Factors influencing the adoption of adaptive policy by water utilities

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Abstract

Over recent decades there have been advances in the research behind adaptive policy approaches. More recently, emerging qualitative approaches for managing deep uncertainty has drawn the attention of planners in the water industry, particularly in water utilities. Despite interest from both the water industry and the research community to see these novel approaches applied, there have been limited applications and no published guidance to support the operationalisation of these approaches in water utilities. This thesis seeks to bridge this gap by answering the question: "What are the factors influencing the adoption of adaptive policy approaches by water utilities?" To answer this question, a design science approach was used to understand current barriers and enablers to the adoption of such methods in water utilities, and to design a framework to support adoption of adaptive approaches. This work was conducted through a grounded theory analysis of interviews of relevant water utility practitioners in Australia and the Netherlands and members of the decision making under deep uncertainty and adaptive planning research community internationally. The outcome of this study is a maturity framework of barriers and enablers to the uptake of adaptive approaches in water utilities, designed to support utilities and researchers in evaluating their level of adoption and to identify strategies for increasing the implementation of adaptive approaches where appropriate.

CONTENTS

1 INTRODUCTION

In the face of a changing climate, demographic change, and shifting regulatory standards, urban water utility planners must make difficult decisions surrounding investment in new infrastructure. Traditional approaches to planning and decision making in the water sector often result in over-investment and 'gold-plating' in investment decisions (Stakhiv, 2011). Adaptive planning approaches for decision-making under deep uncertainty have been successfully implemented in other parts of the water sector (e.g. flood risk management) (Haasnoot et al., 2013b; Lawrence & Haasnoot, 2017), and have drawn attention in recent years from planners in water utilities (Brotchie & Wills, 2020; Launt et al., 2020; Randall et al., 2019; Vega et al., 2020). In the academic literature, there have been some speculative applications of decision-making under deep uncertainty approaches, particularly in relation to water supply planning (Molina-Perez et al., 2019; Trindade et al., 2017, 2019; Zeff et al., 2016) and an opening for the use of more quantitative applications such as dynamic adaptive planning pathways (DAPP) (Haasnoot et al., 2013) for infrastructure planning has been identified (Fletcher et al., 2017). Despite this, the existing academic literature contains little reflection from the perspective of utility practitioners on the application of adaptive planning approaches in water utilities (Fletcher et al., 2017; Viera & Malekpour, 2020). The following sections discuss water utility planning, decision making under deep uncertainty, and current applications thereof in water utilities in more detail, focusing on real-world applications where possible to highlight the current state and gaps in the literature.

The literature reviewed for this study was collected through a variety of approaches. First, relevant studies from study advisors and colleagues working on the topic were reviewed. From there, citations in these important works, and papers citing these studies were searched to identify both important antecedent studies and more recent papers related to the knowledge gap. Following this, searches were conducted using Google Scholar and Scopus databases using the following keyword searches, and a snowballing approach used thereafter:

- "dynamic adaptive policy pathway" – limited to papers on water supply
- "water" AND "utility" AND "infrastructure" AND "investment" – limited to papers on water supply

1.1 WATER UTILITY PLANNING AND DEEP UNCERTAINTY

Traditional approaches to water utility infrastructure investment are embedded in the literature around water utility asset management (Baird, 2010; Cardoso et al., 2012; Stakhiv, 2011). These traditional approaches tend to take a risk-based or plan-do-check-act approach to managing utility assets (Anderson et al., 1994), and focus on using probabilistic information to inform future investments. In contrast to the traditional approach to water utility decision making, the field of decision making under deep uncertainty (DMDU) has emerged in the past twenty years, presenting an alternative approach to probabilistic planning in the face of deep uncertainty presented by climate change, population growth, and a host of other variables (Marchau et al., 2019). One technique of interest to water utilities due to its focus on communication of how planning options respond to external triggers is the dynamic adaptive policy pathways approach (DAPP), which was first developed and applied in the context of Dutch delta management (Haasnoot et al., 2013).

Water utilities are defined for the purposes of this study as organisations responsible for the provisioning of water and/or wastewater services for a given geographical area. Many practitioners in the water utility space are becoming increasingly concerned with the suitability of traditional approaches for the sorts of long term infrastructure investments which will be required in the coming years to close the infrastructure funding gap (Baird, 2010; Rust et al., 2020; Stakhiv, 2011), and are looking to deep uncertainty and pathways approaches to manage this (Fletcher, 2018; Zeff et al., 2016).

In this thesis, the phrase 'adaptive approaches' is used to include both adaptive policymaking and adaptive planning in relation to water utilities. Note that the language used to refer to these adaptive approaches in the literature differs based on authors. This thesis, and the interviews conducted with participants is bounded by two ways of considering planning and policy making in water utilities:

1. Traditional approaches: These approaches reflect how water utility planning has traditionally been performed, where planners and policymakers define or predict a single future and plan according to that. For instance, a water utility might build new pipelines in a region, based on population growth projections that say the city will grow by 30% by the year 2040. This type of planning accounts for uncertainty by building in a margin of error into designs.
2. Adaptive approaches: These emergent approaches consider a greater level of future uncertainty, and account for this in planning. Adaptive planning as a concept exists in literature from DMDU research (Marchau et al., 2019) and from the sustainable water management research (Pahl-Wostl, 2008). This thesis primarily focuses on topics from the DMDU field, and further sub-divides adaptive approaches into:
    - Quantitative adaptive approaches: wherein computational tools and techniques are applied to develop an adaptive plan or policy, via a DMDU approach, including but not limited to robust decision making (RDM), dynamic adaptive policy pathways (DAPP), and engineering options analysis (EOA).
    - Qualitative adaptive approaches: wherein non-computational approaches to developing adaptive plans or policies are used. Ideas or concepts from the DMDU literature may be applied in combination other quantitative tools like yield modelling, but the computational elements of DMDU approaches are not applied.

1.2 Water utility planning

In general, there is limited available literature on the 'current state' of water utility infrastructure investment approaches. This may be due to the practitioner-driven (rather than research-driven) state of planning in water utilities today (Bell, 2012; Furlong et al., 2016), resulting in fewer academic publications. One example of academic writing on the state of 'traditional' water utility planning is a 2010 paper by Baird, which gives a view on current industry perspectives on approaches to managing aging water infrastructure (Baird, 2010). This paper articulates the 'status quo' of water utility infrastructure planning, which DMDU researchers and practitioners will need to understand if these approaches are to gain traction in the sector. Similarly, a paper by Markard (2011) addresses the characteristics of the infrastructure sector that have implications for transformational changes in planning approaches. Markard presents the notion that infrastructure can only evolve gradually with path-dependent changes. This may present challenges then to the operationalization of DMDU approaches for water utility infrastructure.

In a 2011 paper, Stakhiv critically reviews the current planning paradigms within the water resources sector in the United States, and highlights opportunities for adoption of more adaptive approaches (principally, robust decision making) to encourage 'no regrets' decisions (Stakhiv, 2011). The study notes that such a transition may take decades to occur and highlights the necessity of pragmatic steps to begin the transition.

The available academic literature on water utility planning and from water utility practitioners highlights how current approaches to planning may not be sufficient to address the significant challenges presented by an aging asset base, and that no-regrets, path-dependent changes are more likely to be favoured by decision makers. This suggests an opening for adaptive planning and decision-making under deep uncertainty approaches in the water utility space.

1.3 DMDU and adaptive planning applications in water utilities

Several papers by both researchers and practitioners looking to apply DMDU approaches to water utilities have been published in the last decade. Despite this, to date there have been no articles by water utility practitioners published on complete applications of the DAPP approach, and limited applications by researchers of other DMDU approaches.

One early study on the DMDU approach of robust decision making (RDM) demonstrates the application of an adaptive strategy for the planning of water resources for several water utilities in the western United States (Lempert & Groves, 2010). The study notes the benefits of using RDM approaches for bulk water supply planning, particularly as it relates to the risk profiles of water utilities. The study acknowledges the difficulties of applying such computationally intensive and complex approaches when there is a lack of understanding of the underlying methods, noting that this is a barrier to adoption. However, it states that breaking the process down into a discrete set of tools and methods may improve uptake (a notion later reflected in work by Van der Pas et al. (2013)).

In one case study of water utility investment in Melbourne, Australia, Fletcher et al. (2017) develop and apply a decision-making under deep uncertainty framework to assess the cost-effectiveness of different options for bulk water supply augmentation. The work highlights the influence of uncertainties and assumptions on investment profiles. While the work does not directly apply dynamic adaptive planning pathways approach, it identifies the opportunity for using such approaches for adaptive/flexible planning of water supply infrastructure. Further work by Fletcher explores adaptive approaches to water supply infrastructure planning compared to traditional "robust" approaches (Fletcher, 2018). The work found that flexible/adaptive approaches were preferable to robust approaches from a cost perspective, although this is dependent on several other planning variables.

In a case from water utility practitioners in Australia, an abstraction of the DAPP approach using an incremental portfolio of investments is applied to hypothetical projects in a real Australian water utility, Hunter Water (Rust et al., 2020). The study concludes that there are economic benefits to taking such an incremental approach, however the implementation of the pathways approach still relies on probabilistic assumptions, highlighting a need for further examination of how water utilities are interpreting the DMDU approaches in practice.

In a 2016 paper by Zeff et al., a quantitative DMDU approach is applied and combined with risk of failure metrics to develop long-term infrastructure plan for four water utilities in North Carolina (Zeff et al., 2016). This case provides a useful proof of concept that the DAPP approach can be meaningfully applied for projects within water utilities (for bulk water supply augmentation planning). In an extension to this work, Trindade et al. (2019) explore a similar approach to DAPP, named Deep Uncertainty Pathways (DU pathways) approach (Trindade et al., 2019). The approach is again applied to a collection of water utilities in North Carolina to inform infrastructure investments. The authors present the DU pathways approach as an effective tool for applying deep uncertainty and adaptation pathway approaches to the water utility context.

One further example of real-world applications has been the preparation of a water supply policy using Robust Decision Making approaches in Monterrey, Mexico. In the study, an Integrated Assessment Model of the region's water management systems was developed and used to develop insights to support a RDM approach to the development of an adaptive strategy (Molina-Perez et al., 2019). This work is important, due to its relative similarity to the planning activities of many water utilities and is an effective demonstration of how quantitative DMDU approaches can be applied in such circumstances. More recently, a study by Viera & Malekpour study used structured interviews of urban water utilities in Chile to understand the barriers and drivers of adoption of adaptive planning approaches by these utilities (Viera & Malekpour, 2020). Through interviews, the current planning approaches of Chilean water utilities were evaluated, and opportunities for use of adaptive planning identified. While no utilities were currently applying DMDU in practice, the authors identified actions to encourage the uptake of such approaches.

Despite limited publications on quantitative DMDU approaches in water utilities, there are increasing references to adaptive planning approaches being used in Australian water utilities. Applications seen in professional literature explore wastewater system planning (Brotchie & Wills, 2020; Launt et al., 2020), and bulk water supply planning (Vega et al., 2020). Scenario planning is the main adaptive planning tool employed in these examples. In the Vega et al. (2020) project, there is demonstration of a combination of financial evaluation tools with scenario planning, but no explicit indication of the application of quantitative DMDU approaches. Randall et al. (2019) is a further demonstration of an application of adaptive approaches by Australian water utilities, this time for the planning of a biosolids strategy. These practitioner publications demonstrate opportunities for adaptive approaches in water utilities beyond water supply strategies, where it has been traditionally applied in the academic literature.

With adaptive and DMDU approaches being increasingly applied in water utilities both by utility practitioners and researchers, the need and applicability of such tools in water utility contexts is evident. There is a gap, however, in the literature considering the factors leading to the adoption of such adaptive approaches that considers the perspectives of both utility practitioners and researchers. Further to this, there is a lack of literature investigating generalisable trends in the adoption of such approaches across multiple regions and contexts, with current studies focusing either on individual utilities (Brotchie & Wills, 2020; Vega et al., 2020), regions (Molina-Perez et al., 2019; Trindade et al., 2017; Zeff et al., 2016) or countries (Viera & Malekpour, 2020).

This thesis uses a design science approach to explore the challenges and key considerations in applying adaptive approaches in water utilities, posing the question *"What are the factors influencing the adoption of adaptive approaches by water utilities?"*. This thesis investigates the current state of planning and adoption of adaptive approaches in The Netherlands and Australia through semi-structured interviews to identify barriers and enablers for their successful adoption. The findings from this work inform the development of a framework to support adoption of adaptive planning approaches in water utilities. This framework will inform further research and practice to operationalise adaptive approaches and optimise planning and policymaking in the face of deep uncertainty in the water utility sector. Section 2 of this paper contains an overview of the data collection, data analysis, and research approach employed. Following this, relevant theories and the requirements they present for a possible framework are reviewed in Section 3. Section 4 present the results of the interviews, and the subsequent framework that was developed, with discussion of the outcomes and recommendations for policymakers given in Section 5. Finally, concluding remarks and suggestions for further work are shared in Section 6.

2 METHODS

This section details the research design, including the interview process, analysis of interviews, and the design science process. In exploring the factors influencing the adoption of adaptive approaches by water utilities, the research questions framing the research strategy were:

- RQ1: What are the barriers and opportunities for application of adaptive approaches by water utilities?
- RQ2: What practices can water utilities adopt to support the uptake of adaptive approaches?
- RQ3: What can DMDU researchers incorporate into their agenda to support adoption of adaptive approaches by water utilities?
- RQ4: What is a suitable framework for water utilities and DMDU researchers to consider when implementing adaptive approaches?

