015). This complexity is reflected by the interviewees' answers and comments on decision-making. In sum, they highlight three pillars for decision-making: 1) decision-making fundamentals, 2) decision-making support, and 3) decision-making criteria. The decision-making fundamentals (1) include evaluation of scenarios and alternatives to narrow down and understand the sensitivity of the system. Depending on the information basis, the integration of other expert knowledge is common in order to ground the decision on a broader basis. Every decision requires a transparent information basis which points out neuralgic points and the underlying uncertainties. Decision support (2) through group discussions increases the transparency and acceptance of the decision and decreases the risk of overlooking something as the problem is viewed from more perspectives. Additionally, cooperation and participation with stakeholders increases the acceptability of decisions. Being active in networks increases the information basis and opportunities to learn from each other. Some people in the network also have a function as translator or broker who is able to translate or interpret relevant specialist knowledge. With this background the experts have to acknowledge specific decision-making criteria (3). Their thinking is guided by looking at the consequences and risks of their decisions as they feel responsible for their actions towards the stakeholders and public/society. They also feel responsible for delivering cost-efficient decisions and choosing a suitable degree of method complexity in relation to data availability and quality. An evaluation of the boundary conditions helps to estimate the consequences and is more important to the experts than the underlying uncertainties. In general, the experts' resources are limited and they must account for proportionality and economic efficiency, work with the tools available, reduce the spectrum of scenarios with which they work, and develop trust in decision-making material produced by others. This is the case for all experts, who describe that they are confident and have trust in the expertise of others.

Due to the practitioners’ attention to economic efficiency, acceptance of political decisions and legal affairs, experts with a focus on operation and strategy experience a need for specific results and clear numbers rather than an uncertainty bound, as clear and legally safe decisions are required to take further action. Taylor et al. (2015) found out and confirmed that organisations favour information supporting yes/no decisions. The interviewed practitioners, for example, see that there is a need for a design flood to know how high the dam should be built (e.g. IP 1.1). Or, there is a need for a critical threshold to inform or involve disaster management (e.g. IP 3.1.). However, this need is not only guided by the business focus, but also by educational background. For example, the interviewees themselves feel that geoscientists and engineers have different approaches to the uncertainty subject. One expert (IP1.3) states:

> *“As geoscientists we are predestined to work with such things [uncertainty]. An engineer is not capable of doing this (…), he wants it precise to two decimals, I can calculate that, but it is calculated, it is just a number, and in the end he [the engineer] takes twice as much. It [the result] is not much of a difference, but he started calculating precisely.”*

The statement of an engineer (IP3.7) supports this perception:

> *“That is biology, which cannot easily be expressed in rules and numbers. There is more expert knowledge coming into play. From an engineer's perspective this is always dubious.”*

On the other hand, he highlights the conflict or problem that:

> *“we (engineers) are forced to claim accuracy and that we pretend to have a high degree of accuracy that we do not really possess.”*

He also states that engineers are aware of these uncertainties but the legal framework forces them to present precise numbers for e.g. the delineation of flooding area according to the floods directive.

In conclusion, the interviewed experts are aware of the fact that their decision-making and planning is subject to uncertainty. They also see the need to integrate more prominent uncertainties into their decisions or plans even though they are challenged by reducing the uncertainty bound to one number for the final decision.

3.3.5 COMMUNICATION

Communication is a key requirement for sharing and co-producing knowledge (IRGC, 2008). Since uncertainty is part of the knowledge (Blöschl & Montanari, 2010) it should be integrated into the communication processes during assessment and decision-making. The participants in the questionnaire are active communicators of uncertainty with no difference between practitioners and scientists. However, communication activity increases with work experience. There is also a positive correlation between the relevance estimation of uncertainty and participants’ work experience. Additionally, actors who regard uncertainties as more relevant, also communicate more.

The interviewed experts differentiate between communication under uncertainty during the assessment and communication of uncertainty in the decision-making process. The interview partners who mainly work for water agencies found that a sufficient communication process was lacking, especially about the limits of accuracy. In most cases, especially for interviewees working at a strategic level, uncertainty stays with the expert and is often not discussed or explicitly documented. Yet, informal and unstructured oral communication exists. However, Mauelshagen et al. (2014) argue that lateral knowledge transfer is prone to loss of information, affecting the quality of a decision when the transfer is informal and unstructured. On the other hand, the explicit communication of uncertainties is challenging for the interviewed decision-makers as they have to consider responsibility, target group, mode of presentation, and language when communicating uncertainty. Being responsible means two important things for them. Firstly, the consequences of this communication have to be considered: it should neither raise uncertainty in society nor negatively affect people’s savings by e.g. having an effect on the retail price of their houses. Secondly, residual risks have to be communicated in order to enable self-preparedness and pass responsibility. Additionally, being sensitive about the target group means that the interviewees must decide on the most effective mode of presentation.

> *“We have the problem that the annual precipitation amount does not change, but we have intra-annual changes increasing evapotranspiration and reducing discharge into the reservoir. Our board refers to the annual amount and questions the low reservoir level. Hence, the mode of presentation of operating numbers influences the decision-making process and its uncertainty.” (IP 3.1, paraphrased).*

In the end, the experts point out, they have to be convincing with their recommendations and conclude, as Rosenberg (2007: 989) puts in his lesson learnt, that one should “not hide careful analyses of uncertainty, but (…) distinguish the almost certain from the less certain”. Language is another important factor. For example, the distinction of fundamental uncertainties into aleatory, describing the variability of the system, or epistemic, referring to the limited knowledge about the system, is discussed controversially in academia, e.g. while Faulkner et al. (2007:702, note 30) summarize these uncertainties as “risk assessment has been stalled by the different treatment”, Merz (2006) points out the value of this distinction in order to conclude management decisions. On the one hand, Faulkner et al. (2007) are right as none of the interviewed experts were familiar with these terms, and the experts from the district government largely denied the value of this differentiation for their daily work, describing it as too academic. On the other hand, the experts from the water associations and from the state agencies appreciated this information. Some of them already implicitly distinguish these two sources, and two of the experts clearly see an advantage in this differentiation in order to have more arguments to obtain resources, e.g. to reduce uncertainties, and to increase their scope of action.

Kasperson (2010) describes the non-linear linkage of knowledge production between science and practice as a ‘spiderweb’, with multiple actors, dynamic linkages and more or less stable architectures. Our analysis of practitioners’ communication strategies adds another layer to the ‘spiderweb’ as, in addition to the actors’ professions, experience, educational background, employer and business focus govern the direction and intensity of feedbacks and linkages.

3.4 DISCUSSION

Apart from the sciences-practice-gap multiple aspects contest the transfer of knowledge and uncertainty perception and handling. These include business unit, educational background, type of employer, and level of experience (see chapter 3.2). How these factors influence uncertainty recognition, communication and handling is discussed in the following.

3.4.1 SCIENCE-BASED VERSUS PRACTICE/POLICY-BASED APPROACH

The diverse tasks, responsibilities and demands the interviewed planners or decision-makers have to manage only partly overlap with the scientists' approach. A science-based approach is more prone to an inflation of uncertainties compared to a practice- or policy-based approach. The latter 'reduces' the climate scenario-based uncertainties by looking at adaptation measures first and assessing them against scenarios, while the science-based approach evaluates a broad range of climate changes and impacts first, making adaptation responses unfeasible (Carter et al., 2007; Wilby & Dessai, 2010). Our study confirms this mismatch. The practitioners find implementing adaptation measures for climate change scenarios cost-inefficient as the range of climate projections is too broad. Yet, thinking in extremes, sensitivities and vulnerabilities in order to derive no-regret measures is common among the experts and assessed as more effective than climate change projections. The same is true for flood protection measures where practitioners apply vulnerability analysis to confine response strategies and options. Hence, uncertainty routines must take into account these differing approaches and serve as a broker between scientific complexity (Stirling, 2010), practical feasibility and cost-effectiveness.

3.4.2 PARADIGM SHIFT IN WATER MANAGEMENT

The paradigm change from a 'predict and control' approach in water resource management to an 'adaptive management' with learning and flexible management strategies as key factors (Larson et al., 2015) is challenging for the interviewees. In contrast to Petr et al. (2014) we found that the level of management and type of employer do influence acknowledgement and handling of uncertainties. Experts in strategic positions in state agencies and water associations who work with uncertainty bounds are aware of the inaccuracy of their results and want to take into account adaptive management strategies. They must, however, present specific numbers and not ranges to regulatory authorities when asking for permissions.

> *"An administration wants to know the threshold where changes in operation occur. If I say between 50 and 60, then there is no fixed date and I am the one who is in charge to decide. That does not work. If there is flexibility, the regulatory authority has less power but is still responsible. I understand this problem but it makes handling uncertainties difficult" (IP 3.1, paraphrased).*

This tension is not easily released, as rigid regulations prevent a flexible approach.

3.4.3 RISK AND UNCERTAINTY FRAMING

Practitioners define risk and uncertainty mostly through consequences and trade-offs, hereby implicitly using a risk frame. Within this frame and their focus on consequences and vulnerabilities they are able to integrate their process uncertainties into decision-making and compensate for fundamental uncertainties. In order to support this, scientists should think outside the box (Kinzig, 2003) and place more emphasis on what is known than on what is not known (Rosenberg, 2007). Ballard and Lewandowsky (2015) find that the will to adapt is conditional on time- and outcome-uncertainty. While the latter reduces the will, the former is perceived as more urgently requiring measures to be taken. Hence, approaches should focus on the 'when' rather than the 'if', thus leading to a change from uncertainty to risk framing (Corner et al., 2015; Painter, 2015; Pidgeon & Fischhoff, 2011). This reframing effectively supports science-practice communication and facilitates decision-making by preventing delay of decisions or tactical misuse in face of uncertainties (see section 3.4) because the actors have to decide about the 'when' which includes implicitly the acknowledgement of uncertainties by using scenario, vulnerability and sensitivity analysis. Additionally, as uncertainty recognition is more common among employees of water associations than among employees of the district government, reframing is also effective for communication and negotiations between these different groups of practitioners.

3.4.4 EXPERTISE AND EXPERIENCE

The difference in level of experience regarding uncertainty handling is striking and often overweighs the difference in profession (Fig. 3.4a). This cross-cutting property among science and practice actors is rarely acknowledged. While Klinke and Renn (2014) highlight the value of combining scientific and experiential substance in order to integrate expertise and experience for deliberative risk governance, they assign expertise to the experts and experience to stakeholders and public. Our results, however, show that experience is a key property for both scientists and practitioners and influences uncertainty recognition and handling. The experience gained over the years has significantly shaped their uncertainty perception.

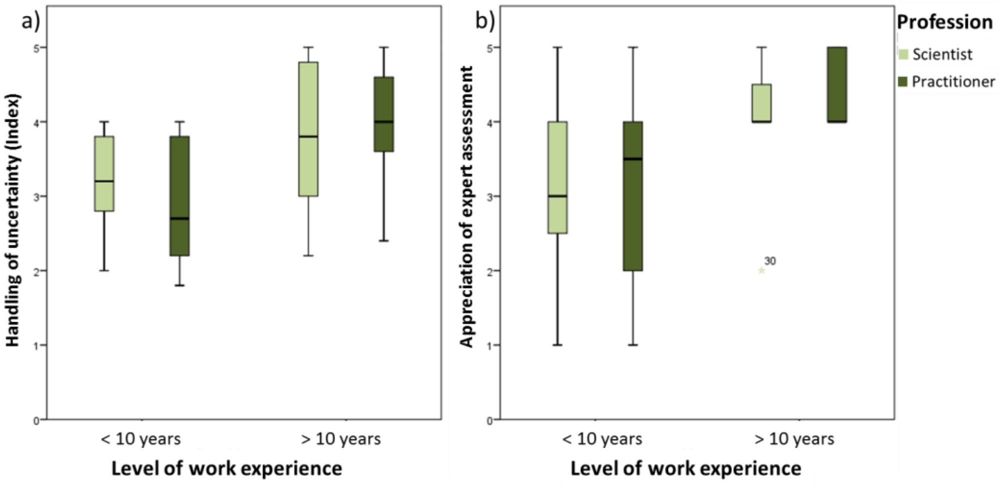

FIGURE 3.4 A) ACTIVITY LEVEL OF UNCERTAINTY HANDLING, AND B) EVALUATION OF EXPERT KNOWLEDGE IS MORE INFLUENCED BY LEVEL OF EXPERIENCE THAN PROFESSION

Interestingly, more experienced practitioners and scientists place more value on expert assessment than the less experienced (Fig. 3.4b). As our interviewees clearly differentiate expert knowledge into expertise and experience, we are confident in assuming that experience is a cross-cutting property able to bridge the science-practice gulf or build a stronger link in Kasperson's (2010) 'spiderweb'.

3.5 CONCLUSION

This research has demonstrated that uncertainties matter for practitioners who regard uncertainty information as a complementary yet essential element of their planning and decision-making. However, the level of recognition and the integration of these uncertainties into the planning and decision-making process varies. The reasons for this are the different perceptions and strategies for handling uncertainty due to group membership regarding type of employer and business unit and - as a cross-cutting property - educational background and level of experience. This insight has some implications for a) the science-practice/policy interface, b) decision-making and c) the water sector in particular.

a) At the science-practice/policy interface it is important to note that practitioners are aware of uncertainties and demand uncertainty information. However, it remains a challenge to them to integrate this information thoroughly into the decision-making process. Being transparent about the way decisions are based on knowledge and assumptions is one key strategy with which to handle and to acknowledge uncertainties.
   A major gap between science and practice/policy is that both approach uncertainty from different viewpoints. While science focuses more on the propagation of uncertainties from climate projections down to impact studies, practice applies a more bottom-up approach in order to keep the involved uncertainties manageable. This implies that - at the science-practice/policy interface - translation is needed and that more experienced researchers and practitioners may play a vital role here. In addition, the importance of process uncertainties for the practice/policy side should be more clearly acknowledged by science.
b) Regarding decision making under uncertainty, the key findings are that both reframing and experience matter. It became clear that practitioners see a close connection between uncertainty and risk and risk perception. Hence, risk framing was shown to be implicitly applied and accepted by a wide range of practitioners. We therefore regard reframing uncertainty into risk as a key routine with which to integrate uncertainties into planning and decision-making, thus preventing the use of uncertainties as a reason for inactivity and delays. The level of experience shapes practitioners' perception and handling of uncertainty and experts become more active in handling and communicating uncertainties with increasing experience. They find routines with which to integrate uncertainties into their planning and decision-making. This implies that tacit knowledge should be made explicit by using e.g. structured communication as proposed by Mauelshagen et al. (2014) with the support of a risk register or, as suggested by Höllermann and Evers (2015b), with the support of the risk-based analytical and integration framework.

c) For the water sector, results showed that the assessment of vulnerability to floods and low flows as well as the sensitivity of the system regarding current boundary conditions (reservoir levels, soil moisture conditions, hydro-power demands, etc.) is central for water managers to be able to deal with inherent uncertainties. When deciding about environmental uncertainties, corresponding process uncertainties such as responsibility for different stakeholder needs shape the final decision and planning process. There is a tension within the practice/policy side where adaptive approaches are stalled in the face of rigid regulations and the command and control paradigm. Here, practitioners from water associations in particular could apply reframing in order to convince policy-makers and promote a more flexible approach.

The findings of this study are based on expert elicitation focusing on participants mainly concerned with water quantity management. However, more general conclusions regarding the science-practice/policy interface and decision-making under uncertainty could be derived and are transferrable to other applications in water management with slight modifications to the focus on environmental uncertainties.

The scope of this paper was to identify how uncertainties are handled at the knowledge/decision interface. Our insights provide a basis for determining routines with which to integrate uncertainty into planning and decision-making and to bridge the science-practice gap. How these routines can be used by less experienced experts and how they influence the quality of decisions is worthy of further research.

