How does regulation affect innovation and technology change in the water sector in England and Wales?

Bora Ristic

Imperial College London, Centre for Environmental Policy

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Supervisors: Zen Makuch, Kaveh Madani

Declaration of Originality

I, Bora Ristic, hereby declare that this thesis is my original work and that where I have drawn upon other work I have referenced this.

Copyright Declaration

Preface

This thesis reports original work drawing also on the following manuscripts written as part of this doctoral research.

1. Ristic Bora; Madani Kaveh; Makuch Zen. (2015) The Water Footprint of Data Centers. *Sustainability. 7*(8), 11260-11284; https://doi.org/10.3390/su70811260

2. Bora Ristic; Maral Mahlooji; Ludovic Gaudard; Madani Kaveh. (2019) The Relative Aggregate Footprint of Electricity Generation Technologies in the European Union: A System of Systems Approach. *Resources, Conservation, and Recycling*. 143, 282-290; https://doi.org/10.1016/j.resconrec.2018.12.010

3. Cheng Chuntian; Chen Fu; Li Gang, Ristic Bora; Mirchi Ali; Tu Qiyu; Madani Kaveh. (2018) Reform and renewables in China: The architecture of Yunnan's hydropower dominated electricity market. *Renewable and Sustainable Energy Reviews.* 94, 682-693. https://doi.org/10.1016/j.rser.2018.06.033

4. Ristic Bora; Madani Kaveh. (2019) A Game Theory Warning to Blind Drivers Playing Chicken with Public Goods. Water Resources Research. 55(3), 2000-2013; https://doi.org/10.1029/2018WR023575

References 1, 2, and 3, are draw on largely for methodological and theoretical considerations in Part 1 of this thesis. Reference 4 provides the core of the model considering myopia in decision making as developed further in Chapter 8 of this thesis.

Acknowledgements

I would like to acknowledge the many wonderful people who helped me greatly over the course of my PhD.

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Finally, but most importantly, I want to thank my parents. I would never have completed this thesis without their unending love and support.

Abstract

This thesis examines the role of regulation in technological change in the water sector in England and Wales. Based on a combination of Social-Ecological Systems (SES) theory and the Multi-Level Perspective on technological transitions a Comparative Information-Graded Approach (CIGA) is developed in Part 1. As part of the CIGA, a series of tools is used for characterizing and evaluating the relationship between regulation and technology.

In Part 2, the CIGA is applied to characterize the relationship between regulation and water innovation in England and Wales based on official publications, Environment Agency data, and interviews. In particular, 7 mechanisms are identified by which regulation affects innovation and 5 issues of trust negatively interact with innovation. As trust is established through these mechanisms, opportunities for innovation are at times sacrificed.

Part 3 develops and analyses a set of models based on findings in Part 2. Dynamical systems and fictitious play analysis of a trustee game model of regulation exhibits cyclicality providing an explanation for observed cycles which create an inconsistent drive for innovation. Trustee and coordination models are evaluated in Chapter 7 highlighting how most tools struggle with the issue of technological lock-in. Chapter 8 develops a model of two innovators and a public good water technology over time, showing the role foresight plays in this context as well as the disincentive to develop it.

Taken together, the CIGA characterization and modelling work provide a series of recommendations and insights into how the system of regulation affects technology change.

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Chapter 1: Research Overview

Key Points

- Social-Environmental Systems (SES) provide a framework for modelling decision-making in the adoption of eco-innovations and transitions in a regulated water sector.
- Aims and Objectives of this research revolve around systematic characterization of SES models of the relevant stakeholders, their options and decision making.
- The methodology will involve a qualitative review of literature, data from regulatory agencies, and stakeholder interview responses to characterize and analyse SES models.

This chapter provides an introduction to the research reported on in this thesis. It sets the context, defining key terms and briefly overviewing core concepts employed in and developed in subsequent chapters. The aims, objectives and research questions are defined. Most broadly, the research question asks, how regulation affects innovation. In structuring how this question will be answered an overview of the methodology employed is given and the final section provides an overview of key sources used for this research which draws on literature, firm-level regulatory determinations, stakeholder interviews and agent-based modelling.

1.1 Context and Justification

Environmental management typically involves multiple stakeholders with conflicting interests over an environmental resource in a so called Social-Ecological System (SES) [*Ostrom*, 2009a]. In the case of a water management in most developed countries, this involves upstream agricultural producers, water suppliers treating water for supply to industrial and domestic users and then treating resultant wastewater for release to the environment, all under a system of regulatory licensing and oversight. These multiple users interact in the water sector, its governance, and the resultant economic and environmental outcomes. With population growth, increased production, and the pressures of climate change, many of the world's water resources are suffering from over-exploitation and pollution [*Gleick et al.*, 1993; *Vörösmarty et al.*, 2000].

In order to manage these problems, new practices and technologies are being developed and employed. Such changes have been understood under the terms 'eco-innovations' and 'transitions' [*Geels*, 2005c; *Díaz-García et al.*, 2015]. Eco-innovations refer to changes in technology and practice aimed at reducing the environmental impact of human activity. The study of transitions understands such changes as part and parcel of changes in the broader social and institutional context. Such context can work to ‘lock-in’ constancy to particular practices and technologies and to enable eco-innovations and a transition to more sustainable practices [*Rip and Kemp*, 1998]. A series of different measures are available to lawmakers to address the challenges of eco-innovation with different policy and regulatory tools affecting the different aspects of environmental externalities and knowledge spillovers involved in this interrelationship [*Popp*, 2019].

Eco-innovation and Transition in Water Management

Key eco-innovations in water management are those reducing water stress and pollution, impact on ecosystems, as well as the carbon intensity of the water sector. Assessing the costs and benefits of water sector eco-innovations involves the complication of multiple outputs (typically on water quality and quantity). For example, wastewater networks are designed to deliver a range of quality parameters as well as environmental flow requirements [*Chen et al.*, 2012]. Additionally, the need for such interventions varies spatially across catchments given their demand-supply balance and pressures on quality.

In the context of water management, such technological changes are also mediated by the institutional context [*Geels*, 2005b; *Van Der Brugge et al.*, 2005; *Green and Anton*, 2012; *Krause et al.*, 2015]. The most widely promoted principles for effective water governance are those of Integrated Water Resources Management (IWRM) which “aims to ensure the co-ordinated development and management of water, land, and related resources by maximising economic and social welfare without compromising the sustainability of vital environmental systems” [*Rogers et al.*, 2003]. The ambitious ideals of IWRM however mean that it has come across substantial problems of implementation [*Voulvoulis et al.*, 2017]. For critics of the concept, this is not unexpected. The ambition of integration inevitably clashes with the allocation of responsibilities across multiple government and industry functions [*Biswas*, 2004]. The principle of integrating, critics argue, fails to acknowledge the fundamentally political nature of water management decisions which by definition involve multiple (typically conflicted) actors in a contest over the allocation of responsibilities [*Saravanan et al.*, 2009; *Giordano and Shah*, 2014]. Conceptual criticisms have also noted that it may not be possible to develop a universal principle for water management in all contexts, and that this is the underlying problem behind many failures of implementation [*Biswas*, 2008].

Inevitably, integration of governance across the many (if not all) sectors interacting with water systems is not effective, with planning and investment decisions residing across a range of authorities and stakeholders. Local or national particularities have important implications for the kinds of solutions (centralized or distributed, myopic or foresighted) that are implemented. In order to ultimately recommend particular eco-innovations or transition-friendly policies, it is important to systematically study, understand, and structure models of the situations decision makers find themselves in and how they go about making decisions.

Decision Making in Archetypal Models of Water Sector SESs

The study of SESs defines the core decision making level as that of an *action arena*, based on game theoretic models of strategic interaction [*Ostrom*, 2009b]. It is helpful to provide first-pass intuitions for these core terms employed by game theory here. A game is understood as a situation in which multiple decision makers. Each has some set of possible actions they can take. Taken together all combinations of the different actions the players take define the possible outcomes of the game. Each decision maker has their own preferences over different outcomes and they choose actions accordingly.

The tools used in game theory to characterize decision making are various [*Fudenberg and Tirole*, 1991; *Perea*, 2012]. However the literature has generally sought to develop a single dominant approach [*Harsanyi and Selten*, 1982]. Most commonly, decision making characterizations draw on the principles of Rational Choice Theory (RCT). Informally stated, RCT characterizes decision making as the selection of those actions which maximize a mathematical function representing the decision maker's preferences (the utility function).

The SES literature has however been critical of RCT [*Ostrom*, 1998], allowing for and even encouraging a relaxation of this conception of 'rationality as utility maximization' in order to allow for alternative characterizations of decision making if and where they are appropriate.

SES models also extend model characterization upwards into institutional hierarchies and downwards into the characterization of the environmental resources involved. While both of these differences allow for a more nuanced characterization of decision making in environmental management, game theory remains an important element in characterization and analysis of decision making in SES.

Game theoretic analysis has been used to study *archetypal* models of water resource management [*Madani*, 2010; *Madani and Hipel*, 2011]. The aim of such archetypes is to determine the most important and common aspects of a set of SES. Characterizing a model capturing these can then provide for analysis and recommendations across a set of particular situations involving such archetypes. Despite differences in water sectors across the world, some characteristics hold across many instances can be captured in archetypes.

The core archetypal characteristic of the water sector (as drawn from micro-economic analysis) is often understood under the term *natural monopoly* [*Mosca*, 2008]. Natural monopoly leads to a single firm supplying the market, the potential for that firm to abuse its market power, and hence calls for regulation to prevent such abuse [*Joskow*, 2007]. Such regulation can involve monitoring and controls on business plans or prices of private water companies (WCs), direct state ownership and control, or indeed various institutional configurations involving these elements.

Given regulation affects WC decision making, it also has the potential to affect innovation and technological change, working as an enabler or barrier to eco-innovation and transition. Under a nationalized system of water and wastewater services, the institutions governing such services (particularly the procurement system) would properly be the focus of study in water innovation. However the focus of this research will be the regulation of privatized utilities as found in the UK, in particular in England and Wales.

Transition and Trust in Regulated and Water Companies in the UK

On the environmental side, the UK water sector faces a diverse set of challenges water scarcity as driven by population growth (particularly in the south-east of England); environmental water quality particularly as driven by wastewater and farm runoff; compliance with and penalties from EU law; and long-term resilience in the face of flooding, drought and the exacerbation of these due to climate change [*Ofwat*, 2015d].

At the time of writing, the UK (particularly in England and Wales) is set to deal with these challenges through a set of regulated water companies. Several authorities act to regulate water companies in one way or another. These include the Environment Agency (est. 1995), the Drinking Water Inspectorate (est. 1990), Natural England (est. 2006), Consumer Council for Water (est. 2005) and local councils. Different configurations also exist across the devolved regions of Wales, Scotland, and Northern Ireland. The Water Services Regulation Authority, usually referred to as Ofwat, is the economic regulator for the WC's in England and Wales.

By way of overview, the core components of the SES of the water environment in the UK are shown in Figure 1-1. The different institutions of government are shown at the top, the main water users are directly below it, with technology suppliers to the right and environmental quality parameters on the left. Signals from the quality parameters feed into governance functions which regulate the use of water. These signals are also considered (to a greater or lesser degree by the suppliers.

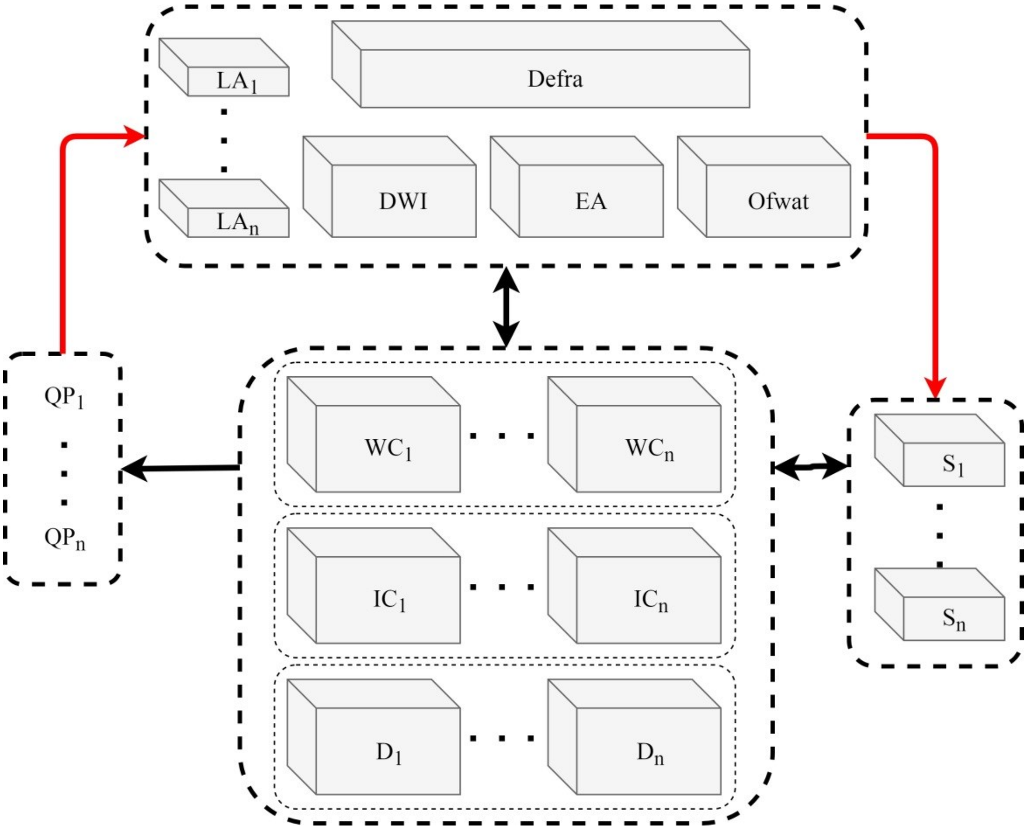


Figure 1-1: Stylized overview of the water sector.

Regulatory authorities are at the top: Department for Environment, Farming and Rural Affairs (Defra), Drinking Water Inspectorate (DWI), Environment Agency (EA), Ofwat, and Local Authorities (LA). Water users are in the middle bottom. Water companies (WC), Industrial Consumers (IC), and developers (D). Drinking water and environmental quality parameters (QP) are on the left and the technology supply chain is on the right. The arrows in black indicate direction interactions. Red arrows indicate information flow and signals.

The system of economic regulation will be the focus of this research for two reasons. Firstly, the UK adopted the internationally rare system of full divestiture and privatization of water assets and the system of price caps [*van den Berg*, 1997; *Thomas and Ford*, 2017]. As such it is an interesting case study how this institutional setting drives or inhibits technological change with important implications for the development and application of effective regulation to drive eco-innovation in the water sector as well as other settings.

The core action arena involves the relationship between the regulator and the water company. Several key mechanisms of this system in relation to eco-innovation have been discussed previously, and will be reviewed further in this thesis [*van den Berg*, 1997; *Thomas and Ford*, 2006; *Joskow*, 2007; *Green and Anton*, 2012; *HM Treasury*, 2012]. This relationship, like many others can involve issues of mutual trust. Ensuring trust in this ongoing relationship between regulator and company is crucial to effective regulation but the mechanisms employed to ensure trust can work to stymie technological change and innovation. How this happens and what implications this has is the core question of this research.

1.2 Research Question, Aims, and Objectives

The overarching research question is:

How does regulation effect innovation and technology change in the water sector in England and Wales?

This relatively loose research question guides the overall aims of the research. It can be reformulated to ask 'Does regulation promote or inhibit innovation in the water sector in the UK?' However, as will be argued the answer to this question is not a *yes* or a *no*, but rather a set of mechanisms by which regulatory instruments affect decision making around technology selection. Hence the '*how*?' formulation offers a more helpful formulation in developing understanding of the instruments of regulation and their relation to innovation.

The key terms in this question can be elaborated on in order to define the scope more clearly.

UK Water Sector – The water sector is understood as the set of firms involved in the provision of water and wastewater services in the UK. These include licensed water and wastewater companies. However, as will be shown, industrial users, construction companies and developers, and the water technology supply chain also play an important role in affecting the water environment. Finally, the nations of the UK (England, Wales, Scotland and Norther Ireland) do all have the same institutional configuration or environmental conditions. As such, the focus of this research will be on the water and wastewater companies of England and Wales as these operate under essentially the same system of economic regulation.

Innovation – The phenomenon of changes in practice and technology. As discussed in section 1.1, innovation is understood in particular with reference to technologies that have the ability to improve environmental outcomes (eco-innovation). Additionally, innovation is understood as a transition from one to another different configuration of technologies, practices, and institutions.

Regulation – Multiple regulatory authorities govern the environmental, drinking water, and economic spheres of the UK water sector. The system of regulators and regulated firms is relatively complex and exploring every implication of this would be difficult. For this reason the entire system will only be given a qualitative overview. In developing quantitative models and approaches the system of economic regulation as employed by the economic regulator Ofwat will be the core focus of this research.

Having clarified the terms of the question a set of sub-questions informing the overarching question are:

- What are the key technologies, practices, and innovations in the water sector?
    - What are the challenges facing the water sector in the UK?
    - Which eco-innovations are best placed given these challenges?
- How does the system of regulation function?
    - How does the regulatory regime promote and/or inhibit eco-innovation?
- How should decision-making of the relevant actors be modelled?
- Which predictions and recommendations can be deduced from this?

In order to answer these questions a series of related aims and related objectives can be stated as follows. For each aim, the relevant chapters where this is objective is pursued is given.

Aim 1: Determine the theoretical framework for understanding and characterizing decision making in the context of water sector transition.

Objective 1.1: Review literature on decision making.

Objective 1.2: Review literature on technological change and eco-innovation.

Objective 1.3: Set out the framework to be employed for this research.

Aim 1 is pursued in Part 1. Chapter 2 reviews the literature on decision making in Socio-ecological systems and provides discussion and justification for the comparative framework developed in Chapter 3. Chapter 3 sets in the place the Comparative Information Graded Approach as the framework employed.

Aim 2: Characterize water sector practices and technologies, regulation, and decision making.

Objective 2.1: Characterize water environment in England and Wales.

Objective 2.2: Characterize the key technologies employed in the water sector.

Objective 2.3: Characterize specifically the system of regulation of the water sector.

Objective 2.4: Characterize decision making of key stakeholders.

Objective 2.5: Conduct interviews with water sector stakeholders for contextualization and validation of findings.

Aim 2 it tackled in Parts 2 and 3. Part 2 provides a qualitative understanding of the objectives in this section drawing on literature and official publications in Chapter 4 and on interviews for Chapter 5. Part 3 then develops a set of quantitative models to apply the framework developed in Part 1.

Aim 3: Evaluate the mechanisms by which regulation promotes or inhibits transition in the water sector.

Objective 3.1: Identify key mechanisms from the literature.

Objective 3.2: Identify and review key mechanisms from interviews.

Objective 3.3: Define and analyse models of regulation and transition.

Objectives 3.1 and 3.2 are tackled in part 2 in Chapters 5 and 6 respectively. Part 3 then provides a series of models as derived from the findings and qualitative characterizations in part 2. Chapter 6 defines the core model applied in evaluating economic regulation – namely the price control process. Chapter 7 applies a comparative approach to decision making as from Part 1 to models of regulation and transition. Chapter 8 explores the role of foresight in a model of water technology investment as a public good.

Aim 4: Provide predictions and recommendations for how the system of regulation can promote transition more effectively.

Objective 4.1: Review key findings and limitations

Objective 4.2: Provide a set of policy recommendations based on the findings.

Chapter 9 in Part 4 provides a summary recitation of main findings and limitations and the key policy recommendations regarding more effective regulation that derive from these.

1.3 Key Sources and Methodology Overview

Key Sources

The key sources used in this research are drawn from a variety of references.

- Literature:
    - Decision Theory
    - Social-Ecological Systems Theory
    - Innovation and Transition Studies
    - Economic Regulation
- Environment Agency data on environmental system and water technologies in England and Wales.
- Thames Tideway Reports
- Stakeholder interviews and survey. Questions and Answers about:
    - Technologies, Environmental Outcomes, Prices and Regulation
    - Decision Making (as informed by analysis framework)
- Ofwat regulatory 'Final Determinations':
    - Firm-level price review data
    - Changes to the system of regulation

The research method draws on literature to develop an analysis framework (the Comparative Information Graded Approach) which is then applied to models of regulation and transition as developed from institutional literature and interviews. Figure 1-1 shows an overview of the research process applied in this research.

Developing the Analysis Framework

The research method involves theoretical work to develop a framework, drawing on decision theory and the Social-ecological systems literature in part 1. This framework, the Comparative Information Graded Approach, CIGA, is applied to the case of transitions in water technology in the UK in the remaining parts of the thesis.

Applying the Framework to UK water innovation

Part 2 develops a qualitative characterization of water technology in the UK. This is done by drawing on Environment Agency data about the performance of different water technologies and relevant institutional and academic publications about the UK water sector.

The framework informs stakeholder interviews

As shown in Chapter 2, the CIGA framework requires interview to supplement characterization of the water technology adoption SES. The CIGA view of decision making and SES characterization informs the interview methodology also. Further detail on the methodology for the interviews is given in Chapter 5.

Models of water sector technology adoption are developed

Based on Part 1 and part 2 formal models of technology adoption are developed in part 3. These are developed and analysed according to the CIGA. In particular, the model of regulation is applied and validated against the official publications of the economic regulator.

Analysis outputs

The results from the analysis of the key models as well as the more qualitative results from Part 2 are collated in Part 4 for conclusions and key policy recommendations.

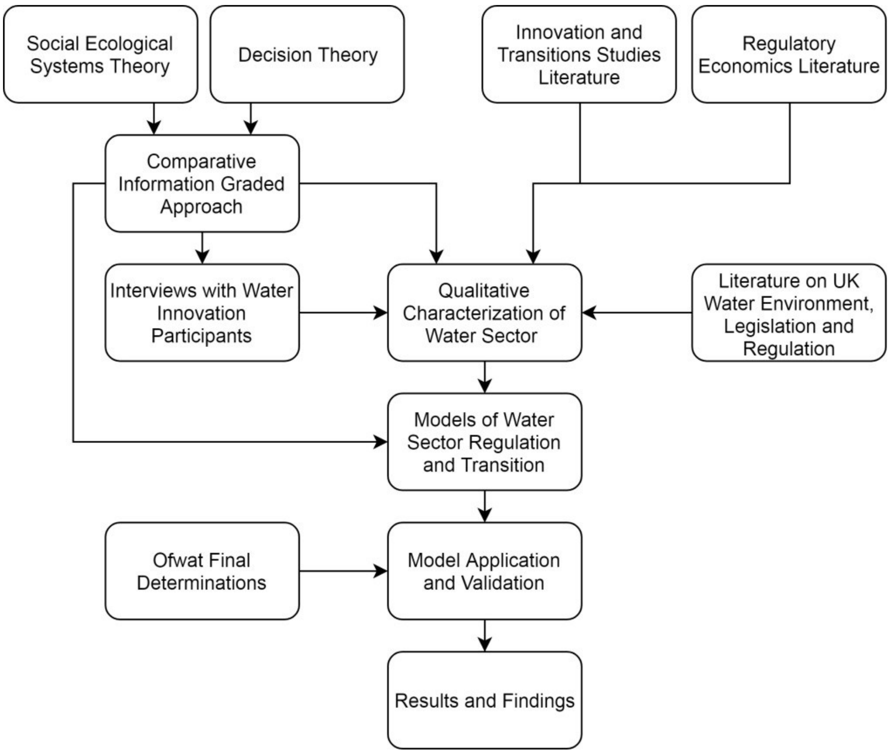


Figure 1-2: **Overview of research method and key sources**

Part 1: Decision Theory and the Comparative Information Graded Approach

Chapter 2: Technology Decision Making in Social-Ecological Systems

Key Points

- Technology decision and eco-innovation is understood to take place in Social-Ecological Systems (SES).
- This requires a choice of decision making model which should be approached comparatively.
- Action arenas must be structured according to higher-order conditions of the institutional context.

Environmental research is increasingly facing the challenge of coupling models of human activity with those of environmental systems [*An and López-Carr*, 2012; *Cosgrove and Loucks*, 2015; *Hale et al.*, 2015; *Lund*, 2015; *Madrid-López and Giampietro*, 2015; *Sivapalan and Blöschl*, 2015; *Troy et al.*, 2015; *Walker et al.*, 2015; *Blair and Buytaert*, 2016]. Social-Ecological Systems (SES) understand multiple decision-makers to interact in the governance and delivery of technology, practice and attendant environmental outcomes [*Ostrom*, 2009a]. Eco-innovation, namely the adoption of technologies with the potential to improve environmental outcomes [*Díaz-García et al.*, 2015], can then be understood as within a Social-Ecological System. This requires an understanding of the decision makers involved in an *action arena*, their options, criteria, decision making method and higher-order conditions of the institutional setting.

A systematic approach, such as the System of Systems (SoS) method [*Hadian and Madani*, 2015], can be applied to evaluating different technologies in a single-decision makers context. This involves a review of options, criteria, weighting, and multi-criteria decision making (MDCM) methods. Such an analysis in itself involves a great complexity due to the nature of water systems and the technologies that affect them. This complexity can be managed with tools such as the environmental footprints, SoS, and MCDM. However, as will be shown, the problem of selecting one of multiple possible MCDMs should be tackled with a comparative approach employing different MCDMs.

MCDMs consider a single decision maker looking across a set of options or outcomes. SESs however usually involve multiple stakeholders. The tools of MCDM can be brought to bear on these situations at two levels. Firstly to evaluate the different possible outcomes. Second, if the stakeholders can take actions within the SES, then MCDM tools can be used to characterize how an individual decision maker evaluates possible outcomes. However, given that multiple decision makers are involved, and regardless of how they evaluate outcomes, each decision makers actions may affect other decision makers. In this case the tools of game theory are also applicable. As with MCDMs themselves, the selection of tool for game theory analysis should also be approached comparatively because alternative tools could either yield better outcomes for the decision makers (prescriptive) or that alternative tools better characterize decision making in practice (predictive).

Finally, SES understand decision making in action arenas as nested within Higher Oder Conditions (HOCs) of an institutional context [*Ostrom*, 2009b]. HOCs set conditions of decision making in the action arena. Hence the comparative approach must structure the action arena under the HOCs.

This chapter develops this line of thought building up a review of relevant theories towards the development of the approach employed in this thesis; the Comparative Information Graded Approach (CIGA). The chapter begins with presenting multi-criteria decision making and the complexities involved in the application of this to the water sector. The argument for a comparative approach is then extended to multi decision maker situations where alternative tools are reviewed. Finally, the role of HOCs and institutional context in water governance decision making and eco-innovation are reviewed. This chapter thereby sets the scene for the statement of the CIGA in Chapter 3.

2.1 Options, Criteria, and Multi-Criteria Decision Making

Before turning to situations involving multiple decision makers, this section will review the SoS approach to decision making for a single decision maker. This approach has been applied to the analysis of energy technology options for member states in the European Union in a manuscript submitted to the *Resources, Conservation, and Recycling* [*Ristic et al.*, 2018] as drawing on earlier work employing this methodology [*Hadian and Madani*, 2015]. While this provides a helpful framework for evaluating different technologies or practices, it faces a challenge. There are multiple MCDMs and no definitive overarching reason for selecting any MCDM over others. While the SOS applies an aggregative approach, a comparative approach is used here instead.