2.1 DATA COLLECTION

To explicate the problem and define requirements for this framework, the perspectives of water utility practitioners and researchers in adaptive planning and DMDU were collected through semi-structured interviews. The interview protocol (see Appendix A) was developed to align with the research questions. The interview questions were grouped around context-setting/problem framing, understanding and knowledge of adaptive approaches, barriers, enablers, and the research to practice space. Semi-structured interviews were used to enable modification of the order, and opportunities for clarifying questions given the varying degrees of practitioner and researcher knowledge and experience in the interview cohort.

Initial interviewees were identified through the author's professional network, with further interviews identified through snowball sampling and referrals. Interviewees were selected based on their experience or engagement with adaptive approaches. Utility interviewees were primarily those working on servicing strategy, asset strategy, and asset planning in urban water utilities. Further, practitioners who work with, but not in utilities were interviewed in both Australia and the Netherlands to provide an overview perspective on each countries' utility sector. Researchers interviewed were selected from a range of adaptive planning and DMDU backgrounds and disciplines, including researchers who have, and have not worked with water utilities. Researchers were from universities internationally, not solely Australia and the Netherlands. Most utility interviews were completed prior to the researcher interviews to allow for sharing of some utility responses for researcher reflection.

The interviews were conducted between March and June of 2022, there were five Australian utility interviews, five Dutch utility interviews, and six researcher interviews for a total of sixteen interviews. More details on specific dates and interview formats can be found in Appendix A.

2.2 DATA ANALYSIS

The interview data collected was analysed using a grounded theory approach. The intention of using this approach was to identify key themes in the responses to define the problem and requirements for a framework from the perspective of utilities and researchers. The interviews were transcribed, and the transcriptions systematically coded in *Atlas TI* (Smit, 2002) following a three-step process:

1. During and immediately following the interviews, memos were written on the content, themes, and key ideas in each individual interview.

2. Interviews were coded using a process of open coding. Statements were coded for responses related to barriers, opportunities, enablers, definitions, challenges, approaches, objectives, uncertainties, and research to practice in relation to adaptive approaches specifically (for instance, challenges related to recruitment were excluded from the coding).
3. Using themes and concepts from the memos in Step 1, in combination with memos written following the open coding in Step 2, categories within each response type emerged and responses were re-classified through selective coding. The translation of open codes to categories is given in Appendix B - Coding approach, code definitions.

The coded data was interpreted in reference to alignment with a maturity framework, which was identified as suitable through a review of frameworks (see Section 3 and Appendix C). Responses were further compared between and across utility and researcher respondents to identify linkages and conclusions for the framework.

2.3 The design science approach

A design science research strategy was used to develop a framework for use by water utilities and researchers to help inform adaptive planning and policy implementation using the analysed interview data and the concept of a maturity scale identified through related literature. This approach is a useful method for producing a generalizable contribution to both the knowledge base and the application domain for a problem (Johannesson & Perjons, 2014). In applying the design science approach, this thesis approaches the question from the perspective of both the researchers (knowledge base) and water utility practitioners (application domain). This work focuses on the first three stages of a design science approach as defined by Peffers et al. (2007): Identify problem and motivate, define objectives of a solution, and design and develop an artifact. The connection of the research questions to the stages of the design science process are shown in Figure 1.

Explicate Problem (RQ1)	**Initial problem**: water utilities wish to implement adaptive approaches, but practice doesn't align with research.
	Explicate problem: Through a grounded theory analysis of interview responses, the main barriers and opportunities for adaptive approaches in water utilities were identified.
Define Requirements (RQ2 & RQ3)	**Problem defined**: With the problems and opportunities for adaptive approaches defined, grounded theory analysis was used again to identify requirements for an artefact from both the utility and research perspectives. This was combined with theoretical requirements from the literature.
	Requirements: Utility requirements were identified in terms of utility objectives, challenges and uncertainties, identification of enablers for adaptive approaches, and how utilities understand and define adaptive policy. Researcher requirements were identified through reflection on these utility requirements, and consideration of the research to practice space.
Design and develop artefact (RQ4)	**Design and develop artefact**: With the requirements in mind, a literature search was conducted to identify suitable theoretical models, which were compared and interpreted for suitability.
	Artefact: The artefact was then developed to fit the utility and researcher requirements to an appropriate conceptual model – in this case, a maturity scale - for utilities and researchers to centre conversations about adaptive approaches around.

Figure 1 The design science stages as applied in this project

3 Theory

To develop a framework for understanding the adoption of adaptive approaches by water utilities, the requirements that such a framework fulfils must first be understood. Here, transition frameworks from the academic literature are considered to identify accepted requirements for the artefact to be designed. Simultaneously, as this work is concerned particularly with the role of DMDU practices in water utilities, this work looks to the DMDU literature to identify requirements for implementing DMDU approaches. Other works considered in defining these requirements are detailed in Table A.13 in Appendix C.

3.1 Transition science and urban water management requirements

In their 2008 book chapter, Pahl-Wostl et al. (2008) define a process for social learning which looks at the connections between context, process, and outcomes. It argues for the interdependence of these three components. This highlights the importance of including components that address Context (which includes governance, institutions, environment, technologies), Process (which includes relational issues, task issues, and the practice itself), and Outcomes (which includes technical outcomes like improved environmental health and relational outcomes like improved capacity in the setting). In accordance with this social learning framework, a framework that considers adoption of adaptive approaches in water utilities should also include consideration of these three components (and their interdependence). The responses of utility and researcher interviewees will guide the details of what constitutes each of these components in the context of this framework.

Further to this, looking to the urban water management practice, the water sensitive cities transitions framework developed by Brown et al. (2009) represents a framework that has captured the sustained attention of the water utility community in Australia and internationally (AWA, 2018). The authors' stated intention for this work is to support benchmarking, assessing progress, facilitating learning and knowledge transfer, and identifying strategies for transition amongst cities. These can be interpreted as suitable requirements for an equivalent framework.

3.2 DMDU requirements

For the purposes of this work, the requirements for undertaking DMDU approaches are considered to be those as specified in Marchau et al. (2019). The work highlights the three vectors to consider: complexity, uncertainty, and number of policy options. The authors argue that DMDU approaches are only the preferred approach when there are deep uncertainties, a greater number of policy options, and higher complexity. In circumstances with fewer policy options or lower complexity, scenario planning may be the preferred adaptive approach. Systems/decision arenas that do not contain uncertainty do not require adaptive approaches, and as a result are not considered in this work. This thesis concludes that for a framework to include consideration of DMDU approaches, it should include consideration of uncertainty, complexity, and the number of available policy options (referred to hereafter as 'optionality').

In combining concepts from adaptive approaches in urban water management and from the DMDU literature, three requirements for the framework to be developed in Section 4.3 are defined:

- The framework should include interconnected context, process, and outcome components.
- The framework should be usable for facilitating benchmarking, knowledge transfer, and identifying opportunities for transition.
- The framework should enable evaluation based on complexity, uncertainty, and optionality.

4 RESULTS

This section details the results of the interviews and the development of the framework. The sections in these results reflect the stages in a design science process as shown in Figure 2. Section 4.1 explicates the problem based on barriers, enablers and opportunities identified by interviewees. Section 4.2 identifies requirements through reflection on perspectives of utilities and researchers (additional requirements from the literature were also specified in Section 3). Finally, Section 4.3 presents the designed artefact based on the problem and requirements. Demonstration and evaluation of the artefact are excluded from this analysis, but a short reflection on how the framework satisfies the requirements is provided in Section 4.3.3.

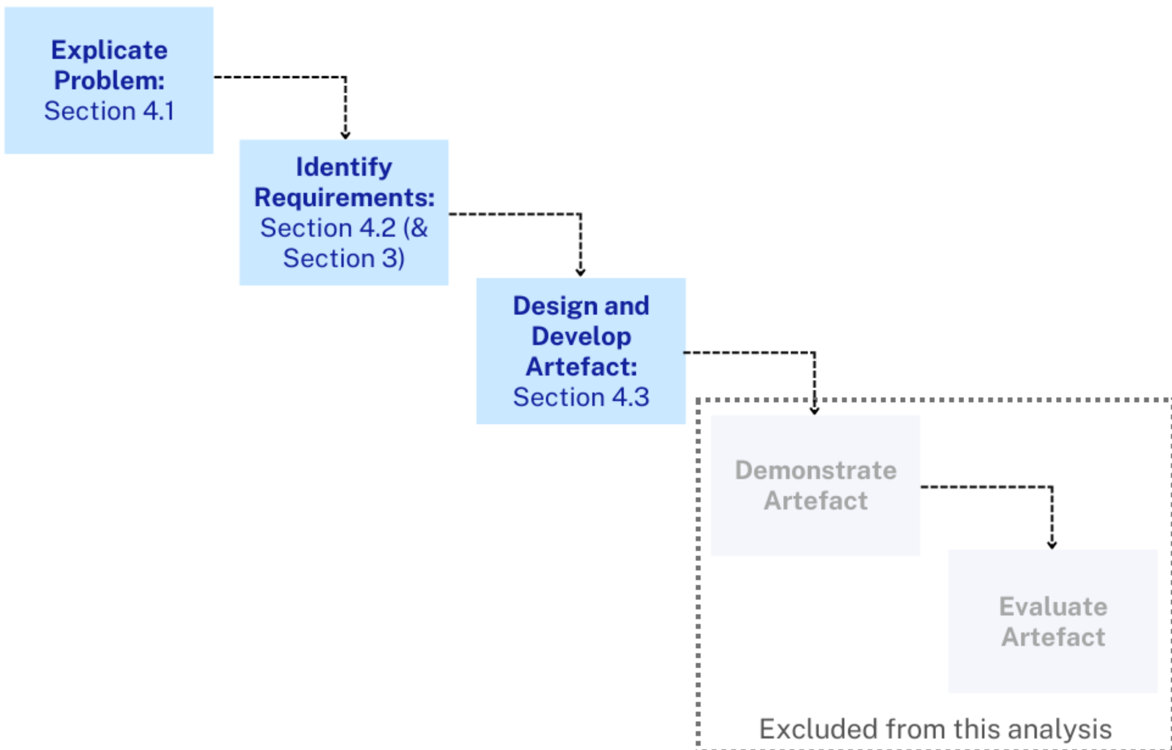

Figure 2 How the sections in the results map to the stages of a design science process. Adapted from Johannesson and Perjons (2014)

4.1 EXPLICATING THE PROBLEM – WHAT ARE THE BARRIERS, ENABLERS AND OPPORTUNITIES?

In this section, the problem area related to the implementation of adaptive approaches in water utilities is further explicated through the responses of water utilities and researchers. First, the barriers facing utility adoption of adaptive approaches are explored, followed by corresponding enablers. Next, the opportunities for adaptive approaches and examples of where it is applied is covered, and the utility ratings of their current state in terms of adoption is noted.

4.1.1 BARRIERS

In response to the interview questions "*What do you perceive as the key barriers to using adaptive approaches?*" and "*Are any of these barriers connected to data or availability of data?*", utilities and researchers identified four principal types of barriers to the adoption of adaptive approaches. The first category was process barriers (55 instances in interviews), related to issues in time/resourcing required, expertise required, technical and computational difficulty of adaptive approaches and communication of results. The next category was institutional barriers (54 instances), which included the governance of utilities, size/scale of utilities, regulatory barriers to new planning approaches, and complications connected to business case development. Third was organisational culture (44 instances), including internal organisational perceptions of adaptive approaches, awareness, mistrust of models, and (lack of) establishment of the need for adaptive approaches. The final category was data barriers (26 instances), connected to quality of available data, availability of relevant sources, and ongoing monitoring and data management needs inhibiting adoption of adaptive approaches. Table A.5 in Appendix B shows a selection of relevant responses from utilities in each category.

Across process, institutional and organisational culture barriers, there was a consensus in the responses of participants (with one only one interviewee disagreeing on the role of regulation as a barrier (R1)). Where there was the most evident divergence of views on barriers came out of responses related to data as a barrier. While most utilities interviewed agreed that either data availability or quality was a barrier, researchers were divided, with some arguing that while data availability was not an issue, utilities did have issues understanding how to handle and process their data in a useful way, while others argued that data quality, availability and use did not constitute a barrier for the adoption of adaptive approaches as utilities were generally "data-savvy" organisations.

4.1.2 ENABLERS

Responses to two interview questions were categorized together in terms of enablers for adoption of adaptive approaches. These responses were about enablers for successful adoption of adaptive plans and policies that had either already been implemented or were suggested by respondents. There was overlap between the defined barriers (as covered in previous questions) and enablers of projects as defined by the interviewees. Again, there were four main categories of responses regarding enablers. The first category were organisational culture factors (with 52 instances), including statements regarding top-down support, bottom-up support, collaboration, and organisational culture itself. Secondly, there were institutional factors (27 instances), where responses related to the role of enabling policy, acting within a policy window, and regulation that facilitates adaptive approaches. The third category was activities (22 instances), which included communication approaches of utilities and researchers, the use of interactive tools and integrated modelling, taking an incremental approach (reflecting theories in the literature from Van der Pas et al. (2013) and Lempert and Groves (2010)), and the role of champions/stewards of adaptive approaches within the water utility. The last category were data factors (8 instances), primarily connected to availability and quality of data in utilities. Table A.6 in Appendix B details noteworthy examples of utility responses to these questions.