4 DECISION-MAKING UNDER UNCERTAINTY: ACKNOWLEDGING PLURALITY OF WATER MANAGERS' UNCERTAINTY HANDLING ROUTINES THROUGH QUALITATIVE SYSTEM ANALYSIS[5]

ABSTRACT

Accelerated environmental and societal change and its dynamic present a challenge for water management. Hence, the relevance of integration of uncertainties into the decision-making process increases. Science informing practice is challenged by making their useful uncertainty information usable for practitioners. We know, that practitioners have developed routines in order to cope with the uncertainties, but to serve transfer of uncertainty information, this study analyses by whom, when and where in the decision-making process uncertainty routines are used. This research contributes to the plurality of practitioners' perspectives on decision-making under uncertainty in water management. Based on expert elicitation we show that depending on the business level unit affiliation and depending on the time horizon of the management object practitioners are using different uncertainty routines and hence are in need of more tailor-made uncertainty information to inform their decision-making. Our qualitative systems modelling approach highlighting a reservoir management example serves as a boundary object visualizing intersection of uncertainty routines and fostering cross-communication and

[5] A version of this chapter is currently under review in Water Resources Research as: Höllermann, B., & Evers, M. (2017). Decision-making under uncertainty: Acknowledging plurality of water managers' uncertainty handling routines through qualitative system analysis.

acknowledgement of different perspectives among practitioners. It, thus, provides a platform for learning. Moreover it provides a clear understanding of uncertainty information needs which scientist may cover and increase the usability of their research findings and closing the science-practice gap with implications for adaptive management and transformation processes.

4.1 INTRODUCTION

Growing environmental and societal change impact water resources and present a major challenge to water resource management with increasing uncertainties (Milly et al., 2008). Already in the 1990ies Funtowicz and Ravetz (1993) point out the importance of addressing system uncertainties in combination with decision stakes in order to reflect the underlying complexity. Due to this complexity Harremoës (2003) argues that uncertainty becomes a major role in political decision-making. Neglecting information on complexity and uncertainty will lead to misinformed decision-making (Stirling, 2010; Winkler, 2016; Zandvoort et al., 2017). Even though uncertainty information and integration into water management are assessed as important by practitioners (Höllermann & Evers, 2017), establishing best practice for decisions and assistance in uncertainty management remains a key difficulty (Bond et al., 2015; Leung et al., 2015).

The usability gap (Lemos et al., 2012), for example, addresses the difficulty that useful information provided by science are often found not usable by practitioners. The usability of information depends on three factors: fit, interplay and interaction. Where fit refers to the user's perception of how the information fits their need, interplay describes how new information interrelate with current knowledge, and interaction evaluates the quality of exchange between producer and user of information. However, knowledge includes not only formal or systematic knowledge, but also tacit knowledge (Ingram, 2013), which organizes new information around specific ideas and contexts (Fazey et al., 2005; Weichselgartner & Pigeon, 2015). It also remains unclear to what extent available information is made use of (Nearing et al., 2016). Hence, a plurality of ways of knowing and understanding exists among practitioners (Zandvoort et al., 2017). Given the usability gap (Lemos et al., 2012), a demand-oriented presentation and evaluation of uncertainty by scientists requires an improved understanding of how differently practitioners might perceive, interpret and react to uncertainty (Briley et al., 2015; Kundzewicz et al., 2018;

Westerberg et al., 2017). Warmink et al. (2017) therefore propose that social learning can be regarded as an enabler to better cope with uncertainties in water management as social learning is situated within a wider community of practice and cherishes from the interaction of learners, hereby gaining knowledge beyond the actors' individual backgrounds (Reed et al., 2010).

Given the complexity of water systems under change, the importance of uncertainty acknowledgement, the plurality of perspectives on water management and the important role of (social) learning and communication to support water-related decision-making under uncertainty our research proposes two contributions to this field of research. First, it presents a theoretical construct explaining the differences among the practitioners and their interrelations by highlighting differences across practitioners' uncertainty handling strategies. Hereby, we identify six uncertainty routines and can differentiate who prefers specific routines, when these routines come into play and where in the decision-making process the different strategies intersect. Second, our findings propose a practical strategy to increase the visibility of the plurality of approaches regarding perception and handling of uncertainties within a decision-making context. With this we show how a deeper understanding of plurality of practitioners' uncertainty management facilitates and promotes social learning with positive implications for adaptive water management.

4.2 MATERIALS AND METHODS

4.2.1 DEDUCTION OF UNCERTAINTY ROUTINES

Uncertainty and uncertainty information do matter for practitioners and they actively develop strategies to cope with uncertainty in decision-making (Höllermann & Evers, 2017). Based on our previous study (Höllermann & Evers, 2017) we deduced and condensed six uncertainty routines which reflect practitioners' strategies to integrate uncertainty or uncertainty information into their planning and decisions: vulnerability (V), responsibility R), transparency (T), framing (F), process uncertainties (PU) and tacit knowledge (TK) (Tab. 4.1). When facing uncertainty, practitioners look at the **vulnerability** and, hence, at the consequences of their decision affecting the current system rather than on analyzing climate ensembles and their uncertainties. Even though uncertainty and complexity are also endemic to vulnerability assessment (Winkler, 2016), it nevertheless fosters a more dynamic and adapted management approach indirectly integrating a broad array of uncertainties. Making decisions is closely related to taking **responsibility**, however, when evidence-based knowledge enters the arena of power relations, restrictions and values the question is who and to what extent somebody or some entity has to take or pass responsibility. And if responsibility is to be passed, it has to be so with all the involved uncertainties, in the sense of co-responsibility (Warmink et al., 2017). Co-sharing of uncertainties for example means as Merz et al. (2015) suggest to indicate flood-protected areas in flood maps as “not inundated unless the flood defense fails” (Merz et al., 2015: 6414). Accountability, legally or morally, is part of the practitioners’ responsibility to adequately address uncertainty in taking actions (see also Zandvoort et al., 2017) and enable other stakeholders to take co-responsibility. **Transparency** is the most obvious uncertainty routine which acknowledges uncertainties by making e.g. the limits of knowledge, the assumptions or way of procedures explicit and formalized. A more implicit uncertainty acknowledgement is the **framing** or reframing of uncertainty into risk by using narratives, bottom- up and risk-based approaches (see also Ballard & Lewandowsky, 2015) which raises different sets of uncertainties (Patt & Weber, 2014).

TABLE 4.1 UNCERTAINTY ROUTINES (SHORT DESCRIPTION)

Uncertainty routines		Description
Vulnerability	**(V)**	Vulnerability as an uncertainty routine rather focusses on assessing the degree of vulnerability and hence the consequences of a potential change/impact than on assessing e.g. the impact of a broad range of ensemble projections regarding potential flooding areas. Looking at vulnerability may therefore foster a more dynamic and adapted management approach.
Responsibility	**(R)**	Responsibility as an uncertainty routine scrutinizes the question of who is responsible and for what. Responsibility with all involved uncertainties can be taken or passed. The question of responsibility especially arises when evidence-based knowledge enters the arena of power relations, restrictions and values.
Transparency	**(T)**	Transparency as an uncertainty routine tries to integrate the knowledge about uncertainties by explicit presentation of assumptions, lack of knowledge, or the way of procedures, etc. A formalized communication is pivotal for transparency.
Framing	**(F)**	Framing as an uncertainty routine translates uncertainty into risk by using narratives, bottom-up and risk-based approaches to acknowledge uncertainties more implicitly.
Process Uncertainties	**(PU)**	Process uncertainties as uncertainty routines describe uncertainties which arise from the planning and decision-making process, e.g. political boundary conditions, availability of resources, social norms, etc. PU are interrelated and affect environmental or fundamental uncertainties and hence govern practitioners’ recognition and handling of fundamental uncertainties.
Tacit Knowledge	**(TK)**	Tacit knowledge as an uncertainty routine describes the implicit knowledge of work experience and its value in evaluating uncertainties and their potential impact. Hence, TK helps supporting judgments and may also guide risk perception.

Uncertainties deriving from **process uncertainties** need special attention as they govern the practitioners' recognition and handling of fundamental uncertainties. **Tacit knowledge** derived from high level of work experience is one uncertainty routine which is seldom acknowledged (Höllermann & Evers, 2017) but has an important impact on uncertainty handling. E.g. highly skilled practitioners are using their tacit knowledge to understand the system around the management object enabling them to make plausible predictions or judgements (Fazey et al., 2005).

In conclusion, these six uncertainty routines reflect the practitioners' different strategies to cope with uncertainties in planning and decision-making processes. In the following we focus on improving our knowledge on 1) by whom, 2) when and 3) where in the decision process these uncertainty routines are applied using expert elicitation and a qualitative systems modelling approach.

4.2.2 Expert elicitation – Focussing on the "who" and "when"

This study is based on our expert elicitation on practitioners perception and handling of uncertainties in water management (Höllermann & Evers, 2017). The expert elicitation followed a semi-structured interview approach (Mayer, 2012) focusing on the experts' expertise and work experience regarding water management and integration of uncertainties into their planning and decision-making. The selection of experts followed an ex ante predefinition (Meuser & Nagel, 2009) to identify experts and set criteria that reflect the properties of the parent population (Mayer, 2012). A total of 20 experts from the German water management community were interviewed covering different employers such as state agencies (6), district governments (4), water associations (9), and private water business (1). These experts also correspond to three business unit affiliations: fundamental (basic) knowledge level (7), operational level (8), and strategic level (5) with different involvement into planning and decision-making. While the latter two are directly involved and responsible for these processes, the fundamental knowledge level is rather indirectly participating in plans and decisions by providing sound and evidence-based decision-making material. Surface water quantity management, flood forecast and reservoir management are the main subject areas by most of the experts.

The analysis of the expert elicitation in this study focused on two aspects: 1) the effect of intra-group variability of practitioners on uncertainty management strategies with respect to business unit membership (eliciting the "who"), and 2) the influence of the time perspective in operational management decisions on demand of uncertainty routines (analyzing the "when"). Thus, we investigate the differences among the three business units and their uncertainty perception and information demand. The interview transcripts were analyzed focusing on codes related to 1) decision-making and to 2) uncertainty handling. Those codes and their sub-codes were quantitatively determined as the most important to the interviewees across all affiliations to business units. Additionally, the interview data were analyzed from a time-dependent perspective focusing only on the operational level. Interview codings of flood and reservoir management were refined by paying attention to the time horizon, either long-term or short-term. After this refinement the code co-occurrence of time specific flood or reservoir issues was visualized to highlight key topics and their time dependency.

4.2.3 QUALITATIVE SYSTEMS DYNAMICS MODELLING – ANALYZING THE "WHERE"

Thinking in systems allows exploring the elements of a system, their interconnections and the purpose or goal of the system (Meadows, 2008). Systems dynamics aim at describing and understanding the time-dependent behavior of managed systems by applying qualitative and quantitative models, hereby, exploring how feedbacks govern the system's behavior (Coyle, 1996). Key strengths of a qualitative system modelling approach are to concisely describe a complex problem narrative, identify feedback loops, analyze the different perceptions of involved stakeholders, and provide a basis and background for quantitative system modelling (Coyle, 2000; Halbe et al., 2013). In our study, a qualitative systems dynamics approach was applied to reflect the interrelations of the different system elements regarding reservoir management under uncertainty. Hereby, we focus on the uncertainty perceptions and diversity of uncertainty management strategies of the practitioners, as conceptual models are one tool to reflect also on uncertainties (Westerberg et al., 2017).

Following Coyle (Coyle, 1996) we deployed a three step approach (Fig. 4.1). First, we defined the problem setting with information gained from extended personal communication with key practitioners from water agencies in reservoir management. The information contributed to develop a narrative about the practitioners' water management problem regarding reservoir release under seasonal and long-term change. Specifying the problem by using a narrative helps structuring the system around and focusing on the management objective (Dee et al., 2017). Second, by using insights from the expert elicitation (section 4.2.2) we developed an influence diagram, which is also called causal loop diagram (CLD) (Powell et al., 2016). This diagram consists of nodes (variables and/or points of decision-making) and their interrelation shown by arrows. In a quasi-participatory manner the interview transcripts of the expert elicitation served as input to reflect the different perceptions of all experts in a common influence diagram (ElSawah et al., 2013; Halbe et al., 2013; Inam et al., 2015). According to ElSawah et al. (2013) we understand the final influence diagram as our conceptualization of the interviewees' mental models which builds the basis for qualitative system analysis. Third, we qualitatively analyzed the diagram by identifying causal loops with respect to underlying uncertainty management routines and strategies (Fig. 4.1). The CLD analysis points out the problem centered system structure with its time dependent feedback processes and reveals objective and subjective dimensions of resource issues. Furthermore, the CLD functions as an interface to facilitate dialogue among the diversity of involved actors (Halbe et al., 2013). We therefore simplified the conventions for drawing influence diagrams/CLDs (Coyle, 1996; Sterman, 2000) by using solid lines to represent both, flows and influences, and by leaving out the polarity of the feedback loops as in our application this polarity is of no analytical and communicative value.

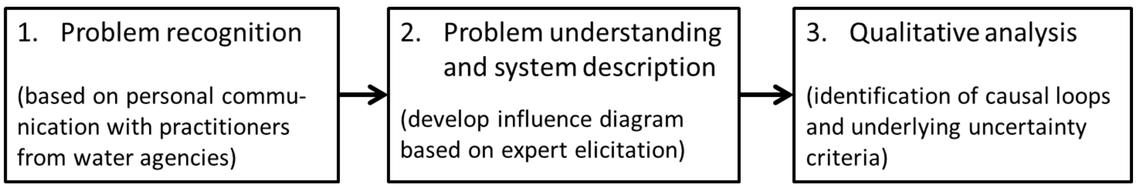

FIGURE 4.1 THREE STEPS APPROACH TO DEVELOP QUALITATIVE SYSTEM MODEL IN FORM OF INFLUENCE AND CAUSAL LOOP DIAGRAM

4.3 RESULTS

The results are analyzed and discussed against the background of the relevance of the uncertainty routines reflecting the plurality of uncertainty perception among water managers. Furthermore, the results show how different timeframes may change foci on different uncertainty routines. The qualitative system analysis informs about the point in decision-making where specific uncertainty routines come into play and intersect.

First, we present results reflecting the effect of intra-group variability of practitioners on uncertainty management strategies with respect to business unit membership, clarifying the “who”. In a second step, the influence of time perspective on operational management decisions on demand of uncertainty routines is demonstrated, analyzing the “when”. Third, important elements of the decision-making are highlighted by pointing at hot spots of uncertainty routine intersection and interrelation. This last step refers to “where”- the location in the process of decision-making.

4.3.1 WHO – INTRA-GROUP VARIABILITY OF PRACTITIONERS’ UNCERTAINTY ROUTINES

Practitioners’ thoughts and behaviour regarding decision-making criteria were grouped into four thematic areas as shown in table 4.2: `consequences and risk´, `risk perception´, ` information basis & transparency´ and `resources´. Their strategies for uncertainty handling were grouped into `cost-benefit analysis & proportionality´ and `transparency´. The analysis differentiated between the participants’ business unit affiliations: fundamental knowledge, operational, and strategic. This approach allowed identifying the uncertainty routines used by practitioners to integrate uncertainty into their planning and decision-making processes (last columns of Tab. 4.2).

4.3.1.1 DECISION MAKING

As shown in table 4.2 the interviewees state that the extent of uncertainty recognition depends on severity of consequences of decisions or events. If severity is assessed high then resources such as time and money are invested to understand the impact of uncertainties. Practitioners from the operational and strategic levels named **consequences and risk** very often to describe decision-making under uncertainty. It is a question of assessing vulnerability and reducing this vulnerability. Hereby, the operational management emphasized the practical aspects like action plans and resilient and flexible measures while the strategic level considers different risks and their trade-offs. Fundamental knowledge level focusses less on this aspect of consequences, risk and vulnerability.

TABLE 4.2 DIFFERENCES AMONG PRACTITIONERS REGARDING HANDLING AND USE OF UNCERTAINTY ROUTINES ON MANAGEMENT OBJECTIVES: THE FIRST COLUMN REFERS TO THE MANAGEMENT OBJECTIVE. THE SECOND TO FOURTH COLUMN PRESENT SELECTED INTERVIEW QUOTES DIFFERENTIATED BY BUSINESS UNIT LEVEL: BASIC KNOWLEDGE LEVEL (B), OPERATIONAL LEVEL (O), AND STRATEGIC LEVEL (S). THE LAST THREE COLUMNS DISPLAY THE PRACTITIONERS' SPECIFIC UNCERTAINTY ROUTINES AS A CONSEQUENCE OF THE DIFFERENT PERCEPTIONS BY BUSINESS UNIT LEVELS.