In the context of greenhouse gases and climate change, eco-innovation has been understood to involve, among other things, substituting, carbon-intensive sources of electricity (e.g. coal) for low-carbon technologies (e.g. wind or solar). Employing MCDM in the SoS approach, (taking into account cost, carbon, water, and land use), renewables like solar and wind perform better than carbon intensive electricity sources [*Hadian and Madani*, 2015]. Figure 2-1 shows how the SoS employs MCDM.

Criteria / Footprints (C)

Tech. Options		c_1	c_j	c_M	Relative Aggregate Footprint (RAF)
	t_1	$F_{1,1}(w_{1,k}p_{1,1})$	…	$F_{1,M}(w_{M,k}p_{1,M})$	$RAF_{1,k}(F_{1,1}, \dots, F_{N,M})$
	t_i	…	$F_{i,j}(w_{j,k}p_{i,j})$	…	$RAF_{i,k}(F_{1,1}, \dots, F_{N,M})$
	t_N	$F_{N,1}(w_{1,k}p_{N,1})$	…	$F_{N,M}(w_{M,k}p_{N,M})$	$RAF_{N,k}(F_{1,1}, \dots, F_{N,M})$
		$w_{1,k}$	… $w_{j,k}$ …	$w_{M,k}$	

Setting (*k*) specific footprint weightings ($w_{j,k}$)

Figure 2-1: **SoS Framework for Technology Sustainability Assessment with One Output**

An N number of technologies or practices $\{t_1 \dots t_i \dots t_N\}$ can be evaluated according to M different performance criteria $\{c_1 \dots c_j \dots c_M\}$. Regarding energy technologies, a commonly employed criterion is the levelized cost of energy (expressed as USD kWh^{-1}). Environmental criteria can be similarly expressed as 'footprints'. For example a carbon footprint ($kgCO_2e$ kWh^{-1}), or a water footprint (litres kWh^{-1}) [*Hoekstra et al.*, 2009]. Each of these criteria is assigned a weight ($w_{j,k}$) given weights assigned to the criteria by conditions in a particular setting or the preferences of a particular decision maker (*k*). Technology performances $F_{i,j}$ are a function of its weighed performance under that criterion ($w_{j,k}p_{i,j}$). The SoS methodology then assigns a Relative Aggregate Footprint (RAF) to each technology by aggregating across each technology's performance and ranking the technologies. Hence the RAF of a given technology is a function of all technologies' performances. Each of these aspects is reviewed in further detail below with respect to water.

Water Criteria: withdrawal, consumption and footprint

In determining a criterion for a technology's impact on water there is a degree of disagreement over different indicators and this can lead to some confusion [*Madani and Khatami*, 2015]. Water withdrawal is the simples as an infrastructure operator will generally have this information readily available as part of the day-to-day operation and longer term planning. This measure however misses out on how water may then return to the environment. Water consumption is a better measure as it reflects only the water removed from the watershed through consumptive use. Water transported out by pipes would count as a water trade and would be considered water consumption. Water lost to evaporation is also removed from the watershed and hence is also considered water consumption. In agriculture this presents a formidable part of water consumed. Plants evaporate water in order to pull more water from the soil and consume the nutrients it contains. Water consumption in industrial applications uses water withdrawal and subtracts the quantity returned to the environment with the resultant difference giving a measure of water consumption.

While water consumption provides a better indicator than water withdrawals it does not acknowledge that the quality of the water may have been reduced. To accommodate for this the Water Footprint (WF) is commonly used [*Hoekstra et al.*, 2009] which includes not only direct water consumption, but also the so called grey water footprint. This reflects the quantity required to dilute a given pollutant back to its natural or legally deemed acceptable concentration. Additionally the water footprint methodology includes indirect water footprint which involves the water footprint of inputs required for a given process. As an example, the water footprint methodology has been applied to data centres [*Ristic et al.*, 2015].

Little work has so far been done to apply this methodology to water technologies themselves. One study which did do this, found that a wastewater treatment plant reduces water footprint by roughly half relative to a no-treatment scenario as it reduces the pollution load in the discharged water thereby more than offsetting the water footprint of its operations [*Morera et al.*, 2016]. Reductions to 72% of no-treatment scenario water footprint occur due to chemical phosphorus removal. (This issue will be further explored in Chapter 4 where carbon footprints of different water technologies will be reviewed.)

Options and Criteria in water technologies

In water infrastructure engineering, multi-criteria approaches have been deployed for evaluating costs and other performance criteria. In assessing London's supply infrastructure for example, studies may review the supply and reservoir reliability, the capital and operating costs, resilience of the infrastructure to shocks (understood as time taken to recover to normal service) and for example and ecological flow shortage index [*Matrosov et al.*, 2015].

Key eco-innovations in water management are those reducing water stress and pollution, impact on ecosystems, and greenhouse gas (GHG) emissions. Regarding water stress and pollution a relatively large set of indicators and parameters used for environmental legislation such as the EU Water Framework Directive [*European Commission*, 2000; *Liefferink et al.*, 2011]. In assessing water quality, multiple parameters are considered: the quality of the water by its physical and chemical indicators such as temperature, acidity, chemical and biological oxygen demand, and Total Suspended Solids [*European Commission*, 1998]. Pollutants such as nitrates, phosphates, and pesticides, as well as any bacteria or viruses are taken into account. Emerging pollutants include hormones, pharmaceuticals, and other chemicals can harm humans or the organisms in the environment [*Diamanti-Kandarakis et al.*, 2009; *Barber et al.*, 2012].

Assessing the costs and benefits of water sector eco-innovations requires assessing the multiple outputs water sector technologies are designed for. The criteria performances in this case would involve a larger matrix than that used for electricity technologies, where footprints are expressed in terms of cost per parameter improvement for each parameter, and then the same for other non-cost criteria such as carbon and water.

Weighting

While some MCDMs employ criteria weighting some MCDMs do not. These are called non-compensatory. The controversial issue of weighting is not dealt with in much greater detail here, save to review a few different approaches that can be taken in setting criteria weights: entropy weighting, stakeholder determined weighting, and data driven weighting.

Entropy weighting captures the dispersion of the values for different criteria assigning the greatest weight to the criteria with the highest dispersion [*Hadian and Madani*, 2015]. In Stakeholder determined weighting options, criteria, performances, and weightings, can all also be determined through a process of stakeholder consultation [*Read et al.*, 2017]. Stakeholders and decision makers can be asked to provide input into a modelling effort whereby they determine the weights attributed to different criteria.

Data driven weighting is used in the SoS approach and assigns weights as a function of some data set for each criteria [*Hadian and Madani*, 2013; *Ristic et al.*, 2018]. In assessing electricity technologies by cost, carbon, water, and land footprints, for different EU member states [*Ristic et al.*, 2018] employ datasets for GDP per capita, CO2 emissions per capita, renewable freshwater resource availability per capita, land availability per capita to weigh each criterion respectively. This way, the variability in the importance of the different criteria across the different countries is included in the analysis. For water technologies this approach could thereby include the different needs watersheds given water quality and the demand-supply balance.

A Comparative Approach to Tools

Decision making in this kind of setting involves choice among options with multiple criteria. The MCDM literature has developed multiple MCDM tools in the form of principles, algorithms, methods, or solution concepts for evaluating competing options. For the purposes of this thesis, the term *tools* will be used to encompass all of these as well as the tools that will be drawn on from outside the MCDM literature.

The existence of multiple tools leads to the problem of how one can choose a tool [*Triantaphyllou*, 2000]. In order to deal with this problem of the choice among different MCDMs and the potentially different results they would yield, the SoS approach has employed a set of multiple MCDMs [*Read et al.*, 2014, 2017; *Hadian and Madani*, 2015]. The MCDMs employed are presented here highlighting their principles in order to highlight differences:

- "*Maximin*: Technologies with the best worst performance are considered the best. Technologies with the highest performance are considered preferable [*Wald*, 1945].
- *Lexicographic*: Criteria are ranked by importance. The technology that performs best under the most important criterion is chosen. If various alternatives are equal, the decision is made based on the second important criteria and so on until obtaining a unique solution [*Tversky*, 1969].
- *The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS):* Technologies are ranked by the minimum distance from the best performance across all technologies under each criterion [*Yoon and Hwang*, 1995].
- *Simple Additive Weighting (SAW)*: Criteria are assigned weights and technologies are ranked by highest weighted performance [*Churchman and Ackoff*, 1954].
- *Dominance*: Each alternative is compared to the others under each indicator in bilateral contest. The alternative that has won the most contests is the chosen one."

This list is quoted from [*Ristic et al.*, 2018] which in turn draws on [*Hadian and Madani*, 2015] for the set of MCDMs employed for an SoS approach to sustainability assessment. In addition to these MCDM tools, tools from social-choice theory have also been applied in the context of water resource planning and strategic decision making [*Read et al.*, 2014, 2017].

As can be seen from the intuitions each appeals to a different approach. Maximin focusses on having the least worst performance while TOPSIS pursues some ideal reference point. Lexicographic and SAW tools give seek to give criteria different relative importance and use this information in evaluation options. Dominance looks at pairwise comparisons between options. Each tool takes a different philosophy to evaluation without being able to disqualify others.

Given these multiple tools, the problem of multiple criteria can be stated like so: Which decision tool do we use to choose a tool? Clearly, this question entails an infinite recursion. In order to avoid this, the SoS approach has employed an aggregative approach. There the results from multiple MCDMs are aggregated into a single indicator. Along this vein, [*Hadian and Madani*, 2015] employ an index for desirability of technologies given by the sum ranks to each alternative is assigned by each MCDM tool. Different technologies are then compared for desirability using this score.

One conceptual issue with this method of aggregation among the MCDMs implies the tool employed in the final aggregation (the Borda Score) is somehow superior as a method of aggregation than other tools employed. This could be seen to somewhat undermine the argument for an aggregative approach. If the Borda Score is used for a final aggregation should the initial multi-criteria assessment not simply use the Borda Score? Using only one tool conflicts with the core motivation of applying multiple tools which is to avoid the reliance on only one tool given their differences and the lack of an overarching criterion for selecting among tools [*Read et al.*, 2014; *Hadian and Madani*, 2015; *Ristic et al.*, 2018]. A conceptual tension then exists to which an alternative approach is the use of a comparative approach to MCDMs.

In this research a comparative approach to tools is employed. This comparative approach relies on an understanding of the differences between the available tools in order to see what drives the possible differences each yields. This comparative approach understands the different tools not as mutually exclusive options from which one should be chosen, but rather as a series of different analyses across which comparative statics can be applied in order to inform decision making. Different tools give differing perspectives on the choice at hand without the need to aggregate across them in a final step of the analysis.

This section has reviewed a single decision maker situation drawing on a SoS approach to multi-criteria technology assessment. Two key issues were highlighted. Firstly, that in the case of water technologies multiple resultant technology-outputs (in the form of water quantity as well as quality parameters) are important to the assessment. Additionally, different catchments and areas suffer from different conditions in the water system. This creates a very complex picture for technology assessment. While not insurmountable, it makes the sort of assessment as conducted for electricity technologies much more difficult. Such an assessment will not be conducted as part of this research. The objective here was to review how such an assessment would take place.

The second and more important point for the purposes of the conceptual framework employed in this research involves the basis of a comparative approach to tools. In order to deal with competing tools, the SoS approach involved a final aggregative step. Results from each MCDM were aggregated into a final value. While this provides an assessment inclusive of multiple tools, it is not conceptually satisfactory due to the reliance on a single tool for the final aggregation. A comparative approach then offers a helpful alternative.

2.2 Comparative Approach to Tools for Cases with Multiple Decision Makers

This section will explore tools in the context of multiple decision makers. Again multiple tools could be employed in this setting and a comparative approach is as worthwhile considering in the context of multiple decision makers as it was for single decision-makers. In fact in the context of water resources and environmental management generally, MCDM has been employed as a method of determining the best outcomes for multiple decision makers where each is considered as a separate criterion [*Madani and Lund*, 2011]. This however overlooks the important difference between what is best for all decision makers taken together, and what the result is each decision maker would choose for themselves given the choice [*Read et al.*, 2014].

This section overviews the core framework employed in modelling decision making in this thesis. It provides a review of different decision making concepts for in the context multiple decision makers. A key point of departure for this research is Elinor Ostrom's *Understanding Institutional Diversity* [*Ostrom*, 2009b], in which the Institutional Analysis and Development (IAD) framework for modelling and understanding SESs was developed.

The IAD focuses on *action arenas* to provide a core starting point in the analysis framework of the more complex institutions. The concept of an action arena is based in game theory models of strategic interaction [*Ostrom*, 2009b]. Given a position in an action situation, a participant is understood to have the *choice* over a set of possible *actions* or *control variables*. These action arenas have a context above and below. The higher level is a set of rules (i.e. institutions) which govern the possible actions and roles in the action situation. (This aspect, in the context of water technology is developed further in section 2.3.) The level below is the environmental system which the outcomes of the action arena effects and the environmental variables which the actors in the action arena may be able to observe in informing their decision making. Taken together, the action arena, its environmental basis, and institutional context constitute a conceptual framework for understanding and modelling SESs.

MCDMs consider multiple options along multiple criteria. Social choice tools, on the other hand, are usually applied in the context of multiple stakeholders. (Voting systems are examples of social choice tools.) Analogous to the multiple criteria used by MCDM, social choice tools consider the preferences of multiple stakeholders as the evaluation criteria. Social choice tools then provide means by which to evaluate different possible outcomes along the preferences of multiple actors involved.

Given a commensurate unit of account, it is possible to talk about the concept of *optimality* in a straightforward way. This is a mathematical term which refers to the best (optimal) value of a given function. For example, for a maximization problem, the optimal solution will be the one which yields the highest value of the function. Formally, applying simple addition over the different performance values, the socially optimal state s^* can be found by:

$$\sum_{i=1}^{N} u_i(s^*) \geq \sum_{i=1}^{N} u_i(s')$$

Eq. 2.1

where N is the number of players or performance criteria; s^* is the socially optimal state, and s' is some other state. Note that there may be multiple optimal solutions where the sum values for two different state are the same $\sum_{i=1}^{N} u_i(s) = \sum_{i=1}^{N} u_i(s')$. Say for example there are three states yielding sum values of {1, 3, 3} respectively, and we are asked to give the social optimum. The second and third options are both optimal as both attain the highest possible value. So in the context of many if not all tools, it is possible that more than one option or outcome is optimal. There is however often a difficulty in determining commensurate values and hence this naïve additive approach is not always easily applicable.

Due to this issue, the dominant approach to evaluating outcomes in economics is the principle of Pareto efficiency. Outcomes where alternative outcomes would be better for at least one stakeholder or performance criterion while leaving others no worse off are considered Pareto dominated. Outcomes where no stakeholder or performance criterion can be improved without making another worse off, is considered Pareto optimal. Drawing on [*Mas-Colell et al.*, 1995] for a formal expression, an outcome or state *s* has an associated set of performance values $\{u_1(s) \dots u_N(s)\}$ for all *N* players or criteria. It is Pareto optimal if there is no other available state *s'* with values $\{u_1(s') \dots u_N(s')\}$ such that $u_i(s') \geq u_i(s)$ for all players $i \in \{1, \dots, N\}$ and $u_j(s') > u_j(s)$ for some player $j \in \{1, \dots, N\}$.

For many situations, there are multiple pareto-efficient outcomes, hence a so called Pareto-frontier exists, defining the set of Pareto-efficient solutions. While Pareto-efficiency considers possible improvements it does not consider the overall performance nor the skew of high and low performance. As with MCDMs there are a set of possible tools applicable in this context adopting different analysis philosophies. Some of the same principles encountered with MCDMs lie behind social choice tools: Pairwise comparisons, weighted sums, and maximin approaches. Social choice tools have not been applied in this thesis but have been considered as part of a broad set of tools used in SoS-style analyses [*Read et al.*, 2014, 2017].

Rationality as Utility Maximization

As discussed with regards to MCDM, commensuration across multiple criteria into a single value is not straightforward. That being said, the dominant approach in economics to characterizing decision making is that of employing a so-called *utility function*. The utility function determines some numerical value assigned by the decision maker to each possible state. In moral philosophy, utility has been understood as the sum of pleasures or satisfactions and the lack of pain or suffering [*Briggs*, 2017]. This is somewhat distinct from the use of the term utility in the context of utility functions as applied in economics where it is understood as an implicit value being maximized by whatever choice behaviour decision makers exhibit [*Steele and Stefansson*, 2015].

The choice behaviour reflects an understanding of the pursuit of more over less preferred states. Preferences can be expressed in simple preference relations. For example, decision-maker *i* may have a preference between states *s* and *s'* such that $u_i(s') \succ u_i(s)$. The curved inequality sign simply represents this preference for *s'* over *s*. This preference relation does not express the degree to which *s'* is preferred over *s*. It does however allow for a ranking or ordering of the different states according to preference. Hence this expression is termed ordinal preferences. A more information rich approach would assign cardinal values to preferences as expressed through a utility function. Either way, given a choice which would lead to different outcomes, the decision maker would choose that course of action which gives the highest utility. For the purposes of this thesis, this conception of decision making is termed 'rationality as utility maximization'. The term rationality is here used to reflect the idea that it would be irrational for a decision maker to take actions which would lead to states less preferred by them.

Commensuration into utility is at times erroneously done using the monetary unit of account. (It should be noted that a utilitarian approach would consider a *valuation of money* as the utility and *not money itself* [*Briggs*, 2017].) This approach to commensuration has had a major influence as the basis of Cost-Benefit Analysis as applied in UK governmental decision making [*HM Treasury*, 2003] and elsewhere. In such an approach costs are assigned to environmental impacts. This can be done through willingness to pay studies where individuals are asked how much they would be willing to pay for an environmental improvement for example. These values are then used to decide if a project or programme is net positive in terms of its costs and benefits. Such approaches are also often applied to water company planning [*Smithers et al.*, 2017].

Game Theory

While multiple "stakeholders" may be involved in a SES, they are for the purposes of social choice analysis not proper "decision-makers" as understood here. This is because a "decision-maker" is one which faces some kind of problem (e.g. selection an outcome or choosing an action). Social choice provides a set of tools a single decision maker could use to decide between some set of outcomes with regards to the preferences of a series of persons. In this sense social choice is similar to MCDM.

While MCDMs and social choice tools involve one decision maker, game theory consists of a set of tools for the analysis of strategic decision making in the context of multiple decision makers with strategic interdependence (e.g. my action affects your payoffs and vice versa) [*Fudenberg and Tirole*, 1991; *Perea*, 2012]. Game theory has found widespread application in economics and social science as a model of decision making. In its essence the question game theory asks is how individuals will make decisions given mutual strategic interdependence. This is distinct from the question asked by MCDM and social choice tools which asks which outcome would be best for all the decision makers taken together.

In the context of a game then, each player takes action a and payoff-functions determine the player's utility $u_i(s)$ as dependant on the strategy profile $s = \{a_1, \dots a_i, \dots a_N\}$. [*Fudenberg and Tirole*, 1991]. Along the principles of rational choice theory, game theory understands decision makers to select strategies to maximize their payoffs. Hence we can talk about 'rationality as utility maximization'. This is related to the concept of optimality, in the sense that decision making chooses optimal strategies. Note however the distinction here with the use of optimality in the MCDM or social choice context. There optimality referred to the maximization of a value for the possible outcomes. In the game theoretic context, game outcomes can also be evaluated using those tools of MCDM or social choice. However, this is distinct from optimality in the context of a single player in the game. The strategies that are optimal for individual decision makers, can differ from the strategies that a social choice approach would identify as optimal.

Nash Equilibrium

Game theory employs 'rationality as utility maximization' but as developed in the context of multiple decision makers. The key extension this requires is that expected utility is maximized given some belief about how the opponent will behave. Nash equilibrium employs a belief in the "rationality as utility maximization" of opponents [*Perea*, 2012; *Briggs*, 2017]. Any combination of actions (strategy profile) for which no decision maker can receive a higher payoff by switching to a different strategy, is understood to be a Nash equilibrium [*Nash*, 1950; *Perea*, 2012]. Note that when considering Nash equilibria players are considered to be placing probabilities on their available strategies. Where players place positive probability on only one of their available strategies is called a *pure-strategy*. Where players randomize between strategies is called a *mixed-strategy*. Formally then following [*Fudenberg and Tirole*, 1991], a mixed-strategy σ^* is considered a Nash equilibrium, if for all players i,

$$u_i(\sigma_i^*, \sigma_{-i}^*) \geq u_i(a_i, \sigma_{-i}^*), \qquad \forall a_i \in A_i$$

Eq. 2.2

where σ_{-i}^* denotes the equilibrium strategy profile of other players from the perspective of i (i's opponents). Given that a pure strategy is simply a mixed strategy with a single strategy having a probability of 1, this same definition applies to pure strategy equilibria.

Since, Nash's development of the concept, the game theory literature has developed a series of refinements [*Harsanyi*, 1967; *Selten*, 1975; *Myerson*, 1978], but the tendency has broadly been to retain the core principles of rational choice and to further refine the Nash equilibrium concept [*Harsanyi and Selten*, 1982].

Before moving on, it should be noted that it is possible to combine the concerns of MCDM and game theory. In MCDM there are multiple performance criteria while thus far for game theory we have considered only a single criterion for each player; namely, utility. It is possible to develop games where each player uses multiple performance criteria without aggregating them into a single utility function. This approach, while not adopted in this thesis, is called vector-valued games [*Maschler et al.*, 2013]..

Archetypal Games

Game theoretic analysis has been used to study 'archetypal' models of water resource management [*Madani*, 2010; *Madani and Hipel*, 2011]. The aim of such archetypes is to determine the most important and common aspects of a set of SES. Characterizing a model capturing these can then provide for analysis and recommendations across a set of particular situations involving such archetypes. Despite differences in water environments and water governance across the world, dynamics which hold across many situations can be helpfully captured in such archetypes.

The tragedy of the commons is arguably the most well-known model involving multiple users of a common resource [*Hardin*, 1968]. Individual's increase their own utility by exploiting the resource but ignore the negative externality this imposes on others. In aggregate this leads to overexploitation and each individual being worse off than if they had reduced their exploitation of the resource.

Similar, simple models are classic in the game theory literature and many complex environmental problems have been modelled previously using similar models. For a generic application to investments for environmental improvements see [*Ostrom*, 2009b]. A seminal work was the application of game theoretic models of cooperation to the regulator-firm relationship in the context of environmental regulation enforcement [*Scholz*, 1984]. Game theory has also been applied to fisheries management [*Bailey et al.*, 2010]. [*Kilgour et al.*, 1992] develop game theoretic models of monitoring through verification and judicial proceedings. For a review of verification and enforcement models of environmental regulation see [*Fang et al.*, 1994]. Game theoretic models have been applied to archetypal water resource situations, in particular focussing on groundwater abstraction among multiple agricultural producers [*Madani*, 2010] with continuous time model in the same context also being examined in [*Negri*, 2010]. Game theory models have also been developed for specific situations such as the case of the San Joachim Delta [*Madani and Lund*, 2012] or water allocation conflicts in Israel-Palestine [*Just and Netanyahu*, 2004]. Finally, game theory has also been used to investigate international climate diplomacy [*DeCanio and Fremstad*, 2013; *Madani*, 2013]

Information Constraints

A core issue explored extensively in game theory and economics is that of information constraints. The core distinction game theory draws is between imperfect (lack of information about past decisions by opponents) and incomplete information (lack of information about the decision maker's or opponents' utility functions) [*Harsanyi*, 1962, 1967]. Simultaneous moves, for example are modelled as games of imperfect information. When decision maker i is considering their choice in a simultaneous move game this can be understood as making a decision given an uncertain decision by the opponent.

In games with incomplete information decision makers usually are understood to face a nature player who probabilistically determines which of a set of possible utility functions the players will face. The possible outcomes are then weighed by their probability to give the expected utility [*Briggs*, 2017]. This has been particularly important in the literature on markets and economic regulation which highlights for example the role of information asymmetries between regulator and firm [*Laffont and Tirole*, 1993].

Expectation formation: Reinforcement Learning and Fictitious Play

These kinds of information constraints can be understood to involve two aspects. Firstly, information about their own preferences and secondly, information about others' preferences. These are both captured under incomplete information in game theory but this information asymmetry can have important implications for both characterizing decision making as well as subsequent outcomes.

Early characterizations of decision making employed a concept termed 'adaptive rationality' for agents' expectation formation [*Kaldor*, 1939]. This characterized decision makers as predicting the future to look similar to today. Optimal actions were made in response to what would be understood as the status quo or some statistical characterisation of the past experiences. This is essentially the core intuition behind the use in game theoretic analyses of the tools of reinforcement learning [*Erev and Roth*, 1998; *Gosavi*, 2003] and fictitious play [*Hannan*, 1957; *Fudenberg and Levine*, 1998].

One of the most longstanding criticisms and alternatives to rational choice theory has been that of bounded rationality [*Simon*, 1957]. The core argument is that the human brain like other control systems studied by the cyberneticists at the time, did not always have the information nor computational capacity necessary to optimize [*Simon*, 1957, 1996; *Dietz et al.*, 2011]. The complexity of multiple criteria and the inability to commensurate across featured heavily in Simon's critique of rational choice theory.

The alternative proposed is a characterization of decision making as bounded rationality which does not optimize but instead *satisfices* [*Simon*, 1996]. This decision making characterization takes actions at an acceptable level of utility. Decision making is then characterized as involving 'aspiration levels' for each criterion. Options which meet these aspiration levels are adopted. If no such option exists aspiration levels are lowered until a 'good enough' option is found. This concept of 'aspiration levels' is employed in theorizing and explaining the values ascribed to actions in reinforcement learning..

Reinforcement learning is a tool from machine learning for determining optimal courses of action in a state-action decision situation. Decision makers are not given full information about the utility function and payoffs immediately. Instead, "values" are associated with actions in a given state and are updated based on "rewards" earned from the action and the "value" of the best action available in the resulting state. In each state, the action with the highest value is selected. The actual algorithm implemented for this tool is called Q-learning (based on the notation for the "values" as "Q-values") [*Watkins*, 1989; *Watkins and Dayan*, 1992]. Formally, this algorithm is stated as:

$$Q_{new}(s,a) = Q_{old}(s,a) + \alpha\left[r_{ss'}(a) + \gamma \max_{b\in A(s')} Q_{old}(s',b) - Q_{old}(s,a)\right]$$

Eq. 2.3

where Q(s,a) represents the reward associated with action a in state s; the subscripts "new"/ "old" refers to the values as they change over the updating process over simulated time; s' is the new state; $r_{ss'}$ is the reward associated with a given action when taken in transitioning from state s to state s' (this value is the same as the payoffs players receive); $b \in A(s')$ is one action of the admissible set of actions A(s) for a given state s; α is the rate at which Q-values are updated (this is set to 1/NOV(s,a) where NOV is the number of times state s has been visited in the learning process); $\gamma < 1$ is the discount factor. Note that the Q-value is equivalent to the aspiration level discussed by Simon.

Under reinforcement learning, an agent can associate a relatively high reward with an action in a given state early in the process and subsequently they would always choose this action. This means that they may not even attempt an alternative course of action which may ultimately yield a higher value to them. To address this issue, an important improvement on this algorithm is to allow for random choices in order for the algorithm to explore the state-space more thoroughly (this is known as ε-greedy) [*Gosavi*, 2003].