As for the barriers, there was some disagreement amongst utility interviewees over the role of data as an enabler. While some argued that, for the level at which utilities are planning (conceptual, not using data driven approaches), the role of data was not relevant to the success of a project. However, others considered data to be integral to their planning methods (despite also not using quantitative approaches to perform adaptive planning). None of the researcher interviewees addressed data-related enablers in their responses.

Further to this, most utilities interviewed noted that it was difficult to call any one adaptive planning project “complete” at this point in time, as, given the time scale on which planning occurs, most will not be realized for another 40-50 years. As such, the results concerning these enablers/success factors should be viewed as enablers of the short-term success of these projects.

Further to this, neither researchers nor utilities shared enablers that corresponded to the “process” barriers highlighted in the previous section. While some of the enablers categorised as “activities” might serve to address some process challenges (namely the communication of complex results), none proposed comprehensive solutions to issues in resourcing, expertise, and time required for implementing adaptive approaches in water utilities.

4.1.3 Opportunities

In response to questions regarding where they have seen adaptive approaches being used in practice, and where they see future opportunities for adaptive approaches, utility respondents gave responses in three categories. The first category was asset-related opportunities (31 instances) where utilities shared examples in wastewater planning, water supply planning and policy, and network planning. The next category was planning-scale related opportunities (19 instances), including discussion of opportunities at the corporate strategy level, system and servicing strategy level, and asset strategy level. The third category was time-scale related opportunities (12 instances) with respondents discussing opportunities for use in near-term planning, mid-term planning and long-term planning. Of note is when considering asset-type opportunities, the frequency of responses is influenced by the fact that interviews were conducted primarily with drinking water utilities in the Netherlands, so there was less mention of wastewater planning in these interviews.

Researchers were asked to reflect on, respond to, and add to these responses, and added a further category of responses, classed in this work as other opportunities. These included opportunities for exploratory modelling and adaptive approaches to water pricing. In their reflections on utility responses, researchers specifically highlighted the interaction between planning at different time scales. They noted they value of using adaptive approaches for making near-term decisions informed by long-term uncertainty. Excerpts of these responses can be reviewed in Table A.7 in Appendix B.

4.1.4 Rating of utility adoption of adaptive approaches

To understand how water utilities and researchers perceived the understanding and application of adaptive approaches in water utilities, interviewees were asked to give a rating from 1-5 of water utilities in their country/region (where 1 is not understood and not applied, and 5 is well understood, state of the art application). The distribution of ratings is given in Figure 3. No utilities rated the adoption of adaptive approaches at a five, with the ratings skewing towards low-average ratings of two or three out of five.

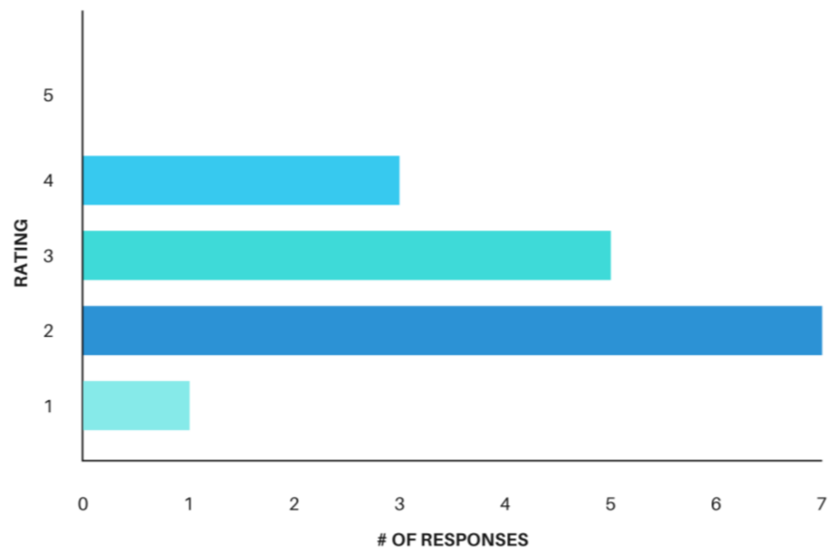

Figure 3 Ratings of adaptive approach adoptions by water utilities

Note that there are more scores than respondents. This was because some respondents gave multiple answers (for example, they would say that utilities sit between a 3 and a 4, or might say that larger utilities are a 4, while smaller utilities are a 3). As only one researcher provided a rating, researcher responses have been excluded. These ratings and their justifications inform the maturity scale to be refined in Section 4.3.

4.2 Identifying requirements

In this section, utility and researcher interview responses are interpreted to identify requirements for a framework. To reveal the utility perspective, this work looked at the challenges, uncertainties, and objectives of utilities. To reveal researcher perspectives, researchers were asked to reflect on the responses of utilities. Finally, responses regarding research to practice are synthesised in terms of what utilities and researchers can learn from each other (what can utilities learn from researchers and vice versa) and what could support improved translation of adaptive approaches from research to practice in water utilities to reveal requirements for the framework.

4.2.1 Utility and researcher perspectives

This section considers the perspectives of utilities regarding their main challenges, their perception of deep uncertainties they face, and the aspirations and objectives of their businesses. For the latter two categories, researcher responses were also captured.

Perspectives on challenges

In response to the question "*what challenges does your utility face?*", utilities gave responses across three main categories. The first were physical and climate related challenges (21 instances) some referred just to climate change, others to more specific factors including drought, flood, emerging contaminants, or extreme weather, as well as urbanization and population growth. The second were asset-related challenges (11 instances), including the aging asset base and 'renewal cliff', and general issues in asset condition. The third category was institutional challenges, with tightening regulations, and challenges in investment prioritization being most frequently cited. A selection of responses are detailed in Table A.8 in Appendix B. Researcher reflections on utility challenges were not collected.

Perspectives on uncertainties

For most respondents, there was significant crossover in what utilities identified as challenges and what they identified as uncertainties. However, while description of challenges was more surface level, responses related to uncertainties allowed respondents to speak in more detail about the location of the uncertainties within these challenges. In response to the question "*What deep uncertainties do you face?*", utility respondents noted four main types of uncertainties which they considered to be deeply uncertain. The first was the nature of future customers (18 instances) including population growth and distribution, changing service needs and expectations, changing land use, and the digital transition. The second category was institutional uncertainty (21 instances) including changes to the operating environment and responsibility for water and wastewater services, and regulatory changes affecting operations. The third was climate and environmental uncertainty (12 instances) mainly in relation to changes in seasonality affecting water quantity and water quality, in addition to other impacts on assets like sea-level rise, and uncertainty surrounding ecosystem services. The last category were socio-political uncertainties (7 instances) including exogenous shocks impacting economy and society or 'Black Swan' type events. Table A.9 in Appendix B gives an overview of excerpts of responses.

During the interviews, researchers were asked to share what they perceived as deep uncertainties facing water utilities, or, in the case of researchers not working with utilities, were asked to reflect on the four main types of uncertainties shared by utilities. Researcher responses were divided on how to handle and classify water utility uncertainties. Of the five DMDU researchers interviewed, when asked about the types of "deep uncertainties" identified by utilities participants, three of the researchers believed that all uncertainties could be classed as deep uncertainties, while two asserted that institutional uncertainties and uncertainties regarding future customers and their demands should not be classed as "deep" uncertainties and are better handled by scenario planning approaches than by DMDU approaches. The main discussion amongst researcher interviewees on this point was related to the ability to quantify sociological factors such as changes to consumer behaviour and changes in the operating environment (e.g., how water and wastewater services are provided and who provides them).

Perspectives on objectives and aspirations

Utilities and practitioners were also asked about the key goals and strategic objectives of water utilities. In their interview responses, utilities highlighted two main types of strategic goals, which were described by one respondent as *"There's what really happens when it comes to the crunch, and they've got to sell their strategies or plans to the bean counters. And then there's what their aspirations are."* (AU3). The first type of goals were defined as objectives (18 instances), which are typically embedded in their act or service obligations and include goals like providing prudent and efficient services, protecting public health, and protecting the environment. The second category were their aspirations (31 instances), which included goals like improving liveability, embedding the circular economy and the energy transition, digitalisation, and creating resilience. This distinction between objectives and aspirations is useful information in the context of adaptive approaches, as it will help in identifying utility preferences in applying approaches, for instance in the context of choosing a suitable robustness metric (McPhail et al., 2018). Examples of interview responses in these categories are given in Table A.10 in Appendix B. The responses here have also been validated by a review of the annual reports of utilities in Australia and the

Netherlands. The responses of utility interviewees were consistent with the annual reports, save for three main ways. Utility documents were more likely than interviewees to reference reliability (objective) and affordability and intergenerational equity (aspirations) in their vision statements or statements of strategic intent. A summary of the results and a list of annual reports review is given in Table A.11 and Table A.12 in Appendix B.

As for uncertainties, researchers were asked for their reflections on water utility objectives and aspirations and how they align with DMDU and other adaptive approaches. The main feedback from researchers on the utility goals was that all of them are suitable for underpinning adaptive approaches, but that utilities will need to ensure that the prioritization of the objectives and aspirations is agreed upon, to avoid confusion or disagreement when comparing options or optimising plans and policies in DMDU processes. One researcher (R2) also noted that specifying resilience as an aspiration is interesting in the context of adaptive planning because resilience might also be inherently embedded in objectives of cost effectiveness (prudent and efficient services) and providing quality service (protecting public health and the environment). This implies that such aspirations and objectives must be well scoped and defined in relation to each other to avoid confusion in computational approaches.

Defining adaptive approaches

One final consideration regarding utility and researcher perspectives on the topic of adaptive approaches is how the interviewees defined adaptive policy/planning. The responses to this question varied amongst participants along two main vectors: flexible-robust, and quantitative-qualitative. This work defines a 'robust' framing as a focus on resilience to uncertain futures, and consideration of impacts of shocks, and a 'flexible' framing as a focus on responsiveness to triggers and tipping points, and on decisions being 'no-regrets'. The quantitative-qualitative vector is concerned with the extent to which use of computational tools are included as part of the definition. The distribution of responses from interviewees across these two vectors are shown in Figure 4, with this distribution informed by the definitions provided and by interpretation of the preliminary interview memos. In general, utility responses tended to focus more on qualitative approaches, while researchers skewed more quantitative. All interviews favoured the flexible, rather than robust, interpretation of adaptive approaches. Interview excerpts of the definitions are provided in Appendix B - Coding approach, code definitions.

Figure 4 The distribution of definitions from flexible-robust and qualitative-quantitative. Australian utility interviewees are highlighted in green, Dutch utility interviewees in orange, and researchers in blue.

4.2.2 RESEARCH TO PRACTICE – WHAT CAN WE LEARN FROM EACH OTHER?

At the close of each interview, interviewees were asked to reflect on the research to practice gap in the application of adaptive approaches in water utilities and share what utilities and researchers can learn from each other in this space. Table 4.1 summarises responses from utilities and researchers to this question.

Table 4.1 Insights from utility practitioners and researchers on what utilities and researcher can learn from one another.

	What utilities can learn from researchers	**What researchers can learn from utilities**
What researchers say	- Risk prioritization requires work to enable use of quantitative decision support tools - Quantifying uncertainty is possible, but will require creative solutions - Improvement in understanding and navigation of trade-offs is needed. It will not be possible to achieve all goals as stated. - Make fewer assumptions about the limitations of adaptive planning and computational tools - Broadening problem analysis/problem area	- Understanding real-world constraints on problem domain (financial, political, regulations) - Jargon, parlance used in DMDU research may be meaningless to utility practitioners - Not every project or framework must be generalizable to be useful - Avoid making assumptions because things are difficult to model or quantify, make more effort to incorporate these into analysis. - Work in collaboration/in a participatory fashion with utilities and practitioners
What utilities say	- Understanding what good looks like through knowledge transfer and case studies. - Looking further into the future and learning new methods to handle uncertain futures - Working together more with multiple utilities (in the same way universities or research groups might collaborate) - Employing more novel visualization techniques - Looking to other industries or sectors for how to apply these approaches	- Work with utilities more to define problems and uncertainties - Tools and frameworks need to be able to work "off the shelf" – they should not require extra time or effort to apply or adapt. - Communities of practice are a good avenue for engaging with multiple interested utilities. - Utilities are not interested in a "bells and whistles" model, but in actionable insights. - Models and methods do not need to be 100% perfect to be useful. "60% is good enough…I just want a global feeling of where to go" (NL3)

Drawing insights from these responses, additional requirements for the framework can be isolated:

- The framework should be usable by utilities "off the shelf" and should not require extra time and effort to apply and understand.
- The framework should contain actionable insights.
- The language used should be simple and avoid jargon wherever possible.

These requirements, in addition to those defined in Section 3, form the basis for the development and evaluation of the framework in the following section.

4.3 Design and develop framework – a suitable framework for utilities and researchers

In this section, a framework is presented addressing the factors influencing the adoption of adaptive approaches by water utilities. In following the search for suitable frameworks from the literature detailed in Section 3, a maturity scale was identified as the most appropriate representation of utility adoption of adaptive approaches and the types of barriers/enablers that are relevant at each stage of adoption.

4.3.1 The framework

In synthesizing the barriers, enablers, and opportunities and ratings shared by interviewees, and considering the requirements synthesized from the literature and utility responses, the maturity framework in Figure 5 was developed.