Topic	example quotes* from practitioners affilitated to different business units:			uncertainty routines**		
	basic knowledge level (B)	operational level (O)	strategic level (S)	B	O	S
Decision Making						
Consequences & Risk	-/-	We must try to minimize this uncertainty using action plans. We have a map and know that the fire brigade has to evacuate this area during specific flood levels. This means by having an action plan available we are in a position to handle the risk and make the uncertainties small. (IP_3.2) 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)	One has to balance and consider, how much we have to invest to protect an area against the costs of restricted building development.(IP_2.1) 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. But it is an interesting approach to make use of uncertainty information to narrow potential failire bounds. (IP_3.3)	-/-	Vulnerability	Framing
Risk perception	-/-	On the other hand there are also weather situations, by which all models have different results on the third day. Then you have to be careful, especially, if dam operation reaches a threshold where a change in discharge rate is necessary. Hence, one must pay more attention if the forecast is uncertain. (IP_3.8) We have a higher level of attention when there are uncertainties. Then I send someone out. The fire brigade drives out first. It is not always for evacuation. Therefore, it is actually very important to distinguish between the uncertainty that I have in my projection and whether it actually can lead to a risk. (IP_3.1)	When it comes to an extreme event with probabilities of a 1000 year flood or a failure of flood protection, we can not care about it. (IP_2.1) The communication of risks of events that normally a human won't experience is fascinating. How do you deal with things that people have never experienced and who are not able to classify it? (IP_3.3) Generally, you have to be cautious. Risk perception is very important to recognize certain conditions to know if you have to do sth. or to steer in another direction. (IP_3.6)	-/-	Tacit knowledge (Process uncertainties)	Framing (Process uncertainties)
Information basis & Transparency	To raise awareness among the colleagues, where the weak points are and their consequences. We try to be as transparent as possible in our actions by making the evaluation steps, the underlying monitoring results and the entire process transparent and comprehensible. (IP 1.4)	That you don't say this is the number, you have to believe it, but that you show that you have thought about it. Then perhaps mention uncertainties to point out that it could also be different number, but the probability for this number is greatest. It would also not work if you try to communicate that it could be just this one number. (IP 3.7)	If knowledge gaps are bridged and information is available, one can also better argue and advance the decision-making process (IP_2.4)	Transparency	Transparency (Process uncertainties)	Process uncertainties (Transparency)
Resources	In practice you have to confine a selection, because time and money are missing, we are usually forced to make some compromise. And, of course, this is a problem in dealing with uncertainty, because we get a number for uncertainty, but it only reflects a small range of uncertainty. (IP_1.5) It is important for us, to point out that financial constraints have consequences. Each measuring point, which we additionally investigate to provide higher quality of a data basis, costs money and binds personnel. That is why you try to make other areas as efficient and economical as possible, so that it is always a matter of showing the consequences of limited resources. (IP_1.4)	If I become more flexible in responding to such uncertainties, the consequence is that the operational cost of training for the handling of such situations increases immensely as you have to consider more than one value to operate the reservoir. (IP_3.1) You must be cautious when calculating a flooding area under economical efficiency aspects to save money. You have to deal with uncertainties, because when it comes to a recalculation with new hydrometric and precipitation data, suddenly there is again a flooding problem. There is the need to plan more security. (IP_3.7)	The spend resources feed into a benchmarking model and it is all about money and personnel expenses. (IP_3.6)	Process uncertainties (Transparency)	Process uncertainties (Vulnerability)	Process uncertainties (Responsibility)
Handling uncertainty						
Cost-Benefit-Analysis & Proportionality	If we have achieved a certain degree of quality of our data, we determine that this basis is sufficient to base on futher calculations and adaptation measures. (IP 1.5) When we determined floodplains for 100 year flood, we had many complaints from landowners who did not accept that their site should be exposed to flooding, since their family never experienced floods. This is why we have always tried to use realistic numbers and not to play safe. (IP 2.2)	By using decentralized measures such as retention areas for flood protection, we are also resilient facing water shortage in case climate variability tends to this direction. As these retention areas also lead to groundwater recharge and an increase in the low flows, which affect the flora and fauna and is effective against heat sinks. No matter how the climate changes, these measures work and that is what I mean by looking at the vulnerability of an area across a plurality of changes. (IP 3.9)	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. Therefore we internally discussed a medium value with which we calculated heryby acknowledging uncertainties. (IP 2.1)	Process uncertainties	Framing (Vulnerability)	Vulnerability (Responsibility)
Transparency	I choose two to three of the most important climatic scenarios, knowing that these have a certain tolerance range, and used them for the rest of the calculation. But I will also explain why I chose those scenarios. (IP 1.2) It is our task to prepare and provide a sound knowledge base for decision-making in form of reports and guidance notes which should give advise and guidance for political decision and judgement. (IP 1.3)	Where uncertainties cannot be reduced one should more explicitly becomes aware of these uncertainties and find ways to deal with them. This was the paradigm shift at the national weather forecast, who started talking about uncertainties and trying to understand them and their influence a bit better rather than completely ignore them. (IP 3.5) Probably one must agree on the fact that the HQ 100 flooding area is a definition. That a certain precipitation and discharge lead to this flooding area. These values should be scientifically sound, however, by defining of this area one simultaneously acknowledges the involved uncertainties. (IP 3.7)	-/-	Transparency	Process uncertainties	-/-

* All quotes are translated from German into English and paraphrised for readability.
** X(Y) reads: X in terms or in view of Y

The perception regarding the consequences and boundary conditions may alter **risk perception.** The more critical these aspects are assessed, the more uncertainties or the potential impact of uncertainties are integrated. The importance and extent of risk perception differ between the business units. Perception of different risks leads the

operational level to differentiated attention regarding critical situations. The strategic level is more concerned with general risk perception among society and the change of her perception.

The basis on how e.g. model results are gained should be clear to implicitly acknowledge uncertainties regarding e.g. assumptions. In the end there should not be only one number but the way how this number was derived should be made explicit**. Information basis and transparency** is highlighted by the interviewees of the fundamental knowledge level and one observes a gradual change from pure transparency of the fundamental knowledge level to a focus on process uncertainties with the support of transparency in order to justify actions and decisions.

Time, money and personal **resources** are limited. Hence, resources and their availability to cope with uncertainty are a source of conflict between the different business units. The fundamental knowledge level points out that resources are needed to provide good and sufficient data basis. The operational level argues that they need more resources for using adaptive and flexible management approaches which acknowledge uncertainties, while the strategic level must balance financial accounts.

4.3.1.2 UNCERTAINTY HANDLING

Decision-making considers balancing **costs and benefits** by assessing whether the costs for precaution measures are found acceptable to decrease potential risk impacts or if those costs are inappropriate and reimbursement of consequences of the risks is more cost-effective. Proportionality therefore is closely connected to the assessment of consequences and the risk perception of these consequences. The different business units put different foci on this issue. Where the operational management focusses on the effectiveness of measures, the strategic level thinks beyond single cases and has a different view on vulnerability based on their societal responsibility.

Transparency is gained by explicit documentation of working procedures, assumptions, choice of results, etc. Furthermore by establishing guidelines, rulebooks one may guide understanding of the limits of results. The fundamental knowledge level is able to stay more descriptive and partly give recommendations while the operational level has to implement the uncertainties into their decisions and for them transparency is key to justify the assertions and actions.

4.3.1.3 UNCERTAINTY ROUTINES AND THEIR IMPLEMENTATION BY BUSINESS UNITS

Table 4.2 and the sections above show that the majority of uncertainty routines are implicitly applied by all levels of business units, however, with slightly different foci. The fundamental knowledge level puts a strong focus on transparency and on process uncertainties with dependency on transparency. On the other hand, the operational level emphasizes vulnerability and process uncertainties for uncertainty integration. Furthermore, they need tacit knowledge and transparency to cope with uncertainties. The strategic level lays foci on process uncertainties, framing and responsibility. In general, process uncertainties are important for all business unit levels. Moreover, the interrelation of process uncertainties (see also van den Hoek et al., 2014; Warmink et al., 2017) becomes obvious as process uncertainties are mostly in dependency with another uncertainty routine.

For example the availability and limitation of resources such as time, financial or personal resources for understanding and solving an environmental problem describe uncertainties originating from the planning process (PU). However, the focus of these process uncertainties is understood differently in terms of transparency for the fundamental knowledge level, in terms of vulnerability for the operational level and in terms of responsibility for the strategic level. The strategic level e.g. is assigned to responsibly govern limited resources among the whole organization which mainly affect expenses. In contrast, the fundamental knowledge level points out the importance of sufficient resources as these are essential for transparency and sustaining the evidence-base of decisions. The operational level argues that uncertainty acknowledgement may need more flexible approaches in order to reduce vulnerability, increasing the need for resources regarding qualified personnel to implement these approaches (see Tab. 4.2 for example quotes).

Another example where the uncertainty routines are dissenting from practitioners is reflected in handling risk perception. Risk perception is important for the operational and the strategic level, however, while the operational level emphasizes tacit knowledge (TK) in terms of process uncertainties (PU), the strategic level uses framing (F) in terms of PU. Here, process uncertainties are related to regulations or (social) norms guiding risk perception as a function of failure to reach the desired regulation or norm. Dealing with the underlying uncertainties regarding this failure leads to different uncertainty routines. While the operational level uses tacit knowledge to assess the impact of environmental uncertainties, the strategic level reframes the (social) norm in order to decide about management options, e.g. risk seeking or risk avoiding.

A final example on the interrelation of uncertainty routines becomes visible when looking at uncertainty handling regarding cost-benefit analysis & proportionality for flood risk management. The different scope of action and job description of the different business unit levels are crucial regarding the choice of uncertainty routines. The fundamental knowledge level experiences restrictions in providing evidence-based decision-making material due to process uncertainties. The available and restricted resources limit the extent of environmental uncertainties exploration. Furthermore, the experience of potentially affected stakeholders must find integration into this knowledge base too in order to adequately address uncertainties from e.g. modelling:

> “When we determined floodplains for 100 year flood, we had many complaints from landowners who did not accept that their site should be exposed to flooding, since their family never experienced floods. This is why we have always tried to use realistic numbers and not to play safe” (IP 2.2).

In contrast, operational level applies reframing in terms of vulnerability to handle uncertainties in a (cost-) efficient and adequate way. They point out measures which reduce vulnerability regardless the direction of change, e.g. retention areas, which are efficient for flood retention but also may serve as a buffer for low flow. Hereby, the operational level effectively integrates a broad array of fundamental uncertainties into their planning. The strategic level regards vulnerability in terms of responsibility to highlight their societal responsibility by balancing the needs of communities to use space along the river for urban or commercial development against the accumulation of values within flood prone areas.

4.3.2 WHEN – INFLUENCE OF TIMEFRAME ON APPLICATION OF UNCERTAINTY ROUTINES

The former section discussed the differences across the three business unit levels. In this section we have a closer look at the uncertainty routines of the operational level regarding different timeframes (Tab. 4.3).

TABLE 4.3 UNCERTAINTY ROUTINES AND THEIR TIME-SCALE DEPENDENCY. THE FIRST COLUMN DISPLAYS THE FOUR MAIN DECISION-MAKING CRITERIA UNDER UNCERTAINTY HIGHLIGHTED BY THE OPERATIONAL MANAGEMENT EXPERTS. THE SECOND COLUMN DIFFERENTIATES THEIR STRATEGIES TO COPE WITH UNCERTAINTY REGARDING LONG- AND SHORT-TERM MANAGEMENT OBJECTIVES.

Operational management perspective on		**Time-scales and uncertainty in**	
		Long-term	Short-term
		Uncertainty routines	*Uncertainty routines*
Decision-making criteria under uncertainty	Consequences & risk	Process uncertainties Framing (Vulnerability)	Vulnerability (Responsibility) Tacit knowledge
	Capacity & ability to act	Process uncertainties Responsibility	Framing (Process uncertainties) Vulnerability (Tacit knowledge)
	Risk perception	**-/-**	Vulnerability (Responsibility) Tacit knowledge
	Political context	Process uncertainties (Framing)	**-/-**

X(Y) reads: X in terms or in view of Y

4.3.2.1 LONG-TERM PERSPECTIVE

When facing long-term consequences and risks affecting the water system, the interviewees favor the establishment of resilient and elastic river management systems by using multi-functional measures to reduce risks. However, a flood may affect regions differently regarding extent of flooding and damage potential. The acknowledgment of this dynamic is assessed important by the operational management practitioners. However, it is still not state of the art, because the operational level faces process uncertainties that affect their ability to act on consequences. As one interview partner stated:

> *"An administration wants to know the threshold where changes in operation occur. If there is a range, I can decide when to act. That does not work. If there is flexibility, the regulatory authority has less power but is still responsible. I understand this problem but it makes handling uncertainties difficult".*

Thus, the adaptive management approach has limitations and much needed opportunities for integrating flexible decisions are lacking (Warmink et al., 2017), e.g. due to rigid legal and administrative settings.

Rather than analyzing climate projections with large ensemble ranges, framing in terms of vulnerability becomes more important for the operational management to cope with large irreducible uncertainties, because the capability to act on a larger ensemble range is limited. First, legal and technical restrictions apply which stall flexible management. Second, they have the responsibility to counterbalance costs and perceived occurrence of consequence by setting a target value. For example, the delineation of flooding areas in national or regional flood maps only reflect ostensible accuracy. Presentation of uncertainties will certainly hinder or manipulate negotiations about e.g. extent of flooding areas, flood marks, etc. as this quote highlights:

> *"I know that 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"*.

Hence, process uncertainties and responsibility are the most important routines for them to mark their scope of action and vulnerability assessment and risk framing allows implicitly uncertainty integration.

Regarding long-term management the political context is one important source of uncertainty which the practitioners have to cope with. There might be paradigm shifts which they have to take into account. E.g. shift from technical flood management to flood risk management; a change in regulations or legal forces affecting minimum flow requirements and safety limits focusing on water quality or political compromise limiting flood protection measures due to restricted availability of land and (financial) resources, etc. Furthermore current investments need to fit political agenda and are also driven by funding programs. The acceptance of dynamic or variable maximum potential flood and hence different flood protection measures is low concerning the perception of social justice. In a long-term perspective uncertainties regarding the natural and resource system are less in focus than process uncertainties which reframe uncertainties into risk in order to cope with the unknown and to derive decisions.

4.3.2.2 SHORT-TERM PERSPECTIVE

When facing short-term changes or disturbances the vulnerability of the system is in focus, especially with respect to the responsibilities of the operational level. Tacit knowledge is key to make decisions about changes in operation or introducing specific steps of emergency or action plans. Here, consequences and risk are assessed against the current vulnerability of the river system. The assessed extent of potential damage or trade-off among different stakeholders decides about the level of risk perception.

The capacity and ability to act is challenged by deriving a final decision from a set of ensemble forecasts during e.g. event of flooding. How to manage the reservoir: play safe and introduce emergency measures or steer dynamically? Assessing the potential vulnerability regarding maximum expected precipitation and balance resources and cost and benefits appropriately provides a critical decision criterion. However, vulnerability assessment needs tacit knowledge and the reframing of forecast uncertainties and process uncertainties.

With the focus on vulnerability, risk perception is a major decision rational. According to the interviewees the more critical boundary conditions are the more risk perception plays a pivotal role. Especially regarding short-term changes the combination of risk perception and taking responsibility guides decision-making hereby implicitly accounting for uncertainties. For example, the acknowledgement of uncertainties increases if the boundary conditions are critical as one interview partner states

> *"If we have weather conditions where all models differ extremely on the third day, than we are cautious, especially if the current reservoir level makes a change in reservoir release necessary."* or as another practitioner highlights *"In balancing the current soil moisture and the forecasted precipitation event, experience shows that the expected amount of rainfall will have no critical impact on the upper catchment, but it may be critical for the downstream catchment."*

Hence, above technical support and decision support systems tacit knowledge is key in assessing the risk potential and perception of vulnerability. Here, tacit knowledge refers especially to the knowledge about and experience of critical boundary conditions, including the use of anchors and the demand of external tacit knowledge.

4.3.2.3 UNCERTAINTY ROUTINES AND TIMEFRAME

Table 4.3 summarizes the results and explicitly shows that uncertainty routines have timeframe dependency. In general, process uncertainties and framing play an important role, especially in a long-term perspective. In a short-term perspective the uncertainty routines tacit knowledge and vulnerability play a major role.