In fictitious play, decision makers do know their own utility but not that of their opponent. Hence they cannot make the assumption of Nash equilibrium about their opponents' 'rationality as utility maximization'. Instead they assign probabilities to their opponents' strategies based on the frequency of those strategies being played over time [*Fudenberg and Levine*, 1998]. They then choose the optimal strategy given this frequency weighting of the opponents' strategies. Following, [*Fudenberg and Levine*, 1998] formally this is expressed as:

$$\rho_t^i(a^{-i}) = \frac{k_t^i(a^{-i})}{\sum_{\tilde{a}^{-i} \in A^{-i}} k_t^{-i}(\tilde{a}^{-i})}$$

Eq. 2.4

Where $\rho_t^i(a^{-i})$ is the probability player i assigns to player $-i$ playing strategy a at a given simulated time step *t*; $k_t^i(a^{-i})$ is the count of how often player $-i$ has played strategy a over the simulated time periods; $\tilde{a}$ is used as an index value in the summation of the frequencies for all strategies available. Given that i has knowledge of their own payoffs for their different actions, they weigh these with ρ to yield a kind of expected value.

For both reinforcement learning and fictitious play it has been shown that if players choose probabilistically instead of deterministically choosing their optimal strategy, these two algorithms will 'usually' approach Nash equilibria over time [*Fudenberg and Levine*, 1998].

Graph Model for Conflict Resolution (GMCR)

The GMCR is a modelling environment for multi-decision maker settings similar to that of traditional game theory [*Kilgour et al.*, 1987; *Fang et al.*, 1993]. [*Madani and Hipel*, 2011] reviewed and applied the non-cooperative tools of the GMCR to generic water conflicts. GMCR does depart from game theory's application of cardinal utility values in favour of representing preferences as ordinal ranks (i.e. decision makers are understood not to give a numerical value to outcomes but rather to rank these in order to preference). This also means that mixed strategy equilibria cannot be computed with this more limited preference information.

The GMCR uses a comparative approach to tools, providing a set of tools in addition to a pure-strategy Nash equilibrium analysis. These tools employ alternative equilibrium definitions. The tools are termed by the terms used in the GMCR software: General Meta-rationality (GMR), Symmetric Meta-Rationality, Sequential Stability, Limited (h)-move Stability, Non-myopic stability.

For GMR, even where a move could improve payoffs, it is not pursued if it leaves the player open to a response that would leave it worse off than initially. Formally, 2.2 is modified to consider not just an improvement given a fixed strategy by the opponent as under Nash equilibrium, but as given some possible "counter-move" strategy (a'_{-i}) by the opponent.

$$u_i(a_i^*, a_{-i}^*) \geq u_i(a_i, a'_{-i}), \qquad \forall a_i \in A_i$$

Eq. 2.5

Symmetric Meta-Rationality, a similar approach is used except that $u_i(a_i^*, a_{-i}^*)$ is not compared against the state corresponding to a counter-move by opponents $-i$ (a_i, a'_{-i}). Instead, the equilibrium payoff is compared to the payoff in the state resulting from i's response (a_i'') to $-i$'s response (a'_{-i}) to i's initial move a_i deviating from the equilibrium state.

$$u_i(a_i^*, a_{-i}^*) \geq u_i(a_i'', a'_{-i}), \qquad \forall a_i \in A_i$$

Eq. 2.6

Sequential Stability takes the same logic as GMR (considering opponents' responses) except it considers only opponents' responses which yield an improvement for the opponent. Limited-(h)-move Stability, takes sequential stability but extends the analysis into an h number of responses. Non-myopic stability takes $h \rightarrow \infty$ in the limit.

Extensions and Alternatives to 'Rationality as Utility-Maximization'

Even as game theory, and its reliance on rational choice has led to major contributions in the social sciences, it suffers from both theoretical and empirical challenges (when tested in experimental settings) leading to the development alternative conceptions of decision-making. Key examples include: bounded rationality [*Simon*, 1996], correlated equilibrium (an extension of Bayesian equilibrium) [*Aumann*, 1987], influences from informal institutions and norms on decision-making [*North*, 1990], rationality as resolve (commitment to a principle regardless of optimality) [*Sugden*, 1991], decision-making as influenced by emotions [*Elster*, 1994], behavioural theories of collective action (focussing on reciprocity, reputation, and trust) [*Ostrom*, 1998] including a swathe of literature on utility function modifiers to model these behavioural theories [*Ostrom*, 2009b], social preferences (others' utilities included in utility functions) [*Fehr and Fischbacher*, 2002], 'warm-glow' (preferences for altruistic acts) [*Andreoni*, 1990], models relying solely on ordinal preferences [*Kilgour and Hipel*, 2005], prospect theory highlighting how real-world decision-making exhibits loss aversion, where greater value is assigned to losses as opposed to potential gains (relative to some baseline) [*Kahneman and Tversky*, 1979; *Tversky and Kahneman*, 1992].

In the environmental context, predictions of the tragedy of the commons were evaluated in empirical case studies finding that characterizing decision making as 'rationality as utility maximization' in fact rarely predict the more cooperative outcomes observed in communities involved with the management of environmental resource [*Ostrom*, 1998]. This motivated subsequent work on SES to theorize and model alternative management regimes and decision making characterizations.

In order to do this, the IAD employs a game structuring of an action arena but relaxes the assumptions of rational choice and Nash equilibrium in order to allow for insights due to other possible tools. As will be shown in the case of the prisoner's dilemma (a very commonly used game theory model) alternative characterizations of decision making do not lead to the same dire predictions of overexploitation.

The framework employed in this research (CIGA), hence allows for a comparative approach to alternative tools. There are many possible options and the remainder of this section considers these. As with MCDMs, these different tools are employed comparatively in the CIGA.

Alternative Decision Making Characterizations

The tools reviewed thus far have been largely driven by the theory of rational choice. Even under reinforcement learning, decision making is driven by assumptions that decision makers are able to indeed make a choice and that despite limitations they will pursue options perceived as good ones. However extensions and alternative tools exist. While a wealth of alternatives exist there is only limited opportunity to explore them here. Below is a list of influential alternatives employed in the literature. Some alternative employ a characterization in line with 'rationality as utility maximization' however noting important factors that shape decision makers' utility functions. There is no judgement involved here as to whether such changes to the utility function involve "irrational" behaviour.

- *Evolutionary Models*: Evolutionary models do not ascribe choice among strategies to individuals. Instead individuals' strategies are fixed and these strategies are promoted among a population of alternative strategies if they compete successfully [*Axelrod and Hamilton*, 1981; *Axelrod*, 2006]. Evolutionary models employing a genetic algorithm provides for a genome determining the strategy employed by an agent in the model, a process by which these agents replicate and their genes mutate to explore the space of possible strategies, and a fitness function determining which agents are successfully reproduced and which are allowed to die off.
- *Risk and Loss Aversion:* Prospect theory employs risk aversion as to explain choices people made in experimental settings, which would appear "irrational" under strict interpretations of "rationality as utility maximization" [*Kahneman and Tversky*, 1979; *Tversky and Kahneman*, 1992]. Developing the notion of an aspiration level from bounded rationality, prospect theory understands evaluations as happening relative to a reference point. Risks and losses are given a stronger utility weighting than potential gains, relative to some reference level.
- *Altruism:* Findings from empirical and theoretical work in environmental management [*Ostrom*, 2009b] as well as in the behavioural economics of the environment [*Dietz et al.*, 2011] has shown that individuals are often driven by

altruistic concerns to satisfy the preferences of others. This kind of altruism can has been understood as social preferences which has formally been expressed as a term reflecting others' utility in a decision maker's utility function [*Fehr and Fischbacher*, 2002]. Alternatively, non-selfish acts have been theorized under the term 'warm-glow' [*Andreoni*, 1990] as has been investigated in experimental setting also [*Andreoni*, 1995].

- *Emotion:* One criticism of rational choice theory is that accounts of rationality exclude emotion from decision-making [*Elster*, 1988]. The characterization under this framework contains the components of rational choice while allowing for emotions to override rational decisions. This is reflected in a series of findings from behavioural economics around how others' actions, self-expectations, and feelings of involvement affect decision making [*Dietz et al.*, 2011].
- *Resolve and Procedural Rationality:* Rational choice decision making suffers from a problem of commitment as portrayed in Newcomb's paradox [*Nozick*, 1969; *Sugden*, 1991]. A decision making style able to constrain itself to a particular course of action can, in that particular thought experiment attain a higher value than 'rationality as utility maximization'. An alternative decision model is that of *resolve*. The decision maker commits to a particular course of action based on reason without pursuing utility optimization at all times. This principle draws on philosophical foundations alternative to the utilitarian framework, namely that of deontology and virtue ethics [*Rawls*, 1971; *Habermas*, 1984; *Sugden*, 1991; *O'Neill et al.*, 2008]. Such resolve, as driven by a priori rules and laws defining a decision procedure can serve and has served as a better basis for institutional decision making than one purely founded in rational choice [*Rawls*, 1971; *O'Neill et al.*, 2008].
- *Informal Institutions:* Informal rules and institutions such as cultural norms and ideology may drive problem conception and decision making as much if not more so than formal ones [*North*, 1990, 1991]. [*North*, 1990] as well as others from the new institutional economics school of thought, highlighted the importance in understanding how formal and informal rules affect individual behaviour and thereby shape economic and institutional change. Formally this would be expressed as modifiers on the utility function specific to certain strategies which would become undesirable (potentially even unavailable) as a result of informal institutions and norms.

The first four characterizations can be seen to provide alternative characterizations for individual decision making. However, under procedural rationality and informal institutions the boundary between individual decision makers and the context becomes less clearly defined than under the conceptions of rational choice, game theory, SES theory and the IAD. This boundary is blurred as broader context is seen to shape individual decision making. The delineation of Higher Order Conditions affecting individual decision making in the context of water sector regulation and technological change is developed further in section 2.3.

Information-Graded Approach for Organizational Decision Making

Given that the decision makers involved in water sector SESs are largely not individuals but organizations this issue is worth exploring in more detail. Particularly, given the importance of multiple influences on decision making in the form of procedures, rules and institutions are in the context of organizational decision making. In developing the framework for analysis for this research a so-called information graded approach is used.

The basis of information-grading draws on the seminal work on organizational decision making from Graham Allison's *Essence of Decision* [*Allison and Zelikow*, 1971]. In developing a detailed case study of decision making in the Cuban Missile Crisis, Allison developed three characterizations of organizational decision making:

- *Rational Actor*: The organization is understood as a single actor whose decision making is characterized by rational choice theory (i.e. optimization with possible extensions into game theory).
    - *Information basis*: Inferred/assumed utility functions about preferences.
- *Organizational Process*: The organization is understood as a set of departments or groups with different jurisdictions and pre-existing plans and procedures. Decision making is characterized by satisficing (i.e. selecting pre-existing plans which are considered good enough).
    - *Information basis*: Rules, plans and procedures as given in organizational mandate and structure. Typically available from organizational publications.
- *Governmental Politics*: The organization is understood as a set of leaders and their teams who politic and negotiate among each other to determine the course of action. Decision making here is not characterized in formal terms but is rather understood to

be the result of soft concepts like charisma, personal relationships, and other non-rational drivers of individual decision making.

- *Information basis*: Individuals' perceptions and opinions as can typically only be elicited from interviews. Individuals may not be willing to partake in interviews and, if they are, they may not be willing or able to disclose detailed information on decision making. This can be understood as the difficulty or cost of acquiring more detailed information.

Across these characterizations, the characterization increases in detail and fidelity however requiring harder to obtain information on the organization. Figure 3-2 represents the trade-off between costly information and detail/fidelity.

The organizational decision making characterizations highlight the trade-off between the costs of acquiring more detailed information on decision making against the costs of greater model abstraction.

The CIGA, as finally stated in Chapter 3, considers a menu of decision making characterizations comparatively using information available to choose the appropriate models to consider. Hence the CIGA is information graded in the sense that the grade of information available determines the fidelity of the characterization employed.

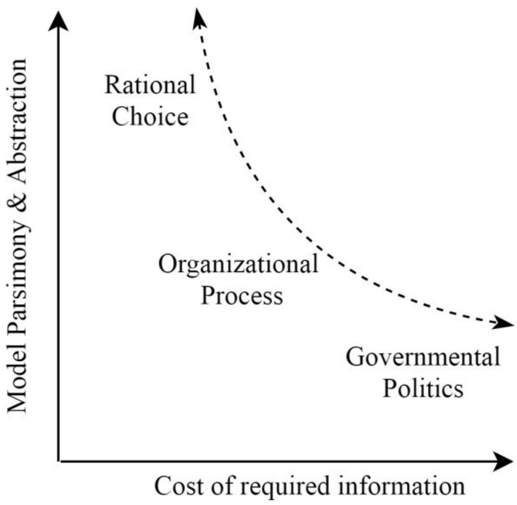


Figure 2-2: A stylized depiction of the trade-off between parsimony versus costs of information in decision making characterization.

2.3 Higher-Order Conditions and Landscape Pressures of Water Regulation

Having reviewed decision making characterizations and tools thus far, the next part of the analysis framework is to delineate and contextualize decision making within its broader context. As shown with decision making characterizations involving procedural rationality and informal institutions such a context can shape individual and organizational decision making. Even with rational choice approaches and the IAD framework, the action arena is determined by the rules of the game as received from higher order conditions.

The framework adopted for this research adopts largely the approach taken in the IAD framework of considering the institutional context as a set of Higher Order Conditions (HOCs) [*Ostrom*, 2009a, 2009b]. These HOCs determine the roles, rules and institutions for decision makers in a given action arena. The action arena is located in a hierarchy of action arenas, with higher levels setting conditions in the lower levels. From the operational level interacting directly with environmental phenomena, through a policy level setting the rules for the operational level, to a constitutional level setting the rules for the policy level [*Ostrom*, 2009a; *Cole*, 2017]. The core intuition behind the notion of the HOC, (and that of landscape pressures as will be argued) is that these conditions are not subject to change by the participants in the action arena.

MLP: *Landscape pressures, Regimes, and Niches*

For the purposes of this research the action arenas of interest, are those involved in the regulation and technology selection of the water sector in England and Wales. In order to be able to accurately characterize these, relevant HOCs and contextual factors will have to be determined.

In the empirical and theoretical work around technological constancy and change a widely applied approach is the Multi-Level Perspective (MLP) [*Geels*, 2002, 2005a, 2011; *Genus and Coles*, 2007] and the associated theory of Strategic Niche Management [*Kemp et al.*, 1998]. Individuals and organisations make decisions over technologies which cumulate in technological constancy and change [*Rip and Kemp*, 1998]. These decisions however are mediated within other higher level structures and pressures which can work to drive or hinder such transitions and effect individuals' decision making [*Geels et al.*, 2017]. The core structure of the MLP is characterized by three elements:

- *Landscape* – The set of technical, material, demographic, ideological, and economic patterns and pressures which are external to and fixed for and beyond the influence of actors.
- *Socio-technical Regime* – social groups of users, regulators, and firms coordinating in a regime of science, markets and policy.
- *Niche* – pilot or demonstration projects where learning, social networking, and development of future expectations takes place.

Technological change is understood to take place as niches develop novel practices and technologies. These would usually not be adopted as part of the socio-technical regime as this is understood to be typically unchanging over time. Landscape pressures however, eventually disrupt the regime. At this point, niche practices and technologies are able to break out into a wider markets and eventually become established in a new regime configuration. This process is facilitated by the disrupted regime which then adopts the niche technology as part of a reconfiguration or transformation into a new regime.

In developing the analysis framework for this research the context of an action arena in an SES embedded with the MLP. The particular action arena considered here is that of the regulator and the firms it regulates. This is then an action arena within the socio-technical regime. The regulatory action arena is then subject to landscape pressures alongside its HOCs.

Transitions in Water Management

It has been argued that transition to a low-carbon energy system requires a transition away from the institutions and systems of governance promoting and locking-in a carbon based economy [*Unruh*, 2000]. Correspondingly, such a transitions require alternate institutions enabling these eco-innovations to substitute existing practices [*Geels et al.*, 2017]. This author was involved with a study considering how the interplay between technology and institutional reform affected the promotion of hydropower as part of China's electricity market reforms and decarbonization objectives [*Cheng et al.*, 2018]. In the context of water management, such technological changes are also mediated by will depend on the institutional context [*Geels*, 2005b; *Van Der Brugge et al.*, 2005; *Green and Anton*, 2012; *Krause et al.*, 2015].

A historical case study of the transition from surface water to piped water for public health reasons identified institutional changes in finance, public or private provision, and other areas that engendered the diffusion of this technology [*Geels*, 2005b]. A study of Dutch flood management, showed how the move from pumping, dikes, and drainage towards retention and natural storage is enabled by a broader shift from agriculture-led to integrated water planning [*Van Der Brugge et al.*, 2005]. The adoption of water conservation measures in the US have been shown to depend on expected water stress, population growth, the availability of new sources, while conservation water pricing policy has been stymied by local economic and political conditions [*Krause et al.*, 2015].

It has been argued that the adoption of distributed interventions such as Sustainable Urban Drainage Systems (SUDS) alongside charges for funding their establishment and maintenance was substantially more successful in Germany than in England due to the differences in governance arrangements between the two countries, in particular the system of economic regulation established for the water companies of England and Wales [*Green and Anton*, 2012]. Indeed the shift towards integrated and adaptive regimes of planning and implementation away from 'prediction and control' regimes has been argued to be a key contributor towards adoption of distributed interventions as opposed to centralized infrastructure [*Pahl-Wostl*, 2007].

Invariably such alternatives compete against the established technological regime of centralized systems of water and wastewater provision. This has been argued in considering how China's water and wastewater technologies are employing the same systems as elsewhere [*Fuenfschilling and Binz*, 2016]. This point is further supported by [*Estache and Iimi*, 2011], who argue that the World Bank Private Participation in Infrastructure Database shows the top 10 percent largest firms by number of contracts awarded, took on about half of all contracts in developing countries. They highlight Veolia and SUEZ as receiving 101 contracts between themselves. They note this pattern of dominant companies was already mentioned in [*Foster*, 2005]. When looking into capital expenditure bias, the economic regulator for England and Wales also found, among other reasons, that companies reported their staff backgrounds and experience with centralized solutions drive a cultural preference thereof [*Ofwat*, 2011].

As existing institutions contribute to locking-in existing practices and technologies, so the transition to alternative regimes (such as integrated and adaptive planning) suffer from their own difficulties and uncertainties. The most widely promoted principles for effective water governance are those of Integrated Water Resources Management (IWRM) which "aims to ensure the co-ordinated development and management of water, land, and related resources by maximising economic and social welfare without compromising the sustainability of vital environmental systems" [*Rogers et al.*, 2003]. In spite of (or maybe because of) the ambitious ideals of IWRM, it has come across problems of implementation and associated conceptual critiques [*Biswas*, 2004; *Voulvoulis et al.*, 2017]. The WFD for example, encourages but does not mandate integration among sectors [*European Commission*, 2000]. One study showed how institutional differences between centralized/local and water-specific/generic authorities given WFD implementation responsibility interact in complex ways with the degree of integration of measures across sectors [*Liefferink et al.*, 2011].

Inevitably, integration of governance across the many (if not all) sectors interacting with water systems is not effective, with planning and investment decisions residing across a range of authorities and stakeholders. Local or national particularities have important implications for the kinds of solutions (centralized or distributed, myopic or foresighted) that are implemented. In order to ultimately recommend particular eco-innovations or transition-friendly policies, it is important to systematically study and understand the situations decision makers find themselves in and how they go about making decisions.

In understanding the action arenas in which eco-innovations and transitions are to take place, with their HOCs and landscape pressures, there are also horizontal relationships between SESs and between different action arenas [*Ostrom*, 2009a]. Multiple games can be played by the same players at an operational level. This can be understood as an ecology of games [*Lubell*, 2013; *Lubell et al.*, 2014] or as interconnected game theory [*Just and Netanyahu*, 2004]. For the purposes of this research the question of interconnection can be understood to relate action arenas of technology transition with those of the regulatory action arena, given a common set of HOCs and landscape pressures.

The Porter Hypothesis: Environmental Regulation and Innovation

Before focussing on the specifics of regulation of the water industry, it is worth noting another important strand of economic literature relating environmental regulation to technological change more generally. Namely, the Porter Hypothesis.

Arguing against the belief that environmental laws, standards, and regulations impose a burden on industry, it was argued that environmental regulation can in fact help to boost innovation [*Porter and Linde*, 1995]. Well-designed environmental regulation can place pressure on firms to become more innovative and adaptive thereby ultimately becoming also more competitive in the marketplace. The authors wrote that: “The focus should shift from pollution control to resource productivity.”

One core criticism of the Porter Hypothesis, is that is relies on the assumption that firms are missing out on cost saving opportunities [*Palmer et al.*, 1995]. Essentially this revolves around the characterization of firm decision-making. The conditions under which the Porter Hypothesis could be true would then require “organizational inertia”. Firm managers and processes are difficult to change and potential opportunities for additional profits are overlooked by this. Regulation could then force firms to explore these opportunities. If however firms are already profit-maximizing (as is assumed in much of the economic literature), then there can be no way that environmental regulation can make them more profitable. Environmental regulation can only narrow the possible range of technologies, thereby raising firm costs. Note that the regulation may still be worthwhile if environmental externalities addressed by the regulation exceed the costs of compliance.

This relatively rebuttal to the Hypothesis was further supplemented by a refinement to three interpretations of the Hypothesis [*Jaffe and Palmer*, 1997]. A “narrow” interpretation is closest to the original argument, namely that properly designed regulation will boost innovation generally. A “weak” interpretation yields the claim that environmental regulation will lead to environmental innovations. A “strong” interpretation claims that properly designed regulations will shock firms into both compliance but also cost-saving or profit increasing innovations.

Subsequently, the Porter Hypothesis has garnered a substantial theoretical and empirical literature. For an in-depth theoretical and empirical review see [*Ambec et al.*, 2013]. Initial empirical research in this area found support for the weak interpretation but not for the narrow or strong one [*Jaffe and Palmer*, 1997].Generally matching earlier findings, a more recent empirical investigation found no support for the “strong” interpretation, qualified support for the “narrow” interpretation, and none for the “strong” interpretation [*Lanoie et al.*, 2011]. In an exhaustive review, [*Molina-Azorín et al.*, 2009] found a positive relationship between environmental management indicators and financial performance in 21 of 32 quantitative studies.

These findings feed into a research direction focussing on a less generalized approach. The conditions under which the Hypothesis holds should be specified as opposed to proving or disproving the Hypothesis in general [*Wagner*, 2003]. [*Petroni et al.*, 2019] for example, note that the possibility of the Hypothesis holding may be mediated the means by which value is created and appropriated in a sector and by the intensity of pollution of the sector as these will affect the relative proportions of compliance costs and the ability to increase profitability. In this context, this thesis asks about the mechanisms in the relationship between innovation and regulation in a non-competitive sector heavily affecting in environment (as is the case with water supply and wastewater management).

Action Arena: Regulatory Economics of Natural Monopoly

The core archetypal characteristic of the water sector is often understood under the term natural monopoly [*Mosca*, 2008]. In fact, some of the earliest debates around natural monopoly emerged in discussions of water supply in 19th century London [*Tynan*, 2007]. The source of natural monopoly is the requirement for large capital investment (for centralized water networks) which creates economies of scale (falling average costs with rising quantity), a potential barrier for firms considering market entry. Importantly, the technology must be such that it is always cheaper for one firm to supply the market than for more than one (think of how much more expensive multiple competing supply networks would be) [*Baumol et al.*, 1988; *Mosca*, 2008]. Also that capital expenditure must be sunk cost, meaning it cannot be quickly adjusted, and if sold or diverted to a different use, it loses its value [*Joskow*, 2007].

Water is among the densest of staple consumer goods, so supplying water demands large capital investments for the supply network [*Bakker*, 2003]. Large capital investments, the networked nature of the infrastructure, and the technical coordination required to operate water supply systems, engender barriers to market entry and a tendency of natural monopoly in water supply [*Spiller and Tommasi*, 2005; *Joskow*, 2007; *Ménard and Ghertman*, 2009]. Natural monopoly leads to a single firm supplying the market, the potential for that firm to abuse its market power, and hence calls for regulation to prevent such abuse.

It has been argued that competition can be created even where there is a tendency towards monopoly through the use of competitive bidding on concession contracts [*Demsetz*, 1968]. However, [*Williamson*, 1989] argues that both sides to the transaction become dependent on each other when the infrastructure is deployed as the procuring authority cannot easily switch suppliers and the supplier cannot find another buyer. Additionally, given the long time horizon involved in water infrastructure, there is substantial uncertainty over many aspects of the contract between these parties. These uncertainties can then be opportunistically exploited by one or the other side. The transaction costs literature based on Williamson's approach argues that when relationship-specific assets are mired in complexity and uncertainty, government ownership, vertical integration or regulation is the efficient institutional arrangement [*Williamson*, 1989; *Levy and Spiller*, 1994; *Menard and Shirley*, 2008]. Regulation can involve monitoring and controls on business plans of privately owned water companies, direct state ownership and control, or indeed various configurations in between [*Williamson*, 1989].

Despite influential critiques of the need for monopoly regulation [*Demsetz*, 1968; *Posner*, 1969; *Dal Bó*, 2006], regulation and nationalization persist in practice. According to a 2014 international survey of regulators, they are most commonly established to protect the public interest, make service providers more accountable, or as part of broader regulatory reform [*OECD*, 2015]. Less commonly, regulators are established to accompany privatization processes, in response to international commitments, to curb corruption or for other reasons. Regulatory authorities are typically given powers to regulate water tariffs paid, set and enforce quality standards, and set incentives for efficiency, investment, innovation, and demand management, alongside a slew of other potential functions [*OECD*, 2015]. Internationally, this single firm is usually under government ownership, although in some jurisdictions such as in England and Wales, water companies have been privatized and operate under a system of economic regulation [*Schiffler*, 2015]. In fact, after private participation in water sectors spread to many countries in the 1990s [*Bakker*, 2003], a marked trend of re-nationalization (more specifically re-municipalisation) has been observed since the turn of the century [*Kishimoto et al.*, 2015].

Archetypal Issues of Trust in the Regulatory Action Arena

The regulatory action arena is marked by archetypal problems of trust. These are largely driven by the mutual dependence that exists between the procuring entity (the regulator) and the supplier (the regulated water company in this case) over the assets specific to their relationship.

The establishment of a regulatory authority opens the potential for governmental opportunism to drive down tariffs or administrative expropriation of value or assets from the suppliers or their investors [*Levy and Spiller*, 1994; *Spiller and Tommasi*, 2005; *Stern*, 2012]. Regulation of critical infrastructures such as those used in water and wastewater services also directly affects the vast majority of the voting population, creating a pronounced tendency for political pressure on regulatory decisions [*Ménard and Ghertman*, 2009]. If the regulatory authority cannot ensure commitment to not abuse administrative powers, as is the case with countries where the institutional context is not conducive to such commitment (corruption, weak judicial independence, poorly defined regulatory authorities and regulatory conflict resolution), there is likely to be administrative expropriation and underinvestment [*Levy and Spiller*, 1994].