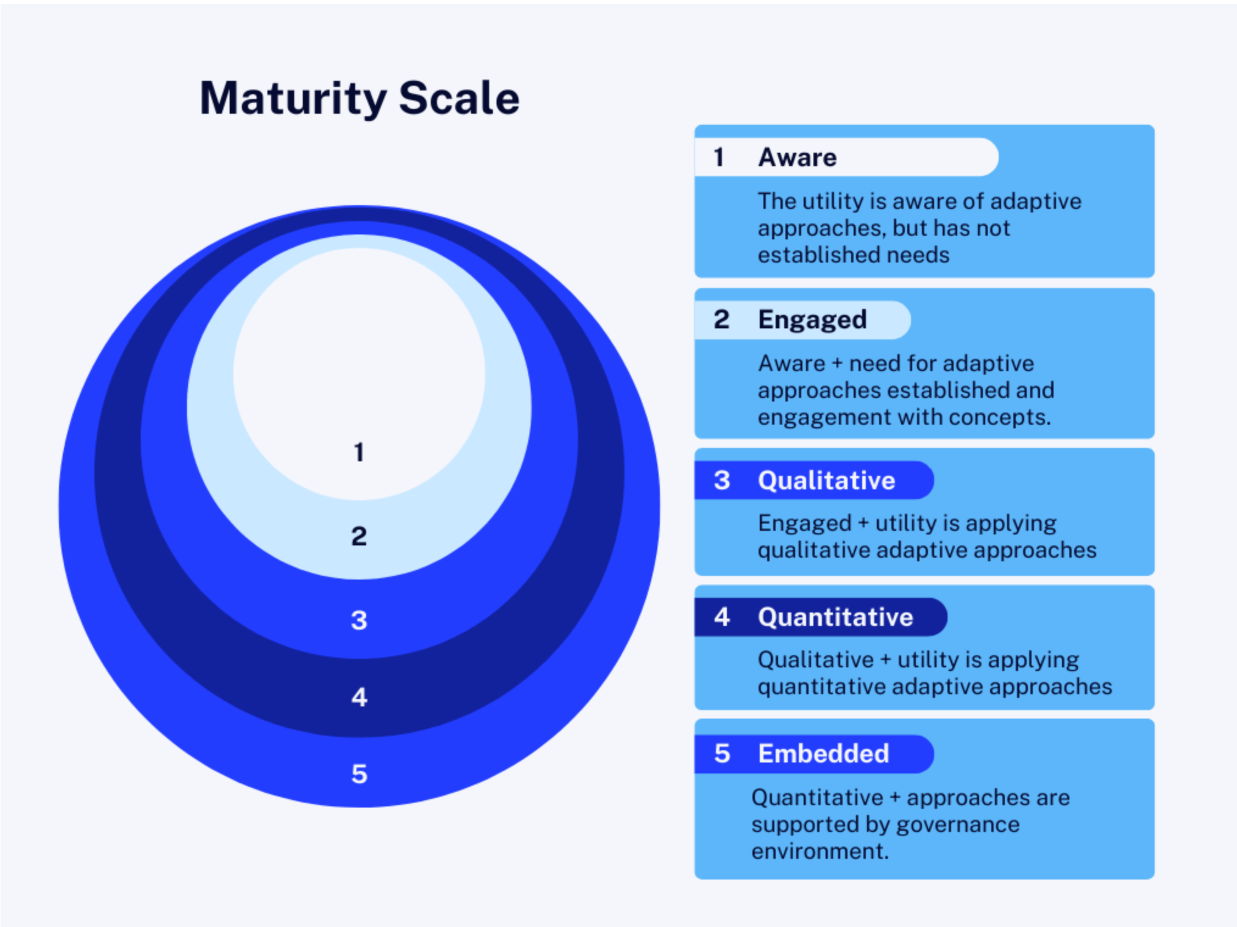

Figure 5 The maturity scale for utility adoption of adaptive approaches

The maturity scale takes the form of nested levels, with each level being inclusive of features of the previous stages. The nature of this framework as cumulative must be considered by users. If a barrier to adoption of adaptive approaches exists in Level 1, it likely also exists in Levels 2-5. Moving between levels does not necessarily eliminate the barriers, but they might be better managed or of less concern relative to new barriers. Further to this, it is not necessary that utilities move through these stages in a stepwise fashion but might move directly from Level 2 to Level 4 or 5 because of a well-managed program of adaptive projects with sufficient institutional support both within the utility and in policy and regulatory environments.

4.3.2 Level definitions

Here, details on what constitutes a utility at each level and the characteristics of barriers across process, institutional, organizational, and data considerations described. For each level, enablers that relate to these barriers and support transition to the next phase are described. For levels that include implementation of approaches, relevant opportunities are described.

1: Aware of approaches

The first stage at which a utility enters this maturity scale is when at least one employee becomes aware of adaptive approaches in the context of their role. At this stage, the utility will not have established a need for adaptive approaches in planning or policymaking and relies on traditional assumption-based planning approaches for all activities. The main process-related barrier at this stage is in the communication of uncertainty concepts and the available adaptive approaches to utility employees. The main institutional barriers at this stage lie in the utility size, with smaller utilities less likely to have the necessary scale to warrant investigation of deep uncertainty/adaptive planning concepts. The main organizational culture barriers at this stage lie in awareness of deep uncertainty and adaptive planning/policy as concepts, and the establishment of the need for such approaches within the utility. At the ‘aware of approaches’ stage, data quality and availability does not yet present a barrier to adaptive approaches adoption.

To overcome these barriers, utilities seeking to transition to Level 2 can consider enablers such as employing communication strategies within the business to raise awareness of the role of uncertainty in planning and how adaptive approaches can address these uncertainties. This can be accompanied with education materials or other engagement activities from professionals and researchers outside of the utility. Two utilities (NL3 and NL5) shared examples of how they used regularly updated creative metaphors related to changing paths/tracks to explain to different levels of the organisation how uncertainty can change plans, and how to embrace adaptive approaches.

2: Engaged with approaches

The second stage of maturity for a utility is engagement with approaches. At this stage, utilities will have established or understood the need for adaptive approaches within their business but will not have started to apply the concepts in practice. Utility professionals might have been engaged with concepts from the literature, conference presentations, communities of practice or other presentations. In some cases, policy-pull might mean that the utility is required to look at adaptive approaches due to requirements in policy or regulatory documents. The main process barrier at this stage lie in understanding the definitions of terms used in adaptive approaches, and ensuring a clear vocabulary is used by practitioners to avoid confusion with other planning concepts. At this stage, there are no distinct institutional barriers, but multiple organizational culture barriers to be overcome before reaching the next stage. The cultural barriers at this stage relate to perceptions of adaptive approaches, with utility professionals highlighting the perception of adaptive approaches as a new concept as anything from too vague or imprecise through to too complicated and technical. Additionally, a traditionally risk averse culture within the water utility sector means that novel approaches to planning and policy making are likely to be treated with caution. As for Level 1, data related barriers are not relevant at this level.

To overcome these barriers, utilities seeking to transition to Level 3 will need to address their utility's willingness to engage with uncertainties and consider the application of adaptive approaches. This can be supported by top-down support from leadership teams, and/or through bottom-up interest and implementation from those in planning and strategy teams. Alternatively, community or customer support for adaptive approaches (or outcomes thereof) can be leveraged at this stage to build interest and momentum either within the utility or from policymakers, although this is only possible in niche situations. A final enabler for overcoming barriers at this stage is the existence of a policy window for adaptive approaches to enter the conversation. Many of the utilities and researchers interviewed noted the influence of the COVID pandemic in promoting utilities to think more about uncertainty and changes in planning paradigms, and that planners interested in implementing adaptive approaches should try to "never waste a crisis" by being prepared.

3: Qualitative approaches

The third stage of maturity for a utility is implementation of qualitative adaptive approaches. At this stage, utilities are implementing adaptive approaches such as scenario planning, or modified versions of DMDU approaches to incorporate deep uncertainty into their planning and policymaking. The main process barriers in this stage are connected to resourcing (the lack of available staffing or time to spend completing the adaptive planning processes), expertise (the lack of knowledge on how to create an adaptive plan), and bad practice or misuse of available tools (connected to expertise, where a utility has learned about adaptive planning but misuses the concepts, for instance by performing probabilistic/deterministic planning and presenting it as an adaptive plan). Institutional barriers at this stage are connected to business case development (traditional financing models requiring utilities to present a single capital plan, rather than one with multiple options/pathways), lack of coordination (different business units creating different or conflicting plans, downstream/upstream planning departments not following the adaptive plan), governance (insufficient governance structures within the utility and between utility stakeholders to enact the adaptive plan) and regulation (principally economic regulation, wherein least-cost servicing rules mean that adaptive plans do not meet regulatory requirements). The main organisational cultural barrier was described by one interviewee (R4) as institutional inertia, the tendency for water utilities to prefer to continue using the current planning paradigm, even in the face of new alternatives which would improve the utility's ability to meet their objectives. As for earlier levels, data barriers are not significant at this level.

Utilities seeking to overcome these barriers to transition to Level 4 should consider engaging in activities to promote coordination between planning departments within the utility. This addresses barriers around lack of coordination, business case development and strengthens governance structures within the utility to support implementation. An additional enabler that addresses these barriers is the introduction of an adaptive planning steward or champion within the organisation. Such an employee can support the implementation, monitoring and evaluation of an adaptive plan or policy, ensure that governance structures are observed, and promote coordination and building of expertise across departments. Expertise and resourcing for such projects can further be enhanced by creating partnerships with research groups and experts. Finally, employing incrementalism in implementing adaptive plans and policies, especially where it is the first time it is employed in an organisation, can be beneficial for their communication and acceptance. For instance, one utility (AU5) shared an example of how their adaptive plan was presented alongside traditional planning work in the early stages of implementation, to allow colleagues and leadership to become familiar with the components and structure of the plan, before slowly transitioning to the adaptive planning approach.

Examples of where adaptive approaches have been or might be applied at this level include in water supply planning, system scale planning, corporate strategy, and place-based planning.

4: Quantitative approaches

The fourth stage of maturity in adopting adaptive approaches is the implementation of quantitative approaches. At this stage, water utilities are implementing quantitative/calculative DMDU approaches in at least one project to develop adaptive plans or policies. The main process barriers at this stage are in quantifying uncertainty, expertise (this time in relation to how to undertake quantitative approaches), time required, and computational intensity (researchers noted the costs associated with computational intensity of modelling complex systems is not often factored into projects by practitioners). The institutional barriers at this stage are the same as for implementation of qualitative approaches. The main organisational culture barrier at this stage lies in mistrust of models. This barrier was noted primarily by researchers and not by the utilities themselves but relates to organizational cultures where the outputs of modelling work is not trusted if the process is not well understood. This is the main stage at which barriers related to data present a problem for water utilities, as the availability of relevant data and ability to use it to derive insights is central to implementing more quantitative approaches. As mentioned in Section 4.1.1 however, this is not a barrier for all utilities, with many utilities already having the necessary data available to implement such an approach.

Suitable enablers at this level include integrated modelling approaches, where models from distinct parts of the utility's operations can be integrated to demonstrate new insights around the role of uncertainty. Another related enabler is interactive tools for displaying the results of DMDU approaches, such tools can enhance comprehension of the outputs of such approaches and build trust as it supports understanding of how results are derived. A key enabler at this stage is sufficient resourcing, in the form of personnel and computational resources. In connection with this, financial commitment by the utility to a project, particularly in the form of partnerships with research groups pursuing adaptive approaches, can improve the willingness to commit to implementation of the outcomes of adaptive planning projects.

Applications of adaptive approaches in this stage have been/might be seen in connection with network asset planning, and asset level planning (in addition to the types of implementations noted in Level 3).

5: Embedded in practice

The fifth stage of maturity in adopting adaptive approaches is the embedding of the approaches in practice and through institutional support. At this stage, a water utility would be using quantitative and qualitative adaptive approaches in all projects where it is appropriate to do so (based on complexity, uncertainty, and optionality), the new planning paradigm would be embedded as best practice within the organization, and the approaches would be supported by enabling policy and regulatory environments. The principal barrier at this stage is again a process barrier related to communication. Communication and engagement with the key stakeholders in the enabling environment are critical to the embedding of the work in practice. All other barriers relevant at this stage are as for the preceding stages.

Suitable enablers to overcome the barriers at this level include enabling policy settings such as requirements for utilities to use adaptive approaches, including an enabling regulatory environment which supports business cases or capital plans with an adaptive focus. As for earlier stages, an organizational culture that is familiar with the role of uncertainty in planning for the future is essential to embedding an adaptive planning paradigm.

An overview of the relevant barriers, enablers, and opportunities at each level within the framework are given in Table 4.2. In examining this overview, note that there is not a 1:1 relationship between barriers and enablers in each category. In many of the examples given by interviewees, enabling activities or cultural/institutional changes were effective in addressing multiple barriers.