4.3.3 WHERE – LOCATION OF UNCERTAINTY ROUTINES IN DECISION-MAKING PROCESS

4.3.3.1 RESERVOIR MANAGEMENT UNDER UNCERTAINTY – A NARRATIVE

The personal communication with managers from different water agencies revealed that for some years they experienced a shift in seasonal rainfall affecting the inflow into reservoirs. In total the precipitation amount in their regions has not changed, however, intra-annual variability of rainfall increased. While there has been usually enough precipitation in March to fill up the reservoirs, rain falls later in the year during main growing season and most of the precipitation is taken up by vegetation and does not contribute to reservoir inflow. Regarding this narrative, the interviewed water managers are challenged with two problems: 1) they have to manage the deficit in reservoir storage within the year without sacrificing flood protection or water quality in a short-term perspective and 2) they have to understand the effects of long-term change on trade-offs among flood protection and low flow support.

4.3.3.2 RESERVOIR MANAGEMENT FROM A SYSTEMS PERSPECTIVE – INFLUENCE DIAGRAM

Using this narrative and additional data from the expert interviews we developed the influence diagram depicted in figure 4.2 in five steps in order to illustrate the plurality of perspectives and strategies on a concrete management object in a structured manner:

I. First step included the physical and control system which is the basis for assessing discharge release. Reservoir discharge is at the core of the influence diagram as at that point the operative management decides about the strategy to cope with either too little or too much water. This decision depends on two external driving forces, where the system has no control and to which it must respond to a change in discharge. The type of driving forces (highlighted in Fig. 4.2 with a black box) has two different natures.

Precipitation is a natural driving force and the desired level of reservoir is a driving force set by human action. Precipitation and its temporal and spatial variability contribute to reservoir inflow due to runoff. The amount of runoff is determined by the rate of evapotranspiration and the initial soil moisture. In order to estimate the effects of an anticipated precipitation event, the operational management needs to translate and interpret climate forecast information, boundary conditions, current inflow and current level of reservoir to base their discharge decision on. Additionally, they have to balance the discrepancy of actual and desired reservoir level.

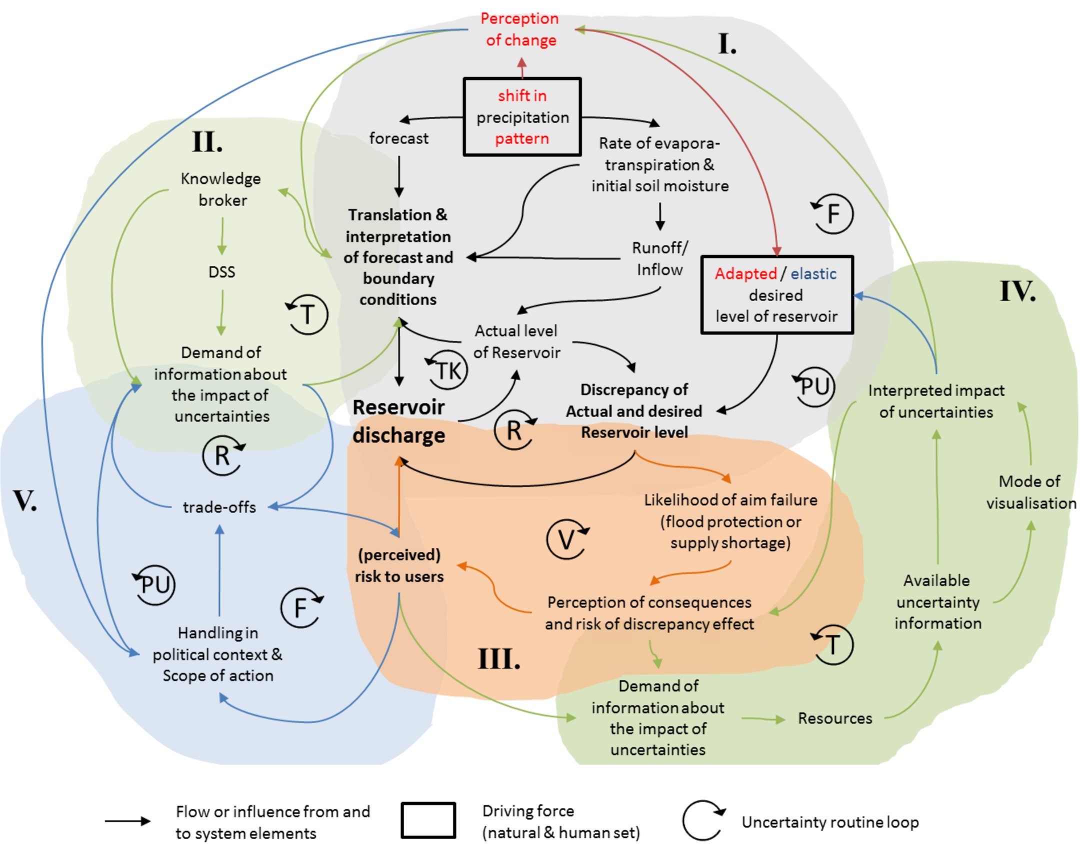

FIGURE 4.2 INFLUENCE AND CAUSAL LOOP DIAGRAM PRESENTING FIVE PERSPECTIVES ON THE MANAGEMENT OBJECTIVE "RESERVOIR DISCHARGE": I. PHYSICAL AND CONTROL SYSTEM, II. REFLECTION ON INFORMATION, III. RISK OF MANAGEMENT FAILURE, IV. IMPACT OF UNCERTAINTIES ON POTENTIAL RISK, AND V. POLITICAL CONTEXT. THE DIAGRAM HIGHLIGHTS THE INTERSECTION AND INTERRELATION OF THESE DIFFERENT PERSPECTIVES. FURTHERMORE CAUSAL LOOPS ARE IDENTIFIED PRESENTING UNCERTAINTY ROUTINES SPECIFIC TO THESE LOOPS. THE VISUALIZATION IN FORM OF AN INFLUENCE AND CAUSAL LOOP DIAGRAM ALLOWS FOR UNDERSTANDING THE PLURALITY OF PERSPECTIVES AND THEIR POTENTIAL SYNERGIES AS WELL AS FOSTERING AND ENHANCING COMMUNICATION AND INFORMATION FLOW BETWEEN THOSE PERSPECTIVES. LABEL IN RED INDICATES CHANGES DUE TO LONG-TERM CHANGE. LABEL IN BLUE INDICATES ADJUSTMENT DUE TO REFRAMING MANAGEMENT GOALS. ABBREVIATION FOR UNCERTAINTY ROUTINES ARE: VULNERABILITY (V), RESPONSIBILITY (R), TRANSPARENCY (T), FRAMING (F), PROCESS UNCERTAINTIES (PU), TACIT KNOWLEDGE (TK). MORE EXPLANATION IN TEXT, SECTION 4.3.3.2.

II. The manifold sources of information which need translation and interpretation to decide about a potential change in reservoir discharge are informed by uncertainty assessment. This might be through e.g. knowledge brokers such as local climate forecaster, and/or decision support systems (DSS) such as catchment models and sensitivity analysis of boundary conditions. The operational managers need information about the impact of uncertainties to improve their interpretation of precipitation forecast and boundary conditions.

III. In a third step, we had a closer look at the discrepancy effect and its likelihood of actual and desired reservoir level such as flood protection or supply shortage. The likelihood decides about the perception of consequences and risk of this effect and results in a (perceived) risk to users. As the reservoir management has the legally binding task to protect against floods, support low flows, etc. this risk to users also determines the rate of reservoir discharge.

IV. Perception about the consequences and hence potential risks of the discrepancy effect depend on the information about the impact of uncertainties which are inherent to this effect. The dimension of satisfying this knowledge demand is restricted by the available resources and uncertainty information. For many of the stakeholders the mode of visualization plays a major role for the interpretation of the information on impact of uncertainties and hence the perception of the severity of consequences and/or magnitude of change which guides the decision about the amount of reservoir release.

V. The responsibility to take care of stakeholders in minimizing their risk is a function of the scope of action and the political context informed by balancing trade-offs, the perception of change, and assessing the impact of uncertainties. Here, the decision about reservoir discharge enters an arena of power relations, restrictions and values the practitioners have to acknowledge in their decision-making process.

4.3.3.3 UNCERTAINTY ROUTINES BECOME VISIBLE - QUALITATIVE CAUSAL LOOP ANALYSIS OF INFLUENCE DIAGRAM

The complexity of the influence diagram shows that besides the physical and control system practitioners experience further decision-making criteria influencing their scope of action and final decision. Even though Döll and Romero-Lankao (2017) find that such a qualitative approach with causal representation does not explicitly address uncertainties, we find that our causal loop analysis reveals that different causal loops are dominated by specific uncertainty routines representing implicitly those uncertainties practitioners have developed strategies to cope with (Fig. 4.2).

For example, while uncertainty management (II. step) emphasizes transparency as the dominating uncertainty routine, risk assessment focusses on the vulnerability routine (III. step) to derive a basis for decision-making on the magnitude of reservoir release. Connecting this insight with findings from table 4.2 shows that both loops informing the management objective intersect and the fundamental knowledge level finds its major responsibility in informing transparently while the operational level integrates a risk perspective.

A closer look at the causal loops regarding **reservoir discharge** reveals that four different loops exist involving also four uncertainty routines. First, for interpretation and translation of current forecast and boundary conditions, together with the actual level of reservoir practitioners' tacit knowledge plays a major role for deciding on the extent of discharge (Fig. 4.2, I. step, loop: TK). Second, responsibility guides the decision-basis to balance the discrepancy between actual and desired reservoir level (Fig. 4.2, I. step, loop: R). Third, the assessment of vulnerability of aim failure drives a risk-based approach to decide about the level of reservoir release (Fig. 4.2, III. step, loop: V). Fourth, under perceived and actual environmental changes framing plays a pivotal role regarding the translation and interpretation of forecast and boundary conditions and the assessment of the severity of the consequences of the discrepancy effect (Fig. 4.2, III./IV./I. step, loop: F). Here, we could show that reservoir discharge can be informed by at least four loops indicating a strong interrelation of uncertainties (van den Hoek et al., 2014). Thus, the interrelation of different uncertainty routines implies that uncertainty information from external sources, e.g. scientific advisors, needs profound understanding of practitioners' preferred coping strategy or uncertainty routine in order to provide tailor-made information. If there is a mismatch, the integration of valuable uncertainty information into the decision-making process is at risk (Briley et al., 2015; Lemos et al., 2012). By highlighting the different mental models in this procedure, areas of knowledge gaps or ambiguity are stressed (ElSawah et al., 2013) and counteract of closing a system without acknowledging the plurality of perspectives (Westerberg et al., 2017).

The intersection of a diversity of loops also applies for the assessment of the (perceived) risk to users with also four loops. Here, we focus on the loop which frames uncertainty into risk within the political context (Fig. 4.2, V. step, loop:Ⓕ). As table 4.2 showed this framing is important for the strategic and operational level. While the latter one has to broker their scope of action regarding the balancing of trade-offs, the former one rather contextualizes the risk into the political agenda and responsibilities.

Timeframe is also important for the two loops referring to the discrepancy between the desired and actual level of reservoir (Fig. 4.3). These loops show, that human defined external driving forces (black box) on the system is challenged either by detailed and new information about consequences due to more transparency about uncertainty or by reframing the perception about climate change. In a short-term perspective, this may lead from simply refining actions to reframing goals of reservoir management, e.g. value of low flow support, in the sense of double loop (Reed et al., 2010; Warmink et al., 2017) or normative learning (Döll & Romero-Lankao, 2017) indicated by the blue label. A long-term perspective may challenge the human set external driving force by transformation to another steering or control parameter indicated by the red label. The results of table 4.3 support these findings as framing is a strategy to redefine the capacity and ability to act on emergent issues in a short-term perspective, but on a longer time scale, framing is less about redefining the scope of action but of transforming consequences and risks. Hence, coping with uncertainties may need this reframing or transformation (Warmink et al., 2017) and by making this link explicit, the CLD may serve as a platform for communication (Halbe et al., 2013) facilitating and fostering social learning (Reed et al., 2010). Time, money and personal **resources** are limited. Hence, resources and their availability to cope with uncertainty are a source of conflict between the different business units. The fundamental knowledge level points out that resources are needed to provide good and sufficient data basis. The operational level argues that they need more resources for using adaptive and flexible management approaches which acknowledge uncertainties, while the strategic level must balance financial accounts.

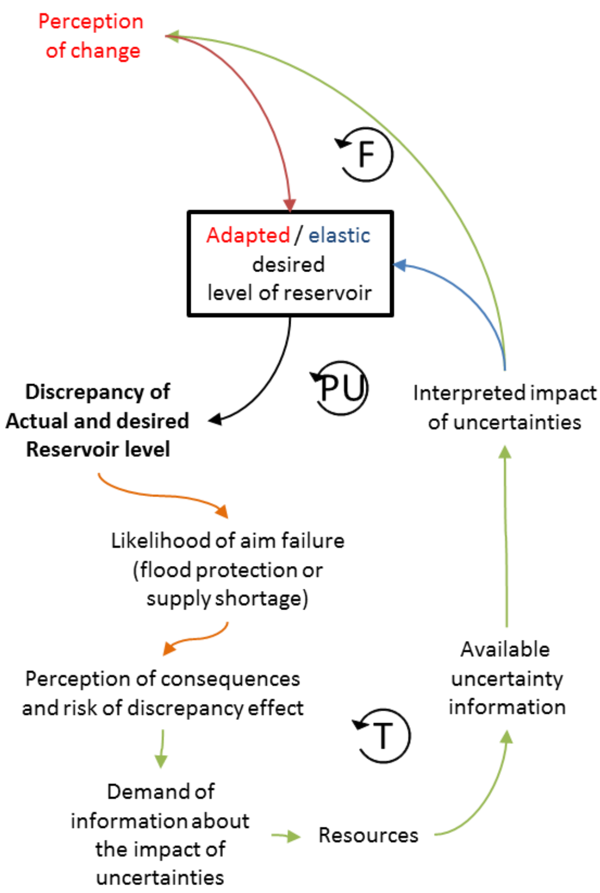

FIGURE 4.3 CAUSAL LOOP REGARDING "DISCREPANCY OF ACTUAL AND DESIRED RESERVOIR LEVEL" (EXCERPT FROM FIG. 4.2) SHOWING THE TIME-DEPENDENCY OF UNCERTAINTY ROUTINES.

In conclusions, the ID/CLD illustrates the plurality of perspectives and strategies on a concrete management object in a structured manner, keeping the systems' and management complexity (Stirling, 2010; Winkler, 2016) and allowing discourse at the boundaries of the different practitioners' perspectives highlighted by the analysis of the expert elicitation. Additionally by stressing the differences regarding the time perspective and point in decisions-making helps fostering cross-communication, connecting perspectives (Powell et al., 2016) and, hence, contributing to robust and well-informed decision-making.

4.4 DISCUSSION AND CONCLUSION

Practitioners of all levels are aware of decision-making under uncertainty (Höllermann & Evers, 2015b, 2017). However, as this in depth study showed, the approaches to handle uncertainties differ with implications for communication, learning for decision-making and plurality of perspectives in water management. In the following we discuss our findings in relation to these topics.

4.4.1 UNCERTAINTY AND COMMUNICATION

Science-practice communication is challenged by the usability gap (Briley et al., 2015; Lemos et al., 2012) to produce not only useful but also usable information. We identified that usability regarding information about uncertainty is perceived differently by practitioners. As Lemos et al. (2012) suggest established routines regarding (uncertainty) information perception and handling aggravate integration of new information if the interplay of this new information and routinely used information does not adequately complement and add value to the decision at hand. By value-adding they mean to transform information into decision-oriented knowledge (Lemos et al., 2012) thus organized knowledge (Weichselgartner & Pigeon, 2015) paying attention to the underlying organizational information flows and realities. The results of our study help in contextualising this information needs and demands and provide insights that help scientific uncertainty evaluation to produce tailor-made information which is relevant and readable to the specific groups (Kundzewicz et al., 2018).