Just as there are a multiple means by which the regulator can work to expropriate value from the regulated firm, the firm can likewise game the regulator in several ways. Particularly where it is costly or otherwise difficult to scrutinize the firm-regulator relationship, captured regulators might change rules to protect incumbent firms or to enable them to accrue surplus rents [*Dal Bó*, 2006]. One issue is that firms may 'gold plate', extracting additional returns by investing beyond levels necessary to meet environmental and supply requirements [*Averch and Johnson*, 1962; *Joskow*, 2007]. 'Gold plating' has also been noted as an issue due to the asymmetry of information between the regulator and firm in the case of England and Wales [*Ofwat*, 2011]. More generally, the problem of how the regulator knows that the firm is undertaking appropriate levels of effort, if this effort is unobservable by the regulator, creates the issue of moral hazard [*Laffont and Tirole*, 1993; *Stiglitz*, 1994; *Joskow*, 2007].

Due to mutual dependence, uncertainty over future costs and other performance risks of the underlying assets, trust between regulator and firm is a challenging issue in the regulatory action arena. Several regulatory instruments are employed in order to provide certainty to the regulated firm and it's investors as well as to promote effective incentives for the firm to provide efficient investments and engage in meaningful effort to deliver and innovate. As will be shown in this research, for England and Wales these instruments of regulation interact with technological change and eco-innovations in multiple ways. Often, such instruments seeking to promote trust and certainty among participants work to inhibit technological change and contribute to locking-in the dominant technological regime.

2.4 Conclusions

This chapter provided an overview of decision making characterizations and tools as employed in the study of SES. In reviewing the SoS approach it was shown how multiple outputs and efficiency parameters usually associated with water technologies could be used assessing different technologies.

The SoS also employed an aggregative approach to multiple MCDMs, to which an alternative *comparative approach* is employed in this research. This comparative approach as employed to multiple decision maker situations was shown to be enabled by the SES conception of action arenas as a more flexible application of game theoretic modelling. Multiple decision models exist, drawing on different characterizations of decision making for individuals and organizations. As with MCDMs, a comparative approach to tools yields a series of alternative perspectives on the action arena. Selection of a predictive decision making characterization is possible at different levels of abstraction given the information available on decision making.

In collecting the necessary information for characterizing the action arena and its decision makers, HOCs and Landscape pressures must be taken into account as these can and do shape the options, preferences, and decision making. Two strands of literature have been drawn on to characterize some archetypal HOCs and landscape pressures for the action arena relevant to this research: the literature on technological change and innovation and the literature on regulatory economics. The core issue, when brought together is how the systems of regulation, which seek to ensure trust and certainty, effect technological change as part of the socio-technical system in which they operate.

Chapter 3 provides an integrative statement of the CIGA, the morphology of decision making characterizations used and apply this to the prisoner’s dilemma archetype. Chapter 4 develops the characterization of the regulatory action arena in England and Wales, including the participants, HOCs and landscape pressures, technological options, and points on the relationship between the system of regulation and the processes of technology selection and innovation. Chapter 5 delves deeper into characterization of the regulatory action arena through interviews with water sector stakeholders. Chapters 6, 7, and 8, develop and analyse models of the action arena as based on the insights from the preceding analysis.

Chapter 3: The Comparative Information-Graded Approach (CIGA)

Key Points

- The Comparative Information Graded Approach (CIGA) is set out in this chapter.
- CIGA locates a focal action arena between Higher-Order Conditions, Landscape Pressures and the underlying environmental systems and adopts a comparative information-graded approach across a set of alternative tools.
- The CIGA is applied to the prisoner's dilemma archetype showing that while the traditional rational choice prediction of non-cooperative outcomes in the prisoner's dilemma holds for most tools considered, some do cooperate in equilibrium.

This chapter provides the overview of the framework adopted in this research. Different decision models are brought together into a morphology feeding into the Comparative Information Graded Approach (CIGA). The CIGA is applied the prisoner's dilemma archetype. Nash equilibria, as well as tools from the Graph Model for Conflict Resolution, and agent-based modelling of bounded rationality on the basis of reinforcement learning.

3.1 Statement of the Comparative Information Graded Approach

The conceptual structure of the CIGA is constituted of four core elements interrelated as shown in Figure 3-1:

- *Higher Order Conditions and Landscape Pressures* – The CIGA consider the action arena as nested in a set of Higher-Order Conditions (HOCs) (as drawn from Social Ecological Systems theory [*Ostrom*, 2009a]) as well as landscape pressures (as drawn from the Multi-Level Perspective [*Geels*, 2002, 2011]).
    a. *HOC's* – this constitutes the institutional context setting out the rules for and roles of the different actors participating in the action arena.
    b. *Landscape Pressures* – this sets out a series of technical, material, demographic, ideological, and economic patterns and pressures which are external to and fixed for the participants in the action arena but nonetheless relevant to them.
- *Action Arena Decision Makers*– a situation of one or multiple decision makers as nested within the HOCs and Landscape Pressures but with resultant impacts on and observation of environmental outcomes.
    a. *Options and Preferences*

b. *Decision Making Characterization*

- *Environmental Outcomes* – the outcomes of decisions in the action arena result in environmental outcomes.
- *CIGA Outputs*
    a. *Prescriptive* – a comparative view of tools allows for the evaluation of which yields better outcomes for decision makers. This offers a prescriptive CIGA output as one tool can thereby be prescribed over another.
    b. *Predictive* – given a degree of information over which tool best describes decision making, an alternative CIGA output is a predictive one. On the basis of the information available for characterization of the core elements of the model, CIGA outputs can be used to predict outcomes of a given action arena.

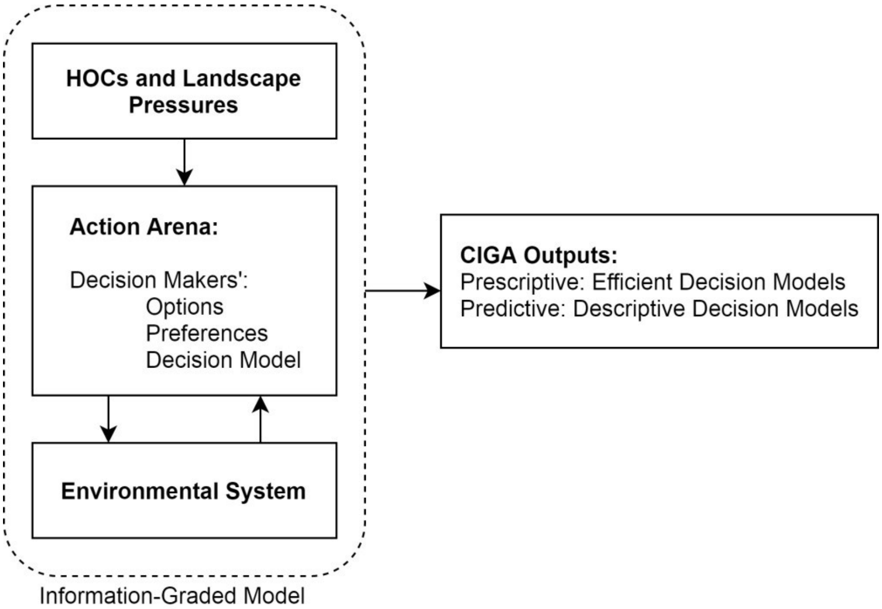


Figure 3-1: The Comparative Information-Graded Approach

Information Graded Approach

Developing and analysing SES models of environmental management, involves three key stages:

1. *Characterization of the environmental system*: How action arena outcomes affect environmental systems.
2. *Characterization of decision making*: options, preferences, tool.
3. *Characterization of the context*: action arena HOCs and landscape pressures.

The characterization of each part is dependent on the degree of information available. This information is not always readily available and modelling must often proceed without complete or perfect information about the SES being modelled. In the face of limited information, the CIGA takes an information-graded approach. Simply stated, the information graded approach uses the degree of information available for modelling. If information is highly constrained, simplified models are employed. If highly detailed information is available then more nuanced models can be characterized.

As argued in Chapter 2, organizational decision making in particular presents the problem of costly information. Characterizing organizational decision making as that of a rational actor provides a solid basis with low informational costs. However, much more nuanced understandings can and should be gleaned. These require more involved processes of information gathering such as interviews with stakeholders involved to gain information on organizational politics.

3.2 Morphology of Decision Making Characterization

In applying exploring high grade information on organizational decision making, stakeholder interviews must be conducted. This creates a bridging problem between the decision making characterizations reviewed in Chapter 1 and the stakeholders that will be interviewed in order to provide high grade information for characterizing organizational decision making. This bridging is hampered by the fact that stakeholders cannot be expected to know the different theories and characterization morphology from the literature including terms such as 'Nash equilibrium', 'satisficing' or 'general meta-rationality'.

For the purposes of the CIGA, a morphology is here developed to aid this bridging. Given a series of tools for any particular research, it is possible to develop a morphology of these in order to compare and determine commonalities [*Ritchey*, 2012]. In reviewing the diversity of tools employed in energy system modelling [*Koppelaar et al.*, 2016] provides a helpful morphology of tools along three dimensions:

- Allogeneity (number of decision makers),
- Decision Response (Homogeneous, Heterogeneous),
- Opsis (knowledge availability across the past, present, and future).

This provides a helpful core to the framework. However, given the tools reviewed, a more detailed morphology can be developed.

Chapter 1 included mention of the Graph Model for Conflict Resolution family of tools. The GMCR works in a series of stages. First, players are defined. Second, each player is assigned a set of possible “moves” (i.e. strategies). These strategies are used to define a set of “states” (i.e. outcomes or strategy profiles). These “states” are interconnected by “moves” yielding a graph of “state” nodes and “move” edges. The final stage in the GMCR process is analysis. Each state is evaluated with each tool employed by the GMCR. Each tool yields a “yes” if decision-making employing this tool would not employ a “move” to switch to a different node. A “state” with a “yes” for a given tool, is said to be “stable” (in language of GMCR).

For the present purposes however, the term “stability” is not used. Instead, the “stability definitions” of GMCR are understood under the term “convergence definitions”. A state deemed “stable” by a GMCR tool is understood to be “convergent”. Equally, under Nash equilibrium analysis, an “equilibrium” outcome is here understood to likewise be “convergent”. The main reason for this terminology is that “stability” has different definitions in the context of different tools. The overarching term “convergence” was deemed broad enough for the tools employed here. In particular, reinforcement learning algorithms iterate Q-values over simulated time and can (depending on the game) “converge” to a given state.

The GMCR already effectively deploys a comparative approach to tools in providing a set of tools for analysing action arenas [*Kilgour and Hipel*, 2005]. In presenting the different tools used for the GMCR, [*Madani and Hipel*, 2011] provide a morphology as presented in Table 3-1. (This table has been amended to include two variants of reinforcement learning applied to the prisoner’s dilemma archetype in section 3.3.) The core morphological characteristics of the tools presented are:

- Temporal Myopia – How many moves ahead does the tool consider?
- Disimprovements – Does the tool consider possible disimprovements? This represents a caution about the possibility that the opponent will punish a move by the focal decision maker.
- Knowledge of Preferences – Which decision makers’ preferences does the focal decision maker have knowledge of?
- Knowledge of others’ action – (added to original table to reflect additional information constraint faced by reinforcement learning tools).

Compared to the first morphology, this structure distinguishes between myopia over time and across others’ decision making explicitly.

Table 3-1: Morphology of Tools

Tool	Tool Morphology				Computation Method	Convergence Definition
	Temporal Myopia	*Disimprovements*	*Know Pref.*	*Know Others' Action*		
Ignorant Myopic	History 1 move	Only ε-greedy	Discover	No	Reinforcement Learning	State count pattern over simulated time.
Adaptive Myopic	History 1 move	Only ε-greedy	Discover	Yes	Reinforcement Learning	State count pattern over simulated time.
Nash equilibrium	Future 1 move	Never	Own	Yes	GMCR, (mix-strategies Formal)	Decision maker cannot unilaterally move to more a preferred state.
General Meta-Rationality (GMR)	Future 2 moves	By opponent	Own	Yes	GMCR	Unilateral improvements (UIs) blocked where others can move to less preferred states.
Symmetric Meta-Rationality (SMR)	Future 3 moves	By opponent	Own	Yes	GMCR	UIs blocked even after possible response to others' move by the original decision maker.
Sequential Stability (SEQ)	Future 2 moves	Never	All	Yes	GMCR	UIs blocked only by subsequent UIs by others.
Simultaneous Stability (SIM)	Future 1 move	Never	All	Yes	GMCR	No subset of players can improve their utility with a simultaneous move.

The morphology of tools considered in the CIGA. The table is adapted from [*Madani and Hipel*, 2011].

Given these characteristics of tools, the following overarching CIGA morphology is developed. This provides a framework integrating the tools reviewed in this section as well as from the tools reviewed in Chapter 1.

- Allogeneity (single or multiple decision makers)
- Knowledge Availability Across…:
  - Time
  - Options and Preferences (Option Discovery)
  - The decision-making of other decision makers'
    - Options and Actions
    - Preferences
- Forecasting and Expectation Formation (e.g. Expected Utility, Adaptive)
- Objective Variables (single or multiple criteria)
- Pursuit mode (i.e. maximization, satisficing, resolve)
- Risk Aversion and other decision making modifiers (e.g. Procedure, Emotion, Culture)

This morphology covers the different tools reviewed in Section 2.2 in Chapter 1. From this morphology a set of core characteristics is derived as given in Table 3-2. These function to bridge these tools in stakeholder interviews (more detail on the statements provided to stakeholders in the interview process is given in Chapter 5).

Table 3-2: Key of core tool characteristics as derived from morphology of tools.

Code	Key Characteristic	Relevant Tools
CBA	Quantitative costs and benefits	Tools relying on cardinal preferences.
Deliberate	Qualitative considerations for and against	Procedural rationality and deliberative institutions [*O'Neill et al.*, 2008]
Selfish	Pursue actions good for themselves	Self-interest presumption in rational choice and game theory.
Satisfice	Pursue actions considered good enough	Satisficing aspiration levels as a model of bounded rationality [*Simon*, 1996].
Rule	Pursue a rule regardless of outcomes	Resolve driven decision making [*Sugden*, 1991] and procedural rationality [*O'Neill et al.*, 2008]
Response	Consider how others will respond	Best responses/Unilateral improvements in Nash and GMCR tools. [*Kilgour et al.*, 1987; *Brams*, 1994]
Punish	Prepared to punish others when punishment is costless	Sequential Stability. [*Kilgour et al.*, 1987; *Brams*, 1994]
Punish+	Prepared to punish even when costly	GMR and SMR [*Kilgour et al.*, 1987; *Brams*, 1994]

RiskAverse	Risk and Loss aversion	Prospect theory [*Kahneman*, 2011]
Altruist	Pursues the preference satisfaction of others	Social Preferences [*Fehr and Fischbacher*, 2002; *Ostrom*, 2009b]
Emotion	Driven by emotion	Emotion [*Elster*, 1994]
Culture	Driven by cultural norms	Culture and informal institutions
Ideology	Driven by party political ideology	Ideological

3.3 Comparative Approach in the Prisoner's Dilemma Archetype

This section reviews the tools that will constitute the comparative approach: Nash equilibria and associated mixed-strategy equilibria, the tools of the GMCR, and reinforcement learning variants. This section will exemplify the CIGA through applications to the example of the PD, a very popular game structure.

In the PD (arguably the most widely studied game structure), two players choose between cooperation and defection. Under cooperation they would achieve the best aggregate outcome. However, for each option of the other player, each player is better off defecting meaning defection is strictly dominant. Mutual cooperation in not convergent under Nash equilibrium since either player can improve their position by defecting. Since no player has a strategy by which to improve their outcome from mutual defection, there is a Nash equilibrium in this state. Figure 3-2 shows the PD in normal form with utility values represented as ordinal rankings of the different states.

		Prisoner 2: Cooperate with 1	Prisoner 2: Defect
Prisoner 1	Cooperate with 2	**3** , 3	**1** , 4
Prisoner 1	Defect	**4** , 1	**2** , 2

Figure 3-2: The PD in normal form. Utility values in the cells are expressed as ordinal rankings not cardinal payoffs.

[*Scholz*, 1984] used the prisoners dilemma as a model of enforcement of environmental regulations. The firm is considered to have the option of complying or evading and the regulator chooses between being stringent or flexible with monitoring and enforcement. The cooperative state is then the state where regulators work collaboratively with firms in dealing with sector challenges. Defection from the cooperative state for the firm would mean duping the lenient regulator into not monitoring the non-compliant firm. Defection for the regulator would involve over-zealous application of rules to broadly compliant firms. The mutually defective state is one of adversarial relations often fraught with legal processes which are more costly to both players.

Mixed Strategy

In many games there is no strictly dominant strategy and hence the equilibrium will not involve the use of a pure strategy (i.e. only playing only one of the strategies available). By randomizing between strategies – using so-called mixed strategies – an equilibrium point exists for any game [*Nash*, 1950; *Perea*, 2012]. Three standard interpretations of the mixed strategy are: actual randomization (i.e. coin flipping or generating random numbers to select strategies), equilibrium beliefs [*Harsanyi*, 1973], and shares in a population under an evolutionary interpretation of games [*Smith and Price*, 1973].

Equilibrium beliefs interprets mixed-strategy probabilities as Bayesian subjective probability beliefs. Games with full information are understood to include random perturbations to the utility payoffs. These variations induce players to have strictly dominant choices in the games sampled from the random perturbations so players will choose pure strategies in each of the deterministic games. The equilibrium beliefs interpretation then finds that as these perturbations tend to zero the ratio of chosen pure strategies in the deterministic games will the same as the mixed strategy.

While the GMCR determines pure strategy Nash equilibria, it does not compute mixed strategy equilibria which are here added to the analysis separately. Mixed strategy equilibria are computed with a strong simplifying assumption: ordinal preference rank values are used as cardinal utility values in computing mixed equilibria and reinforcement learning values. The aim of this study is to understand archetypal structures and so the actual choice of cardinal values is not important as long as they maintain the general ordinal rankings of the states and this assumption is consistently applied throughout the analysis.

GMCR Tools

Figure 3-3 shows the PD in a graph form as generated by the GMCR+ software and Table 3-3 shows the results for each of the GMCRs tools in the PD. The nodes in the graph depicted in Figure 3-3 are the possible states of the game. In Table 3-3 the states are given as columns, defined by the strategies adopted by the players as given in the first two rows. For example, the node labelled “4” in Figure 3-3 is a state where both players are cooperating as indicated by the last row in Table 3-3. The directed edges connecting the nodes are the moves available to the players from each state. They are color-coded for the players Looking again at node 4 we can see two edges leading away from it towards other nodes. In GMCR representations, the thicker edges between nodes, represent moves which improve the payoff for the player who's action the edge represents. Both of the edges leading away from node 4 lead to states where the moving player has a higher payoff. Hence both edges are thick. We can see also that edges leading towards state 4 (meaning moving from non-cooperation to cooperation) are not thick meaning these do not yield increased payoffs. Finally, States without any thick edges leading away from themselves are Nash equilibria. They are convergent.

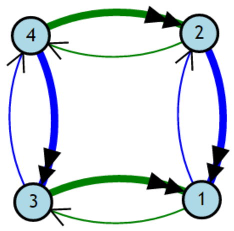


Figure 3-3 The PD in graph representation.

Table 3-3: GMCR Analyses of the PD.

Prisoner 1	Cooperate with 2	N	Y	N	Y
Prisoner 2	Cooperate with 1	N	N	Y	Y
Payoff For:	Prisoner 1	2	1	4	3
Payoff For:	Prisoner 2	2	4	1	3
	Mixed Strategy	1	0	0	0
	Nash	Y	N	N	N
	GMR	Y	N	N	Y
	SEQ	Y	N	N	Y
	SIM	Y	N	N	Y
	SEQ & SIM	Y	N	N	Y
	SMR	Y	N	N	Y

The first two rows define the outcome in terms of the players' moves (or strategies), where Y means "yes" and N means "no". So, the first row defines the outcome where neither player cooperates. The third and fourth row indicate the ordinal preference ranking of the states for each player. The subsequent rows indicate the convergence of the states for each tool used.

The Payoffs are cardinal values generated by the tool to determine relative performances of the different states given the ordinal rankings entered into the software. The subsequent rows show convergence analysis for each state under each tool. For mixed strategy equilibria, the probabilities assigned to the different moves by different players are used to give a probability of that state happening. The analysis output cells are colour coded with red indicating a non-convergent state and green coding for a convergent state.

The PD provides a good example to compare the Nash equilibrium with the other the concepts employed in the GMCR. Except the Nash equilibrium, all other GMCR tools find cooperation to be convergent. This is because of the concern over disimprovements. Defection is an improvement available to players not taken as it opens the possibility of defection from the other player leaving the focal player worse off. This caution and awareness of possible counter-moves, allows for cooperation even under the condition of strict dominance in the PD.

Reinforcement Learning for Bounded Rationality

In addition to Nash equilibria and the GMCR group of tools, reinforcement learning tools are also included in the comparative approach taken here. [*Madani and Dinar*, 2013] evaluated different institutional arrangements for managing a groundwater problem by their performance under different assumptions behind agent decision-making based on temporal myopia and awareness of the effect other players have on the situation (externalities). Here only two simple variants were used as the GMCR and Nash tools already capture 'smart' and 'non-myopic' characterizations of decision making. [*Madani and Hooshyar*, 2014] applied the reinforcement learning tool to find optimal management policies for a multi-reservoir hydropower system when managed separately or as a whole. The reinforcement-learning tool used was *Q-learning* with an *ε-greedy* search heuristic. Agents perceive payoffs as rewards for actions they take which feed into the Q-values they associate with these actions. They associate rewards with actions and update these values with subsequent new rewards. To make decisions, agents choose the action with currently the highest updated value. In order to discover new options, agents' are also programmed to randomly choose a different option (as from the ε-greedy heuristic in [*Gosavi*, 2003]). For the tool implemented here, the probability of a random choice simply falls over time until it reaches zero.

Table 3-1 is adapted from [*Madani and Hipel*, 2011] with the inclusion of two reinforcement-learning tools. Under the morphological category 'knowledge of preferences', these tools are coded as 'discovered' to reflect the bounded rationality approach. This reflects that under all other tools the players are assumed to have full knowledge of their options. The tool used here does not assume that and hence it is indicated that these agents discover their options through the *ε-greedy* heuristic.

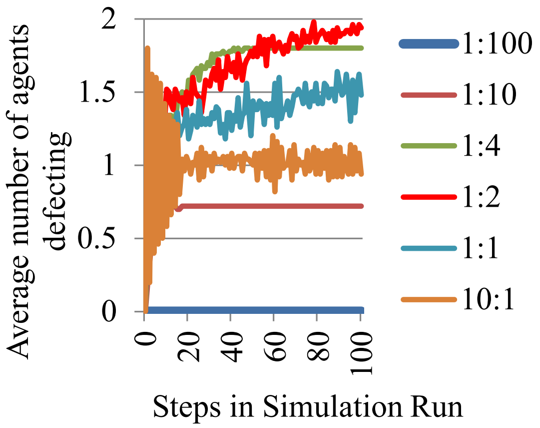
Both agent types employ reinforcement learning, the only difference being that the 'ignorant myopic' agents understood their state as being only differentiated by the action they have chosen. In the 'adaptive myopic' variant, the agent can differentiate between states based on not only their own action but also the action of the other agent. Agents then choose their best option assuming that the opponent will play the same strategy next turn as they did last turn. The term "adaptive" was chosen to reflect the concept of adaptive expectations which models agent predictions as based on past events.

Figures 3-4a and 3-4b show simulations for the two algorithms. The simulations are run over 100 repetitions (simulated time) 50 times. The average number of agents defecting (of the 50 runs) is plotted over simulated time. Given there are two agents in each run the scale goes from 0 to 2.

The *ε-greedy* heuristic requires a random search initially, so different initial values for the amount of randomness were used to run this 100 × 50 analysis. If there is a very small probability of a random choice the agents will not defect as they start in the cooperative state and will not attempt any random moves. As the likelihood of random choices increases, the number of runs where agents try defection increases. Over simulated time, the randomness falls eventually allowing convergence.

Of the considered values, once again 1:2 converges the fastest. In other words, starting with 1:2 odds of a random choice almost all runs of iterated PD will end up defecting after 100 repetitions of the PD. Given enough time, and a low enough degree of randomness, a wide range of randomness strengths lead to both agents defecting. This is how convergence applies in this context. The agents "settle" into a given state (mutual defection in this case) as their Q-values are updated over simulated time.

Compared to the ignorant myopic agents, these agents are able to converge to the defection Nash equilibrium much faster, reflecting their better knowledge of the state they are in. The reinforcement learning agents were not able to cooperate given discovery of the possibility of defection. The PD was also used as a calibration exercise and hence 1:2 will be used as the initial ε-greedy value for all subsequent reinforcement learning analyses (see Chapter 7).



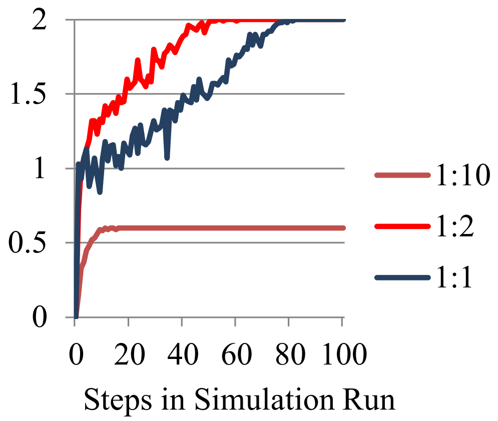


Figure 3-4a. Ignorant agents

Figure 3-4b. Adaptive agents

Figure 3-4:Repeated PDs for agents with differing starting odds of a random choice (each line follows the average defections of 50 runs with a given starting odds of a random choice over a 100 step simulation)

3.4 Conclusions

The CIGA was presented in this chapter presenting the core structure (action arena, HOCs and landscape pressures, and environmental system). The CIGA relies on a series of tools. A morphology was developed around these to distil core distinguishing features of each tool. From these a series of core characteristics were determined as will feed into the interview process (see chapter 5).

The CIGA allows for two sets of outputs: prescriptive and predictive. The predictive set relies on information to characterize an action arena and select a tool. The set of characteristics as combined with literature and interviews aims for this branch of outputs. This is pursued in part 2. The prescriptive approach is used to review a series of tools in an action arena and evaluate which performs better. A set of tools including the GMCR and Reinforcement learning was applied to the prisoner's dilemma archetype. It was shown that for tools prepared to punish non-cooperation, cooperation is convergent. Note that this is not a novel finding. The aim of this section was to illustrate prescriptive branch of CIGA outputs.

Part 2: Characterizing UK Water Sector Regulation and Innovation

Chapter 4: Characterizing the Water SES in England and Wales

Key Points:

- The water sector is characterized qualitatively in a structure based on the CIGA model.
- The economic regulation action arena involves the water companies and regulators.
- Water innovation involves two key types of technology: centralized and distributed.
- Technology options are reviewed according to carbon footprint.
- The case of the tideway tunnel highlights a tension between centralized and distributed technologies and how this is mediated in the institutional setting.

This chapter develops the characterization of water technology adoption in the UK along the lines of the CIGA focussing on the regulatory action arena and interactions between regulation and technological change. The legislative and environmental context, technologies and practices available for improved water management are reviewed to provide insight into the action arena (decision makers, options, and preferences). EA data on WFD non-compliance shows the water companies play an extremely important role both as sources of non-compliance but also as providing the funding stream for delivering measures to address non-compliance. The focal action arena is that of economic regulation, in particular providing and overview characterization of how this system works and its relation to technology selection.