Table 4.2 The levels within the maturity framework and corresponding barriers. Note that under barriers and enablers, where a category is labelled as NA, this means that there are no new *barriers or enablers within this category at the level, but that barriers from previous levels still apply.*

MATURITY	**1: AWARE**	**2: ENGAGED**	**3: QUALITATIVE**	**4: QUANTITATIVE**	**5: EMBEDDED**
Description of maturity	Awareness of concepts, but need for adaptive approach not established	Level 1 + Organisational needs established, practitioners are engaged with the literature, but no implementation in planning or strategy	Level 2 + Adaptive approaches implemented non-quantitatively (e.g., scenario planning)	Level 3 + Quantitative adaptive approaches used to develop adaptive plans	Level 4 + Implementation of adaptive approaches integrated in policy and regulation, and governance structures support implementation.
Relevant barriers	*Process*: Communication (internal) *Institutional*: Utility size *Culture*: Awareness, needs *Data*: NA	*Process*: Definitions *Institutional*: NA *Culture*: Perception, organisational culture, risk aversion *Data*: NA	*Process*: Resourcing, expertise, bad practice *Institutional*: Business case, lack of coordination, governance, regulation *Culture*: Institutional inertia *Data*: NA	*Process*: Quantifying uncertainty, Expertise, *Time*, Computational expense. *Institutional*: NA *Culture*: Mistrust of models *Data*: Data availability, data use	*Process*: Communication (external) *Institutional*: NA *Culture*: NA *Data*: NA
Relevant enablers	*Activities:* Communication about uncertainty, education. *Cultural*: NA *Institutional*: NA *Data*: NA	*Activities*: Communication about adaptive approaches *Cultural*: Utility willingness, top-down or bottom-up support, customer, or community support. *Institutional*: Policy window. *Data*: NA	*Activities*: Partnerships with research, stewards/champions, incrementalism. *Cultural*: Cooperation between planning departments *Institutional*: NA *Data*: NA	*Activities*: Integrated modelling, interactive tools. *Cultural*: Trust (in models or process) *Institutional*: Financial commitment, resourcing *Data*: Available and quality data, expertise.	*Activities*: Communication (external) *Cultural*: NA *Institutional*: Enabling policy, enabling regulation, *Data*: NA
Relevant opportunities	No application at this stage.	No applications at this stage.	Corporate strategy, servicing and system level strategies, place-based planning.	Asset-level planning, detailed design of servicing and system-level strategy.	As for previous levels.

4.3.3 EVALUATION BASED ON REQUIREMENTS

Given time and resourcing constraints within this project, it is not possible to complete steps four (demonstrate artefact) and five (evaluate artefact) of a typical design science approach. To validate the framework developed, it can be compared against theoretical and user requirements to determine its suitability.

Does the framework include context, process, and outcome components and are they interconnected?

In terms of alignment with Pahl-Wostl et al.'s 2008 process for social learning, the context components of this framework are embedded in the institutional and organizational culture barriers and enablers. The process components are the process and data barriers and enablers. The outcome components are utility objectives and aspirations which are consistent across all levels of the framework. Interconnection of these components is acknowledged through the thematic linkages of these barriers and enablers between the levels of the framework.

Does the framework support benchmarking, facilitate knowledge transfer, and inform about transition opportunities?

In being formulated as a maturity scale, the framework supports utilities to benchmark their application/implementation of adaptive approaches relative to other water utilities. The structure and definitions of utilities at each level are designed to support knowledge transfer between utilities at different levels, and between utility practitioners and researchers. The definition of effective enablers to overcome barriers at each level informs users about transition opportunities.

Does the framework address complexity, uncertainty, and optionality in utility planning?

The framework addresses uncertainty but should be paired with educational materials from the DMDU literature (e.g. Marchau et al. (2019)) to support utilities to evaluate the role of complexity and optionality in selecting a suitable adaptive approach.

Is the framework usable "off the shelf"?

The framework should be usable by a utility practitioner, who might be able to identify the maturity of their utility based either on the description of a utility at said level or through the overview of factors in Table 4.2. From this, it should be possible to identify the barriers to move to subsequent levels, and actions that they might take to move to other levels.

Is the framework actionable?

The framework is designed to be actionable for utility users to identify their state of maturity and, from the description of the stage, identify relevant barriers and enablers. It contains suggested activities to transition between levels.

Does the framework contain jargon?

The framework avoids common jargon from the academic arena, focusing primarily on qualitative and quantitative adaptive approaches, rather than specific tools or methodologies.

5 DISCUSSION

Out of this study comes several relevant insights for policymakers that are applicable across all stages of the framework. Firstly, that education, awareness, and shared language is critical to supporting adoption of adaptive approaches within the water utility sector more broadly. Using simple language and educating users on the need for such approaches helps in overcoming organisational culture barriers and potential negative perceptions of adaptive approaches as being either too vague or too complex. For supporters and advocates of the approaches within utilities, having a plain language and definitions can aid in clearer communication of outcomes and intentions of projects. Further to this, using shared definitions and improving understanding of the concepts across the industry can help to avoid diluting the actual meaning of adaptive approaches (as has been seen for terms like sustainability or resilience).

Secondly, researchers interviewed highlighted the importance of using the right approach in the right context. Some utilities interviewed mentioned how policy documents and organizational visions include some instruction that water utilities must employ adaptive planning or adaptive policy, without further explanation of the meaning. There must be an understanding that adaptive planning is not a panacea, and the right planning approach at the right time must still be used. As one interviewee suggested, the adoption of adaptive planning in Australia may already be at a tipping point, wherein failure to successfully implement adaptive approaches may inhibit further opportunities for practitioners. There is a need for building understanding within the industry of when it is suitable to use traditional planning approaches, when to use scenario planning/qualitative adaptive approaches, and when to use qualitative/computational approaches, so that the right techniques are used for the right situations.

Thirdly, the interviews highlighted improvements to be made institutionally to address the research to practice gap in this area. There needs to be improved institutional settings for establishing mutually beneficial projects between research and practice. Given the relatively low risk tolerance of the urban water sector (Farrelly & Brown, 2011), utilities noted a preference towards collaborative research projects and case study implementations. Researchers cited an appetite for involvement in more longitudinal studies, where the full lifecycle of adaptive plans can be observed and learned from. For utilities (or researchers, in the case of longitudinal projects) this may include creating an adaptive policy steward or champion role within water utilities to ensure policies are followed, monitoring plans for triggers are in place, and stakeholder engagement and buy-in within planning, regulation and policy are maintained.

Finally, while the framework developed from this study is established as a maturity scale, this is not intended as a normative assessment of utility practitioner performance. Rather, the scale is meant to assist utilities to understand their progress in implementation of adaptive approaches, and to support conversations between practitioners and the research community about the application of such approaches in water utility practice.

6 CONCLUSIONS

This paper presents a maturity framework as a means of answering the question "*What are the factors influencing the adoption of adaptive approaches by water utilities?*". Interviews with utility practitioners and adaptive planning and DMDU researchers revealed the ways in which utilities experience different barriers and enablers to implementing adaptive approaches depending on the extent of their implementation. Barriers ranged from those related to communication of the concept of uncertainty and optionality for preliminary stages of adoption through to barriers related to resourcing requirements, computational difficulty, and embedding in policy and regulation for utilities that are further along with adaptive implementations.

The review of the existing academic literature identified a gap surrounding the realities of applying adaptive approaches to utilities in practice. Existing cases in the literature centre on DMDU tools and techniques, or experiences of DMDU applications in individual utility, region, or country settings. This thesis increases the generalisability of finding regarding the factors influencing adoption of adaptive approaches in water utilities through identifying consistencies in utility perspectives from two countries: Australia and the Netherlands, and researcher perspectives internationally. Further, applying a design science approach to these perspectives enabled the development of a framework to assist future researchers and utilities in overcoming barriers to ensure effective adoption of adaptive approaches.

Time and resourcing constraints resulted in several methodological limitations in this study, which might be addressed through further work. Firstly, time and network restrictions meant that only four utilities and one practitioner from each country, and six researchers were interviewed and analysed. Utility interviewees were predominantly with asset planners or servicing strategists within water utilities. Further to this, utilities considered were all urban water utilities in high income countries. Therefore, the scale likely only applies to larger organisations with the institutional capacity to be considering adaptive approaches, and not to water utilities at all scales and configurations. Additionally, there may be some sample bias in the researcher responses around perceptions of utility competence in employing adaptive approaches as utilities currently engaged with research groups to conduct adaptive approaches have distinct cultural and institutional norms that led them to that engagement in the first place.

Secondly, climate and geopolitical events at the time of the interviews may have skewed responses. Interviews with Australian practitioners were conducted shortly following the Russian invasion of Ukraine, and consequently, several respondents reflected on socio-political uncertainties such as supply chain disruptions and economic instability. Australian interviews were also happening during record-breaking flood events on Australia's east coast, leading to more focus on extreme weather events in responses about challenges and uncertainties. Dutch interviews took place during an extended dry period in the Netherlands, potentially leading to more interviewees raising the topic of drought and water availability in their uncertainties/challenges. Researcher interviews took place around the time of interest rate rises by several central banks in response to rising inflation, which may have influenced the increased attention to economic factors influencing utility planning. Finally, all interviews were performed during/after the COVID pandemic, and societal changes and shifts in utility customer behaviours because of this influenced responses.

Finally, in relation to the use of a design science research method. The demonstration and evaluation of the framework was not completed. Again, due to time and capacity constraints, this project only went so far as to *develop* a framework for water utility practitioners and researchers. As such, the framework has not been *demonstrated* or *evaluated* within water utility or research settings. In Section 4.3.3, the framework was validated against some relevant requirements from literature and from interviewee perspectives, however more robust testing and implementation is necessary.

Given these limitations, potential directions for further research work include:

- Expanding the requirements and problem explication through further expert interviews or surveys of utility professionals and researchers: The work would benefit from including professionals from a larger sample of countries to reflect the influence of different institutional settings. It would also benefit from eliciting the perspectives of a wider range of utility professionals within a single utility, to understand how the perceptions and understanding of adaptive approaches can vary within a single entity. Another group of potential interviewees would be policymakers and regulators, to reveal further insight into overcoming external institutional barriers.
- Implementation and evaluation of the framework in real world cases: This research only reached the first three steps of a design science approach. Further work could look to implementation of the framework within a utility setting, and evaluation of its effectiveness. This could be completed through field work, case studies, or workshops.

This work has implications for the adoption of adaptive approaches not just in water utilities, and has the potential to be adapted for use, especially in the context of other types of critical infrastructure areas where generationally significant investments are required (e.g., transport, logistics, energy). It is hoped that this work provides a tool and starting point for water utilities and researchers to increase the successful adoption of adaptive approaches to address growing uncertainties facing the water sector.

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Appendix A INTERVIEWS AND INTERVIEW PROTOCOL

Researcher interviews were conducted primarily after utility interviews, to invite researcher reflection on preliminary findings from the utility interviews. Businesses defined as utilities for the purpose of this project were any businesses or organisations providing drinking and/or wastewater services to a defined geographical area. Due to necessary confidentiality agreements, it is not possible to publish complete interview transcripts.

Table A.1 details each of the interviews conducted, including the type of interviewee and the date of the interview.

Table A.1 The interviews conducted and means of interviewing

Number	Interviewee	Meeting Type	Interview Date
AU1	Australian utility professional	Online, video recording, transcript	17/3/2022
AU2	Australian utility professional	Online, video recording, transcript	23/3/2022
AU3	Australian adaptive planning practitioner	Online, video recording, transcript	29/3/2022
AU4	Australian utility professionals	Online with multiple participants, video recording, transcript	5/4/2022
AU5	Australian utility professional	Online, video recording, transcript	7/4/2022
NL1	Dutch planning practitioner and researcher	Online, video recording, transcript	2/5/2022
R1	Adaptive planning researcher	Online, video recording, transcript	4/5/2022
NL2	Dutch utility professional	Online, video recording, transcript	5/5/2022
NL3	Dutch utility professional	Online, video recording, transcript	6/5/2022
R2	DMDU researcher	Online, video recording, transcript	11/5/2022
R3	DMDU researcher	Online, video recording, transcript	16/05/2022
NL4	Dutch utility professional	Online, video recording, transcript	17/05/2022
R4	DMDU researcher	Online, video recording, transcript	18/05/2022
R5	DMDU researcher	Online, video recording, transcript	19/05/2022
R6	DMDU researcher	Online, video recording, transcript	19/05/2022
NL5	Dutch utility professional	Online, video recording, transcript	27/5/2022
NL6*	Dutch utility professional	Online, video recording, transcript	15/6/2022
NL7*	Dutch utility professional	Online, video recording, transcript	16/6/2022
*Not included in this document's analysis			

Table A.2 outlines the interview protocol used for utilities and researchers. The questions appear in the table in the order in which they were typically asked. In some interviews, questions were asked in a different order in response to the conversation. Additionally, some questions were skipped if an interviewee had already answered a question, in the interests of time, or where an interviewee did not have the domain knowledge to answer. For instance, for DMDU researchers not doing research with utilities, questions RIQ2, RIQ5, RIQ6, RIQ10 were either skipped or modified to ask for reflections from their own experience with applying DMDU concepts to real world cases (e.g., transport, logistics, security, other water sector applications).

Note also that the numbers assigned to the interview questions do not align with the order in which they were asked. These numbers were assigned to assist in coding of the questions and connect to their related research question.