Apart from bridging the science-practice gap, the communication of different strategies on uncertainty handling for solving a management objective may also enhance understanding and transfer of uncertainty information between the different business levels. As Nearing et al. (2016) point out, that it is important to assess what kind of information is available and how much of it is actually used. A more formalized internal communication can support this effort (Mauelshagen et al., 2014). Here, our influence diagram or CLD enables such cross-communication at the intersections of different ways of knowing and uncertainty handling (Powell et al., 2016) by highlighting the personal context surrounding the decision criteria and routines. This enhances the sharing of experiences which is a central part of the decision-makers' evaluated and reflected knowledge (Weichselgartner & Pigeon, 2015). In general, the knowledge that different views and hence different approaches exist already improve communication by building trust (Westerberg et al., 2017), fostering discourse (Zandvoort et al., 2017) and negotiating over meanings (Ingram, 2013) and, hence, support decision-making under uncertainty.

4.4.2 UNCERTAINTY AND LEARNING FOR DECISION-MAKING

Given the complexity of water management (Stirling, 2010; Winkler, 2016) and its non-stationarity (Milly et al., 2008) water managers need continuous learning in order to cope with uncertainty and surprise in their decision-making. By learning we mean the individual understanding of an environmental system in combination with on-going personal experiences of how those systems work (Fazey et al., 2005; Weichselgartner & Pigeon, 2015). Tacit knowledge is a key element of these learning processes as formal and the experiential knowledge interplay (Ingram, 2013) and help contextualizing and structuring new knowledge along relevant concepts (Fazey et al., 2005). The presented influence diagram / CLD approach may serve here as a (learning) platform to bring to light the different perspectives either between science and practice or within practice by presenting how information e.g. on uncertainty are dynamically built into 'personal' knowledge (Weichselgartner & Pigeon, 2015) and guiding decisions. Referring to the example where the practitioners have to evaluate the discrepancy between actual and desired reservoir level, we could show that uncertainties may challenge first loop learning as the uncertainties cannot be simply reduced (Warmink et al., 2017) but induce second or third loop learning. We show that in a short-term perspective the questioning of the current context and its assumptions presents an uncertainty routine (2^{nd} loop learning). Regarding anticipated long-term change third loop learning contests the underlying norms and values of current practice changing the human set driving force, the discrepancy of actual and desired reservoir level, from elastic to adapted. Hereby, the visualization of a management issue in form of an ID/CLD may foster learning processes in general and may specifically enable social or participatory learning by changing the understanding through integration of a wider social setting and network (Döll & Romero-Lankao, 2017; Reed et al., 2010). Especially Warmink et al. (2017) postulate the importance of social learning in order to increase uncertainty handling.

4.4.3 UNCERTAINTY AND PLURALITY OF PERSPECTIVES IN WATER MANAGEMENT

Several authors stress the importance of uncertainty integration into water management due to the increasing complexity of the water system (e.g. Ceola et al., 2016; Harremoës, 2003; Winkler, 2016) fostering a paradigm change from a predict and control approach towards adapted management (Halbe et al., 2013; Larson et al., 2015; Warmink et al., 2017). Through such an empirical iterative approach (Harremoës, 2003) - which may prevent lock-in situations (Warmink et al., 2017) - water management builds capacity and flexible response in order to deal with unpredictability or uncertainty (Larson et al., 2015). In addition to an adapted approach, Larson et al. (2015) argue that a transformation process may also be an option to cope with this complexity. While these approaches seem suitable to acknowledge uncertainty the question if decision-making processes kept pace accordingly remains.

Our analysis of the plurality of perspectives of practitioners on uncertainty perception and handling provide some insights on this issue. We showed that uncertainty perception and handling routines vary depending on the business unit affiliation. The representation of this plurality in form of an ID or CLD visualized that uncertainty information entering the decision-making process are assessed in relation to e.g. political power, legal forces, responsibilities, etc. and can therefore not be regarded as a linear causal chain of information (Larson et al., 2015) but rather as a web of different ways of knowing (Ingram, 2013; Zandvoort et al., 2017). Making these different ways of thinking transparent allows debating for consensus or accepting incompatibility, for example regarding the demand of uncertainty information. It also may increase the practitioners' acceptance of fuzziness of scientific evidence as best expression of expertise and competence (Harremoës, 2003) and may reveal ambitions to politicize uncertainty (Kundzewicz et al., 2018). As we showed, the operational level focusses mainly on vulnerability while the strategic level emphasizes the relevance of process uncertainties for their decision-making under uncertainty. Another example regarding the time-horizon of a management objective showed that uncertainty information which are important for a short-term perspective are of no use regarding long-term perspective. This usability gap, which is also fed by the plurality of practitioners and their management objectives, can be visualized by using a CLD and improve fit and interplay of information either from science to practice or within practice. Therefore the CLD provides a platform for open discussion about how to address different sources of uncertainty, which is seen as an advantage by Westerberg et al. (2017).

Finally, deriving from our identification of the plurality of perspectives in water management and their explication in form of a CLD we highlight three positive implications of plurality on adaptive management. First, an increased awareness on which perspectives are included in the adaptation processes and which perspectives have been neglected so far, help decreasing the potential of misinformed decisions (see also Ingram, 2013; Patt &

Weber, 2014; Powell et al., 2016; Winkler, 2016). Second, the usability gap (Briley et al., 2015; Lemos et al., 2012) decreases with open discussion about user needs (Westerberg et al., 2017) and a visualization of how much (uncertainty) information are actually integrated into the decision-making process (Nearing et al., 2016). By closing this gap the implementation of adaptation measures in response to changes works at a faster pace reducing resources demand and increasing adaptive capacity. Third, the explication of a plurality of perspectives which opens up room for organizational learning (Warmink et al., 2017) and is the cornerstone of transformation processes (Larson et al., 2015). Here, in our view, the acknowledgement of plurality can be regarded as an enabler for deeper learning processes challenging values and norms supporting current assumptions. One example for such a transformation process, which goes beyond incremental adaptation, is the paradigm change from ‘flood control’ to ‘flood risk’ management. We therefore find the acknowledgement of plurality of knowledge and perspectives to present a prerequisite for effective adaptation and transformation processes under complex and uncertain water management issues and to support the decision-making processes.

4.4.4 CONCLUDING REMARKS

In general, our research contributes to a better understanding of uncertainty perception and handling by highlighting the plurality of perspectives of and within science and practice. Hereby, our research on the elicitation of user and time specific uncertainty routines application and their visualization in an ID/CLD has been twofold. First, it presents a theoretical construct to rethink uncertainty implications and their interrelations with respect to a plurality of perspectives, especially regarding diversity of practitioners. Second, it gives implications for increasing usability of uncertainty information and enables second or third loop learning for adaptive or transformative water management by fostering cross-communication within practice and between science and practice, thus offering a practical strategy to increase the integration of uncertainties into decision-making processes.

5 CONCLUSION AND OUTLOOK

General aim of this research was to improve the understanding of how scientific uncertainties can find better integration into planning and decision-making processes in model-based water management. One basic but crucial finding of this research is that uncertainty does matter for decision-makers. They regard information about the robustness and reliability of (model) results as complementary and essential for their planning and decision-making. With this in mind, the research was then able to analyse how uncertainty information is best transferred into practice, how it is integrated into planning and decision-making processes, which potential limitations regarding uncertainty acknowledgement exist, and how these limitations may be overcome.

5.1 CONTRIBUTION TO UNDERSTANDING AND IMPROVING UNCERTAINTY INTEGRATION

Three major working steps – elucidated in chapters 2 to 4 – contributed to the general aim of this thesis by analysing different aspects during the decision-making process.

The first part of the research focussed on the differences of how science and practice approach and acknowledge uncertainty. Based on a literature review on uncertainty categorisation (see chapters 1.4, 2.3.2) a 2x2 uncertainty matrix was developed which covers the different uncertainty dimensions in a condensed way and highlights the interrelations of fundamental and process uncertainties. Results indicate that practitioners cope as much with process uncertainties as with fundamental uncertainties. Even though the former were only implicitly defined as such, they showed a high impact on the practitioners' actions and rules of arguing. Furthermore, compensation of fundamental uncertainties by decreasing process uncertainties or vice versa is good practice among planners and decision-makers. Following the assumption by Willows et al. (2003) that practitioners rather use risk-based approaches to acknowledge uncertainty and that risk framing was shown to be implicitly applied and accepted by a wide range of the interviewed practitioners, the developed uncertainty approach with its 2x2 uncertainty matrix was embedded into a risk-based integration and analytical framework, hereby, recognizing the different analytical and decision steps during risk governance. In addition, the risk-based approach also allows assessing the scope of action within a wider political and societal context, hereby mirroring the practitioners' actual working conditions. In general, the integration and analytical framework builds the basis for a structured transfer and exchange of uncertainty information, highlights neuralgic points and may positively influence practitioners' anchors by providing sound uncertainty information and/or making missing information visible in order to base decisions on.

The second part of the research analysed the knowledge/decision interface, where evidence-based knowledge with all its limitations due to epistemic and/or aleatoric uncertainty enters the decision-making process. At this point, evidence-based knowledge becomes one of many decision-making criteria and is assessed in relation to e.g. political power, legal forces, responsibilities, etc. and can therefore not be regarded as a linear causal chain of information (Larson et al., 2015). Nevertheless, uncertainties are central aspects of any decision in water management. Additionally, the importance of process uncertainties for the practice/policy side should be more clearly acknowledged by science. Because the assessment of fundamental uncertainties of e.g. precipitation forecast is evaluated in relation to perceived process uncertainties - such as responsibility for stakeholder needs – which influence and shape the final decision and planning process.

Having a closer look at uncertainty acknowledgement, the research suggests that perception and handling of uncertainties varies between science and practice but also within these different professions. While, for example, scientists prefer top-down approaches from climate projections down to impact studies which are prone to propagation of uncertainties, practitioners rather apply bottom-up based approaches to keep uncertainties manageable and to focus on vulnerability aspects. Here, practitioners reframe uncertainty into risk and consequences of their action. Besides this difference between the professions, this research revealed that the level of work experience is a cross-cutting property of uncertainty handling. Beyond affiliation to science or practice more experienced persons (>10 years of working experience) are more sensitive to uncertainty perception and handling. This tacit knowledge should be made explicit by using more structured communication in form of e.g. the integration and analytical framework proposed in chapter 2. In sum, the level of recognition and the integration of uncertainties into planning and decision-making processes vary due to group membership regarding the type of profession (science or practice), employer and business unit and - as cross-cutting properties to the former groups - educational background and level of experience (Fig. 5.1).

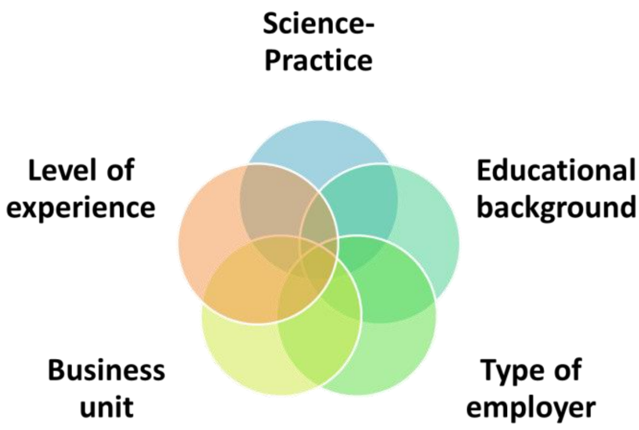

FIGURE 5.1 ASPECTS WHICH INFLUENCE AND DECIDE ABOUT UNCERTAINTY PERCEPTION AND HANDLING

In a third step and due to the multitude of aspects influencing uncertainty perception and handling, this doctoral research laid focus on the plurality of practitioners. Hereby, it broadened the current academic view by acknowledging that practitioners cannot be handled as one homogenous group but must rather be treated as different users with specific uncertainty information needs and demands. Hence, the usability regarding information about uncertainty is perceived differently by practitioners with implications for uncertainty integration and a need for more tailor-made approaches. These approaches must ensure that the interplay of new information and routinely used information complements and adds value to the decision at hand in order to be integrated into the decision-making process. Therefore, the insights of this research provide a basis for determining routines with which to integrate uncertainty into planning and decision-making and to bridge the science-practice gap. Consequently, six uncertainty routines were developed representing the pool of practitioners' uncertainty handling strategies (Fig. 5.2). The dominant usage of the different strategies hereby varies depending on business unit affiliation. While the practitioners working at the basic knowledge level focus on e.g. transparency, the operational management emphasises vulnerability and tacit knowledge and the strategic level highlights responsibility. Hence, depending on whom scientists approach, different needs and demands of uncertainty information are required to ensure target-group specific information and ensure uncertainty integration. This is also true regarding the time horizon of a management issue as the findings also suggest that uncertainty routines change depending on the time frame (see chapter 4.3.2).

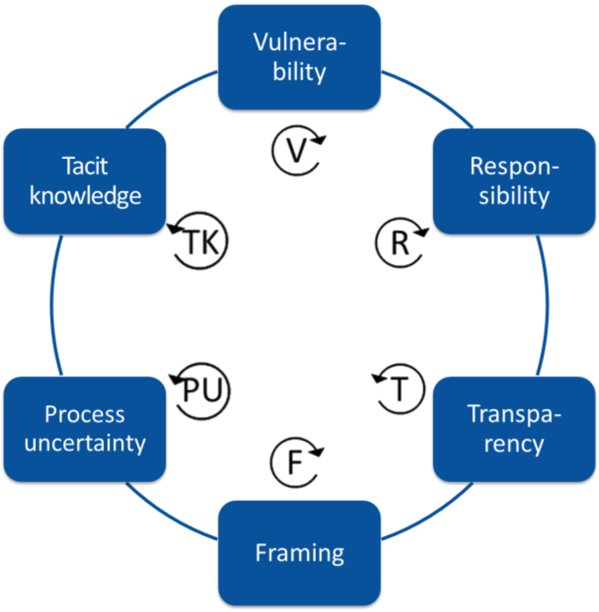

FIGURE 5.2 POOL OF UNCERTAINTY ROUTINES APPLIED BY PRACTITIONERS

The main finding of this last working step consists in showing a visual representation of the different usage of uncertainty routines in a qualitative system model (see Fig. 4.2). Thus, it provides a vehicle to foster cross-communication and organizational learning among and between the different professions. Moreover, it provides a practical strategy to increase fit and interplay of uncertainty information. Accordingly, it supports the integration of uncertainties in water-related planning and decision-making as it links transparently to the different needs and demands of practitioners.

Thus, the compilation of this research was able to identify the criteria, describe the prerequisites and provide a practical strategy to improve the integration of scientific uncertainties into planning and decision-making process in model-based water management.

5.2 CONTRIBUTION TO SCIENCE-PRACTICE-GAP RESEARCH

This doctoral research has contributed to two important research fields. First, it filled a gap regarding uncertainty perception of practitioners by in-depth analysis of their uncertainty handling and by highlighting the relevance of uncertainty integration for decision-makers which has been neglected so far. Secondly, it contributed to the general science-practice gap research by adding uncertainty as an important part of information and by emphasising the plurality of practitioners' perception of uncertainty. Acknowledging this plurality overcomes the thinking of a linear causal chain of information and opens up room for a plurality of knowing and, hence, different ways to cope with and to integrate uncertainties into final decisions.

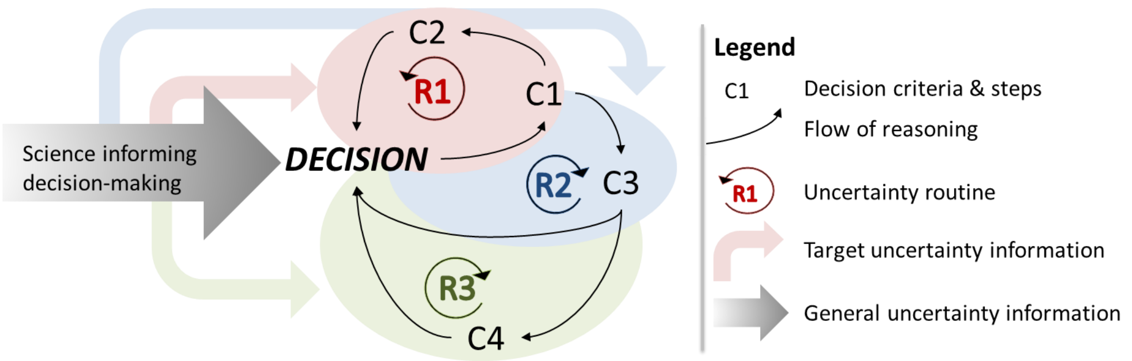

FIGURE 5.3 SCHEMATIC REPRESENTATION OF IMPLICATION OF CAUSAL LOOP DIAGRAM FOR SCIENCE-PRACTICE INTERACTION

As illustrated in figure 5.3, science informing decision-making has to acknowledge not only the decision but rather the different ways practitioners approach it to close the gap and ensure usability. On the right side of the figure a schematic causal loop diagram represents three potential loops and its related uncertainty routines informing the final decision. Hereby, the different loops may represent different practitioners with their specific view on the decision at hand. They may also represent only one type of practitioner but focussing on different time horizons. By closing the science-practice gap, science has to address especially the fit and interplay of their uncertainty information regarding the specific needs and context of the practitioner in order to ensure usability. Analysing the decision-making process in form of a qualitative system model, e.g. a causal loop diagram, supports targeting the tailor-made information, which is indicated by the coloured arrows in the figure. Thus, to ensure integration of uncertainties into the final decision-making, scientists, who inform at one point in the planning or decision-making process, must make sure that they address the same loop and issues as the practitioner.