The regulatory mandate for the economic regulator establishes a requirement for reasonable rates of return. This system of regulation has been shown to create a capital expenditure bias. This bias contributes to the system of regulation systematically locking in centralized approaches. A review of alternatives to centralized technologies, namely distributed technologies, are thereby under developed. This issue is highlighted in the history of the Thames Tideway tunnel. Ultimately the regulatory and government worked to promote the centralized solution despite controversy around whether alternatives including more distributed technologies as a part of the solution would be better.

4.1 HOCs and Environmental System

This section characterizes HOCs and the Environmental System of the SES for water in the UK, focussing on England and Wales. The first set of HOCs are the conditions imposed within the UK establishing the authorities and mandates of governing institutions and decision making organizations. From this a stylized overview of the SES can be determined. Subsequently, relevant EU legislation (as noted by the economic regulator as a key driver of investment in the water sector) is reviewed as another set of HOCs. The EU Water Framework Directive, in particular is important as it sets out a system of classification used across the EU and in the UK for assessing the status of bodies of water. This forms the basis of the characterization of the environmental system characterization which is done using data from the Environment Agency.

HOC: UK Water Governance

At the time of writing, the UK (particularly in England and Wales) regulates a set of privately owned regional monopolist water companies. The first of London's water utilities emerged in the 16th century and were privately owned, growing in size and number over 400 years and eventually being brought into public ownership and amalgamated in the Metropolis Water Act of 1902 [*Tynan*, 2002]. Despite a series of reforms and restructurings during the 20th century, the Regional Water Authorities across England and Wales were privatized in 1989 and their attendant economic regulator, the Office of Water Service Regulation (Ofwat) was established [*Page and Bakker*, 2005]. It should be noted that several other authorities also act to regulate the activity of water companies in the UK in one way or another. These include:

- *Local councils* have a role in the governance of water in some areas. These include adopting the optional stricter building water efficiency requirement for planning applications: 110 litres per person / per day as opposed to the national standard of 125 in Building Regulations 2010 [*Crown*, 2010]).
- *Environment Agency (EA)* was established by the Environment Act 1995 [*Crown*, 1995] taking on the roles of the previous authorities designated with environmental monitoring and law enforcement. The EA is tasked with implementing EU law. Note that there is a separate environmental quality regulator for Scotland, namely the Scottish Environmental Protection Agency (SEPA).
- *Drinking Water Inspectorate (DWI):* established in 1990, the DWI is responsible for monitoring and regulatory drinking water quality and has authority in approving products employed in drinking water supply [*DWI*, 2018].
- *Natural England:* established in 2006 this agency is responsible for managing conservation at national parks and other designated sites with attendant authority in establishing requirements for water quality and quantity affecting these.

- *Consumer Council for Water* (est. 2005) the main purpose of CCWater is to represent consumer interests through research and disseminating findings as well as contributing to water sector consultations and supporting customers with potential questions or complaints [*CCWater*, 2018].

It should also be noted that different configurations exist across the devolved regions of Wales, Scotland, and Northern Ireland.

UK Water Sector SES Overview

From environmental need, through regulation, to technology implementation. The way the system works is broadly the EA implementing EU legislation by imposing environmental requirements on the firms. The firms are then made to deliver *investigations* into the environment and develop the capital investment plans for meeting environmental requirements. These are then reviewed and challenged by the economic regulator.

HOC: Relevant EU Directives

EU law plays an important part in the water sector as a driver of required investments, thereby driving demand for water technologies able to deliver on environmental law requirements, hence boosting the water technology market and ultimately driving water innovation [*Thomas and Ford*, 2006]. Here an overview of the key legislation is given. These directives in particular were selected due to their prominent mention the economic regulator as key drivers of investment [*Ofwat*, 2014]. They are listed along with associated timelines and comment on how these relate to water companies. Note that for these timetables, extensions are usually permitted due to special circumstances. However these timelines do provide a good overview of when the largest investments can be expected to take place.

The Urban Wastewater Treatment Directive (UWWTD) [*Council of the European Union*, 1991]

- 1991: Directive adopted requiring wastewater collection systems and secondary treatment for urban wastewater.
- 2000: Secondary treatment for agglomerations of 15,000 p.e.
- 2005: Secondary treatment for agglomerations 10,000 and 15,000 p.e.

The UWWTD establishes a legal requirement that wastewater from cities and towns is collected and treated before being discharged back into the environment. This imposes an investment requirement on water companies for secondary treatment (biological treatment to remove nutrients from wastewater).

Habitats Directive [*Council of the European Union*, 1992]

- 1992: Directive adopted requiring the designation, maintenance, and restoration of sites serving as habitats for species protected under this directive.
- 1998: Draft list of sites.
- 2004: Final list of sites.

These sites (Special Sites of Conservation) alongside Special Protection Area's as determined under the Birds Directive 2009 [*European Parliament and Council of the European Union*, 2009], form the Natura 2000 network of protected sites. The protections given to these sites impose duties on national environmental regulators, who in turn impose duties water companies, to ensure these sites continue to serve as favourable habitats for the protected species.

Water Framework Directive [*European Commission*, 2000]:

- 2000: Directive adopted requiring integrated river basin management and providing relevant environmental standards.
- 2009: Final River Basin Management Plans (RBMPs) including Programme of Measures (PoM).
- 2012: Operationalize PoM.
- 2015: First management cycle ends and expected compliance with environmental objectives.
- 2021: Second Management cycle ends.
- 2027: Third management cycle ends.

Alongside the principles of integrated water management (which were discussed in section 2.3) which require RBMPs, the WFD sets standards for different quality parameters in the status classification of bodies of water [*European Commission*, 2000]. Under WFD ecological status of bodies of water is defined by Biological Quality, Hydromorphological Classification, Chemical and Physico-Chemical Standards (general components, specific pollutants, priority substances). As an example, one of the general components is Biological Oxygen Demand (BOD) the standard for which the WFD applies to rivers and transitional bodies of water but not lakes or coastal waters. Water companies play a crucial role in determining and implementing RBMPs and their attendant PoMs.

Bathing Waters Directive [*European Parliament and Council of the European Union*, 2006b]

- 2006: Directive adopted requiring monitoring, classification, management and public information for bathing water quality according to focussing in particular on faecal bacteria.
- 2008: Bathing waters and bathing seasons are defined by member states.
- 2015: All bathing waters achieve at least the 'sufficient' classification and proportionate measures seen as appropriate for increasing the number of bathing waters classified above this level are undertaken. Where bathing waters fail to achieve this, and are classified as 'poor', there must be a prohibition or advice against bathing for the relevant waters.

The Bathing Waters Directive lays out requirements for bathing waters (understood as those where the public is expected to swim), including inland and coastal waters. Where water companies discharge water to ultimately receiving bathing waters this can be expected to lead the EA to require measures and investments to meet the bacterial requirements of the Bathing Water Directive.

Shellfish Directive [*European Parliament and Council of the European Union*, 2006a]

- 2006: Directive adopted requiring protections and measures supportive of shellfish life and shellfish products for human consumption.
- 2012: Programmes for reducing pollution to values established by the member state and values set out in the directive.

The Shellfish directive targets discharges to shellfish waters which are expected to negatively impact a set of parameters covering pH, temperature, coloration, suspended solids, salinity, dissolved oxygen, petroleum hydrocarbons, chemicals, metals, and faecal coliforms, and toxins. As with other directives, where water companies discharging treated wastewater to shellfish waters this directive can be expected to impose the duty to implemented measures and invest in technologies to reduce the incidence of relevant pollutants.

The Environmental System of England and Wales

The UK water sector faces a diverse set of challenges [*Ofwat*, 2015d]: water scarcity as driven by population growth (particularly in the south-east of England); environmental water quality particularly as driven by wastewater and farm runoff; compliance with and penalties from EU law; and long-term resilience in the face of flooding, drought and the exacerbation of these due to climate change.

The characterization of the pollution in the environmental system here is done largely using data from the Defra and EA. Figure 4-2 shows data from Defra on abstraction from both surface waters and groundwater. The water sector is responsible for the majority of abstractions with abstractions for cooling in the power sector second. Figure 4-3 shows the EA data on sectors indicated as responsible where a measurement parameter is not meeting moderate status as given by the WFD. As indicated, agriculture is the leading cause of parameters being of particularly poor performance. However the water sector is second with approximately one quarter of reasons for poor status due to its activities. Table 4-1 shows the same EA data on reasons for below moderate status parameter classification as classified by the relevant activity. It gives only the top 10 activities by their share of activities leading to below moderate performance. Some activities listed can be attributed to multiple different sectors. Groundwater abstraction for example is done by both the agricultural and water industry. This view of the reasons for below-moderate parameter performance reflects again how agricultural and water industry activities are leading causes of non-compliance. However it highlights that the single activity most commonly participating in a body of water attaining below moderate status is wastewater discharge. This activity can only be attributed to the water industry.

While the water industry is a leading contributor to pollution and water quality concerns, it is also the key sector responsible for measures to improve environmental water outcomes. Figure 4-4 highlights the extent to which this is the case in the Thames water district by showing the lead organization by sector responsible for measures undertaken to improve on the environmental outcomes. Water supply and wastewater treatment together constitute more than three quarters of measures being undertaken in this area. These include measures are usually the implementation of new water treatment facilities or managing abstraction and discharges differently in order to promote environmental improvements.

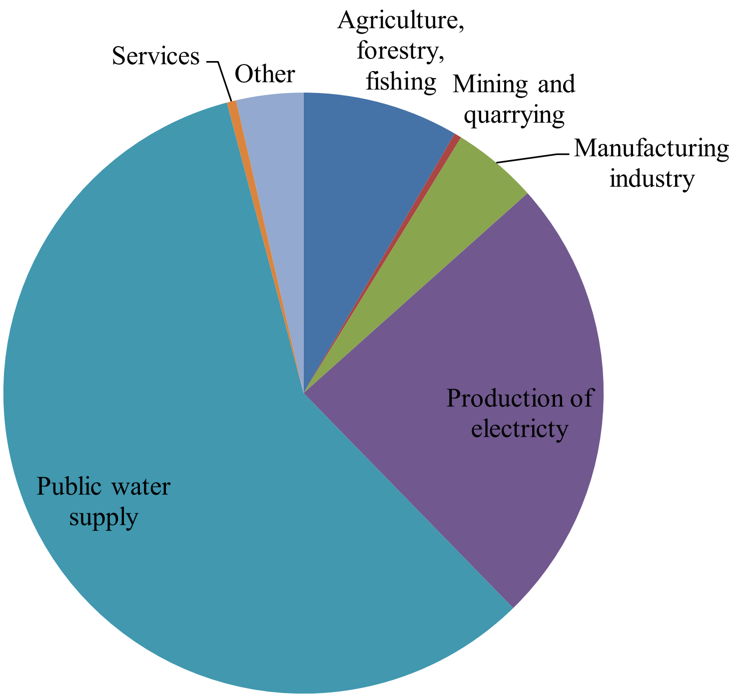


Figure 4-1: Direct Abstraction from All Freshwater Sources Mm3 England and Wales 2011[*Defra*, 2013]

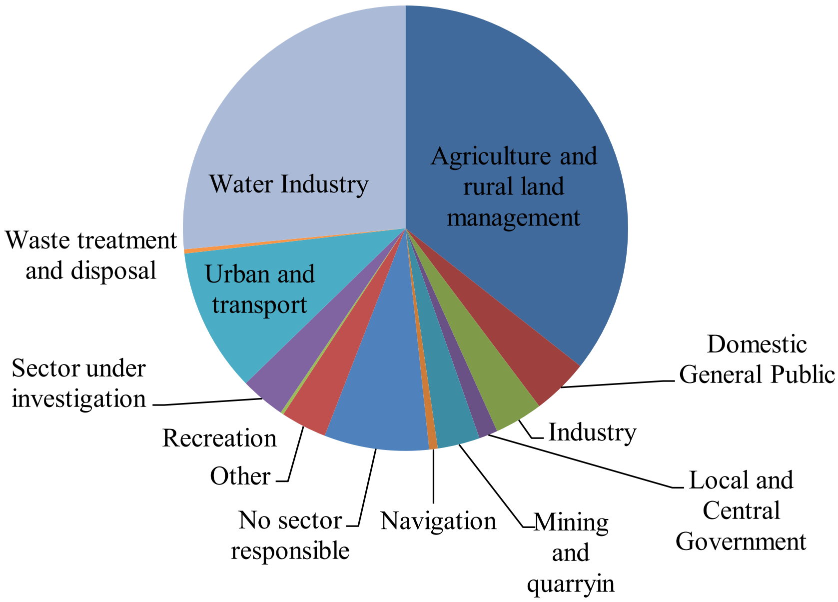


Figure 4-2: Sector responsible for element not achieving moderate or good status in cycle 2 [*Environment Agency*, 2018]

Table 4-1: Top 10 activities responsible for water bodies not meeting moderate status with activities that water companies participate in shaded in blue (data from EA Catchment Data Explorer [*Environment Agency*, 2018].

Activity	Share of reasons for not meeting moderate status

Sewage discharge (continuous)	17.28%
Poor nutrient management	11.67%
Livestock	8.06%
Groundwater abstraction	5.15%
Sewage discharge (intermittent)	4.72%
Unknown (pending investigation)	4.43%
Urbanisation - urban development	4.35%
Barriers - ecological discontinuity	3.90%
Poor soil management	3.82%
Private Sewage Treatment	3.19%

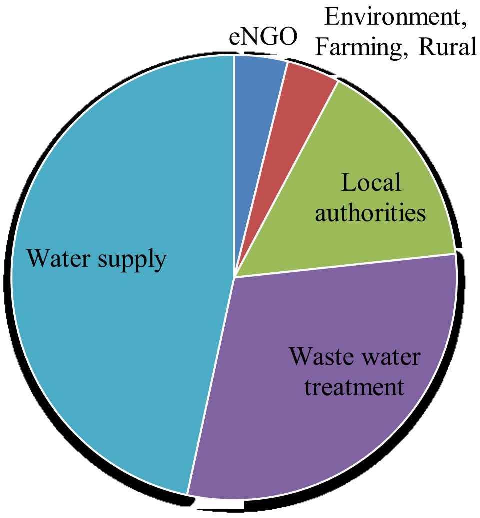


Figure 4-3: Number of Measures undertaken for Environment Improvement by Sector of Lead Organisation in the Thames River District in Management Cycle 1 ([*Environment Agency*, 2018].

Data from the second WFD management cycle as given by the EA provides a total of 19 measures across all districts in England that the EA is responsible for [*Environment Agency*, 2018]. 15 of these measures are due to wastewater treatment with 1 due to agriculture and the remaining 3 not providing a sector. This further supports the view that most measures undertaken are by the water sector. However this data is not reviewed more thoroughly here as it is not likely to be complete. Given that data from the first WFD management cycle for the Thames district alone accounted for 103 measures and that only 3 of the 11 river districts reported any measures at all for the second management cycle it is not likely that this data reflects the reality of different sector's involvement in environmental improvement schemes.

On the whole the data from Defra and the EA represented here highlights how the water sector is the key player in funding and implementing measures to support environmental improvements. The mechanism by which environmental legal requirements are translated into water catchment specific needs, and ultimately the funding and implementation of measures and scheme to address these needs through the water sector is the focus of this research and is the focus of section 4.2.

4.2 Focal Action Arena: Economic Regulation

The action arena of economic regulation is the focus of this research. As such the core decision makers in this area are the economic regulator, Ofwat, and the water companies that it regulates. Their interaction takes place through the periodic Price Reviews. In characterizing this action arena Ofwat's preferences are imputed from its mandate. The preferences of the companies can be assumed to centre on maximizing returns for its owners subject to the regulatory system.

Ofwat Mandate

Ofwat's mandate is determined by the HOCs of the legislation establishing Ofwat and assigning it's roles and responsibilities – namely the Water Act 1991 [*Crown*, 1991] and subsequent amendments. Among other documents and publications [*Ofwat*, 2018c], the sum understanding of its mandate is given in:

- "protecting the *interests of consumers* wherever appropriate by promoting effective competition;
- securing that the *functions* of a licensed infrastructure provider and the functions of undertakers *are properly carried out*;
- securing that an efficient licensed infrastructure provider and an efficient undertaker, are able (in particular by securing reasonable returns on their capital) to *finance the proper carrying out of those functions*;
- performing our regulatory duties in the manner which we consider best calculated to *promote economy and efficiency* on the part of a licensed infrastructure provider and an undertaker in the carrying out of its functions;
- contributing to the achievement of *sustainable development*; and,
- in the case of undertakers, securing the *long-term resilience* of water supply and wastewater systems and securing that undertakers take steps to enable them, in the long term, to meet the need for water supplies and wastewater services."
  [*Ofwat*, 2015b] (italics added)

From this mandate Ofwat's preferences (in terms of a CIGA model characterization) can broadly be deduced. These preferences are a composite of the different aspects of the mandate.

Protecting interests of consumers largely reflects the protection against monopoly power of the water companies that Ofwat is regulating. This is done by controlling the maximum price that companies are allowed to charge their customers. However, as the first mandate stipulates, Ofwat must also promote competition where appropriate. The regulatory system promotes competition in a number of ways as discussed further below.

Securing functions of the undertakers (water and water and wastewater companies) reflects Ofwat's responsibility to ensure that these firms deliver on their statutory obligations arising from drinking water supply as well as compliance with environmental regulations (often derived from UK implementation of the EU directives considered earlier). Related to this is the subsequent mandate to ensure that these functions are adequately financed (i.e. regulated prices must be sufficient to cover the expenses incurred for operation and investment to meet statutory requirements). It is known that different systems of regulation create different incentives for firms and hence the subsequent mandate on Ofwat to employ a system of regulation promoting cost effectiveness and efficiency in the regulated companies. The final point of the mandate reflects the need for a long-term view of water and wastewater service resilience.

As part of a UK government wide effort to promote sustainable development, Ofwat have the pursuit of sustainable development as part of their mandate. This has been interpreted to reflect a further subset of challenges including adaptation to and mitigation of climate change, international water scarcity, a growing national population, compliance with environmental standards, customer expectations around choice, service levels, environmentally-friendly and socially conscious services and affordability [*Ofwat*, 2010a].

Delivering this set of objectives clearly is no simple task. Not least because some of these objectives are not always obviously reconcilable. In particular, the core tension is between the increased prices required for investments (and reasonable returns thereupon) arising from environmental and drinking water requirements as opposed to the price reduction pressure required for promoting the consumer interest.

Price Reviews (PRs)

Ofwat must balance the different aspects of its mandate through the system of regulation as applied to review and approval of company business plans and prices. A typical price review involves 5 key stages as shown in Figure 4-5.

First the government department or ministry responsible gives its directions as determined by governmental policy. Recently, this has involved a National Environmental Plan [*HM Government*, 2018]. Such a plan is not mandated in law although proposals for this have been made [*Environmental Audit Committee*, 2018]. Alongside other governmental and ministerial direction, this sets the direction for the regulatory agencies. Under the Water Act 2014 such ministerial direction has been formalized, allowing Defra to issue strategic objectives for Ofwat but subject to consideration of Ofwat's independence and mandate under the Water Industry Act 1991 [*Defra*, 2017; *Ofwat*, 2018c].

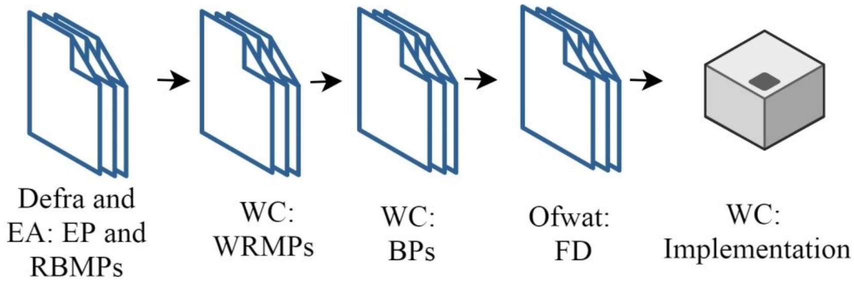


Figure 4-4: Stylized overview of the Price Review

Subsequently in consultation with stakeholders, but the EA in particular, and it's River Basin Management Plans (RBMPs), WCs develop their Water Resource Management Plans (WRMPs). These drive much of their investments which, alongside operational and financial matters such as a proposed price increase are reported to Ofwat in a Business Plan (BP). This is then reviewed by Ofwat, which then ultimately makes Final Determinations (FDs). The FD then sets out investments that will be made as well as the prices required to pay for the delivery of the plan (including returns on capital). The companies then deliver these plans over the course of 5 years after which another PR begins. Table 4-2 provides an overview of the timeline for this process for PR09.

Note that this is in fact a simplified version highlighting key stages. In fact, multiple consultations are involved as part of the PR and in preparation for it.

The core formula used in determining price caps [*Ofwat*, 1994; *Joskow*, 2007] is termed RPI – X and can be written as:

$$P_t = P_{t-1}(1 + RPI - X + Q)$$

Eq. 4.1

Where P_t is the price in the time period *t*, *RPI* is a measure of inflation, *X* is the efficiency challenge, expressed as a percentage value by which the regulator expects prices to be reduced and *Q* represents the amount by which prices increase due to greater investment required for compliance with quality regulations. In fact, the licenses given to the water companies reflect a K-factor which sums the X and Q percentages to give the net percentage change in allowed revenues [*Ofwat*, 2015c]. Given a certain revenue allowance, the firm is then left to determine how to set prices for different customers such that the average price will create revenues not exceeding the revenue allowance.

Table 4-2: Typical Price Review Process as adapted from [*HM Treasury*, 2012]

Autumn 2007	Statement of Obligations
Autumn 2007	DBPs
Spring 2008	FBPs
July 2009	DDs
August 2009	Representations on DDs
November 2009	Final Determinations

In determining the K factor, Ofwat must take into account the different aspects of its mandate. Two key regulatory tools are employed in determining the K factor. The regulator takes a comparative efficiency approach to assessing X assessing the efficiency improvement potential of a firm based on the improvements of other regulated firms. In ensuring that the firms are able to finance the delivery of required investments, the regulator employs an instrument called the Regulatory Capital Value (RCV) [*Joskow*, 2007; *CCWater*, 2011; *Ofwat*, 2015c]. RCV is essentially a quantity to which required capital expenditures are added as they arise, (and subtracted from as they depreciate). These capital investments usually arise from investment requirements for ensuring resilient supply for the future or compliance with drinking water and environmental requirements. The firm will propose these in the BP which the regulator scrutinizes and, if deemed a necessary investment at efficient cost, this quantity is added to the firms RCV in the FD. Per annum price changes required to pay returns to investors for these investments are then determined based on the RCV. (The specifics of the price control regime are developed in more detail in chapter 6.)

Regulatory Interactions with Innovation

There are two key mechanisms by which regulation interacts with innovation: competition and capital bias. Before turning to these, it is worth noting that a series of other interactions between the system of regulation and innovation also exist and have been identified in the literature:

Regulatory Gaps in Functional Integration: The separation of regulatory functions led to a regulatory gap [*OECD*, 2015], with potentially detrimental effects on efficient investment [*van den Berg*, 1997]. A later report found this not to be the case with the system largely functioning well even finding benefits to multiple regulators as their interactions and underlying trade-offs are made more explicit [*Gray*, 2011] The Water Act of 2014 also sought to align RBMPs and PRs, as well as drought plans and WRMPs [*Defra*, 2014]. The allocation of responsibilities for surface water drainage systems lead to distributed interventions (particularly SUDS schemes) being under-employed [*Green and Anton*, 2012].

Supply Chain Integration: A study commissioned by UK Water Industry Research (UKWIR) identified that the system of regulation adopted in the UK may have detrimental effects on water company supply chain integration and hence for innovation generally [*Thomas and Ford*, 2006]. The 5 year investment cycle is detrimental to supply chain consistency [*HM Treasury*, 2012]. This cycle is further explored in Chapter 6.

Low-powered cost reduction incentive: The rule for price controls creates incentives for WCs to deliver cost reductions in early stages of the 5 year cycle as the price review 'ratchets up' cost estimates and creates weak incentives for cost reduction in the latter parts of the cycle [*van den Berg*, 1997; *Joskow*, 2007; *Cave*, 2009]. This ratchet is also further explored in Chapter 6.

Comparative efficiency, NAVs, and Non-household Retail Competition

Competition is usually understood as a key driver of innovation in a market [*Fudenberg and Tirole*, 1986; *Baumol et al.*, 1988; *Cave*, 2009]. In a competitive market, firms would pursue innovations in order to reduce their costs and thereby gain market share. Without competitors or even the potential of new entrants to the market, the incentive for monopoly firms to innovate is reduced as they do not risk losing out to cost reducing competitors if they do not invest in innovation [*Baumol et al.*, 1988].

Given the water companies were assigned statutory monopolies in their licenses, they do not face direct competitive pressure in their appointed area. As presented in Chapter 2, the water sector is not well suited to competition. Hence competitive pressures to innovate can also be expected to be low. Given Ofwat's mandate to pursue competition however, this has been done in various areas and has been increasing over time.

Some competition, has been in place in the form of comparative efficiency between the companies [*Ofwat*, 1994, 2010b; *OfWat*, 2004]. Ofwat's relative efficiency assessments, penalize companies with operating expenditure efficiency below the average of other companies, and has driven operating efficiencies in these companies as shown in the Ofwat determinations.

Competition is also promoted through the system of New Appointments and Variations (NAVs) [*Ofwat*, 2018b]. Here the licenses for who supplies a given area can be changed in order to allow for a company different to the established monopoly incumbent to provide water and/or wastewater services. Figure 4.6 shows the number of NAVs commencing per year since 1994.

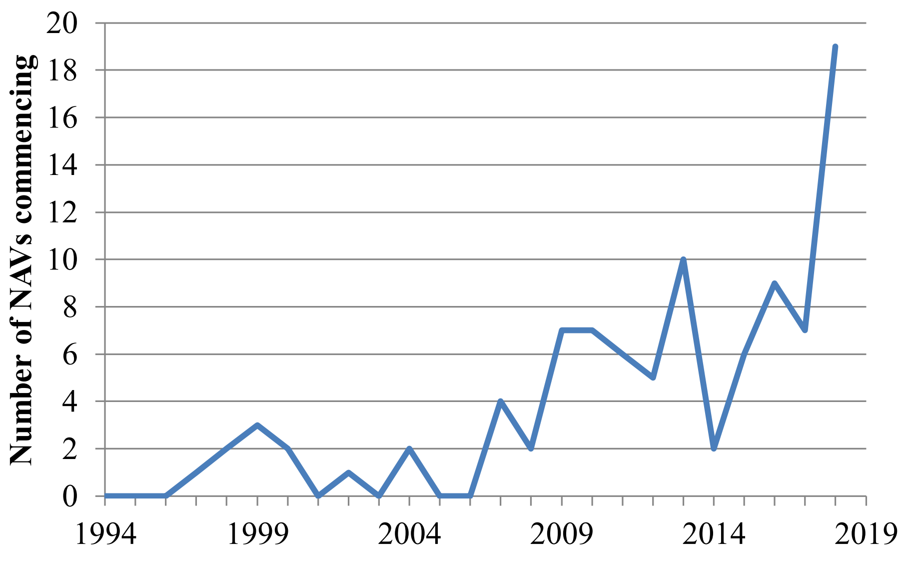


Figure 4-5: Number of NAVs commencing by year.