Table A.2 Interview protocol for utilities and researchers

Topic area	Question for Utilities	Question for Researchers
Introduction/opening questions	Tell me a little bit about yourself and your current role. IQ8: What challenges is your business facing? IQ9: What are the goals/long term strategic objectives of your business? IQ10: To what extent does data play a role in your planning and strategic objectives? IQ11: What deep uncertainties do you face? (Definition of deep uncertainty* provided on request)	Tell me a little bit about yourself and your current research. What challenges is your research focusing on? RIQ10: How do you define adaptive policy and adaptive planning? RIQ11: How would you rate the current understanding of adaptive principles in water utilities (scale of 1-5)? Why this rating? RIQ9: What kinds of deep uncertainties exist for utilities that can be served by adaptive approaches? Share strategic objectives of utilities – ask to reflect on these.
How is adaptive policy/planning defined and understood?	IQ12: How do you define adaptive policy/planning? IQ5: What adaptive policy tools and techniques are familiar to you? IQ13: How would you rate the current understanding of adaptive planning principles in Australian/Dutch water utilities (scale of 1-5)? Why this rating?	
Where are the opportunities for adaptive policy in utilities?	IQ6: How have you seen adaptive approaches being used by utilities? IQ4: What parts of utility planning hold the most promise for adaptive approaches?	RIQ3: How have you seen adaptive approaches being used by utilities? RIQ4: What parts of utility planning hold the most promise for adaptive approaches? Share utility responses – ask to reflect on these.
What are the barriers to adaptive policy in utilities?	IQ1: What do you perceive as the key barriers to using adaptive approaches? IQ2: Are any of these barriers connected to data or availability of data?	RIQ1: What do you perceive as the key barriers to using adaptive approaches? RIQ2: Are any of these barriers connected to data or availability of data?

What practices are in place to enable adaptive approaches?	IQ6: How have you implemented/tried to implement adaptive approaches in your utility? Was it successful or not, **and why?**	RIQ6: How have you implemented/tried to implement adaptive approaches in water utility settings? Was it successful or not, **and why?** (Include hypothetical and real-world cases)
What practices need to be improved to enable adaptive approaches?	IQ7: How could these barriers be overcome? IQ14: What do we need to learn from each other? What can utilities learn from researchers and vice versa?	RIQ7: How could these barriers be overcome? RIQ12: What do we need to learn from each other? What can utilities learn from researchers and vice versa?
Closing questions	Is there anything you wanted to mention that we didn't cover today? Is there anyone else in the industry who you would recommend I speak with?	Is there anything you wanted to mention that we didn't cover today? Is there anyone else in the research community who you would recommend I speak with?
*Definition of deep uncertainty provided was from the Decision Making Under Deep Uncertainty Society: *"Deep uncertainty exists when parties to a decision do not know, or cannot agree on, the system model that relates action to consequences, the probability distributions to place over the inputs to these models, which consequences to consider and their relative importance. Deep uncertainty often involves decisions that are made over time in dynamic interaction with the system."* (DMDU Society, 2015)		

Adaptive planning/policy definitions

In each interview, interviewees were asked to give a definition of adaptive planning/adaptive policy, in their own words. This question was asked as a means of framing further questions, but also provides useful insights into the differences in how utilities and researchers think about adaptive approaches.

Utility definitions:

- "adaptive planning is about putting ourselves deliberately in a position that we can respond to whatever comes our way. And instead of just letting ourselves slide between decisions… it's putting ourselves in a position so that we can adapt to what happens as it happens, rather than needing to react." (AU1)
- "it's about being able to quickly respond to the changing environment and having a plan that is able to adapt or respond to what's happening around them." (AU2)
- "it's a planning tool to help you deal with future uncertainty and it's designed to avoid locking in options that might be regretful in the future, and keep options open that might be attractive to the business in the future. It's intent is to, rather than trying to project and plan for the long term, it's to work out what your least-regrets short term investment decisions are, taking into consideration the future uncertainty and the different features that could unfold." (AU3)
- "adaptive planning is actually planning in a way that you're not basically locked into a set perception of the future. And basically having the flexibility to actually adjust course as needed

based on the events that come into it, as new information becomes available within reason." (AU4)

- "So in terms of how we invest and manage services into the future, we want to be flexible and adaptable to change and uncertainty …We want to do it in a way that minimizes the regretful investment decisions in the short term… So keeping the optionality open, so that we can be nimble to uncertainty, risks change, trends, and shocks. Not locking in that entire investment program." (AU5)
- "I always have this picture in my mind, I think it was from the original paper by Jan Kwakkel, with these different horizontal lines and some of them are cut off and then moved to other horizontal lines. So it's keeping open and keeping an eye open for all the adaptation measures that you that you have. Trying to work out to what degree of change these may still be applicable and which measures make it impossible to take other measures in that way." (NL1)
- "adaptive planning is when it is possible to rethink every after a period with new knowledge if we still are making good decisions." (NL2)
- "you choose your strategy in such a way that when there are certain tipping points or things happening that you can still choose another path. So I look at it from a metro path metro map kind of way, that's my definition of adaptive planning." (NL3)
- "It's continuously learning and developing in all kinds of cycles on all levels and then also having a line of sight in place." (NL4)
- "adaptive planning is closing the loop between utilities their performance and also their failure and using that information to analyze what's the cause? And what are the solutions? And analyze what's the best solution, investment or maintenance or modification? And also looking at the context. And so if I have a solution, how does it affect related utilities and then execution… in that way you can close the loop, but that's a continuous circle, based on information about the performance of the assets and the costs of keeping it that way." (NL5)

Researcher definitions:

- "the key message would be it's all about keeping options open. It's not about deciding on a specific pathway…focusing on what your investment needs to be in the current moment and then when more information comes to hand like in the next five years, you'll have better information. You can then refine that decision and then to what do we not have to do? And then what is next? And so you just keep shifting that frame based on whatever information is the best information you have at hand at the time of the decision making rather than plotting out the best combination of options that you think will deal with anything in the future." (R1)
- "it's being developed in this DMDU field, but it's also very closely related to other systems and control kinds of things. Right? Where you try to update your actions depending on what's happening … it is a great tool to already take into account the long term effects of your short term decisions" (R2)
- "In two words, be prepared…that does not mean that you do not anything. Just that you say, "OK, I'm waiting here and I'm just preparing everything. But I don't do anything now." You have a plan. You take a certain route, but in the meantime, you are already prepared for everything that might happen as much as possible." (R3)
- "So the way that we define adaptive planning which I think is not universal or I wouldn't even say defined the way that I would advocate for adaptive planning is to formulate decisions rather than a static set of actions that are gonna happen…we've been doing that by formulating adaptive rule systems. So using our risk of failure measure. And we can update our knowledge about the the state of the the world and use that knowledge to inform the actions that we take in light of that future condition. Adaptive planning in general would be rather than coming up with a fixed set of

actions, planning to have a set of responses that will change depending on the future conditions.” (R4)

- “building computational systems to simulate the future where these systems that represent utilities or some other large actors can respond to uncertainty and implement some sort of mitigation actions over time, so dynamically, adaptively in order to mitigate risk” (R5)
- “what we try to do when we help people build adaptive tools is kind of impress upon them that it's really hard to understand what's the best thing to do right now in the future. And so a lot of times the best things can be to like kind of keep your options open. And to allow yourself the ability to kind of change course if conditions change” (R6)

Appendix B CODING APPROACH, CODE DEFINITIONS AND INTERVIEW RESPONSES

A grounded theory approach was taken to coding the interview transcripts. This process started with writing memos for each interview, from which concepts for codes were initially derived. Following this, a process of open coding of the transcripts were used, in which the interviews were inspected line by line, identifying quotes/passages with relevant statements and adding codes to those quotes, connected to the interview question it was responding to. In some circumstances, responses to one question were coded as responses to another, for instance, if the respondent started talking about approaches for overcoming barriers when discussing barriers. Once the open coding of the interviews was completed, memos were written to process the outcomes of the open coding and to develop key categories for responses to the interview questions and grouped responses into useful categories for responding to the research sub-questions.

The translation from open codes to categories is shown in **Error! Reference source not found.** and Table A.4.

Table A.3 Codes applied for interview questions in the open and axial coding stages for utility interviews

Research Question	Interview Protocol Question	Open Coding	Axial Coding
RQ 1: Barriers and opportunities	IQ1: What do you perceive as the key barriers to using adaptive approaches?	Expertise Time	Process
		Business case Governance Regulation	Institutional
		Awareness Organisational culture Perception	Organisational culture
	IQ2: Are any of these barriers connected to data or availability of data?	Data availability Data quality Monitoring	Data
	IQ3: How have you seen adaptive approaches being used by utilities? IQ4: What parts of utility planning hold the most promise for adaptive approaches?	Long-term Mid-term	Time scale
		Corporate strategy Place based planning System level planning	Planning scale
		Network assets Monitoring Water supply Water treatment assets Wastewater treatment assets Waterways	Asset type
RQ 2: Utility practices	IQ5: What adaptive policy tools and techniques are familiar to you?	Multi-objective optimization Pathways Real options analysis Robust decision making	DMDU approaches
		Scenario planning	General adaptive approaches

	IQ6: How have you implemented/tried to implement adaptive approaches in your utility? Was it successful or not, and why? IQ7: How could barriers be overcome?	Bottom up support Collaboration Organisational culture Top-down support	Organisational culture
		Data availability Data quality	Data
		Enabling policy Policy window Regulation	Institutional
		Champion/steward Communication	Activities
RQ 3: Research opportunities	IQ8: What challenges is your business facing?	Aging assets Demand growth	Asset
		Climate change Drought Emerging contaminants Extreme weather Flood Heat Urbanisation Water quality	Physical and climate
		Prioritisation Regulation	Institutional
	IQ9: What are the goals/long term strategic objectives of your business?	Environmental protection Prudent and efficient services Public health	Objectives
		Circular economy Digitalisation Energy transition Liveability Resilience Sustainability	Aspirations
	IQ10: To what extent does data play a role in your planning and strategic objectives?	Not coded	Not coded
	IQ 11: What deep uncertainties do you face?	Land use Population distribution	Future customers

		Population growth Service needs	
		Operating environment Regulatory change Technological change	Institutional
		Climate change Ecosystem services	Climate/hydrologic
		Sociopolitical events	Sociopolitical/exogenous
	IQ 12: How do you define adaptive policy/planning?	Adapt Decision support Flexibility No regrets Path dependent lock-in Respond	Not coded
	IQ13: How would you rate the current understanding of adaptive planning principles in Australian/Dutch water utilities (scale of 1-5)? Why this rating?	1 2 3 4 5	NA
	IQ14: What do the research and utility communities need to learn from each other?	Case studies Collaborative research Communities of practice Framework Knowledge transfer	NA

Table A.4 Codes applied in the open and axial coding stages of the researcher interviews

Research Question	Interview Protocol Question	Open Coding	Axial Coding
RQ 1: Barriers and opportunities	RIQ1: What do you perceive as the key barriers to using adaptive approaches?	Bad practice Communication Computationally expensive Definitions	Process

		Resourcing Time Definitions Difficulty Expertise Quantifying uncertainty	
		Business case Coordination (lack of) Governance Politics Regulation Utility size Water laws	Institutional
		Institutional inertia Mistrust of models Perception Needs Risk aversion	Organisational culture
	RIQ2: Are any of these barriers connected to data or availability of data?	Data availability Data use Data barriers	Data
	RIQ3: How have you seen adaptive approaches being used by utilities? RIQ4: What parts of utility planning hold the most promise for adaptive approaches? RIQ5: Share utility responses – ask to reflect on these: - Time scale: long term planning - Planning scale: System-scale, followed by corporate strategy, place-based and finally asset-scale - Part of servicing: In Australia, most commonly wastewater treatment, but water supply and network assets (both water and wastewater) were highlighted.	Wastewater Water supply	Asset type
		Place based Servicing strategy Asset-level	Planning-scale
		Long-term Time scale	Time-scale
		Exploratory modelling Pricing	Other opportunities

RQ 2: Utility practices	RIQ6: How have you implemented/tried to implement adaptive approaches in water utilities? Was it successful or not, and why? RIQ7: How could barriers be overcome?	Utility willingness Awareness Coordination Bottom-up Top-down Trust	Organisational culture
		Financial commitment Community/customer support Policy window Resourcing Utility size	Institutional
		Education Partnerships Communication Integrated modelling Interactive tools Incrementalism Steward/champion	Activities
RQ 3: Research opportunities	RIQ8: Share strategic objectives of utilities – ask to reflect on these: Non-negotiable: - Prudent and efficient (i.e. cost-effective) services - Protecting public health (safe drinking water) - Environmental health Aspirational: - Circular economy - Energy transition - Liveability - Sustainability	Affordability Circular economy Environmental Health Liveability Providing quality water Resilience	NA
	RIQ9: What kinds of deep uncertainties exist for utilities that can be served by adaptive approaches? Share utility responses of deep uncertainties:	Population distribution Population growth Land use Water demand Future customers	Future customers

	- Future customers - Operating environment - Regulation - Climate - Water quality and quantity	Implementation Regulatory change Institutions	Institutional
		Rainfall Sea level rise Water quality Water quantity	Climate
	RIQ10: How do you define adaptive policy/planning?	Not coded	NA
	RIQ 11: How would you rate the current understanding of adaptive planning principles in water utilities (scale of 1-5)? Why this rating?	Not coded – only one respondent provided a rating.	NA
	RIQ 12: What do the research and utility communities need to learn from each other?	Case studies Collaborative research Community of practice Experimentation Language Requirements mismatch Research as theoretical P2R R2P	NA

Here, examples of interviewee responses across the different questions are shared relative to their categorisation. Explanation of the interviewee codes are given in Table A.1 in Appendix A.

Table A.5 details the responses of utilities and researchers regarding barriers to adoption of adaptive approaches, as discussed in Section 4.1.1.