These theoretical insights are also complemented by a practical strategy to integrate uncertainty in planning and decision-making. During the course of this doctoral research a total of three tools were developed to support uncertainty integration into planning and decision-making. The first tool is presented by the 2x2 uncertainty matrix which transparently shows level and location of uncertainties, and links the different causes of uncertainty to explicate how one copes with and compensates uncertainties either indirectly by considering fundamental uncertainties or by planning process uncertainties. The second tool is the integration and analytical framework which puts the matrix into the planning process and relates the implications of the level of uncertainty of certain actions or processes with the judgement phase in order to acknowledge the wider political and societal context. In general, both tools support the planners and decision-makers in their wish to transparently document involved uncertainties in a condensed and structured manner. Furthermore, they adequately influence practitioners' anchors by providing sound uncertainty information and making missing information visible with these tools. While these two tools focus on the transparency of uncertainty itself, the third tool, the causal loop diagram (CLD) emphases the transparency of uncertainty perception and handling of different practitioners and, hence, gives hints to close the usability gap by addressing fit, interplay and interaction. Therefore, a CLD gives implication for increasing fit of uncertainty information, fosters cross-communication, and enables learning (processes). Cross-communication at the intersections of different ways of knowing and uncertainty handling (crossing/intersecting loops) allows sharing of experiences. These experiences are a central part of decision-makers evaluated and reflected knowledge and central for adequate interplay with new or external information. By fostering discourse it also supports building trust and negotiating over meanings, hereby enabling interaction between different users of uncertainty information as well as producers of uncertainty information. In general, CLD as a tool can be used to support and structure participatory processes and may eventually foster social and/or organizational learning. These learning processes potentially increase the awareness of which perspectives to include, opens up discussion about users' needs and are a cornerstone of necessary transformation processes due to deep uncertainty.

5.3 RESEARCH LIMITATIONS

This research contributed substantially to increasing the understanding of practitioners' uncertainty perception and possibility to integrate uncertainty information into water-related decision-making (see sections 5.1 and 5.2). However, there are also some limitations in this research, more precisely three methodological constraints that potentially impact the results.

First, the sample of the survey with only 19% response rate presents a relatively small sample, possibly limiting generalizing results. This response rate results from the short sampling time during the one and half day conference "Day of Hydrology". The choice to only survey participants of the "Day of Hydrology" was made because this conference presents a well-established platform with intense interaction between science and practice thus enabling a closer analysis of the exchange at the science-practice interface. Main outcome of the survey is that the level of work experience has an impact on the degree of uncertainty acknowledgement. There is the possibility that this result may turn less distinctive in a greater sample. The same might be true for the uncertainty acknowledgement influence from the educational background. This influence, however, is also confirmed by the results of the extensive expert elicitation, which in turn also increases confidence regarding the results of level of work experience. Future research might follow-up the working level hypothesis and test again using a larger sample.

Secondly, due to the strong focus on the practitioners and their uncertainty handling and perception, scientists' perspective is mainly assumed to be homogenous. Chapter 4 of this thesis highlights, the importance to regard practitioners not as a homogenous entity but as a heterogeneous group with a plurality of perspectives and approaches to uncertainty handling. Treating scientists' perspective homogeneously and not conducting in-depth expert interviews with scientists to analyse their perspective might therefore present a certain weakness. However, the scientists' perspective was also asked for in the survey including the limitations mentioned above. Also, the choice to focus primarily on the understanding of water managers' perception and handling of uncertainty was made because such an approach was missing so far and more in-depth information promised to help increasing uncertainty integration into decision-making. Therefore, not focusing stronger on the scientists' perspective appears valid. Yet, future research should further investigate factors influencing scientists' uncertainty handling and communication to complement the picture. The first step in that direction was made by recognising the level of work experience as a cross-cutting property of science and practice.

Thirdly, the choice to derive the influence diagram from information from the expert elicitation rather than from an actual participatory process confines the final diagram to the researchers' conceptualization of the interviewees' mental models. By applying a semi-participatory approach in drawing the influence diagram, the diagram might miss technical details regarding the practical management task. The main focus of this technique, however, was not on improving or changing reservoir discharge, but on the different ways to reason about appropriate reservoir discharge. Therefore, the semi-participatory approach can be justified, because the missing technical details would not have changed the general reasoning. Nevertheless, future research on implementing systems model thinking in a participatory manner with focus on the robustness of the final management decision may complement this research.

5.4 OUTLOOK: UNCERTAINTY IN WATER MANAGEMENT

Uncertainties have always been part of water management. Due to the increasing complexity induced by global change and increased socio-hydrological interactions, however, integration of uncertainties becomes increasingly important for adequate management of water resources (e.g. Harremoës, 2003; Milly et al., 2008; Winkler, 2016). Adaptive water management is regarded as one strategy to cope with uncertainty (e.g. Harremoës, 2003; Warmink et al., 2017). This empirical iterative approach should help building capacity and flexible response in order to deal with unpredictability or uncertainty. However, thorough integration of uncertainties remains a challenge for many of the interviewed practitioners as there is a tension within the practice/policy side. Here adaptive approaches acknowledging uncertainties are stalled in the face of rigid regulations and the command and control paradigm. Furthermore, such an approach binds highly qualified personnel and requires additional monitoring resources. Here, practitioners from water associations in particular could apply reframing in order to convince policy-makers and promote a more flexible approach. For example, if the signal regarding the impact of climate change is ambiguous indicating water excess or water scarcity, one could reframe their management objective by asking for the optimal management instrument not ‘if’, but ‘when’ there is water excess or how to prepare when water scarcity appears. By asking ‘when’, the focus is on vulnerability of the systems’ stakeholder including society, economy and environment. In this case, decentralized measures, such as establishment or extension of retention areas may be one answer to reduce the vulnerability and integrate the involved uncertainties. Scientific research may support such efforts by informing practice with user-specific and usable uncertainty information and by providing an assessment of confidence.

While these approaches seem suitable to acknowledge uncertainty, the question if or if not decision-making processes kept pace accordingly remains. Furthermore, evidence-based knowledge as well as its uncertainty assessment enter an arena of power relations, interests, legal forces and other decision-relevant criteria, and will be assessed or viewed in relation to these other factors. Only a proactive communication strategy acknowledging the plurality of actors and their perceptions and agendas may give the well-deserved weight to this kind of information. The tools developed in this thesis provide a basis for such a substantially new communication strategy. Especially the cross-communication fostered by the CLD may induce second or third loop learning, where current context and its assumptions are questioned or underlying norms and values of current practice are contested. An example for the latter is the change from flood to flood risk management, hereby acknowledging or admitting that we are not able to fully control floods, but to assess risks and take precautions. These two learning cycles will become more important when dealing with irreducible uncertainty and when the stakes of decision-making are high. As this research showed, scientists as well as practitioners with a high level of work experience share their uncertainty sensitivity and coping capabilities and can contribute to this communication. While the 2x2 uncertainty matrix and the integration and analytical framework provide an opportunity to make their tacit knowledge available to others, the question of how uncertainty routines can be used by less experienced planners and decision-makers, and how they influence the quality of decision is worth further research.

6 REFERENCES

Abbott, J. (2005). Understanding and managing the unknown - The nature of uncertainty in planning. Journal of Planning Education and Research, 24(3), 237-251. doi: 10.1177/0739456x04267710

Akremi, L., Baur, N., & Fromm, S. (2011). Datenanalyse mit SPSS für Fortgeschrittene 1: Datenaufbereitung und uni-und bivariate Statistik (Vol. 1): Springer-Verlag.

Aven, T. (2010). Misconceptions of risk: John Wiley & Sons, Ltd.

Bakker, K. (2012). Water Security: Research Challenges and Opportunities. Science, 337(6097), 914-915. doi: 10.1126/science.1226337

Bakker, K., & Morinville, C. (2013). The governance dimensions of water security: a review. Phil. Trans. R. Soc. A, 371(2002), 20130116. doi: 10.1098/rsta.2013.0116

Ballard, T., & Lewandowsky, S. (2015). When, not if: the inescapability of an uncertain climate future. Phil. Trans. R. Soc. A, 373, 20140464. doi: 10.1098/rsta.2014.0464

Beven, K. (2008). Environmental modelling: an uncertain future? : Taylor & Francis.

Blöschl, G., & Montanari, A. (2010). Climate change impacts-throwing the dice? Hydrological Processes, 24(3), 374-381. doi: 10.1002/Hyp.7574

Bond, A., Morrison-Saunders, A., Gunn, J. A., Pope, J., & Retief, F. (2015). Managing uncertainty, ambiguity and ignorance in impact assessment by embedding evolutionary resilience, participatory modelling and adaptive management. Journal of Environmental Management, 151, 97-104. doi: 10.1016/j.jenvman.2014.12.030

Briley, L., Brown, D., & Kalafatis, S. E. (2015). Overcoming barriers during the co-production of climate information for decision-making. Climate Risk Management, 9, 41-49.

Brugnach, M., Dewulf, A., Pahl-Wostl, C., & Taillieu, T. (2008). Toward a Relational Concept of Uncertainty: about Knowing Too Little, Knowing Too Differently, and Accepting Not to Know. Ecology and Society, 13(2), 30.

Brugnach, M., Tagg, A., Keil, F., & de Lange, W. J. (2007). Uncertainty matters: Computer models at the science-policy interface. Water Resources Management, 21(7), 1075-1090. doi: 10.1007/s11269-006-9099-y

Carter, T. R., Jones, R. N., Lu, X., Bhadwal, S., Conde, C., Mearns, L. O., et al. (2007). New Assessment Methods and the Characterisation of Future Conditions. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson (Eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 133-171). Cambridge: Cambridge University Press.

Ceola, S., Montanari, A., Krueger, T., Dyer, F., Kreibich, H., Westerberg, I., et al. (2016). Adaptation of water resources systems to changing society and environment: a statement by the International Association of Hydrological Sciences. Hydrological Sciences Journal, 61(16), 2803-2817. doi: 10.1080/02626667.2016.1230674

Corner, A., Lewandosky, S., Philips, M., & Roberts, O. (2015). The Uncertainty Handbook. Bristol.

Coyle, R. G. (1996). System dynamics modelling: a practical approach (Vol. 1): CRC Press.

Coyle, R. G. (2000). Qualitative and quantitative modelling in system dynamics. System Dynanics Review, 16(3), 225-244.

Dee, L. E., Allesina, S., Bonn, A., Eklof, A., Gaines, S. D., Hines, J., et al. (2017). Operationalizing Network Theory for Ecosystem Service Assessments. Trends in Ecology and Evolution, 32(2), 118-130. doi: 10.1016/j.tree.2016.10.011

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J. L., & Blöschl, G. (2013). Socio-hydrology: conceptualising human-flood interactions. Hydrology and Earth System Sciences, 17(8), 3295-3303. doi: 10.5194/hess-17-3295-2013

Döll, P., & Romero-Lankao, P. (2017). How to embrace uncertainty in participatory climate change risk management—A roadmap. Earth's Future, 5(1), 18-36.

Eller, E., Lermer, E., Streicher, B., & Sachs, R. (2013). Psychologische Einflüsse auf die individuelle Einschätzung von Risiken. Emerging Risk Discussion Paper Munich RE.

ElSawah, S., Mclucas, A., & Mazanov, J. (2013). Using a cognitive mapping approach to frame the perceptions of water users about managing water resources: a case study in the Australian Capital territory. Water Resources Management, 27(9), 3441-3456.

Faulkner, H., Parker, D., Green, C., & Beven, K. (2007). Developing a translational discourse to communicate uncertainty in flood risk between science and the practitioner. Ambio, 36(8), 692-703. doi: 10.1579/0044-7447(2007)36[692:Datdtc]2.0.Co;2

Fazey, I., Fazey, J. A., & Fazey, D. M. A. (2005). Learning More Effectively from Experience. Ecology and Society, 10(2).

Funtowicz, S. O., & Ravetz, J. R. (1993). Science for the Post-Normal Age. Futures, 25(7), 739-755. doi: 10.1016/0016-3287(93)90022-L

Gabbert, S., van Ittersum, M., Kroeze, C., Stalpers, S., Ewert, F., & Olsson, J. A. (2010). Uncertainty analysis in integrated assessment: the users' perspective. Regional Environmental Change, 10(2), 131-143. doi: 10.1007/s10113-009-0100-1

Halbe, J., Pahl-Wostl, C., Sendzimir, J., & Adamowski, J. (2013). Towards adaptive and integrated management paradigms to meet the challenges of water governance. Water Science and Technology, 67(11), 2651-2660.

Harremoës, P. (2003). The need to account for uncertainty in public decision making related to technological change. Integrated assessment, 4(1), 18-25.

Höllermann, B., & Evers, M. (2015a). Ein risikobasiertes Integrations- und Analysekonzept zur Berücksichtigung von Unsicherheiten bei wasserwirtschaftlichen Entscheidungen. Hydrologie und Wasserbewirtschaftung, 59(5), 255-263. doi: 10.5675/HyWa_2015,5_6

Höllermann, B., & Evers, M. (2015b). Integration of uncertainties in water and flood risk management. Proc. IAHS, 370, 193-199. doi: 10.5194/piahs-370-193-2015

Höllermann, B., & Evers, M. (2017). Perception and handling of uncertainties in water management—A study of practitioners' and scientists' perspectives on uncertainty in their daily decision-making. Environmental Science & Policy, 71, 9-18. doi: http://dx.doi.org/10.1016/j.envsci.2017.02.003

Hooijer, A., Klijn, F., Pedroli, G. B. M., & Van Os, A. G. (2004). Towards sustainable flood risk management in the Rhine and Meuse river basins: Synopsis of the findings of IRMA-SPONGE. River Research and Applications, 20(3), 343-357. doi: 10.1002/Rra.781

Hulme, P. E. (2014). EDITORIAL: Bridging the knowing–doing gap: know-who, know-what, know-why, know-how and know-when. Journal of Applied Ecology, 51(5), 1131-1136. doi: 10.1111/1365-2664.12321

Inam, A., Adamowski, J., Halbe, J., & Prasher, S. (2015). Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: a case study in the Rechna Doab watershed, Pakistan. Journal of Environmental Management, 152, 251-267. doi: 10.1016/j.jenvman.2015.01.052

Ingram, H. (2013). No universal remedies: design for contexts. Water International, 38(1), 6-11.

IRGC. (2005). Risk Governance - Towards an Integrative Approach (Vol. 1). Geneva.

IRGC. (2008). An introduction to the IRGC Risk Governance Framework. Geneva.

Irwin, A., & Wynne, B. (1996). Misunderstanding science?: the public reconstruction of science and technology: Cambridge University Press.

Janssen, P. H. M., Petersen, A. C., van der Sluijs, J. P., Risbey, J. S., & Ravetz, J. R. (2005). A guidance for assessing and communicating uncertainties. Water Science and Technology, 52(6), 125-131.

Kasperson, R. (2010). Science and disaster reduction. International Journal of Disaster Risk Science, 1(1), 3-9. doi: 10.3974/j.issn.2095-0055.2010.01.002

Kinzig, A. (2003). Uncertainty and the Scientist. AMBIO: a Journal of the Human Environment, 32(5), 329-329.

Kinzig, A., Starrett, D., Arrow, K., Aniyar, S., Bolin, B., Dasgupta, P., et al. (2003). Coping with uncertainty: a call for a new science-policy forum. AMBIO: a Journal of the Human Environment, 32(5), 330-335.