Although the data on NAV's does not indicate the size of the area served or the quantity of water services provided in that area it does show increasing use of this instrument over time. This instrument can be beneficial for promoting innovation in the water sector as it allows smaller companies with potentially different technologies and practices to deliver water services in an innovative way for a new build housing development, industrial park or other area.

As part of the Price Reviews, Ofwat commissions independent reports into key concerns of the sector. In 2009, the Cave Review focussed on competition and innovation in the water sector. It highlighted multiple issues preventing innovation in the water sector and recommended the introduction of opening competition in water retail. This would entail ending the statutory monopoly that water companies have in the area their serve with customers then being able to select their water supplier. The motivation behind this is to boost competition among different providers (and hence possible technologies and practices) in order to drive more investment in innovation.

The Cave Review was taken on board by Defra which subsequently passed legislation in Parliament to introduce retail competition [*Crown*, 2014]. The Cost Benefit Assessment of the policy introducing competition to non-household retail would deliver a net benefit yielded a total net present value of £211 million which, due to this relatively small value given typical sector expenditure, was classified as a net zero cost measure [*Defra*, 2015b]. In addition to retail competition, competition has also been introduced to bioresources, where companies can now buy and sell sludge [*Ofwat*, 2017a].

Regulation-induced Capital Bias

The system of regulation works to create incentives towards capital expenditure (capex). Despite the putative use of a regulatory price cap rule, the implementation of RCV as a driver of the pricing system worked to turn the price cap system in to one of rate of return regulation [*van den Berg*, 1997; *Green and Anton*, 2012]. Rate of return regulation creating a bias towards capital intensive centralized technologies [*Averch and Johnson*, 1962; *Joskow*, 2007]. Ofwat conducted a report into capital expenditure bias [*Ofwat*, 2011]. It found that companies perceived there to be a capital investment bias in the regulatory framework. In particular that the adoption of distributed systems such as sustainable drainage systems (discussed in section 4.3) were not being implemented due to the capital bias.

Perceived regulatory drivers of capex bias identified were:

- Capital investments earn a regulator allowed return through RCV remuneration.

- Capex, once included in the RCV commits to remunerating investors while opex is can be challenged in the next PR.
- Companies and investors see RCV as a measure of company growth.
- Opex incentives (operating efficiency assessment) being greater and therefore creating a greater risk than incentives around Capex incentives (Capital Expenditure Incentive Scheme (CIS)) leading to Capex bias.
- Reputational effects of publishing relative opex efficiency disincentives opex
- Capex costs are recovered over the lifetime of the asset while opex has immediate bill impacts.
- CIS gives more flexibility to manage overspend in capex than exists in opex.

While these drivers of capex bias were largely driven by regulation, some were on the company and technology side. Namely:

- Capex and Opex decisions were separated in corporate decision making within companies, with ultimate expenditure decisions favouring capex.
- Company engineering culture creates a preference for capex solutions which their employees have more experience and background with.
- A direct control and ownership improves the company's ability to service assets creating a preference for capex. (Note that under the Water Act 2014, companies are now allowed to construct and maintain SuDS).

Ofwat conducted its own financial modelling of the issue showed that the system of regulation does create biases. It was found that the bias depended on the incentives in play for a given firm, in particular given its position as one of outperforming or underperforming. This analysis however was constrained to a single review period and the report noted that the RCV created a clear capex bias.

It is interesting to note that among the options presented as solutions to this issue are:

- Totex: both capex and opex are added to RCV.
- Menu incentives
- Outcome based incentives

Each of these reforms subsequently influenced PR14 [*Ofwat*, 2014], with Outcome Delivery Incentives (ODI's) and a menu of totex incentives being adopted. The exact changes to the regulatory system are considered in more detail in Chapter 6.

4.3 Technology Options: Centralized and Distributed

Water sector technologies with the potential for eco-innovation can be categorized as 'distributed' interventions and technologies in the 'centralized' water and wastewater networks. Distributed interventions include technologies such as water efficient domestic appliances, rainwater harvesting, grey-water recycling, Sustainable Urban Drainage Systems (SUDS), and measures to reduce pollution at source in agricultural, industrial, or urban runoff. Centralized technologies include an array of treatment processes as applied in treatment plants.

To this distinction should be added 'auxiliary' eco-innovations. This catch-all term can be employed to enhance either or both centralized [*Tchorzewska-Cieslak*, 2009] or distributed systems [*Cembrano et al.*, 2004], typically involving the integration of sensors and information technologies for monitoring and control of systems and catchments [*Rosen C.*, 1998; *Ivan et al.*, 2018]. While these are not reviewed in further detail here, they have been mentioned as important innovations by several interviewees as noted in Chapter 5.

Table 4-3 gives a list of centralized and distributed water and wastewater technologies as reviewed by the EA and [*Fuchs et al.*, 2011] in the case of drainage systems. Table 4-4 provides the list of references employed in collating this list as well as sources of the carbon intensity data for these technologies as shown in Figure 4-7.

Table 4-3: Overview of key centralized and distributed water technologies			
Technology	**Cent./ Dist.**	**Description**	**Fig. 4.7 Code**
River Intake	C	Water is taken (abstracted) from a river usually involving minimal pumping.	River Intake b
Groundwater abstraction	C	Water is abstracted from underground aquafers requiring to be pumped to the surface.	GroundW b
Reservoir	C	A reservoir is used to store and supply water.	reservoir max b
Water Transfer	C	Water is pumped in from another catchment.	Transfer b
Indirect reuse	C	WW is discharged to be abstracted downstream.	Indirect reuse b
Desalination	C	Salt is removed from brackish water or seawater.	Desalination b
WW pumping	C	After use, WW is pumped to treatment	WW Pumping b
Thames Tideway Tunnel	C	A tunnel to capture waste- and stormwater overflowing from sewers and get it to treatment.	TT Tunnel c
Chemical Dosing	C	Fertilizers are removed from WW by adding chemicals to make them coagulate and settle. p.e. is person equivalent a capacity indicator based on mean WW per person.	Chemical (2k p.e.) d
Chemical Dosing	C		Chemical (100k p.e.) d
Granular Activated Carbon	C	WW passes through the pores in activated carbon where many different pollutants will be caught.	Granular Activated Carbon d
Biological Nutrient Removal	C	The use of bacterial action to remove nutrients from WW (e.g. Trickling filter, activated sludge)	BNR d
Trickling Filter	C	WW is sprayed over a filter which on biological treatment removing organic matter.	Trickling Filter d
Activated Sludge	C	Sludge is added to WW to encourage bacterial breakdown of nutrients.	Activated Sludge d
Membrane Bioreactor (MBR)	C	A membrane is used as part of activated sludge treatment to filter the effluent within the same tank where biological treatment is taking place.	MBR d
Small MBR for greywater reuse	D		GW sMBR a

Large membrane bioreactor greywater reuse	D		GW lMBR a
Reverse Osmosis	C	Requires membrane treatment first, then, pressurized water passes through a membrane allowing only water through. ‘p.e.’ as used in the figure code here means ‘person equivalent’ – a capacity indicator.	ROsmosis (2k p.e.) d
Reverse Osmosis	C		ROsmosis (100k p.e.) d
Sand Filter	C	Sand is slow but effective for most non-dissolved pollutants and is used widely for drinking water.	Sand Filters d
Header tank rainwater harvesting	D	Rainwater is collected and stored locally. A header tank keeps some of the water above appliances so these can be gravity fed.	RW header tank a
Direct feed rainwater harvesting	D	Rainwater is collected and but without a header tank the water must be pumped to appliances.	RW direct feed a
Ultraviolet oxidation	C	WW is exposed to ultraviolet rays to eliminate bacteria and viruses. Only applied after previous stages of treatment.	UV d
Advanced oxidation	C	Hydrogen peroxide or ozone is applied to eliminate bacteria and viruses. Only applied after previous stages of treatment.	Advanced Oxidation d
Constructed horizontal wetlands (SUDS)	D	Wetlands are used as SUDS. WW moves horizontally through the wetland, undergoing biological treatment and oxidation.	hWetland e
Constructed vertical wetlands (SUDS)	D	Wetlands are used as SUDS. WW moves vertically through the wetland, undergoing biological treatment and oxidation.	vWetland e
Reed beds (SUDS)	D	Wetlands where WW is aerated by the roots of reeds allowing bacteria to remove organic waste.	Reed beds d
Small scale biological greywater reuse	D	Greywater is treated a medium conducive to aeration and bacterial treatment or organic waste.	GW sBio a
Large multi media greywater reuse	D	Wastewater is processed through multiple stages and returned to use locally.	GW lMM a
Short retention greywater reuse	D	Wastewater from a shower is stored and minimally treated then being used to flush a WC.	GW 1WC a
Short retention greywater reuse	D	As before, a second WC immediately below is assumed.	GW 2WC a

A simplified way to approach the issue of comparing different centralized and distributed technologies is to consider their carbon footprint, expressed in terms of kilograms carbon dioxide equivalent per cubic meter of treated water ($kgCO_2e / m^3$). Two reasons for this are that firstly, as shown in Table 4-4, the EA has conducted a series of reports on the carbon intensity of different interventions which have served to inform policy. As noted by several interviewees in chapter 5, this data drove institutional perception of the effect of different technologies on the underlying environmental system.

Table 4-4: List of references for carbon footprint of water technologies

Fig. 4.7 code	**Reference**	**Comment**
a	EA [*Parkes et al.*, 2010]	Carbon intensity of greywater recycling and rainwater harvesting.
b	EA [*Reffold et al.*, 2008]	Carbon intensity of water supply and demand
c	[*Thames Water*, 2013]	Calculated from project's projected total carbon divided by projected prevented sewer overflows.
d	EA [*Georges et al.*, 2009]	Evidence review of carbon footprints for treatment technologies.
e	[*Fuchs et al.*, 2011]	LCA of constructed wetlands

Secondly, the carbon footprint provides a helpful metric for comparison across a range of technologies. While centralized technologies tend to have higher energy intensity, distributed systems tend to have their own emissions which do not necessarily derive from electricity consumption but from storage tanks' embedded emissions or the release of greenhouse gasses from natural processes of digestion in a constructed wetland SuDS system for example.

A final note on comparing carbon intensities of these technologies by carbon intensity of treated water is that these values will depend on the parameter being treated for and the stringency of parameter performance required.

Figure 4-7 shows carbon intensity of the technologies presented in Table 4-3, separating out water supply and wastewater technologies. The figure uses a series of abbreviated codes labelling the different technologies for which the reader is referred back to Table 4-4.

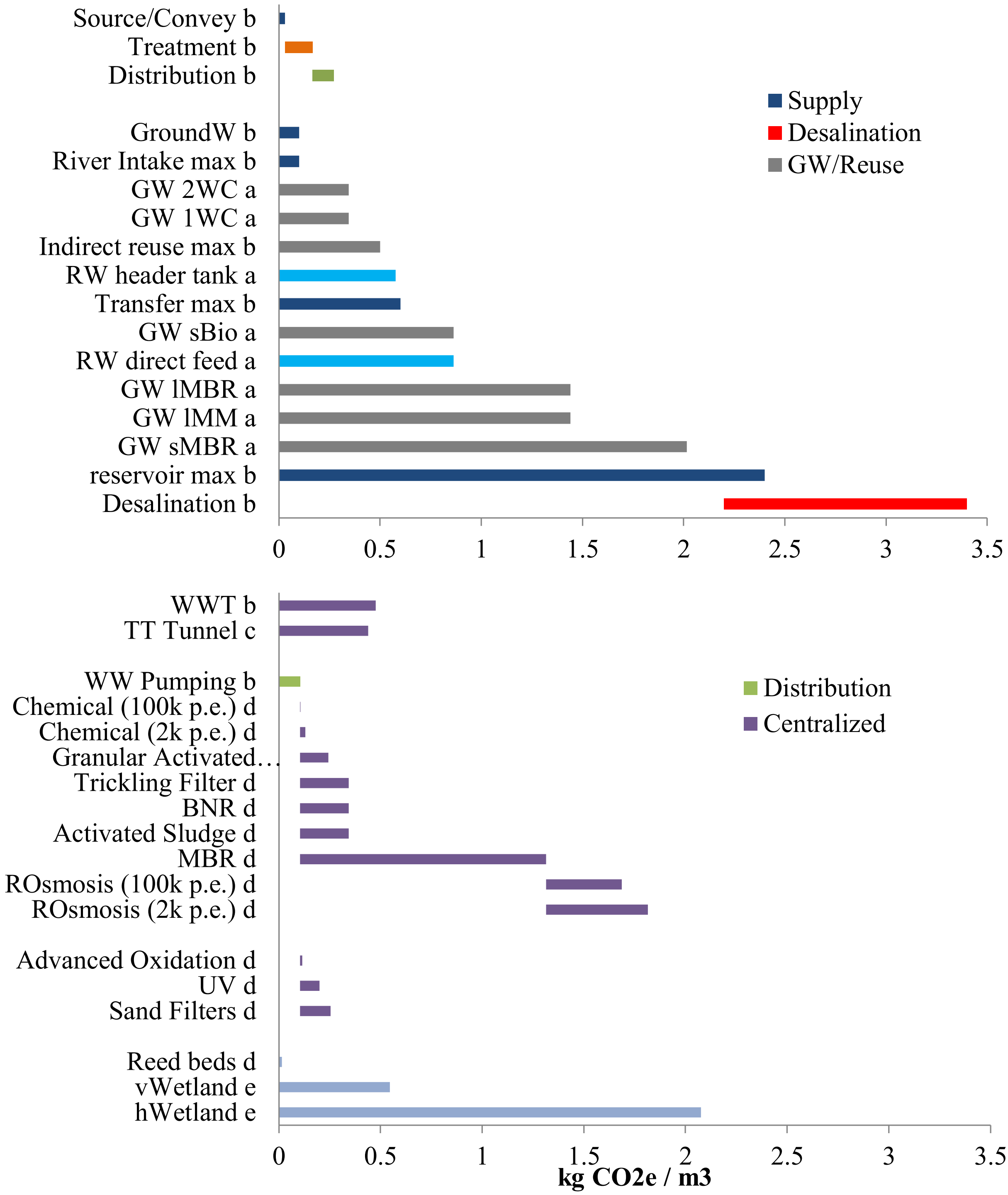


Figure 4-6: Water Supply Technologies (top) Wastewater technology options (bottom) and by their carbon footprint.

Average carbon intensities of the existing water supply and wastewater treatment systems are given at the top of their respective figure segment. In the case of water supply (top segment), there is a cumulative effect as the carbon footprint of sourcing cumulates for treatment and distribution. Below are then presented alternative supply options. Those coloured in dark blue are those considered part of a traditional centralized supply system, while those in grey show greywater recycling options. Note that for the blue supply options and desalination the value range is given. For most of the supply options, the values range from new 0. They are sorted by the maximal end of the range.

In both figures the values separated at the top indicate estimates of the current mean carbon footprint in wastewater treatment or water supply. The letter at the end of each technology label indicates the source of the data as can be referred to in Table 4-4. Where technologies depend on a previous process step, this is shown by a gap of equivalent size. (Note the values for desalination reflect a range rather than such a dependence. Note also that the values for supply options coded 'max' range from near 0 to their maximal values as indicated.)

In the case of wastewater (bottom segment), the average carbon intensity of the wastewater system is again shown at the top. The projected carbon intensity of the Thames Tideway tunnel (currently under construction) is also provided. This value for the tunnel is calculated from the project's projected total carbon divided by projected prevented sewer overflows. Below is then given the mean carbon intensity of wastewater pumping with all subsequent centralized technologies requiring this initial value in order for the wastewater stream to be delivered to the treatment site then providing carbon intensity in excess of this initial carbon footprint of pumping. For the case where wastewater is delivered through the Tideway tunnel, this initial value will be higher.

Values for disinfection, (advanced oxidation and UV), and sand filters are separated out because this treatment stage is not always required. Values for SuDS are provided at the base of the lower figure. The EA value for the reed bed variety of SuDS is very low and so was compared with an academic publication [*Fuchs et al.*, 2011] which showed much higher carbon intensity even for both vertical and horizontal varieties of constructed wetlands.

These values show that distributed systems do not necessarily outperform or underperform centralized systems on carbon intensity. A regulatory decision maker seeking to reduce the carbon intensity of the water sector would then have to make decisions based on which technologies are available for which given circumstance. In particular, for the different supply options ranges were provided. When looking for new sources, groundwater and surface water may be restricted. If this is the case, then the next option to consider are small scale greywater systems and indirect reuse. However this depends on the relative carbon intensity of alternatives like the transfer or reservoir options depending on where across these ranges they perform. Similarly, for wastewater technologies, if constructed wetlands in combination with a biological treatment technology are able to successfully reduce wastewater stream parameters to compliance levels, such a technological mix would be advantageous as compared to membrane systems in terms of carbon intensity.

This approach of comparing different water technologies by their carbon intensity provided a rough insight into water technology appraisal. Under the SoS approach discussed in Chapter 2, these can be considered as performances along multiple criteria. Carbon intensity per volume of treated water was considered here as a simplified metric of comparison. It showed that even for this one indicator, no single technology will prove the best for all conditions. Even for a general class of technologies, such as centralized technologies it is not the case that these will always outperform distributed technologies or a combination of the two. These should be explored in parallel in option discovery. Unfortunately this is not always the case as capex bias and other regulatory effects on technology selection identified lead to a historical underdevelopment of distributed interventions.

4.4 The Case of the Thames Tideway Tunnel

The case of combined sewer overflows in London is a case in point highlighting the tension between centralized and distributed interventions for wastewater management.

The UK was prosecuted by the EU Commission for non-compliance with the Urban Wastewater Treatment Directive due to the releases of wastewater from London's sewerage network into the Thames. This is a design feature of the sewers which combine wastewater with rainwater runoff, allowing them not to backup and flood properties in the city. As the city has grown however, more rainwater is collected into the sewers during rainfall, leading to more frequent overflows [*Thames Tideway Steering Group*, 2005].

In response, a massive project has been in the planning since 2005, and in 2007 the tunnel option was endorsed by the government [*NAO*, 2017]. Planning application was submitted in 2013 and government approval to this was given in 2014 [*Rankin*, 2014]. Attendant to this process was a series of criticisms that similar results could be obtained "cheaper and greener" using distributed interventions like Blue Green Infrastructure as part of a package of measures including a smaller tunnel [*Byatt*, 2013].

The project was headed by an independent chairman, Professor Chis Binnie, who initially supported the process and the conclusion that a tunnel would have to be dug under the Thames, connected with the existing sewerage in order to catch the would-be overflows and deliver them to Beckton Sewage Treatment Works wherefrom these flows could be released into the environment again [*Thames Tideway Steering Group*, 2005]. By 2013, Binnie himself was opposed to the scheme, calling it a waste of money, (cost estimates had risen from £1.7bn to £4.2bn), in light of the developments in distributed and ancillary technologies [*Griffiths*, 2014; *Berkeley et al.*, 2016].

Binnie issued a further notes on the topic (as published on the website bluegreenuk.com) giving more detail on his change of position citing that spills were lower than at the time of the ECJ case and that dissolved oxygen and hence the ecology for fish would now be in line with the aims of the original project (largely due to the newly completed Lee Tunnel and upgrades to treatment works at Mogden) [*Binnie*, 2015].

An independent report commissioned by Ofwat in 2005 found that under slightly altered objectives an alternative solution would be cheaper and deliver the most of the same benefits [*Honeyman*, 2006]. This was however rejected with alternatives to the tunnel deemed unviable to meet stated objectives [*BNEF*, 2013; *Berkeley et al.*, 2016]. In 2011, Defra reviewed strategic and economic considerations again, finding the £4.2bn project to deliver benefits of £3bn - £5.1bn, concluding that this was a net benefit and alternatives were unviable [*Defra*, 2011]. These estimates were updated in 2015 to take into account the increased cost estimates and found that the benefits had also increased (from in 2011 to £7.4bn - £12.7bn in 2015) [*Defra*, 2015a]. These changes were driven by higher population growth estimates and a revised approach to determining willingness to pay for environmental improvements. At each of these Defra also highlighted that further delay risked ECJ penalties of potentially £100m [*Defra*, 2011, 2015a].

In a House of Lords, Natural Capital Committee debate in 2013, the choice of the tunnel was criticised by Lord Berkeley (drawing on Binnie's reports) but both Labour and Conservative peers spoke in support of the project [*Berkeley and De Mauley*, 2013]. In particular, a Defra official argued that alternative projects had been considered and none were found viable. Regarding SUDS, "Unlike London, Philadelphia and Portland have a geology which is suitable for SUDS. The soils underlying the cities' SUDS areas are more porous and more able to soak up excess rainwater." [*Berkeley and De Mauley*, 2013]. Several days prior to this debate Bloomberg New Energy Finance published a white paper with the British Geological

Survey indicating that in fact only 33% of London was impermeable allowing abundant opportunity for SUDS as part of a portfolio of measures [*BNEF*, 2013].

A subsequent review by the National Audit Office found that prior to the 2007 government endorsement, 'considerable time' was taken to explore options while after that analysis was less detailed and scrutinized. It also found that improved modelling could have led to a smaller cheaper solution although the tunnel would still have been the strategic approach "given assessments that alternatives would either fail to meet all key objectives or do so at significantly higher cost." [*NAO*, 2017]

In his 2013 critique, Byatt (the first Ofwat chairman), mentioned that Thames Water has "damaged itself by paying very large dividends", saying this was partly responsible for why it needed government support. These dividends had come at the expense of sewerage maintenance which was contributing to the issue of overflows and hence "It would be perverse to reward Thames with a major increase to RCV as a consequence of the decision to improve profitability by neglecting maintenance of the sewerage network" [*Byatt*, 2013]. Byatt hereby highlights how under the RCV system, the centralized tunnel option is preferable for Thames Water over smaller scale interventions which would entail a greater operational expenditure without an accompanying increase in RCV.

In order to ameliorate bill rises two important steps were taken. Firstly, Defra and the Treasury provided a Government Support Package de-risking the project substantially [*Secretary of State for Environment Food and Rural Affairs et al.*, 2015]. This support insulates the risks from changes in the capital markets, substantial cost overruns, and large scale engineering failure and helped to make the financing of the project feasible (which it would not have been had it have been Thames Water that financed it).

Secondly, and more importantly for the purposes of understanding the role of the regulator in this project, Ofwat developed a novel financing method to support the delivery of this project and reduce costs on customers through the use of 'direct procurement'. Traditionally, such capital expenditure would be financed via water company borrowing and increased RCV leading to increased prices. However, under direct procurement, financing of the project was put out to for a competitive process to determine the cost of capital. Ofwat claimed to have achieved a substantial reduction in financing costs through direct procurement claiming a reduction in the impact on average water bills from £70-£80 to £20-£25 [*Ofwat*, 2015a].

The case of the Tideway Tunnel is indicative of the tension between centralized and distributed water technologies and how this is mediated by the institutional context. EU legislation exerted pressure on the government for a solution to be implemented while the governmental and regulatory system developed to accommodate the project as it progressed. Given the success of direct procurement in this case, Ofwat exploring how far and in what shape direct procurement could take in future applications in order to reduce costs to customers [*Bush and Earwaker*, 2017; *KPMG*, 2017; *Ledger et al.*, 2017]. If direct procurement proves a generalizable model, it will further reduce the costs of particularly large capital projects.

As a means of review and summary it is worth considering the argument that the tunnel was chosen due to its cost performance and that this is sufficient to warrant it as the appropriate solution. If the tunnel is the cheapest option for delivering the required environmental outcomes then it is surely the best option. In response to this line of argument three points should be noted.

First, that the tunnel may not be the cheapest option. This was the crux of the argument presented by Charles Binnie. Additionally, had there been a GSP and direct procurement process for alternative options these could potentially further have skewed the relative performance of the alternative options.

Second, the relative costs of the options themselves are subject to change over time. Three elements in this story point to the dynamic nature of costs. Firstly, Binnie's 2013 review pointed out that while the tunnel option was becoming more expensive, options involving distributed interventions were becoming cheaper as the result of cost learning in other cities employing distributed interventions. Finally the GSP and direct procurement led to substantial reductions to the costs of the tunnel option. This is part of the difficulty involved in the assessment and decision making around large projects where circumstances change over time. These changes are hard to model precisely as they typically involve unexpected changes which could not easily be predicted. However the transitions literature highlights these types of cost learning as core drivers of technology selection and change.

Third, auxiliary benefits of alternative options appear as externalities to the question of environmental outcomes and their inclusion in the decision making process is difficult and can skew the process. The process needed a clearly defined question which focussed on how to manage the issue of stormwater overflows and Thames river pollution. However, had the question been framed in a broader way to consider auxiliary benefits a different result may have ensued. SUDS and other interventions yield co-benefits to the urban environment which, if included in a monetary assessment, could improve the relative performance of these technologies. The fact these are not included clearly disadvantages these options. The fact that surveys were conducted including willingness to pay assessments for the tunnel option indicates that externalities such as people's preferences for a clean environment were included for the tunnel shows how this can be done. This was not done for the other options, potentially skewing the decision making and options evaluation process.

Ultimately, it is not the place of this relatively brief review to decide on which option is the best for the issue of London's stormwater overflows and wastewater management. Rather it is to highlight the interdependent and dynamic nature of technology selection and performance as mediated through the institutional context.

4.5 Conclusions

This chapter has developed a CIGA characterization of the focal action arena of economic regulation. HOCs identified were those of EU environmental law and the laws establishing the mandate of the economic and other regulators. In characterizing the environmental system, data was reviewed on sector and activity responsible for WFD below moderate classification status for bodies of water, water abstraction by sector, and measures for environmental improvement. It was shown that the water sector plays an important role as both a source of problems and solutions for the water environment.

For the purposes of a CIGA characterization, Ofwat's mandate is understood here to drive the regulator's preferences. Ofwat's system of regulation in turn shapes the preferences of the water companies. This was shown through the discussion of the Capex bias. Overall the regulatory system, through the PR system, the promotion of competition, and the effect this has in shaping company preferences ultimately has important implications for technological change in the water sector.

Taking account of the issue of Capex bias in particular, in combination with literature on water transitions reviewed in Chapter 2, a tension between centralized and distributed technologies is identified. These technologies form the basis of technological options facing the water companies and ultimately the regulatory authorities. As discussed in Chapter 2, comparing different water technologies is inherently fraught with complexity due to their multiple parameter impacts and multiple assessment criteria. In reviewing the carbon intensity of these technologies, as an indicative metric of commensuration, it was shown that these centralized technologies do not consistently outperform distributed systems. The capex bias introduced by regulatory incentives is then unhelpful for effective technology selection in the water sector.

The case of the Thames Tideway Tunnel reflects how the HOCs (in the form of EU legislation) in combination with the landscape pressures from the material base (combined sewage overflows leading to UWWTD non-compliance) drove an investment requirement. Government (through the government support package) and Ofwat (through the development of direct procurement) worked to enable the adoption of the tunnel solution, despite being challenged by multiple relevant commentators who showed that a different plan, involving more distributed systems, had in the meantime become a better alternative.

Chapter 5: Interviews on Regulation, Innovation, and Decision Making

Key Points

- 724 key claims were extracted from 17 in-depth interviews with stakeholders with the aim of contextualization and validation.
- Support was found for positive externalities, a key role for foresight, and the Theory of Price-Investment Cycles.
- 7 mechanisms by which regulation affects innovation were identified.
- 5 key mechanisms for managing trust which have a detrimental effect on innovation were identified.
- Support was found for Nash decision making albeit with strong evidence for risk aversion, deliberation, and (for regulators) disimprovements.