Table A.5 Responses of utilities and researchers regarding barriers to adaptive approach adoption

Barrier type	Interviewee responses
Process (55 instances)	“I think the learning cycle for adaptive planning is quite long because of that, the length of time that you're planning for. So, it's going to take a while for us to truly learn lessons and how to do it better and when plans haven't worked and I think that's challenging because the people who then develop those plants might not be around or might not be the ones who learn the lessons. So that's another challenge of adaptive planning.” (AU2) “I don't necessarily have the time or energy to dedicate to exploring different ways of being able to do this.” (AU1) “there's not a lot of expertise out there, particularly with consultants. There are very few that you can actually go to to get assistance in this.” (AU4) “The amount of research in time and amount of work it actually takes to do it properly. Yeah. We just don't have the people to do that. So that's, I think, the main one because everybody sees that it's useful, but I think it's also underestimated how much work it is to do it properly.” (NL3) “One of the largest challenges for our implementation and the implementation of DMDU in general for decision makers is how do you narrow it down, how do you refine your message in a lot of cases to a recommendation without betraying the complexity and the uncertainty within the analysis that you've done” (R5) “Especially dynamic adaptive policy pathways is a computationally super expensive approach. You have to do so many runs. I think in the in the 2013 paper they talked about like 200,000 runs, but that's even for like a relatively simple map in the end. If you increase the complexity like the internal complexity of your model, if you have more policy levers or you've increased the uncertainty around like your system performance, these numbers just explode.” (R2) “Too technically difficult. That's one thing. The other thing is the amount of results that come out of such an adaptive study are so overwhelming and hard to interpret and to translate into concrete measures.” (R3)
Institutional (54 instances)	“I think there is still a gap around, if we're going to assess different pathways, how do we do that with confidence, particularly when viewed from financial regulator perspective” (AU5)

	"I think the thing that we probably need to work better on at [Utility], particularly, is the governance around adaptive planning. So, I think we've done some good adaptive plans and that look at what are the future pathways but then do people actually follow with them after that first investment?" (AU2) "Finance teams are not on board yet, they don't really get it. And if they do get it, they still see a lot of barriers to being able to adopt it. And the reason they're worried is because treasury and the "I" bodies are not on board. [economic regulators] …I think they've been thinking about it, but they're not really set up for it." (AU3) "We have a traditional organisation, we have to do it with the same people and we have to transfer to an organization that has to act in this situation. And that of course asks for differences in governance in accountability and that makes it very difficult at this moment" (NL2) "I think institutionally water laws and water rights have been a large barrier out there in terms of implementing things. So there's been a lot of research in terms of, how can you kind of overcome or work within the existing legal framework to come up with policies that are adaptive and efficient?" (R4) "Often the blame gets put on the regulator. It's like, "oh, we can't do that because the regulator won't let us." And what you'll probably hear quite a bit is that the regulator won't let us spend on adaptive planning, which I think is nonsense because I think if you can demonstrate that. If it can be demonstrated that, doing something now to build robustness or being flexible will save you in the long run" (R1) *Note: contrary view to that of utilities*
Data (26 instances)	"we've got a lot of people who are doing a lot of very good data collection in the organization. But it's not necessarily translating into something we can use to make decisions quite yet" (AU1) "I guess the barrier for me in terms of successful implementation of an adaptive plan beyond that first decision point is we're not monitoring and keeping track of those pathways and those decision points to then know "We should probably pull that plan out and think about whether that still makes sense." (AU2) "[the reason] we don't go so quantitative is because we really don't have the data and the ability to get too quantitative with this stuff in the water industry yet." (AU3) "One challenge we had was probably the lack of data and wanting to do adaptive planning without actually having a proper understanding of your system. Understanding how it will change over time and I think that's actually a big barrier." (AU4)

	"There is a lot to be said about the availability and quality of data with water utilities and it's a constant struggle, but I don't think that is the reason for now that these methods are not being adopted, but I can see that when they start getting ready to adopt these methods, this will become an issue." (NL1) "I think a lot of the limitations are in the data and how to use it and what sort of analysis to do on the water demand side of things. I would say the water supply availability can be very well quantified, but how people will use water or won't use water there's a lot of very cool new data coming up, like for instance the utility I drink water from is installing smart meters on every on every user in their service area, which is an amazing amount of data that I don't think the utility certainly has nobody prepared to make use of it to figure out what to do with it because it's an insane amount of data" (R5) Data *not* a barrier: "Everybody I've talked to in water utilities is pretty data savvy, so I wouldn't say that's a water utility specific issue." (R4) "I'm not sure whether the quality of data is a problem. No, I don't. I think that the data is not that. And if it's not there, we could easily get it. I would say relatively easily, yeah. It's just it's a way of… it's a paradigm shift that is needed." (R3)
Organisational culture (44 instances)	"What is, I think, a huge barrier, but the culture, and the leadership mindset of an organization can play a huge role. It can be a huge barrier or can set us up for success" (AU5) "So, I think that sometimes adaptive planning can be used as a reason to defer investment and to spend less now. That can be good, but that can also be problematic." (AU2) "it's perceived as fluffy. It's perceived as not concrete and technical and decisive." (AU1) "People in the servicing strategy teams tend to be pretty strategic thinkers. They tend to be looking for new approaches to apply and innovative ways to do things. The planners meanwhile are smacked over the head if their cost estimates are out by 20%, that's what they're worried about. You know, they're worried about defining a piece of infrastructure so that the infrastructure delivery team doesn't throw it back in their face and say you haven't done this right, or the business doesn't come back to them and say you've got your cost estimate wrong." (AU3) "I think that people are not fully aware of their [adaptive approaches] existence and their potential. And I'm also not sure that many people are sufficiently aware of the need to apply such an approach." (NL1) "It's supposed to make it more clear to deal with uncertainties, but also makes it very clear that there are so many uncertainties and that it also

	paralyzes the decision making of people in the asset management process. So it conflicts with the regular asset management cycles" (NL3) "Institutional inertia is probably one of the biggest barriers we see in that changing your policy is always a risk" (R4) "Adaptive, although over the last year, two years, it's getting better…was often seen as doing nothing, delaying things. So, the very negative selling point, so to speak. Because in adaptive plans …you're not saying I'm going to build a bridge now, you say I might build a bridge if…" (R3)

Table A.6 excerpts responses of utilities regarding enablers of adaptive approach adoption.

Table A.6 Interview responses regarding enablers for implementing adaptive approaches

Enabler type	Interview responses
Organisational culture factors (52 instances)	"The value was really hard to articulate and it was more strategic and high level. Which is plagued with the same issue of "What does strategy ever do for us?" The first thing is awareness and understanding." (AU5) "So having the buy in from stakeholders and bringing them along the journey and demonstrating that the learnings from their experience, we've tried to address them and done it in a pragmatic way. And hopefully that means that they feel ownership of the plan. So that when we are in drought, they want to follow it because they informed what it looked like." (AU2) "I think one of the things that is helpful is having that top-down support of this because we've got a chair and a board that that's very keen and the further down you go, the more diverse the views and the perceptions are of this." (AU4) "it was successful because there is a new way of thinking now and people realize that we can do different things in the future." (NL3) "I think you're well aware of the fact that everything is organized in like columns. You know, the money's getting into columns and the responsibilities are divided like that also. And you know you need these Co creation initiatives to move on." (NL4) "I think a lot of that is just again interpersonal stuff within the utilities. Who's actually making the call. And how much they're really understanding, or you know back to how do you really get people to believe and be afraid of risks that you don't have a lot of data for?" (R6) "Going in very open minded as a researcher has been really helpful and then kind of working from the bottom up to build trust in our relationship and trust in the modelling process." (R4)
Data factors (8 instances)	"Data is our number one risk or opportunity." (AU5)

	"we've got a lot of people who are doing a lot of very good data collection in the organization. But it's not necessarily translating into something we can use to make decisions quite yet, and I think that's the step change that we're trying to make as an organization." (AU1) "Exchange of data between water utilities and water boards and water authorities also in other countries will be very important for doing the adaptive pathways" (NL1)
Institutional factors (27 instances)	"Engaging with our regulators around the complexity of, there's so many challenges in the future and so many unknowns and this is how we're trying to manage them in this adaptive approach and that, if we keep deferring things that compromises our ability to deliver on these adaptive plans." (AU2) "The role of government when it comes to stipulating things like some basic tenets or guidance for utilities to do adaptive planning in a more consistent manner so that it becomes accepted by other agencies and other regulators as well." (AU4) "A crisis can also mean that people want only very safe solutions and not do the innovations. So, you have to be ready with your innovative solutions, but it's not enough sometimes." (NL2) "I think for the utilities it's very interesting that when they are faced with a problem and when their back's against the wall, they seem to understand these things a lot better. It's easier to explain to them the benefits behind these things when they can see them for themselves" (R6) "I think they just have to make it their main focus for a particular season or to the point where something can be included in the next iteration of their five-year master plan" (R5)
Activities (22 instances)	"One thing which is actually probably needed within Australia is people who are trusted advisors. On adaptive planning and that's probably might be a better fit for academia and sort of practitioners who have lot of respect and expertise in this area, especially for the water utility sector" (AU4) "And so now we have two times a year the…we call it the lighthouse meeting where I tell them, "OK, these are the boats that were. This one's gone. This is a new one and the lighthouse is actually moved a little bit to the left because we've found these tipping points" and you know, so the organization knows where we are in the adaptive planning pathways" (NL3) "I think oversight, steering, and being able to weigh all the elements in the best way possible to make integral decisions." (NL4) "You have to find champions within the organizations who are open to coping with uncertainty." (R3)

	“What we weren't necessarily prepared for was in order to get at some of the deeper financial questions we needed to sort of build out an entirely new financial modelling framework and computational system to match the models that they already had in-house for the water supply side, but did not have in terms of finance that could, you know, sort of communicate with what was happening in the water supply models and then react to it” (R5) “That transition between making sure any solution or any challenges is there making it known and then saying it the right way to the right people enough times so that it becomes of interest to the planners and the actual decision makers” (R5)

Examples of responses from utilities and researchers regarding areas of opportunity for adaptive approaches in water utilities are given in Table A.7.

Table A.7 Responses of utility practitioners and researchers related to opportunities for adaptive approaches

Opportunity type	Interview responses
Asset type (31 instances)	“we've created literally a handful maybe about 3 different examples. All wastewater related, network and treatment around the servicing strategy space, which is preceding the detailed planning.” (AU5) “they’re looking at just wastewater treatment in a particular catchment. Using adaptive planning as a means to map out their different options for how they might go about treatment and what things might interfere or interact with that so that they are making considered and no regrets decisions.” (AU1) “Some areas have always been more adaptive. Usually, water resources management tends to be more mature across utilities” (AU4) “we're looking at water sources, water treatment and water distribution. Actually, I see the potential for all three of them. But probably in that order. So first for sources and then for treatment and then distribution.” (NL1) “They use the adaptive pathway method of deltas in different provinces. And then for every province they looked at, how can we accommodate the water demand in the worst-case climate scenario, which is very high and with high peaks. And then there were all these different paths and ways to deal with it.” (NL3) “I've mostly been working in water supply. So, with water supply policy.” (R4)
Planning scale (19 instances)	“I've seen them at a strategic level when we're looking at place-based strategies for different areas like west of the city, east of the city. I think it's quite interesting to do it at that strategic level for looking at different futures and what are their opportunities for land-based planning… we've

	also seen it done at a system level. So, looking at water master plans and wastewater master plans and that sort of thing, I think where it can get quite interesting as well is at that optioneering stage or looking at different pathways when looking at an asset and what you might build and why and how that can set you up in the future.” (AU2) “we are using it at a system level like we're looking at the water system and the wastewater system and trying to use adaptive planning at that level and and starting at the level of the system and then rolling down into part of the process is one of the subprocesses under that and the rolling down into more detailed use of adaptive planning.” (AU1) “So, the servicing. So what sources are there and how can you change sources, but also of course the effect of saving water, I think.” (NL3) “And then [utility] not so much with existing infrastructure that they had some adaptive planning looking at the [treatment plant] upgrade, but it's more around [suburb] and the whole region. Looking at adaptive responses there and what might make sense, regarding recycled water and when you might put things in place.” (R1)
Time scale (12 instances)	“And so we want to structure our approach so that we have high confidence in the short term, 0 to 5 years or thereabouts with basically framing the most likely or preferred medium to longer term servicing alternatives we think we need to entertain.” (AU5) “we've been trying to use adaptive planning kind of across the organization at that strategic mid to long term planning level.” (AU1) “Trying to keep working on shorter cycles when a lot of the adaptive planning issues are long term issues” (AU4) “I feel like DMDU is traditionally most applied in a strategic decision making which also kind of ties in with it being applied to long term decision making where you have a planning horizon of hundreds of years or climate change and like those kinds of systems are where it's most typically applied.” (R2) “Everything that we've heard from utilities here that for their planning horizons, which are, you know, at the most, it's like the 45 years that they're either required to plan for in their long-term documents or it's shorter. They are less concerned about long term water availability and the risks to that, whether it's climate change or something else that I think that differs quite a bit from place to place” (R5)
Other opportunities (4 instances)	“Depending on the water utility, just incorporating modelling more not necessarily as a prescriptive tool to dictate what actions they'll take, but as an exploratory tool. So, I think there's a lot of opportunity for water utilities, especially the ones we've been working with to use models as a grounds for experimentation and saying what if we took this type of policy action or what if the world ends up changing in a way that looks like that” (R4)

	"I think on the research side, everyone is rightly concerned with not prescribing or recommending an option but using DMDU as a way to explore the uncertainties, to let decision makers see the different ways in which a choice can have implications. That is not what a utility wants." (R5) *Note: contrary view to R4, exploratory modelling interesting, but not useful to utilities.* "They will now use what we've built to make water rate change recommendations to their board and do other you know and think about this in concert with this specific water supply project decisions that they're thinking about" (R5)

Excerpted statements regarding challenges faced by utilities are given in Table A.8.