Klinke, A., & Renn, O. (2014). Expertise and experience: a deliberative system of a functional division of labor for post-normal risk governance. Innovation: The European Journal of Social Science Research, 27(4), 442-465. doi: 10.1080/13511610.2014.943160

Kuckartz, U. (2010). Einführung in die computergestützte Analyse qualitativer Daten Lehrbuch (3., aktualisierte Auflage ed.). Wiesbaden: VS Verlag für Sozialwissenschaften / GWV Fachverlage GmbH, Wiesbaden.

Kuckartz, U., Rädiker, S., Ebert, T., & Schehl, J. (2013). Statistik: eine verständliche Einführung: Springer-Verlag.

Kundzewicz, Z., Krysanova, V., Benestad, R., Hov, Ø., Piniewski, M., & Otto, I. (2018). Uncertainty in climate change impacts on water resources. Environmental Science & Policy, 79, 1-8.

Larson, K. L., White, D. D., Gober, P., & Wutich, A. (2015). Decision-Making under Uncertainty for Water Sustainability and Urban Climate Change Adaptation. Sustainability, 7(11), 14761-14784. doi: 10.3390/su71114761

Lemos, M. C., Kirchhoff, C. J., & Ramprasad, V. (2012). Narrowing the climate information usability gap. Nature Climate Change, 2(11), 789-794.

Leung, W., Noble, B., Gunn, J., & Jaeger, J. A. (2015). A review of uncertainty research in impact assessment. Environmental Impact Assessment Review, 50, 116-123.

Mauelshagen, C., Smith, M., Schiller, F., Denyer, D., Rocks, S., & Pollard, S. (2014). Effective risk governance for environmental policy making: A knowledge management perspective. Environmental Science & Policy, 41, 23-32. doi: 10.1016/j.envsci.2014.04.014

Maxim, L., & van der Sluijs, J. P. (2011). Quality in environmental science for policy: Assessing uncertainty as a component of policy analysis. Environmental Science & Policy, 14(4), 482-492. doi: 10.1016/j.envsci.2011.01.003

Mayer, H. O. (2012). Interview und schriftliche Befragung: Grundlagen und Methoden empirischer Sozialforschung: Oldenbourg Verlag.

Meadows, D. H. (2008). Thinking in systems: A primer: chelsea green publishing.

Merz, B. (2006). Hochwasserrisiken: Grenzen und Möglichkeiten der Risikoabschätzung: Schweizerbart'sche Verlagsbuchhandlung.

Merz, B., Vorogushyn, S., Lall, U., Viglione, A., & Blöschl, G. (2015). Charting unknown waters-On the role of surprise in flood risk assessment and management. Water Resources Research, 51(8), 6399-6416. doi: 10.1002/2015wr017464

Meuser, M., & Nagel, U. (2009). Das Experteninterview—konzeptionelle Grundlagen und methodische Anlage. In S. Pickel, G. Pickel, H.-J. Lauth & D. Jahn (Eds.), Methoden der vergleichenden Politik-und Sozialwissenschaft (pp. 465-479): Springer.

Milly, P. C., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., et al. (2008). Climate change. Stationarity is dead: whither water management? Science, 319(5863), 573-574. doi: 10.1126/science.1151915

Nearing, G. S., Tian, Y., Gupta, H. V., Clark, M. P., Harrison, K. W., & Weijs, S. V. (2016). A philosophical basis for hydrological uncertainty. Hydrological Sciences Journal, 61(9), 1666-1678.

Nilson, E., & Krahe, P. (2012). Zum Transfer der Unsicherheiten von Abfluss-Projektionen des 21.Jahrhunderts in den politisch-administrativen Raum. Forum für Hydrologie und Wasserbewirtschaftung, 31(12), 287-298.

Olsson, J. A., & Andersson, L. (2007). Possibilities and problems with the use of models as a communication tool in water resource management. Water Resources Management, 21(1), 97-110. doi: DOI 10.1007/s11269-006-9043-1

Painter, J. (2015). Taking a bet on risk. Nature Climate Change, 5(4), 286-288. doi: 10.1038/nclimate2542

Pappenberger, F., & Beven, K. J. (2006). Ignorance is bliss: Or seven reasons not to use uncertainty analysis. Water Resources Research, 42(5). doi: 10.1029/2005wr004820

Patt, A. G., & Weber, E. U. (2014). Perceptions and communication strategies for the many uncertainties relevant for climate policy. Wiley Interdisciplinary Reviews: Climate Change, 5(2), 219-232.

Petr, M., Boerboom, L., Ray, D., & van der Veen, A. (2014). An uncertainty assessment framework for forest planning adaptation to climate change. Forest Policy and Economics, 41, 1-11. doi: 10.1016/j.forpol.2013.12.002

Pidgeon, N., & Fischhoff, B. (2011). The role of social and decision sciences in communicating uncertain climate risks. Nature Climate Change, 1, 35-41. doi: 10.1038/nclimate1080

Powell, J., Mustafee, N., Chen, A., & Hammond, M. (2016). System-focused risk identification and assessment for disaster preparedness: Dynamic threat analysis. European Journal of Operational Research, 254(2), 550-564.

Reed, M., Evely, A., Cundill, G., Fazey, I., Glass, J., Laing, A., et al. (2010). What is social learning? Ecology and Society, 15(4).

Refsgaard, J. C., van der Sluijs, J. P., Højberg, A. L., & Vanrolleghem, P. A. (2007). Uncertainty in the environmental modelling process – A framework and guidance. Environmental Modelling & Software, 22(11), 1543-1556. doi: 10.1016/j.envsoft.2007.02.004

Reichert, P., Borsuk, M., Hostmann, M., Schweizer, S., Sporri, C., Tockner, K., et al. (2007). Concepts of decision support for river rehabilitation. Environmental Modelling & Software, 22(2), 188-201. doi: 10.1016/j.envsoft.2005.07.017

Renn, O. (2008). Risk governance: coping with uncertainty in a complex world: Earthscan.

Rosenberg, A. A. (2007). Fishing for certainty. Nature, 449(7165), 989-989. doi: 10.1038/449989a

Roux, D. J., Rogers, K. H., Biggs, H. C., Ashton, P. J., & Sergeant, A. (2006). Bridging the science-management divide: Moving from unidirectional knowledge transfer to knowledge interfacing and sharing. Ecology and Society, 11(1).

Sigel, K., Klauer, B., & Pahl-Wostl, C. (2010). Conceptualising uncertainty in environmental decision-making: The example of the EU water framework directive. Ecological Economics, 69(3), 502-510. doi: 10.1016/j.ecolecon.2009.11.012

Smith, L. A., & Stern, N. (2011). Uncertainty in science and its role in climate policy. Phil. Trans. R. Soc. A, 369(1956), 4818-4841. doi: 10.1098/rsta.2011.0149

Sterman, J. D. J. D. (2000). Business dynamics: systems thinking and modeling for a complex world.

Stirling, A. (2010). Keep it complex. Nature, 468(7327), 1029-1031. doi: 10.1038/4681029a

Taylor, A. L., Dessai, S., & de Bruin, W. B. (2015). Communicating uncertainty in seasonal and interannual climate forecasts in Europe. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, 373, 20140454. doi: 10.1098/rsta.2014.0454

Toomey, A. H. (2016). What happens at the gap between knowledge and practice? Spaces of encounter and misencounter between environmental scientists and local people. Ecology and Society, 21(2), 28. doi: 10.5751/es-08409-210228

UNESCO-IHP. (2011). The Impact of Global Change on Water Resources: The Response of UNESCO's Internatinal Hydrological Programme.

van Asselt, M. B., & Rotmans, J. (2002). Uncertainty in integrated assessment modelling - from positivism to plurality. Climatic change, 54(1-2), 75-105.

van den Hoek, R. E., Brugnach, M., Mulder, J. P. M., & Hoekstra, A. Y. (2014). Analysing the cascades of uncertainty in flood defence projects: How "not knowing enough" is related to "knowing differently". Global Environmental Change-Human and Policy Dimensions, 24, 373-388.

Vogel, C., Moser, S. C., Kasperson, R. E., & Dabelko, G. D. (2007). Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. Global

Environmental Change-Human and Policy Dimensions, 17(3-4), 349-364. doi: 10.1016/j.gloenvcha.2007.05.002

Walker, W. E., Harremoës, P., Rotmans, J., van der Sluijs, J. P., van Asselt, M. B., Janssen, P., et al. (2003). Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. Integrated assessment, 4(1), 5-17.

Wardekker, J. A., van der Sluijs, J. P., Janssen, P. H. M., Kloprogge, P., & Petersen, A. C. (2008). Uncertainty communication in environmental assessments: views from the Dutch science-policy interface. Environmental Science & Policy, 11(7), 627-641. doi: 10.1016/j.envsci.2008.05.005

Warmink, J., Brugnach, M., Vinke-de Kruijf, J., Schielen, R., & Augustijn, D. (2017). Coping with Uncertainty in River Management: Challenges and Ways Forward. Water Resources Management, 31(14), 4587-4600.

Weichselgartner, & Kasperson, R. (2010). Barriers in the science-policy-practice interface: Toward a knowledge-action-system in global environmental change research. Global Environmental Change-Human and Policy Dimensions, 20(2), 266-277. doi: 10.1016/j.gloenvcha.2009.11.006

Weichselgartner, & Pigeon, P. (2015). The Role of Knowledge in Disaster Risk Reduction. International Journal of Disaster Risk Science, 6(2), 107-116. doi: 10.1007/s13753-015-0052-7

Westerberg, I. K., Di Baldassarre, G., Beven, K. J., Coxon, G., & Krueger, T. (2017). Perceptual models of uncertainty for socio-hydrological systems: a flood risk change example. Hydrological Sciences Journal, 62(11), 1705-1713.

Wilby, R. L., & Dessai, S. (2010). Robust Adaptation to Climate Change. Weather, 65(7), 180-185. doi: 10.1002/wea.543

Willows, R., Reynard, N., Meadowcroft, I., & Connell, R. (2003). Climate adaptation: Risk, uncertainty and decision-making. Part 2. UKCIP Technical Report. Oxford: UK Climate Impacts Programme.

Winkler, J. A. (2016). Embracing Complexity and Uncertainty. Annals of the American Association of Geographers, 106(6), 1418-1433. doi: 10.1080/24694452.2016.1207973

Zandvoort, M., Van der Vlist, M. J., Klijn, F., & Van den Brink, A. (2017). Navigating amid uncertainty in spatial planning. Planning Theory, 1473095216684530.

7 APPENDICES

7.1 EXPERT ELICITATION

In the following the guideline and questions of the semi structured expert elicitation are presented. The interviews were held in German and the guideline was translated into English for the purpose of this publication:

EXPERT**elicitation**
Uncertainties in water management

universitätbonn Geographie

Introduction

Thank you for the opportunity to carry out this interview! I would like to briefly introduce myself and my research project, before we start the Interview.

My name is Britta Höllermann and I am currently doing my PhD at the Department of Geography of the University of Bonn on the topic of consideration of uncertainties in model-based water management. My topic has developed from many years of researching hydrological topics at the interface of science and management, and I am pleased to be able to exchange with you today.

Our conversation will last about 1 hour. I would like to record the interview, if you do not have any objections. All answers will be treated confidentially and anonymously.

The interview is divided into the following sets of questions:

1. Professional background
2. Definition, perception and evaluation of uncertainties
3. Handling of uncertainties
4. Knowledge transfer for knowledge-based decisions
5. Role of uncertainties in the decision-making process
6. Conflict potential, risk management and uncertainty

---

1. Professional background

- May you briefly outline your current position and your career development?
- What is the scope of your task?
- (How are you involved in decisions?)

Dipl. Geogr. Britta Höllermann * Department of Geography * University Bonn
Meckenheimer Allee 166 * 53115 Bonn 0228-73 3365 * bhoellermann@uni-bonn.de

EXPERT**elicitation**
Uncertainties in water management

2. Definition, perception and evaluation of uncertainties

Uncertainty and risk are terms that are used not only in many scientific disciplines, but also in everyday life. The problem with this broad use is that often different things are meant and a sharp definition is particularly important. Therefore especially your definitions and perception of uncertainties are of interest to me, which I would like to query in the following:

- Do you make a difference between risk and uncertainty? If so, how do you define the difference?
- What types of uncertainties are known to you? Can you further break it down into types, causes and /or sources?
- What kinds of uncertainties are familiar to you? Or rather what are the most relevant and crucial uncertainties in water management for you?

In science, a distinction is made between aleatoric and epistemic uncertainties. Aleatoric uncertainties are uncertainties that occur due to the variability of the system and are not reducible. Epistemic uncertainties are uncertainties that occur due to our limited knowledge of the phenomenon and are in principle reducible. Do you distinguish between the two possible definitions of uncertainties? If so, why do you think the difference is relevant / not relevant?

(Example: Dike as a protective device: aleatory → which altitude, epistemic → which areas are affected, understanding of the hydrology or construction measure)

- What information about uncertainty creates trust in model results? Which sources of uncertainty (such as input data, model structure, etc.) are of particular importance to you, and should be given special consideration and communication by the modellers?

The topic of uncertainty affects different areas of knowledge: on the one hand the natural processes such as climate, water availability and quality, but also technical infrastructure such as dams and on the other hand societal issues such as socio-economical, legal and political aspects.

- Do you consider uncertainties in all three areas of knowledge or do you focus on, for example, the natural processes and use the other areas more as a framework?
- What are the goals of an uncertainty analysis for you? And why are you dealing with this topic?

Dipl. Geogr. Britta Höllermann * Department of Geography * University Bonn
Meckenheimer Allee 166 * 53115 Bonn 0228-73 3365 * bhoellermann@uni-bonn.de

3. Handling of uncertainty

- How do you deal with uncertainties? How do you think you should handle uncertainty?
- How are uncertainties addressed at your working place? How one should address uncertainties?
- How do you record information about uncertainty in your company/authority?
- Do you think it is possible to sufficiently quantify uncertainty? Do you think that is enough? Which qualitative aspects can you imagine in addition?
- For example, are bandwidths and sensitivity parameters helpful to you while dealing with uncertainties?
- Do legal regulations and requirements have an influence on your handling of uncertainties? For example, do you anticipate potential guidelines from Brussels? What requirements must be met during managing your water resources, e.g. general legal framework, contracts with municipalities or other stakeholders?

Change and adaptation are two key words that have been particularly important in recent years. In general, human intervention in natural systems leads to complex socio-hydrological systems where the management of water resources is associated with uncertainties. I am therefore particularly interested in the importance of climate change for you and your area of responsibility.

- What importance does this have in comparison with social change or land use change?
- How does knowledge about global change affect your handling of uncertainties?

4. Knowledge transfer for knowledge-based decisions

- Which flow of information exists between decision-makers and employees or rather external experts (vertical exchange)?
- How does the internal exchange work? What does the information flow include? How is information exchanged between employees (lateral exchange)? Do they follow a protocol for this or is it an informal exchange?
- How do external reports aid in decision-making? How does the exchange of knowledge with externals work? In particular, at the interface between practice and science: What are your requirements to science with regard to the provision of information on the topic of uncertainties, for example, in modelling, forecasting, action planning, etc.
- How are uncertainties from external institutions, e.g. DWD provided? Is this information helpful? What is missing?

Dipl. Geogr. Britta Höllermann * Department of Geography * University Bonn
Meckenheimer Allee 166 * 53115 Bonn 0228-73 3365 * bhoellermann@uni-bonn.de

EXPERTelicitation

Uncertainties in water management

universitätbonn Geographie

5. Role of uncertainties in the decision-making process

- At the beginning you outlined your role regarding decisions. Can you possibly go into more detail on how you are involved in decision-making processes and what kind of decisions or rather which decisions you make?
- How are decisions made in your authority? You can name one or two examples.
- Are there rules regulation the internal procedures for example?
- Do information about uncertainty play a crucial role at this?
- Which (further) criteria are used for decisions? Which criteria are often decisive? (legal requirements? financial aspects?, etc.)
- It is often said that uncertainties lead to delayed action, in some cases information about uncertainty should be used tactically. How do you rate this statement?
- In which areas would more clarity about uncertainty lead to improved decisions?
- Risk management as a keyword: what significance does risk management have for you? What does belong to risk management for you?