In order to give broader context and external validation to the research conducted in this thesis, interviews were conducted with stakeholders participating in UK water sector. This chapter reports on the process, results and findings from the 17 in-depth interviews which were conducted over the month of July 2017 and January 2018.

This chapter is structured as follows. First, the aims and objectives of this thesis are related to aims and objectives of this interview process. Every objective is defined in terms of 'characterization' on the basis of respondents' views and not a definitively correct characterization, as stakeholders may hold incorrect beliefs. These are important as the perceptions and beliefs of stakeholders drive their behaviour regardless of the degree to which these are correct.

Second, the methodology for the interviews is presented regarding style, structure, targeting respondents, and transcript coding. Third, results from interviews are presented in three parts: top agreements, top disagreements, and thematic summaries. Fourth, data from the supplementary survey and results from some simple statistical tests on these are presented. Finally, findings are identified and related again to the research aims and objectives. The conclusions present a review of the most pertinent of these findings and relate these to the other chapters.

5.1 Aims and Objectives of Interviews

There were two key aims of conducting the interviews for this research:

Aim 1: Provide context and validation of the models analysed.

While it is important to conduct analysis of specific models to evaluate specific incentives under differing regulatory arrangements, these will inevitably be simplifications of the variety and complexity of different interactions taking place. Interviews provide first-hand accounts of stakeholders' perceptions of the action arena's they participate in to validate the models employed, put them in a broader context and provide a more granular level of detail highlighting limitations where these exist.

Aim 2: Characterize and validate tools employed

Chapter 7 evaluates different tools under the prescriptive branch of CIGA outputs. Interviews reported on here are descriptive of decision making employed by stakeholders contributing to the predictive branch of CIGA outputs.

Objectives Derived from Aims

From these aims the following specific objectives are derived which directly feed into research design for the interview process and the subsequent structure for presentation of results and findings.

The objectives for meeting Aim 1 are:

- *A1O2: Characterize the key stakeholders.*
- *A1O2: Characterize the key action arenas in water sector innovation.*
- *A1O3: Characterize the role regulation plays in innovation.*

The objectives for meeting Aim 2 are:

- *A2O1: Characterize how actors or stakeholders make decisions in action arenas characterized in A1O2.*
- *A2O2: Characterize stakeholder decision makings within the morphology of decision-making methods developed in Part 1 of the Thesis.*

5.2 Interview Research Method

The methodology for the interview process is based in the CIGA. This section outlines and justifies the style used for the interviews (passive, semi-structured), the questions asked, procedure for getting respondents and the results compilation and analysis method. Among other consultations, [*Bryman*, 2016] was used to inform interview design and conduct generally.

Collaboration and Originality

The interviews were conducted by myself as part of this research and with Elzavira Effendi as part of her MSc research [*Effendi*, 2017]. In the interests of clarity around responsibilities authorship it should be noted how our work relates and how authorship is divided. Effendi's research focusses specifically on water reuse technologies and as such her questions were specifically targeting this area and came first in the course of the interview. These in part replicated questions used in [*Thomas and Ford*, 2006] as noted in [*Effendi*, 2017]. Subsequently came my interview questions as developed from the CIGA. We each asked our own questions. With Effendi's permission responses to both sets of interview questions were used here. The responses to her questions also yield interesting inputs for the research here as water reuse technologies are among the decentralized water technologies. They constitute a small share of the key claims extracted from the interviews. The subsequent method of analysis and conclusions have no further interaction with Effendi's work.

Passive Semi-Structured Interview Style

The interview style was semi-structured in order to ensure consistency of questions across interviews but also to allow for follow up questions of clarification and further detail. The interviews were conducted in a passive style, seeking not to influence or lead the respondent in any way but to try to elicit their views.

For example, the interviewer may be very interested in a particular instrument of economic regulation but would not highlight this to the interviewer. The aim here was to note what phenomena came to the respondents minds in response to the question in order to see what they saw as important and relevant and not what the interviewer found important or relevant. Accordingly the interviewer would only prompt the respondent on topics they had already brought up and would only pursue follow up questions for clarification and additional detail on topics they already mentioned as opposed to introducing new ones.

Procedure for Reaching Interviewees

Across water companies, suppliers, regulators and other organizations involved in the water sector 61 invitations were sent out during the months of June 2017. The invitation letter and the supporting information sheet sent to them can be found in APPENDIX I and II. These were sent to contact details provided on the organizations websites. 2 interviews were arranged through personal contacts.

Anonymity

Interviewees were guaranteed anonymity for their responses. The aim of this was to allow them to speak freely without concern for whether their response could be traced back to them with possible repercussions to them for disclosing views their employer would not approve of. For this reason transcripts are not included in this thesis and claims.

Question and Interview Structure

Appendix III provides the question sheet that was sent to the respondents and used during the interview. There were three sections of the interview which was followed up with a supplementary survey.

First, questions focussed on water reuse technologies [*Thomas and Ford*, 2006; *Effendi*, 2017]. The second set of questions aimed to contribute to objectives for Aim 1 and asked about relationships between prices, environmental outcomes, technological innovations, and regulation. These were largely open ended questions.

The final set of questions asked respondents to identify two key stakeholders (encouraging themselves or their organization to be the primary stakeholder) and asked questions to characterize the information base of the stakeholders and their decision making in line with the CIGA.

Subsequent to the interview, respondents were sent an online supplementary survey. The aim of the supplementary survey was to separate the open ended questions from the questions with structured answers. Questions were asked on decision maker foresight and discounting (see Appendix V) as well as relating to the CIGA tool morphology developed in Chapter 3.

Interview Transcriptions Coding

There were two data sources for the compiling results. Transcriptions of the interviews and data from the supplementary survey. To maintain anonymity full transcripts have not been appended and quantitative results were anonymised.

Transcribed text was coded for ‘key claims’. When the interviewee made a statement regarding an area relevant to a research objective, this was highlighted and added to a list of ‘key claims’ along with a respondent label. For example, if the respondent was 14th on the list of respondents and was currently employed with a supplier then the label appended to their key claim would be *14s*.

It was then possible to identify key claims made by multiple respondents. A problem in the reliability of this method of is the interpretation of which key claims are in fact similar enough. Conversely, which claims are different enough to merit a separate key claim? In doing so the statements had to be evaluated and judgments made as to the degree of similarity. Judgments on this issue usually sought to err on the side of more different claims leading to 724 unique claims. The raw list is not included in this thesis.

5.3 Overview of Respondents

Table 5-1 shows the number of interviewees for each stakeholder category:

Table 5-1: Interview Respondents by stakeholder category

Total	**17**
Regulator	5
WC	7
Supplier	5

Under regulator are defined any respondents who identified as working in one of the following organisations: Government, Civil Service, Defra, Natural England, Ofwat, DWI, Environment Agency, or CCWater. Under water company (WC) are considered any respondents who identified as working in one of the water and wastewater companies or water only companies serving consumers in the UK. Under supplier are considered any respondents who identified as working for a company supplying water technologies including water storage, treatment, system design, or consultation services.

Table 5-2 shows the frequency distribution of the length of work experience respondents have in the water sector.

Table 5-2: Frequency distribution of respondents by years of water sector experience

Range of Years of Experience	Number of Respondents
0-2	1
2-5	0
6-10	2
11-20	4
>20	10

Broadly, the sample set has a bias towards those with a long work experience in the water sector. While this allows the results to draw on a wealth of experience it may create a bias towards traditional or established perceptions without including those of participants new to the action arenas in question.

5.4 Results from Qualitative Analysis of Key Claims

In reviewing the results of the interviews the following three stages are used: 1) Top agreements, 2) Top Disagreements, 3) Summary of the key claims for each of thematic category. Note key claims regarding decision making (which relate to Aim 2) are reviewed in the subsequent section.

Below are given the top agreements, top disagreements and thematic summaries. The top agreements claims are those with 6, 7, or 8 respondents making the same claim. These claims are commented on briefly. Subsequently, the top disagreements are given also. These are claims for which contradictory claims were also made. Each of these disagreements is also reviewed briefly.

Key Claims with Highest Agreement

Prices and Assets (8 Agreements)

- Prices are driven by costs of required investment in assets. (16s, 15s, 14wc, 12r, 7r, 3r, 2wc, 1r)

This claim is the one with the most support. It reflects a core element of how WC prices are determined through the AMPs. It is worth noting 3 points around this. 1) The respondents on the whole seem to clearly aware that water (like other utilities) is a capital intensive sector. 2) The function of the regulatory system is to deliver required investment under a controlled price and this is the core relationship driving decision-making in the sector. This relationship has been modelled further in developing and exploring the Theory of Price-Investment Cycles. 3) While the focus on assets in economic regulation is a reasonable conclusion from the capital intensity of the sector, decision-maker focus on capital assets leads to underdevelopment and weak incentivizes for the adoption of distributed systems.

WRT Drivers and Barriers (7 and 6 Agreements)

- Dual reticulation creates risk of misconnection and health risks which deter adoption (13wc, 12r, 8wc, 7r, 3r, 2wc, 17a)

- Rainwater and recycling systems are being considered by WCs in stressed areas. (15s, 13wc, 10r, 8wc, 6wc, 3r, 5wc)

These two key claims offer insight into issues for distributed systems. The first highlighting a perceived barrier to adoption (health risks) and the second highlighting both a driver as well as a differentiating factor in the adoption of distributed systems (water stress).

- WRT R&D is important (14wc, 12r, 8wc, 3r, 2wc, 5wc)
- WR Awareness raising is important (14wc, 12r, 10r, 2wc, 9s, 5wc)

Two further key claims at this level of agreement indicate that research and development as well as awareness raising with the public and other stakeholders are important for water reuse. This indicates that the role of information, both technical as well as at layman level is considered important by the respondents.

Policy and Regulation (6 Agreements)

- Regulation is not a driver of reuse. (16s, 15s, 12r, 10r, 4s, 5wc)
- National policy must be sensitive to local water conditions. (15s, 14wc, 10r, 8wc, 7r, 5wc)

These two claims regarding policy and regulation offer a relatively good summary of the role of regulation in distributed systems. Regulation is not a driver of reuse (NB: this is an area of some disagreement) and it is not a driver because policy making is careful not to institute rules which are not sensitive to local conditions. Policy makers choose instruments that can be sensitive to promoting reuse where applicable and not forcing it where local water conditions do not mandate it.

Top Disagreements

Excluding claims around decision making, two key areas of disagreement were highlighted: that of the role of regulation in innovation and WRTs and the effect of Brexit on environmental standards. Tables 5-3 – 5-5 below show the key claims made and the number of interviewees agreeing with each.

The role of regulation in Innovation and WRT

Table 5-3: Disagreement over the Role of Regulation in Innovation and Technological Change

Key Claim	Number of Agreements
Price controls encourage new technology (312)	3
PRs do not encourage new technology (313)	4
Current regulatory systems promotes incremental efficiency gains rather than radical step change (201)	1
There is nothing in current legislation that inhibits innovation (200)	1

Table 5-4: Disagreement over the Role of Regulation in WRT adoption

Key Claim	Number of Agreements
Regulation is not a driver of reuse (256)	6
Regulation and legislation does not prevent adoption of WRT (257)	3
Regulation is a barrier to WRT (258)	1

Brexit and Environmental Requirements

Table 5-5: Disagreement over the Effect of Brexit on Environmental Requirements

Key Claim	Number of Agreements
Expect environmental standards not to deteriorate (219)	1
Regulators are signalling there will be no changes (217)	2
UK will continue to draw environmental standards from international standards (218, 225)	2
Changes after Brexit are uncertain (215)	5
Expect lower standards post Brexit (216)	2

Claims by Thematic Categories

Appendix IV reports the raw list of key claims extracted from interview transcripts. These were regrouped into the following themes:

List of Thematic Categories for Respondents' Key Claims

- The Innovation System and Innovation Dynamics
- Procurement and Specifications
- General Claims about Distributed Systems
- Water Reuse Technologies
- Other Areas of Technology and Practice Innovation
- Regulatory, Legislative, and Governance Relation To Innovation
- Drinking Water Quality Regulation
- Economic Regulation
- Existing Instruments of Economic Regulation
- Recent Reforms to Instruments of Economic Regulation
- Competition Reforms
- Environmental Regulation
- Drivers of Water Price
- General Claims about Collaboration
- General Claims about Information Flows
- Characterizing Stakeholder Decision Making and Information Bases

In order to provide a coherent overview of responses, a brief summary is provided for each thematic area is provided in Appendix IV. Statements for the last theme are reviewed in section 5.5.

5.5 Results for Decision Making Characterization

This section reports on results from the supplementary survey and interviews regarding characterization of decision making, as related to objectives A2O1 and A2O2. First a quantitative view is taken of the responses to the supplementary survey. Subsequently, narrative summaries are provided for key claims related to decision making as raised during the interviews. These are reviewed alongside quantitative results from the supplementary survey.

It must be noted that the responses to the supplementary survey were relatively poor. 6 of 17 respondents did not provide any responses to questions regarding decision-making of stakeholders. In particular, responses for the questions about time horizons and discount rate were very limited. The data that were collected for these are presented in Appendix V but are not reviewed in any more detail here.

Overview Supplementary Survey Statements on CIGA Tool Morphology

In the supplementary survey respondents were presented with statements regarding decision-making and asked to provide responses on a Likert scale asking how accurately this statement represents the decision making of a stakeholder: always, most of the time, about half the time, sometimes, and never. These statements were formulated to test for CIGA toolss. The statements in the order they were presented are shown in Table 5-6 with an accompanying code, and the associated tool.

Taking responses to these statements together it is possible to evaluate which decision making methods reflect decision making of stakeholder categories. Responses from the Likert scale (always to never) were quantified with a value of 1, 0.75, 0.5, 0.25, or 0. The sum of quantified responses was averaged over the number of responses to give the mean quantified response. Note that respondents who did not submit any responses to this part of the survey are excluded from this analysis. Respondents who indicated 'don't know' are still included but do not feature in calculating the average response. Instead, these responses contribute to a confidence value that is given by the share of respondents indicating 'don't know' over the 10 respondents who responded to this part of the survey.

Table 5-6: Statements given in supplementary survey as associated with abbreviated label and decision making method

Statement	Code	Associated DMM
This stakeholder acts on the basis of a monetary cost-benefit analysis.	CBA	Quantification
This stakeholder acts on the basis of a deliberative process considering qualitative arguments for and against different courses of action.	Deliberate	Deliberative Model
This stakeholder takes actions best for themselves and their self-interest.	Selfish	Self-interested DM
This stakeholder takes actions they see as "good enough".	Satisfice	Bounded rationality
This stakeholder acts on the basis of a rule regardless of circumstance or outcome.	Rule	Resolve, Organizational Processes
This stakeholder considers how others are likely to respond to their actions.	Response	Nash, GMCR
If punishment is costless, this stakeholder is prepared to punish inappropriate behaviour of others.	Punish	Sequential Rationality
This stakeholder is prepared to punish inappropriate behaviour even when this is costly.	Punish+	GMR, SMR
This stakeholder avoids taking risks even if potential rewards are high.	RiskAverse	Loss and Risk aversion
This stakeholder acts on an altruistic concern that the preferences of others are satisfied.	Altruist	Social Preferences
This stakeholder is driven by emotions.	Emotion	Emotion
This stakeholder is driven by cultural norms.	Culture	Culture
This stakeholder is driven by party political ideology.	Ideology	Ideology

Conclusion on Statistical Tests for Primary-Secondary Stakeholder Difference

This data was tested for whether the difference between primary and secondary drove stakeholder responses. This analysis is given in Appendix V: the statistical addendum to this chapter. Differences in means between primary and secondary reject the claim that primary-secondary distinction drove differences in means. Regarding distribution of differences, it is unlikely that the perceptions stakeholders have of primary and secondary stakeholders' decision making are randomly distributed. Although the data should be considered with caution as the sample set was very small and Pratt's tests did not reject null hypotheses for all statements. Use of supplementary survey data should proceed in the knowledge that these results are not well characterized by a random distribution and hence bear information about stakeholder decision-making perceptions.

The tests show that these aims can be met and that the review of the data can proceed to make inferences about respondents' perceptions of stakeholder decision-making. These are reviewed on the basis of the sample set as a whole (to draw conclusions for modelling homogenous decision-making styles) and then for regulators and WCs specifically. At that stage key claims regarding decision making are considered alongside supplementary survey responses with the aim of characterizing decision making in line with Aim 2.

Decision Making Statements: All Stakeholders

First a base-line analysis is conducted of all the responses taken together. While this does not give insight into a particular stakeholder group it may help to identify trends in the data and lend support to the characterization of appropriate tool given an assumption of homogeneous decision making characterizations. Raw data can be found in Annex V.

Figure 5-1 shows responses for statements on decision making for all stakeholder categories. The figure shows quantified Likert scale responses against the standard deviation of responses for each statement. Note that the standard deviation reflects both disagreement between respondents as well as de facto heterogeneity in decision making characteristics among WCs. As such the standard deviation is an indicator of confidence in the value.

It is worth briefly reflecting on the implications of these results for the potential applicability of different decision making models. Nash: there is relatively low standard deviation around high accuracy for claims relating to the Nash model of decision making; namely, CBA, Response, Selfish. While was only 5th highest in terms of the mean quantified survey response, Altruist, showed the third lowest mean quantified response and second lowest standards deviation indicating support for Nash style decision-making. Deliberative: The results give relatively strong support to the deliberative model of decision making based. It is second highest in terms of mean survey response and has the third lowest standard deviation. GMR, SMR and Sequential Rationality: Willingness to punish when costless which relates to the model of GMR/SMR showed relatively strong support. Alternative influences on decision making, such as altruism, culture, emotion, and ideology were generally considered inaccurate characterizations of decision making.

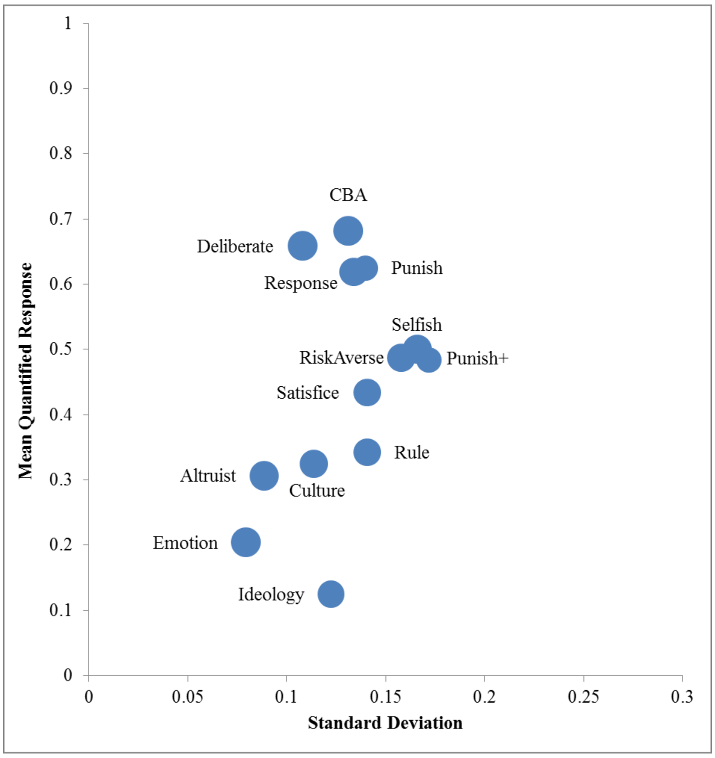


Figure 5-1: Supplementary survey responses on decision making for all stakeholders by mean quantified response on Likert scale and standard deviation for each statement

Results for Water Company Decision-making Key Claims and Supplementary Survey

Hence, on the basis of interview responses, WCs' information base can be characterized as:

- Good information on own costs (638, 639, 640) but lack granularity on assets (642, 643, 644).
- Good information on regulatory requirements (647, 648)
- Poor information on customers (653, 654, 651, 659) and supply chain (661).

There were 10 survey respondents who indicated WC as ether primary or secondary stakeholder. Figure 5-2 shows mean response against standard deviation for these.

As compared with homogeneous decision making, WC decision making is more clearly driven by Nash style characteristics (CBA, Response) with Selfish featuring a higher mean and being more clearly separated from other characterization dimensions. WC decision making is poorly characterized as involving Ideology, Culture, Emotion. Deliberate, has strong support.

The key question is whether WC are free to make decisions or whether their decision making is largely driven by regulation. 4 respondents indicated that WCs essentially do what Ofwat tells them to, while 3 indicated that WC are free to make their own decisions. One particular issue noted was that WC time horizons are based around 5 year AMPs (601) and that technologies with returns beyond these are less favoured (611, 612). Regarding the issue of risk aversion, 4 respondents agreed that regulation drives risk aversion in the water industry (544, 545). Regulators are not alone in this effect as interviewees noted that investors, in affecting management and WC direction, can also change the risk attitude of WCs (623, 624). In interviews, 7 interviewees agreed WCs are risk averse and 6 agreed WCs are conservative and reluctant to change. Indeed if these two claims were taken together they would have 12 respondents agreeing with them making this the most agreed upon claim in the research. While the statement on risk aversion in the supplementary survey did not garner as much support, it still received a mean response much higher than most other alternative influences.

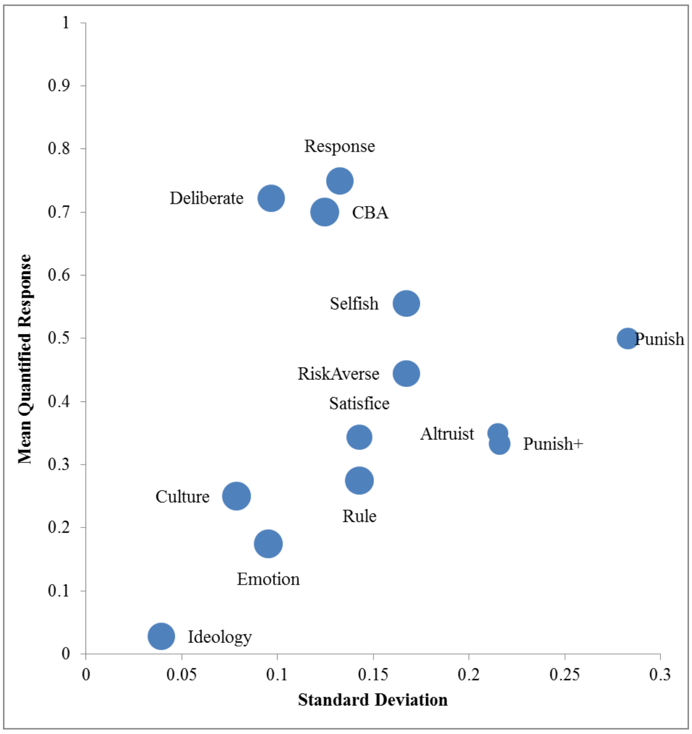


Figure 5-2: WC decision-making by mean quantified response and standard deviation

Results for Regulatory Decision Making Key Claims and Supplementary Survey

Ofwat Decision Making – driven by personalities of regulators (550), customer cost, WC financability, and resilience (551), an erroneous economic philosophy pursuing WC competition (552, 553), and a strategy on incentives for customer outcomes (553). Ofwat's information base includes: expertise through a revolving door dynamic with the WCs (554), modelling of future prices (555), relies on WCs for their business plans (556) and information about customers (557). Ofwat lacks information on what the public expects from them (558).

EA Decision Making – EA is driven by EU directives (559), is risk averse (560, 561), considers water need, impact on environment and abstractors (562), carbon, water quality, and cost (563). It uses CBA, scenarios and managed adaption pathways (564), and operates on 5 year plans (565). The EA has good environmental information and expertise (566, 568), environmental modelling (567). The EA does not consider or has little information on WC costs (572), and gets this from Ofwat and WCs (573). Innovations are reviewed by an innovation panel at director level (583) but innovations must not risk environmental quality (581).

DWI Decision Making – DWI takes a risk based approach to regulation (587, 588). Risk assessment values are known through experience but change (598) and may be subjective until a more standardized approach is developed (597). DWI evaluates technologies by 1) solving the problem, 2) quickly, 3) cheaply, 4) sustainably over time (593). Innovations are encouraged but not at the expense of water quality (595).

In the supplementary survey, Ofwat, the EA, and CCWater (considered as a consultative regulator) were selected as either primary or secondary stakeholder by respondents. As such it should be noted that the responses provide insight into an abstracted characterization of the decision-making of regulatory authorities in general and not any regulator in particular.

Generally speaking, responses regarding regulators had a higher standard deviation (0.16) than those for WCs (0.14). This is likely due to the fact that a more diverse set of organisations were included under 'regulator' than under WC. Figure 5-3 shows the values and standard deviation for regulators' decision making.

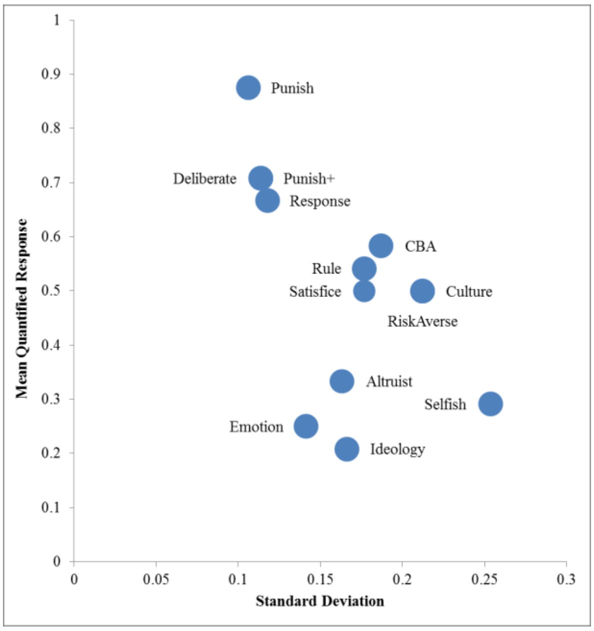


Figure 5-3: Mean quantified response vs. standard deviation with bubble size indicating response rate as a share of responses to those questions.

Punish and Punish+ were of relatively low mean value and of relatively high standard deviation for WC but of a very high mean value and lower standard deviation for regulators. Deliberate and Response showed relatively high values for both regulators and WCs with similar standard deviations indicating these statements reflect characterizations of decision-making well across both stakeholder groups. Emotion, Ideology, and Culture presented relatively low means for both WC and Regulator.

Other Stakeholders

Supplier Decision Making – Suppliers have very good information on their own costs (677). Suppliers look to demand and are mainly interested in growing sales (664, 670), looking to regulation, standards, and consents to target innovation (664, 667) with national targets driving their sales, sales pitch and prices (665). Their market is driven by incumbent WC (669) whose needs they respond to reactively not proactively (668). While suppliers may know how industrial customers justify business cases (685), they do not know WC specific problems which are diverse (684), the stringency of local consents (686), and the purchasers, budgets, and procurement processes in WCs (687, 678). Suppliers prefer technologies they can export also (672), where they have IP (673). Suppliers choose technologies by risk, performances, costs, time (674), energy, water, and flood reduction (675) and the fit with their customer requirements (692). Suppliers operate in a competitive market (671), do not know the costs of their competitors (679, 682) and their position in a fragmented market

(683). The supply chain drives technological innovation (694). A key issue for suppliers in innovation is the pre-sale investment (691) without which it's difficult to make accurate or detailed costings and quotes for customers (690). Estimating demand for the investment is difficult (689) as WC cut in and out of the market (688). Some suppliers do not want to work with smaller WCs on innovative approaches in order not to risk relationships with larger WCs (700, 701).