Table A.8 Interview responses regarding challenges faced by utilities

Challenge	Interview responses
Asset (11 instances)	"We have a wave; we call it a wave or a cliff of significant renewal investment coming because back in the day when in boom times we put a whole bunch of assets in the ground. And so now it's time to renew them all. According just on the basis of age. Therein lies the complexity around well, you can't only replace them on age." (AU5) "Historically we've gotten so much out of our assets, but we've sort of transitioned to what people have referred to as over designing, or gold plating or overengineering to these very optimized solutions and they're optimized in a very, very narrow operating window." (AU2) "The system we have is old and needs to be improved or replaced in order to also serve for the future." (NL3)
Physical and climate (21 instances)	"Consistently climate change and population, and urbanisation come up as top challenges. During the pandemic, population and urbanization probably temporarily dropped a little bit." (AU4) "We also know huge challenges in terms of heat and with the changing climate, particularly how hot the west of the city can get and will continue to get. And the role that water can play in making that a healthy and vibrant place for people to live." (AU2) "Implications from climate variability. And everything that comes with that, both wet and dry." (AU5) "a changing climate, which makes the availability of water more variable on the short term and more uncertain on the long term." (NL1) "it's extremes that make that such a technical water system more vulnerable than we had in the past decades or more." (NL2)
Institutional (8 instances)	"The key strategic challenges I think are probably similar across and most of the water utilities in Australia and there's changes in regulation

	coming up. Which you know it will always be a thing, risks of licenses, codes, Acts those kinds of things getting stricter" (AU1) "Water utilities are trying to say, 'OK, we need to optimize the wastewater system, but we want to produce recycled water for liveability and then you've got [purified recycled water] which then interacts with the water system,' and they're struggling to work out how to do adaptive planning with so many competing objectives." (AU3) "Knowing how to prioritize those between the obligations and the aspirations and I think becoming less compliance driven as well. It's that transition we need to go through. But that's gonna take time." (AU2) *Note: Institutional challenges were not mentioned by any Dutch utilities interviewed.*

Excerpted statements regarding deep uncertainties faced by utilities are given in Table A.9

Table A.9 Interview responses related to deep uncertainties in utilities

Uncertainties	Interview responses
Future customers (18 instances)	"We are facing things like changing land use in the future and demand profiles. Really questioning how it has been for the way we currently practice with changing land use, significant land use and density changes in growth projections and it's making it really challenging to maintain how we plan for that." (AU5) "there's uncertainties around future requirements that have been going to be placed on us. What the community expects from us, how the city is being shaped. If there's lots of people moving to regional areas after COVID or there's people working from home. There's all these different uncertainties in terms of how people engage in, live in the city." (AU2) "These things that I'm putting in the ground right now, I'm expecting to last 100 years and yet I don't know what 100 years is gonna be like, what condition this piece of pipe is going to be in in 100 years' time. What I'm actually trying to operate." (AU1) "I think one of the ones that we don't necessarily consider that well is around community expectations and we quite often make assumptions about what we think the community wants or what where the community will be in 10 years' time or what their perceptions would be then. But I'm not sure that we actually do have enough in that space to really understand community perceptions and where it could go, what could happen in the future and how could they perceive things in the future? What their expectations of us could be so different." (AU4) "But in the end, it's not only about your technical asset, it's also about environment of your asset changing. So, the society in the Netherlands is also changing a lot. There are much more people coming to live in our

	area. So, we can optimize our assets, but can they grow together with the more people coming." (NL2)
Institutional (21 instances)	"they're optimized in a very, very narrow operating window. And so, we optimized our assets in isolation in that narrow band. So, when the operating environment changes we're not particularly resilient to then adapt to that without things falling apart." (AU2) "a lot of the stuff we cover in uncertainty in the water industry, it's really not … often it's regulatory uncertainty, it's not deeply uncertain, it's more ambiguous or volatile. Probably more ambiguous. It's not deeply uncertain. It's uncertain, but it's not deeply uncertain." (AU3) – *opposing view, suggests regulatory uncertainty is not a deep uncertainty* "For years we were able to facilitate all the building and all the other functions and we see more and more that the current water system in Netherlands, it's very sophisticated technically though probably in the low part of the Netherlands, it really reaching its borders. So, we really have to transform as a utility to a different role" (NL2)
Climate and environment (12 instances)	"So, working out what sea level rise is going to be tomorrow, is very different to working out what sea level rise is going to be in 50 to 100 years' time. In 50 to 100 years' time, it's deeply uncertain what the impacts of climate change are going to be." (AU3) "A lot of the uncertainty we have, and they're at probably different levels, a lot of it comes with the challenges associated with climate especially, and how that is actually changing rapidly and that's probably the biggest issue that we have." (AU4) "How the climate crisis and the effects on the availability and quality of water will unfold" (NL1) "there's, quite some deep uncertainties that we face in our system. So, it's for example, the whole working of the dunes. It's actually not really known. So that's for us, a big one because it defines our quality." (NL3)
Sociopolitical (7 instances)	"So, a good example is COVID, and from a [Utility] perspective, it's not something we really thought about and there's certainly no scenario planning or strategic plans that thought about what would happen if there was a pandemic, how would this play out?" (AU2) "Some things that are probably fairly deeply uncertain, like war and international migration, socioeconomic disruption in the Southeast Asia region." (AU3) "There is a small but nonnegligible possibility that that's the way we are as a society acting right now and transgressing planetary boundaries will result in a slow or in a rapid collapse of modern society. And that's I think something that utilities should also think about and in such a scenario. they would need to fall back too much. Simpler systems which do not rely on the availability of technology, of a lot of energy of, of data transmission systems" (NL1)

Excerpted statements regarding utility goals are given in Table A.10.

Table A.10 Interview responses regarding strategic goals set by water utilities

Goal type	Interview responses
Objective (18 instances)	"Prudent and efficient water and wastewater services etc.. I won't go into detail on that, but that's obviously the light on the hill." (AU5) "We are a water and wastewater services provider. And I think our intention is to continue to provide water and wastewater services. It's a place where we can innovate and we can be better, but we're not necessarily driving for more profits or those kinds of things in the same way that other businesses might be." (AU1) "When it comes down to it, it really is about maintaining acceptable levels of service for the most efficient costs." (AU3) "Main objective is to continue supplying water of the highest possible quality to customers, could be consumers, could be industry" (NL1) "Strategic goals were always on the level of the second part you know, so the climate neutral, et cetera. But actually, since five years it's also necessary to have a goal on our continuity, on our main services. And we never used to have it because it was just, we had a system and we were improving it. It was business as usual." (NL3)
Aspiration (31 instances)	"The aspirational side of things, like the water industry wants to embrace the circular economy and generate resources from waste. And they wanna close the water cycle so that they're not, you know, not relying on dams, but they're using recycled water for potable reuse." (AU3) "The circular economy, IWM, liveability" (AU4) "Next to this big challenge is digitalization" (NL2) "it's also digitalisation and the energy transition. Everybody has to be off gas in the coming years." (NL3)

A review of water utility annual reports was performed to validate these aspirations and objectives. Table A.11 shows the frequency with which these terms appeared across 18 water utility annual reports from Australia and the Netherlands.

Table A.11The frequency of occurrence of different utility aspirations and obligations within water utility annual reports

Category	**Code**	**Frequency**
Objective	Public health	23
	Environmental health	22
	Reliability	19
	Affordability	13
	Prudential responsibility	12
Aspiration	Intergenerational equity	15
	Livability	14
	Resilience	12
	Energy Transition	10

	Digital Transition	9
	Efficient	8
	Circular Economy	7

Table A.12 details which utility annual reports were reviewed for this. Australian utility reports were chosen for the utility (or utilities) supplying the largest city in each state or territory. Reports for Dutch water utilities were reviewed where available (two utilities were excluded due to unavailability of an annual report document). Where necessary, reports were translated to English with the assistance of translation software.

Table A.12 Utility documents reviewed for strategic goal validation

Utility Name	**Report Title**	**Reference**
SA Water	2020-21 South Australian Water Corporation Annual Report	(SA Water Corporation, 2021)
Water Corporation	Water Corporation Annual Report 2021	(Water Corporation, 2021)
Icon Water	2020-21 Annual Report to the ACT Government	(Icon Water, 2021)
Seqwater	Seqwater Annual Report 20-21	(Seqwater, 2021)
Urban Utilities	Urban Utilities 2020/21 Annual Report	(Urban Utilities, 2021)
Sydney Water	Sydney Water Annual Report 2020-2021	(Sydney Water, 2021)
Melbourne Water	Melbourne Water Annual Report 2020/21	(Melbourne Water, 2021)
TasWater	TasWater Annual Report 2020/21	(TasWater, 2021)
Power and Water	Power and Water Annual Report 2020-2021	(Power and Water, 2021)
City West Water	City West Water 2020-21	(City West Water, 2021)
Western Water	Western Water Annual Report 2020-21	(Western Water, 2021)
Yarra Valley Water	Yarra Valley Water Annual Report 2020-2021	(Yarra Valley Water, 2021)
South East Water	South East Water Annual Report 2020-21	(South East Water, 2021)
Evides Waterbedrijf	Evides Waterbedrijf Jaarverslag 2020	(Evides Waterbedrijf, 2021)
Brabant Water	Natuurlijk varanderen Jaarverslag 2020	(Brabant Water, 2021)
WML	Jaarverslag 2020	(WML, 2021)
WMD Water	WMD Jaarverslag 2020	(WMD Water, 2021)
Vitens	Vitens Jaarverslag 2021	(Vitens, 2022)
PWN	Duurzaam Samenspel Jaarverslag 2020	(PWN, 2021)
Dunea	Dunea Annual Report 2020	(Dunea, 2021)
Oasen Drinkwater	Oasen in Beweging Jararverslag 2020	(Oasen Drinkwater, 2021)

Appendix C THEORETICAL MODELS REVIEW

An overview of literature considered when searching for requirements for a suitable conceptual model are summarised in Table A.13.

Table A.13 Literature reviewed to identify suitable requirements for a conceptual model/framework

Reference	Description	Category
Pot et al. (2018)	Developed a framework that identifies the ways in which planners and decision-makers make forward-looking decisions. The authors note the role of political influence on the scenarios used in decision making and future vision setting.	DMDU
Crewe and Young (2002)	This working paper focuses on research to policy in development contexts, but highlights three relevant key success factors for translating concepts from research to policy; fitting withing institutional limitations, shared networks, and chains of legitimacy between research and practice, research outputs are based on local and credible cases.	Research to policy
Kiparsky et al. (2013)	Presents a model of innovation in urban water systems. The paper focuses on the connection between technological researchers and urban water innovation, but parallels can be drawn between policy research and urban water planning. This is because of many shared barriers, including company culture and financial regulation of urban water systems.	Urban Water
Farrelly and Brown (2011)	Focuses on the need to create a culture and policy environment that supports experimentation in urban water planning. Notable for the similarity in methodology with this thesis and focus on the Australian context.	Urban Water
De Haan et al. (2015)	A journal special issue on the relationship between urban water and sustainability transitions. The editorial focuses on applying transition science to changing planning paradigms in the urban water sector.	Urban Water, Transition science
Marchau et al. (2019, p. 9)	This seminal work in the DMDU literature presents a framework for considering levels of uncertainty relative to four locations of uncertainty in a given model.	DMDU
(Garcia et al., 2019)	This work focuses on transition dynamics and “periods of accelerated change” that occur in sustainability transitions of water utilities. The work highlighted several factors that influence such sustainability transitions.	Urban water, transition science
(Ferguson et al., 2013)	This work tested five different types of transition frameworks as applied to a case study of sustainable urban water management (storm water management in Melbourne, Australia). The study focused on deriving answers to diagnostic questions about transitions to identify current states and potential next steps/trajectories.	Urban water, transition science
(Brown et al., 2018)	Developed the Water Sensitive Cities urban water transitions framework.	Urban water

Appendix D EPA Programme requirements

Table A.14 describes how this thesis meets the programme requirements of a thesis in the Engineering and Policy Analysis Masters.

Table A.14 The alignment of this thesis to EPA programme requirements

Element	Explanation
Focus on grand challenge	This thesis focuses on the grand challenge of urban water utility infrastructure planning under deep uncertainty.
Situation where policies are failing or need to be designed	Traditional approaches to investment in urban water infrastructure aren't adequate to deal with dynamic uncertainties facing utilities including population growth, changing water quality and water shortages driven by a changing climate. Despite this, many utilities struggle to apply adaptive concepts from DMDU research.
Relevant for people, planet, profit, and science	Decisions related to urban water infrastructure can have significant impacts on the communities serviced (through reliability and cost of water services), the environment (in relation to the location and types of asset investments), and often most critically, for the financial outcomes of utilities and governments (in the form of timing and scale of investments).
Applying analytical techniques	Design science and grounded theory analysis methods were used to analyse the current problem and to propose potential solutions.
Culminates in advice to a problem owner/decision maker	The main outcome of this work is a framework for utilities or related practitioners looking to implement adaptive approaches to improve decision making under deep uncertainty. The framework will also be of use to DMDU researchers interested in working with utilities.