6. Conflict potential, risk management and uncertainty

- What are the potential conflicts of interest and objective in your thematic setting?
- Are the conflicts of objectives related to the areas of responsibility or to the actors?
- How do you deal with that?
- Can detailed and open information about uncertainties be an aid in solving these conflicts of objective?
- Does your risk perception decide upon the degree of attention to uncertainties?

Conclusion

Before I finish the interview, I would like to know if you missed any important question?

Or did you notice particularly relevant points during the interview, which I should definitely pay attention to?

Thank you again for your time and the very interesting conversation!

Dipl. Geogr. Britta Höllermann * Department of Geography * University Bonn
Meckenheimer Allee 166 * 53115 Bonn 0228-73 3365 * bhoellermann@uni-bonn.de

7.2 EXPERT SURVEY

The questionnaire of the expert survey was distributed among conference participants of "Tag der Hydrologie" 2015 in Bonn. The questionnaire was originally written in German and translated for this publication.

EXPERTsurvey
Uncertainties in water management

universitätbonn | Geographie

Dear participants of the day of Hydrology 2015 in Bonn,

as part of my research project „Consideration of uncertainties in water management from the perspective of science and practice", I would like to ask you to share your expertise in this survey. The data will be anonymized and used only in the context of the research project. If you have any questions about the project and / or this survey, feel free to contact me.

I am pleased if you could drop the completed questionnaire at the reception in the box provided.

I would like to thank you for your participation, time and support of the project.

Best regards,

Britta Höllermann

1. **To what extend are you dealing with the topic: „Consideration of uncertainties in your research and planning and decision-making process"**

   Please rate on a scale from 0 to 10 by ticking:

   Do not bother me | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | I am extremely engaged with

2. **Uncertainties are often only named qualitatively. Please assign quantitative values to the following qualitative statements:**

   You can highlight a specific value as well as a range of values:

	0	10	20	30	40	50	60	70	80	90	100 %
Very likely											
Likely											
50/50 chance											
Less likely											
Unlikely											

3. **How do you define and distinguish between uncertainty and risk?**

   Please explain briefly:

   Uncertainty

   Risk

Dipl. Geogr. Britta Höllermann * Department of Geography * University Bonn
Meckenheimer Allee 166 * 53115 Bonn 0228-73 3365 * bhoellermann@uni-bonn.de 1/4

EXPERTsurvey
Uncertainties in water management

universitätbonn Geographie

4. How do you rate the following statements about uncertainty analysis?

Please tick the left box (0), if you do not agree to the statement. If you fully agree, place your cross on the far right (4).

Do not agree 0	1	2	3	Fully agree 4	Don't know	Statement
☐	☐	☐	☐	☐	☐	Uncertainty analysis is not necessary in face of physical realistic models.
☐	☐	☐	☐	☐	☐	An uncertainty analysis is not helpful for understanding hydrological and hydraulic processes.
☐	☐	☐	☐	☐	☐	Uncertainties in form of probability distributions are not understood by decision-makers and the public.
☐	☐	☐	☐	☐	☐	Uncertainty analysis cannot be integrated into planning and decision-making processes. For example, bandwidths are often too wide to choose between different scenarios.
☐	☐	☐	☐	☐	☐	Conducting an uncertainty analysis is too difficult, costly and time consuming.
☐	☐	☐	☐	☐	☐	Information about uncertainties has no influence on the final planning or decision.
☐	☐	☐	☐	☐	☐	Uncertainty analysis helps to identify knowledge gaps.
☐	☐	☐	☐	☐	☐	Uncertainty analysis increases confidence of practice in the robustness of scientific statements / results.
☐	☐	☐	☐	☐	☐	Uncertainty analysis increases the quality of decisions (e.g. about parameters, scheduling options, etc.).
☐	☐	☐	☐	☐	☐	Uncertainty analysis increases public and stakeholder confidence in decisions.

5. What uncertainties do you consider to be particularly relevant to your professional environment?

Please tick, how important the different sources of uncertainty are for your daily work.

Not important	Important	Very important	Source
☐	☐	☐	Model structure
☐	☐	☐	Model technique
☐	☐	☐	Boundary conditions
☐	☐	☐	Parameters
☐	☐	☐	Measured data
☐	☐	☐	Socio-economic szenarios
☐	☐	☐	Climate scenarios
☐	☐	☐	Model system data (e.g. land use, etc.)
☐	☐	☐	External driving forces, that can change the (model) system

Not important	Important	Very important	Source
☐	☐	☐	Legal requirements (changes)
☐	☐	☐	Standards (conversion)
☐	☐	☐	Availability of knowledge
☐	☐	☐	Selection of Knowledge/Sources
☐	☐	☐	Expert knowledge
☐	☐	☐	Human ressources
☐	☐	☐	Financial resources
☐	☐	☐	Other:

Dipl. Geogr. Britta Höllermann * Department of Geography * University Bonn
Meckenheimer Allee 166 * 53115 Bonn 0228-73 3365 * bhoellermann@uni-bonn.de

EXPERT**survey**
Uncertainties in water management

universität**bonn** Geographie

6. How do you rate following statements? Think of how you deal with uncertainties in your professional responsibilities. Each statement therefore begins with „In my daily business…“

Please tick the left box (0), if you do not agree to the statement. If you fully agree, place your cross on the far right (4).

Do not agree 0	1	2	3	Fully agree 4	Don't know	
0	1	2	3	4	☐	… I do not expect uncertainties to play a significant role.
0	1	2	3	4	☐	… I also take into account uncertainties that arise from the planning process.
0	1	2	3	4	☐	… I am aware of the uncertainties of models, etc., but do not integrate them into my planning and decision-making processes or research processes.
0	1	2	3	4	☐	… uncertainties play a role with regard to the short- and medium-term forecast.
0	1	2	3	4	☐	… uncertainties play a role in terms of long-term forecasting.
0	1	2	3	4	☐	… uncertainties are given too little attention.
0	1	2	3	4	☐	… I lack resources to take uncertainties sufficiently into account.
0	1	2	3	4	☐	… the robustness of results / plans / decisions is examined taking into account the underlying uncertainties.
0	1	2	3	4	☐	… I also identify the various sources of uncertainty and their contribution to overall uncertainty.
0	1	2	3	4	☐	… I use bandwidths from predictive models.
0	1	2	3	4	☐	… I try to reduce the uncertainties with more information.
0	1	2	3	4	☐	… I attach great importance to expert assessments to counter uncertainties.
0	1	2	3	4	☐	… I explicitly or implicitly use risk-based approaches to take the uncertainties into account.
0	1	2	3	4	☐	… I transparently show my work stages that have led to the result / decision, to communicate implicitly also uncertainties.
0	1	2	3	4	☐	… there is a good and efficient exchange of knowledge also regarding the limits of knowledge.
0	1	2	3	4	☐	… if uncertainties have a decisive influence on results or plans, they are explicitly communicated.
0	1	2	3	4	☐	… I talk with colleagues and / or stakeholders about uncertainties when confronted.
0	1	2	3	4	☐	… uncertainties are communicated target-group-specific.
0	1	2	3	4	☐	… I feel sufficiently informed about the limits of e.g. model results, etc.

Dipl. Geogr. Britta Höllermann * Department of Geography * University Bonn
Meckenheimer Allee 166 * 53115 Bonn 0228-73 3365 * bhoellermann@uni-bonn.de

EXPERT**survey**
Uncertainties in water management

universität**bonn** Geographie

7. Which aspects promote or intensify your consideration of uncertainties?

Please judge the following statements by how much this promotes your consideration of uncertainties.

Promotes 0	1	2	3	Does not promote 4	Don't know	
0	1	2	3	4	☐	Different assumptions and boundary conditions are considered critical.
0	1	2	3	4	☐	Limit values with regard to (legally) standards or goals could be exceeded or fallen short of.
0	1	2	3	4	☐	Sensitivity of the system is high and small changes have a significant effect on costs and risks.
0	1	2	3	4	☐	Great uncertainties exist regarding the social system.
0	1	2	3	4	☐	Great uncertainties exist regarding the natural system.
0	1	2	3	4	☐	Planning and decisions are of high relevance for the society, the company, etc.
0	1	2	3	4	☐	There is no agreement on (planning and decision) goals.
0	1	2	3	4	☐	There are many different actors and stakeholders involved.
0	1	2	3	4	☐	The used information comes from different sources and has not been prepared by oneself.
0	1	2	3	4	☐	I am responsible for the robustness of my results / decisions.
0	1	2	3	4	☐	It should create (public) confidence in results / decisions.

8. Background information

Which Gender are you? ☐ Female ☐ Male

Which role is most applicable to you? ☐ Scientist ☐ Practical actor ☐ Political decision-maker ☐ Exhibitors ☐ Student ☐ ________________

How long are you working in this function? ☐ < 5 ☐ 5 - 10 ☐ 10 - 20 ☐ > 20 years

What is your thematic focus? ______________________________

Which discipline do you come from? ☐ Earth science ☐ Humanities ☐ Engineering science ☐ ________________

Do you have any further comments to the topic „Consideration of uncertainties“?

Thank you for your support!

Please enter the completed questionnaire at the reception in the box provided there

Dipl. Geogr. Britta Höllermann * Department of Geography * University Bonn
Meckenheimer Allee 166 * 53115 Bonn 0228-73 3365 * bhoellermann@uni-bonn.de

4/4

8 PUBLICATIONS

8.1 PEER-REVIEWED JOURNAL ARTICLES / BOOK CHAPTERS

Höllermann, B. & Evers, M. (2017). Decision-making under uncertainty: Acknowledging plurality of water managers' uncertainty handling routines through qualitative system analysis. Water Resources Research (under review).

Evers, M., Höllermann, B., Almoradie, A., Garcia Santos, G., & Taft, L. (2017). The Pluralistic Water Research Concept: A New Human-Water System Research Approach. Water, 9 (12), 933.

de Brito, M. M., Evers, M., & Höllermann, B. (2017): "Prioritization of flood vulnerability, coping capacity and exposure indicators through the Delphi technique: A case study in Taquari-Antas basin, Brazil". International Journal of Disaster Risk Reduction, 24, 119-128. doi: https://doi.org/10.1016/j.ijdrr.2017.05.027

Höllermann, B. & M. Evers (2017): "Perception and handling of uncertainties in water management—A study of practitioners' and scientists' perspectives on uncertainty in their daily decision-making". Environmental Science & Policy, 71, 9-18. doi: http://dx.doi.org/10.1016/j.envsci.2017.02.003

Johannsen, I., J. Hengst, A. Goll, B. Höllermann & B. Diekkrüger (2016): "Future of Water Supply and Demand in the Middle Drâa Valley, Morocco, under Climate and Land Use Change." Water 8(8): 313.

Höllermann, B., & Evers, M (2015): Ein risikobasiertes Integrations- und Analysekonzept zur Berücksichtigung von Unsicherheiten bei wasserwirtschaftlichen Entscheidungen. – Hydrologie und Wasserbewirtschaftung 59 (5), 255–263; DOI: 10.5675/HyWa_2015,5_6

Höllermann, B., & Evers, M. (2015). Integration of uncertainties in water and flood risk management. Proc. IAHS, 370, 193-199.

Giertz, S., Diekkrüger, B. & B. Höllermann (2012). Impact of Global Change on water resources in the Quémé catchment, Benin. In K.J. Bogardi, J. Leentvar & H.-P. Nachtnebel (Eds.): River basins and Change. GWSP and UNESCO-IHE. p. 34-40.

Höllermann, B., S. Giertz & B. Diekkrüger. 2010. Benin 2025 - Balancing future water availability and demand using the WEAP 'Water Evaluation and Planning' system. Water Resources Management. doi:10.1007/s11269-010-9622-z

Giertz, S., B. Diekkrüger, C. Hiep, & B. Höllermann. 2010. Water related Problems. In: Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa, eds. P. Speth, M. Christoph and B. Diekkrüger, Springer: 484-511.

Hadjer, K., B. Höllermann & M. Bollig. 2010. Social organization, livelihoods and water supply in Benin. In: Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa, eds. P. Speth, M. Christoph and B. Diekkrüger, Springer: 286-304.

Höllermann, B., B. Diekkrüger & S. Giertz. 2009. Bewertung der aktuellen und zukünftigen Wasserverfügbarkeit des Ouémé Einzugsgebiets (Benin, Westafrika) für ein integriertes Wasserressourcenmanagement mit Hilfe des Entscheidungsunterstützungsmodells WEAP. Hydrologie und Wasserbewirtschaftung 53 (5): 305-315.

8.2 CONFERENCE CONTRIBUTIONS (SELECTED)

8.2.1 ORAL PRESENTATIONS[6]

Höllermann, B. & Evers, M. (2018): “Wahrnehmung und Umgang mit Unsicherheiten in den M³ Bereichen- Studie über Strategien zur Integration von Unsicherheiten in Entscheidungsprozesse“. Tag der Hydrologie 2018 in Dresden.

[6] First author equals presenter unless otherwise stated.

Höllermann, B. & Evers, M. (2017): "Insights into water managers' perception and handling of uncertainties – a study of the role of uncertainty in practitioners' planning and decision-making". Geophysical Research Abstracts, 19 (EGU): 2162.

Evers, M., Höllermann, B., Almoradie, A., Taft, L., & Garcia-Santos, G. (2017): "The pluralistic water research concept – a new human-water system research approach". Geophysical Research Abstracts 19 (EGU): 14371.

Evers, M., Höllermann, B., Almoradie, A., & Taft, L. (2016). Benefits from a geographers' perspective on human-water systems - the waterscape concept. Geophysical Research Abstracts, 18 (EGU), 8402.

Höllermann, B. & Evers, M. (2015). Integration wissenschaftlicher Unsicherheiten in Entscheidungsprozesse - Ein risikobasierter Ansatz zur verbesserten Berücksichtigung von Unsicherheiten im Wassermanagement. In M. Evers & B. Diekkrüger (Eds.), Tag der Hydrologie (Vol. 35.15, pp. 77-87). Forum für Hydrologie und Wasserwirtschaft, Bonn.

Giertz, S., Diekkrüger, B., & Höllermann, B. (2010): „Assessment of the current and future water balance of the Ouémé catchment (Benin) for an integrated water resource management by using the WEAP water planning model". Geophysical Research Abstracts, 12 (EGU 2010): 8934.

Giertz, S., Diekkrüger, B. & Höllermann, B. (2010). Impact of global change on water resources in the Ouémé catchment, Benin. In The Global Dimensions of Change in River Basins - Threats, Linkages and Adaptation (pp. 57-65). GWSP.

8.2.2 POSTER PRESENTATIONS

Höllermann, B., & Evers, M. (2018). "Coping with change and its uncertainty in water management – Qualitative system analysis as a vehicle to visualize the plurality of practitioners' uncertainty handling routines". Geophysical Research Abstracts, 20 (EGU 2018): 13585.

Höllermann, B (2018). "Berücksichtigung von Unsicherheiten im Wassermanagement aus der Perspektive von Wissenschaft und Praxis. Ausgewählte Ergebnisse der Umfrage im Rahmen des Tags der Hydrologie 2015 in Bonn". Tag der Hydrologie 2018 Dresden.

Höllermann, B., & Evers, M. (2015). “Umgang mit Zielkonflikten und Unsicherheiten im Wassermanagement - Ein Analysekonzept am Beispiel der Talsperrensteuerung“. Deutscher Kongress für Geographie 2016 in Berlin.

9 ABOUT THE AUTHOR

Britta Höllermann is a geographer and currently works as a research assistant and PhD candidate at the University of Bonn. Her research addresses human water interactions, water resources management and uncertainty perception and handling at the science-practice interface. Interdisciplinary thinking and integration of insights from social and natural sciences builds the basis for her investigations regarding human water interactions for example by calculating the water balance of the Ouémé catchment in Benin or by developing a pluralistic water research concept together with her working group. The overarching question is how do the different disciplines contribute to answer relevant water-related challenges, foster discourse and allow contextualization of own research results. With her PhD thesis she investigates the different dimensions of uncertainty in water management, their perception by scientists and practitioners and their final role within the decision-making process. The research aims at identifying routines for uncertainty integration to improve the quality of decisions. In general, Britta Höllermann's research is characterized by working at the interfaces of social & natural science and science & practice/policy. Her current engagement with the socio-hydrology community by e.g. co-convening sessions and as a member of the IAHS Panta Rhei working group on transdisciplinarity support this work.