Industrial Consumer Decision Making – Industrial consumers asses options by CAPEX and OPEX (702). They have poor information on their wastewater stream (706) and their environmental obligations (703), and what technologies are available (704).

Consumers and Customers – Customers have little information on water processes (707), standards (708), and their own consumption (713) and water costs (713). The public has little awareness or interest in standards (708), policy and R&D (709), and water quality (717). The information they receive comes from their bill (713), the media (714) and if they engage with the WCs on twitter (715). Customers trust tap water (711) and this trust is driven by regulation (710). Customers do not trust the WCs (718). The public has a focus on leakage (723), and believe WCs should act more on leaks (722). The public think water savings are up to someone else (721). Customers generally only want to pay for what works and not for failed innovations (724).

5.6 Findings

The following is a review of the findings from the stakeholder interviews and supplementary survey with regards to the objectives identified at the beginning of this chapter.

A1O2 & A1O2: **Key Stakeholders and Action Arenas**

The key actors and stakeholders can be divided into 4 levels.

Government and regulators (DWI, EA, Ofwat, and local authorities). CCWater as the representative of consumers in the sector plays a soft regulatory role. The second level are the WCs. The third level involves the supply chain. This is where the majority of technologies reside and are supplied to the sector. The core function of the supply chain is to make pre-sale investments in R&D or technology imports to drive down the costs of transition and innovation. The market for suppliers is driven by WCs and the end-users in the fourth level. Suppliers and water sector associations also play an important role in setting technology and practice standards and guidance as well as information sharing and developing evidence base for supporting confidence in new and established technologies. The fourth level involves water users which can helpfully be divided into industrial users, developers, and household customers. These are ultimately the adopters and end-users of distributed interventions.

From the content of the responses and the thematic groupings of the key claims, the follow key action arenas were identified:

- Government Policy Making
- Local Authority Planning and Permitting requirements
- Inter-Regulator Relations
- Drinking Water Inspectorate Regulation
- Environment Agency Planning, Licensing, and Enforcement
- Ofwat Price Controls and Competition Reforms
- Developing Technical Standards
- The Market for Water Technologies

A simple representation of the interrelationships in this system is given below in Figure 5-4.

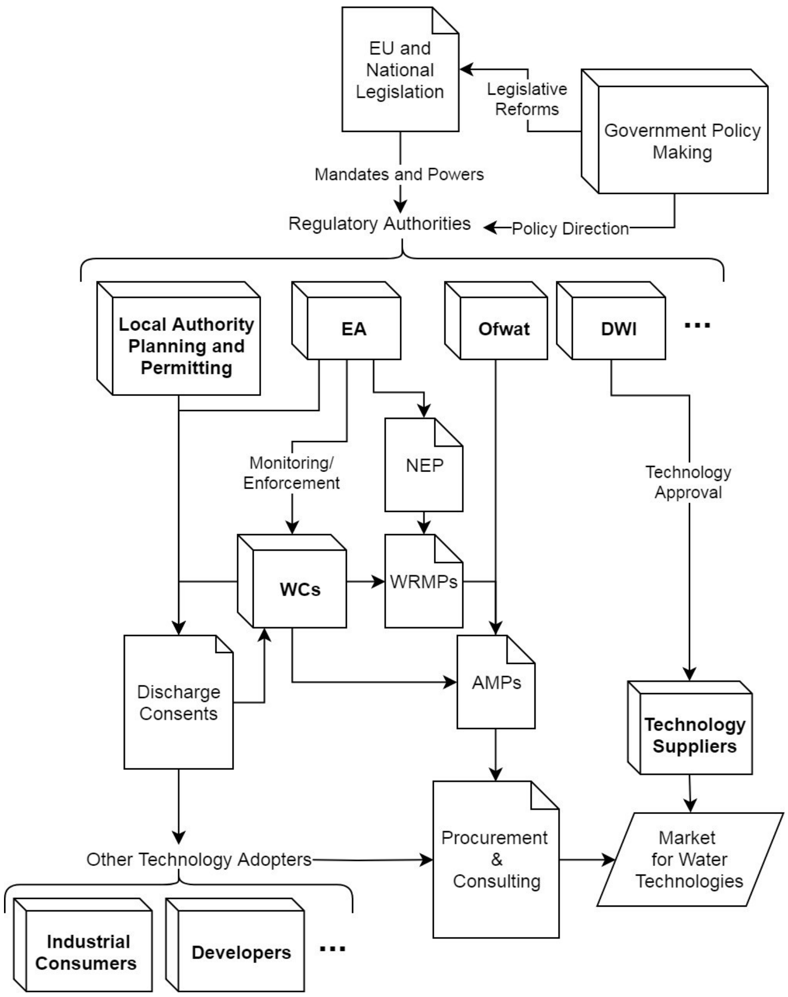


Figure 5-4: The system of action arenas involved in the regulation and adoption of water technologies in the UK as derived from stakeholder responses.

A1O3: **Characterize the role regulation plays in innovation.**

General claims about innovation reflect some relatively typical innovation dynamics. Novel technologies and system optimizations are developed through technical expertise and the involvement of universities, other novel technologies as well as actors. Typically initial costs are high due to health and performance risks and deter adoption. Competition between suppliers also drives innovation. Piloting novel techniques and technologies, as well as general diffusion of them improves understanding and reduces risks all contributing to falling costs over time.

Distributed systems such as WRTs, RWH, and SuDS, are seen as having the potential to reduce costs and improve environmental outcomes with a particular driver in areas of water scarcity. However they are considered relatively novel in the UK and seen to require more R&D and awareness raising hence facing the typical issues of novel technologies. WRTs in particular are seen to generate health risks due to the use of dual reticulation and the risk of misconnection. Distributed systems also face specific problems regarding the capital asset preference of WCs and issues around governance reconfiguration.

Another area of innovation repeatedly highlighted was that of data, smart systems and the Internet of Things. These technologies have the potential to contribute substantially to catchment monitoring, network optimization, and demand side interventions. The key issue with regards to these systems relate to governance of security, consent, and ownership of data.

Regulation plays a key part in the development and adoption of novel technology. More generally, 7 key mechanisms relating regulation to innovation and technological change were identified.

It is noteworthy that all the main disagreements among respondents involve regulation: the role plays in innovation, WRT uptake, and the effect of Brexit on environmental requirements and the role of regulation in shaping WC decision making. Regarding WRTs, 6 respondents claimed regulation generally is not a driver, 3 claimed it is not a barrier, and 3 responded that it is a barrier to WRT. Regarding price controls, 3 respondents claimed it does encourage new technology while 4 claimed it does not. Regarding the question of whether WC are free to make decisions or whether they decision making is largely driven by regulation, 4 respondents indicated that WCs essentially do what Ofwat tells them to, while 3 indicated that WC are free to make their own decisions.

1. *Regulator R&D funding*: It was noted the EA had supported industry research into technologies and techniques for treating WFD priority substances and emerging pollutants.
2. *Demand Driver*: it was widely agreed among respondents that regulation in the form of EU legislation and tightening consents on wastewater discharges was a key driver of rising demand for innovative water technologies.
3. *Signal for the supply chain*: it was agreed that legislative and regulatory requirements on WCs and industrial consumers were a key signal that suppliers looked to in developing their expectations and making pre-sale investments and R&D.
4. *Technology review and approval*: Defra, DWI, EA and Ofwat each were seen to play a role in collecting evidence, reviewing and approving technologies. That being said it was clarified that these functions were typically performed in such a way as to pursue technology neutrality seeking to maintain a level playing field and not be seen to favour some technologies over others.
5. *Economic regulation directing WC decision making*: although disagreement existed over this, there were multiple stakeholders who claimed economic regulation affected WC decision making quite directly while others saw it as leaving freedom for WCs to decide.
6. *Securing or excluding funding for technologies*: economic regulation has the function of securing funding for innovation. The system of price controls and AMP scrutiny was the most obvious of these being related to how savings from cost reduction innovations are shared with customers and the lack of approval for an industry innovation fund. Regulatory and legislative mechanisms for funding, natural capital accounting, and surface water drainage charges were all mentioned in relation to distributed interventions and for technologies with flooding and biodiversity co-benefits.
7. *Promoting Competition*: Opening the market for bioresources was unanimously seen as a boon to innovation by those who mentioned it, while competition reform to retail were seen negatively in light of the effect on household bills. Multiple interviewees claimed increased competition would hamper information exchange between WCs and raised concerns over oligopolistic collusion in retail.

Novel instruments of economic regulation are perceived to reflect an interest in promoting innovation and are perceived to do so relatively effectively: the innovation pillar, TOTEX, ODIs, and price control separation when mentioned are claimed to have a positive effect on innovation. It was claimed that information share between WC is important (530, 531), there was insufficient opportunity (529) and 4 respondents claimed that information exchange between WCs would be reduced under greater competition (528). One respondent argued that information would still be available through academia (17a). However interactions between WCs and academia already take place and additional exchanges would presumably be on the basis of a paid-for consultation.

A2O1: **Characterize how actors or stakeholders make decisions in action arenas characterized in A1O2.**

At each of these action arenas several of the most pertinent and agreed upon claims mentioned by interview respondents should be highlighted.

Government Policy Making – The government is concerned with imposing uniform rules across national heterogeneous economic and environmental conditions. Additionally, the policy making system is prone to inertia and changes only when placed under significant pressure from a problem, crisis or change in government. The current Conservative government has pursued competition reforms and rejects policies which would target particular technologies or a more interventionist industrial policy in the water sector. That being said the government did offer a Government Support Package to the development of the Thames Tideway Tunnel. A possible future Labour government has renationalization of water companies as a clear element of its manifesto. Other important landscape pressures are those of Brexit and attendant concerns over environmental legislation subsequent to the UK leaving the EU.

One of the core issues driving these differences is the view that the governance context pursues technology neutrality which may not be sufficient in promoting innovation. This was helpfully highlighted in one interview:

> "I think what we do is quite neutral in terms of a technological change, however the risk is that if the sector is culturally risk-averse, technologically averse, then we reinforce it rather than challenge it by the way that we make our decisions."

Local Authority Planning and Permitting requirements – This plays an important part in driving industrial consumer demand for water technologies as well as imposing duties on developers. Broadly local councils are resource constrained and do not want to erect barriers to development of new housing. Exceptions are driven by local water reliant industries or councils unwilling to encourage new development.

Inter-Regulator Relations – Regulators impose duties and conditions on the WCs and review WRMPs, AMPs, and are broadly the ones overseeing how the tension over environmental outcomes and cost of interventions plays out at WC level. Regulators are largely driven by their statutory mandates and the policies and preferences enacted by government and the Secretary of State Defra. Within this purview, regulators do have some discretion on implementation and this is governed by internal established procedures but can also be mediated by the personalities of the regulators. The current governance configuration requires a large degree of cross-regulator coordination for which processes are in place but are seen as inefficient at times.

Drinking Water Inspectorate – Two core action arenas the DWI participates in are technology review and approval processes with suppliers and drinking water quality risk based regulation with the WCs. The DWI seeks to ensure high quality drinking water and to leave discretion to the WCs to manage their risks, and to ensure a level playing field without technological preferences.

Environment Agency Planning, Licensing, and Enforcement – The core functions of the EA are the implementation of EU environmental law, drafting and implementation of the National Environmental Plan (NEP), abstraction licensing, developing and implementing the Drinking Water Framework, reviewing the WRMPs, and monitoring and enforcing compliance with statutory requirements. Local EA offices are responsible for issuing local licenses and consents to WCs and industrial users.

Ofwat - Price Reviews are the main action arena Ofwat participates in. This involves reviewing AMPs by the instruments of the price control: RCV, TOTEX, ODIs. Ofwat must in this action arena mediate consumer price pressure, political pressure on profits, and the Cost of Capital and Investor Confidence. Ofwat is also involved in reviewing New Appointments and Variations where entrants must demonstrate the ability to outperform incumbents on cost in order to deliver lower bills to customers. Ofwat is also responsible for reviewing and changing the mechanisms of regulation as well as implementing the government's policies on water market opening.

Developing Technical Standards – The development of technical standards is typically done by industry associations and standard setting bodies such as British Standards and WRAS. This activity involves bringing together suppliers and other experts in the field to review technical, performance, risks and cost evidence. The development of the evidence base is crucial for this activity and involves, academia, suppliers, and industry associations.

The Market for Water Technologies – A competitive market for water technologies exists where many different technology suppliers make contracts for design and delivery of different systems with buyers. The buyer side involves WCs but also industrial consumers. This is not a spot market but rather contractual arrangements mediated by consulting companies who bring together the buyer and seller side. It is here where costs and prices are discovered through procurement, tendering and negotiation. Pilot scheme and system design arrangements are also developed here. The supply chain innovates and invests for expected market as driven by WCs, industry, developers and the requirements they face from regulation. As is the case in many markets, technology buyers do not have good information on the supplier costs and profits (537) but build up information on costs from previous experiences (536). New technologies and approaches are discovered by WC from suppliers approaching them (625), stakeholder discussions (626), in-house R&D (627).

Trust in Key Action Arenas

Trust was repeatedly mentioned as a core difficulty in decision making for innovation. 5 key mechanisms by which issues in trust can inhibit innovation were identified:

1. *Suppliers extracting informational asymmetry rents from outcome based procurement*. This problem is managed through stricter specifications or through using Tier 1 consultants. Both of these responses can have a dampening effect on innovation.
2. *A lack of trust in WC leading to more constraining environmental requirements*. While the EA seeks to use a collaborative approach, breaches continue and enforcement and legal proceedings are continuously applied.
3. *Public trust in water quality and the water companies*. The DWI as guarantor of public trust in water supplies seeks to avoid being detrimental to innovation however its technology approval process still imposes an additional hurdle to novel technologies. The lack of trust customers have in leakage reduction can lead to customers being reluctant to adopt water conservation measures as they do not see a reason to.

4. *The trust by investors in the regulatory system as ensured by the RCV*. The RCV system of ensuring investor trust has led to a preference for capital intensive assets and insulated WCs from the risks of stranded assets reducing the incentive for efficient investments. Changes to this system are risky as they can drive up cost of capital and as such any changes to the systems are slow and incremental.
5. *The lack of trust between Ofwat and WCs*. One of the core motivations of the system of economic regulation is for WCs not to abuse their monopoly power. The result of this system of regulation means that WCs have sought to exploit the regulatory system put in place. It is worth highlighting one quote from the transcript to highlight how such issues of trust have played out in the price reviews:

   > "…PR99, very very little trust. Companies gold plated. PR04 absolutely no trust at all. Ofwat felt quite offended. Since then trust has been building. PR14 the biggest companies were allowed to do more of their own thing. There was a bit more trust there. But I would say there isn't that much trust between Ofwat and the companies. […] I think PR99 we played the game and they realized that it was a very, very generous settlement. A donation. They clamped down beyond what they probably should have in PR04. After that it has been building up. PR09. PR14. Rebuilding of trust or building of maturity perhaps because I think the companies behaved better."

   One of the results of these issues of trust between Ofwat and WCs the lack of an innovation 'catapult' such as exists in the energy sector. Several respondents criticised the lack of such a common innovation fund noting that Ofwat has been reluctant to include allowances for WCs to receive additional funding for a sector wide innovation fund. One respondent highlighted this issue:

   > "At the moment the closest you come to what the catapults can do is either we set up a project or Water UK set up a project. It's quite a random process and it is inevitably captured by whoever owns it. Water UK Long Term Resources. It looks and feels like a product that's done by a big incumbent monopoly. No other way of describing it because 'you know, what it needs is lots more work and money going to incumbent monopolies'. That might be the right, but you can't help but distrust it because it's been written by the people who will benefit from it. So, you know, it just feels wrong. Where the catapult could introduce a

level of independence to this and a level of if you like non-executive scrutiny that would really drive things forward.”

Clearly, finding an appropriate system of governance and oversight is a challenge for the establishment of an innovation catapult.

A2O2: **Relate characterizations to the morphology of decision-making methods.**

Supplementary survey responses found support for the Nash model of decision making (CBA, Response, Selfish, Non-Altruist) as extended with GMCR and deliberative rationality when considering homogenous decision making. Alternative decision influences were generally considered of low accuracy in characterizing decision making. Disimprovment as from GMCR models differentiated regulators most strongly from WCs.

Table 5-7 represents a characterization of decision making for the different stakeholders as per the morphology of tools given in Chapter 3.

5.7 Conclusions

This chapter has sought to provide three contributions to the understanding developed in this thesis as based on the responses from interview respondents. Firstly, a qualitative contextualization of action arenas in the UK water sector. Secondly, a focus on stakeholder perceptions of the process of innovation and the role regulatory instruments play in this. Thirdly, a more specific focus on decision making characterization and an external validation of the tools employed for modelling in this research.

Action Arenas

Interviews showed that stakeholders interact in a series of action arenas. The core interactions focussed on were the relationships between regulators, WCs, and technology suppliers. A core issue of linkage between these action arenas was identified regarding the integration of WRMPs and AMPs. Interviewees highlighted that these could be further integrated amongst themselves as well as with the Building Code, Local Authority permitting, EA consents and the supply chain to boost the uptake of distributed systems taking into account their multiple co-benefits.

Table 5-7: Characterization of Decision Making in the CIGA

Morphological Dimension	Regulators	WCs	Suppliers
Allogeneity	Single DM	Multiple DMs	Single DM
Objective Variables	Multiple Statutory Mandates, Ministerial Preference, stakeholder preferences.	Multiple Leading: Shareholder returns.	Multiple Leading: business growth, shareholder returns, customer-capability fit. Relationships.
Time Horizons	NEP – 25 years AMPs – 5 years	WRMPs – 25 years AMPs – 5 years *Mean: 20 years*	1 – 5 years
Forecasting and Expectation Formation	Adaptive to WC performance.	Adaptive for costs. Expectations from regulatory signalling.	Adaptive to WC requirements. Expectations from regulatory signalling.
Knowledge across space	Limited across national heterogeneity.	Own costs but not granular.	Own costs.
Knowledge across decision-making of others	Rely on WCs for costs.	Good information on regulators bad on supply chain.	Bad information on WC needs and differentiated environmental requirements.
Option Discovery and Availability	Consultation, government direction, and international standards.	Supply chain and internal R&D.	Trial and error and experience.
Pursuit mode	Maximization/ Resolve	Maximization	Maximization.
Risk Aversion	Loss aversion	Loss aversion	Loss aversion
Alternative Decision Influences	Rational with Political Pressures	Low alternative influences	Low alternative influences

Regulation and Innovation

7 key mechanisms were identified by which regulation effects innovation. Direct regulatory funding for R&D, regulatory requirements as drivers of demand, regulation as a signal to the suppliers, regulatory review and approval of technologies, economic regulation shaping WC decision making, economic regulation securing or precluding WC funding for technologies, and the promotion of competition where desirable. Recent changes to the system of economic regulation are seen to boost innovation. TOTEX reduces the capital bias, ODI's help signal WC needs more clearly and place clearer monetary valuation on these, and market opening for bio resources is seen by respondents as a driver of innovation.

Decision Making Characterization

Findings on decision making characterization support a characterization of decision making as one of optimizing agents with good information on their own costs but incomplete information on the costs and preferences of others. Deliberative models also accurately characterizing decision making. Regulatory decision making characterization includes disimprovements of the GMCR group of tools.

Among the most agreed upon claims made by interviewees was the claim that WCs are risk averse and that the system of regulation may to some extent exacerbate this.

Transitions and Trust

A core argument of this thesis is that trust plays an important part in technological constancy and change. Interviewees highlighted the role of trust in the core action arenas of regulator-WC and WC-supplier relationships. Lack of trust were identified in 5 key areas where the mechanisms for overcoming this problem can act as barriers to transitions to alternative practices and systems of delivery and governance: outcomes-based procurement, collaborative environmental regulation, public trust in water quality, investor confidence in economic regulation, and mutual distrust between Ofwat and WCs. The issue of trust create problems for the adoption of distributed interventions specifically and it is worth highlighting two of these areas more directly. The RCV supports a system of regulatory commitment which broadly supports capital intensive solutions and from which it is difficult to move away. Another important example is that mistrust in WC-Supplier procurement is overcome by Framework Agreements and Tier 1 consultants which do not always efficiently promote transition or distributed interventions.

5.8 Relation to other Chapters

Key claims collected support the selection of modelling approach deployed in Chapter 7. Claims largely support innovation dynamics such as learning and scale effects. That being said, interviewee claims identified important exceptions to positive returns to scale were identified. In particular with regards to the extent to which technologies develop verification across applications in different water companies.

Chapter 6 and 7 develop understanding of price investment cycles in trustee models. Key claims collected through interviews support the notion that the dynamics of trust highlighted in those chapters do play an important role in both intra-period investment patterns, as well as in inter-period cycles.

Foresight plays an important role in the incentive to invest and innovate as shown in Chapter 8. The adoption of novel or alternative technologies with environmental benefits is typically driven by foresighted stakeholders such as the role of the Government Support Package in the Thames Tideway Tunnel, the role of long-term homeowners in adopting WRTs, and the effect of the price review cycle on technology selection. Decision making of WCs is to a significant degree driven by investor preferences as mediated through the system of economic regulation. An important part of the role foresight plays here is that of the 5 year price cycle. This creates does not support a continuous incentive to innovations and reduces supply chain investment confidence.

Part 3: Modelling Transitions and Trust in Water Sector Regulation and Innovation

Chapter 6: Cycles of Trust in Monopoly Regulation

Key Points

- The regulatory action arena is formally characterized here drawing on the microeconomic literature of monopoly regulation and Ofwat's system of regulation.
- A trustee model is used to highlight the issues of trust involved in water technology investment.
- The Price Control Rule is understood to provide for a dynamical systems representation of decision making.
- Dynamical systems and fictitious play models shows cyclicality around an equilibrium point prompting a Price-Investment Cycle trust in regulation.
- Evidence for this is explored in Price Review data and changing system of incentives over time.

This chapter develops a formal model of trust in the regulatory action arena. Namely, the relationship between regulator and regulated monopolist water company. Drawing on literature about regulation and the regulatory system in England and Wales (in particular to support decision making characterization and HOCs), the action arena is characterized under the CIGA. The decision making of firm and regulator are characterized and three tools are used in a comparative approach: Nash equilibrium, dynamic systems model, and fictitious play. The regulator-firm relationship has been presented as part of a broader SES in Chapter 4. The hierarchy between firm and regulator is the focal action area for this research which this chapter develops in more detail.

Monopoly regulation faces three interrelated problems [*Laffont and Tirole*, 1993; *Joskow*, 2007]. Monopolists are able to affect prices in their market and with this market power they can extract surplus profits at the detriment of consumers. To ensure this does not happen, regulators are established to control prices but ensure that the firm is still able to finance its operation and required investments [*Joskow*, 2007; *OECD*, 2015]. The system of regulation imposes a new set of incentives on the regulated firm possibly in undesirable ways such as the capex bias [*Averch and Johnson*, 1962; *Joskow*, 2007; *Ofwat*, 2011]. As shown in Chapter 4 each of these concerns features in Ofwat's mandate [*Ofwat*, 2018c]. Noteworthy here is also a model presented by [*Damania*, 1996] which shows how under oligopoly where few firms are colluding to attain a monopoly price, a pollution tax can lead profit-maximizing firms to avoid adopting pollution abatement technologies even when these would reduce costs. This is due to the strategic effects of oligopolistic collusion but highlights ways in which regulatory intervention can have unintended consequences on firm incentives. An exploration of dynamic models of oligopoly shows that a multitude of different incentives can create perverse incentives encouraging over- or under-investment [*Fudenberg and Tirole*, 1986].

The chapter reviews models of monopoly and instruments used to regulate it, ultimately focussing on a trustee game as a characterization of the regulatory action arena. The first set of models are standard microeconomic models of the competitive and monopolist firm showing the potential for regulatory intervention to improve outcomes in a monopoly market. The second set, models the firm under 'cost plus / rate of return' regulation, fixed price regimes, yardstick / benchmarking regulation and the regulatory ratchet.

The trustee model is used to depict two-sided trust issues arising in the regulatory action arena: the firm's potential to hold-up regulators or gold-plate, and the potential for the regulator to expropriate value from the firm after investment has taken place. It is shown that in this characterization, cyclical patterns emerge for dynamical systems and fictitious play tools.

This cyclical pattern predicts instability in the relationship. This cyclicality is interpreted in a Theory of Price-Investment Cycles. Investment cycles have previously been identified *within* the price review period and have been shown to be disruptive to innovation and the supply chain. PI Cycles motivate these more clearly and contributes to understanding of investment cycles *between* price review periods. Evidence of cyclicality is reviewed in firm-level data from regulatory 'Final Determinations' and the difference between company proposed price increases and the final determinations (FDs) made by the regulator.

The discussion highlights how over time, the regulatory system has adapted to try to counteract these issues through greater use of regulatory incentive mechanisms while external pressures are growing on the sector which can work to undermine these efforts.

6.1 Monopoly and Instruments of Economic Regulation

A simple profit function for a firm can be characterised as:

$$\Pi = pq - \int_0^q \big(MC(q)\big) - FC$$

Eq. 6.1

Where Π if the net profit, q is quantity, p is price, $MC(q)$ is marginal cost as a function of q, and FC are the fixed costs (or sunk costs).

In a competitive setting, the firms take marginal revenue as given by the market price, $\mathrm{MR(q)} = p$. Hence the First Order Condition (FOC) for the firm choosing output quantity is where price equals marginal cost:

$$\frac{d\Pi}{dq} = p - MC(q) = 0$$

Eq. 6.2

In a market with only one supplier, the monopolist has power to effect the market price. The firm will again seek to maximize profits, however now with knowledge that changing the quantity will affect its price. This relationships is determined by the demand function which characterizes the willingness to pay (WTP) for the quantity supplied. A simple model of the price consumers are willing to pay is:

$$D(q) = p_0 - bq$$

Eq. 6.3

Where $D(q)$ is the WTP for a given quantity, p_0 is the WTP for some initial quantity, and b is rate at which the WTP falls for an added unit of quantity. With this information about the WTP of its customers, the monopolist is able to set its output in a different way to the competitive firm. To show this, the demand function is substituted for price in the profit function 6.1:

$$\Pi = p_0 q - bq^2 - \int_0^q (MC(q)) - FC$$

Eq. 6.4

The FOC then becomes:

$$0 = p_0 - 2bq - MC(q)$$

$$q = \frac{p_0 - MC(q)}{2b}$$

Eq. 6.5

For comparison, the competitive firm, operating under the same demand would substitute 6.2 into 6.3 to supply:

$$q = \frac{p_0 - MC(q)}{b}$$

Eq. 6.6

Because the monopolist can exercise market power by supplying less, thereby raising the price and increase its profits it supplies less than a competitive firm. This protection of consumers is of the leading motivations for regulatory intervention in the UK as well as other countries around the world [*OECD*, 2015].

The incentive to innovate can also readily be evaluated in this model. The unregulated monopolist faces an incentive to reduce costs. This can be seen from its utility function where both fixed and marginal costs are detrimental to profits (the derivative of both MC(q) and FC are negative). However, as regulatory intervention is usually enacted this regulatory system can have unintended consequences regarding the cost reduction incentive.

There are several key instruments that can be used for economic regulation of natural monopoly. A review of these is given in [*Joskow*, 2007]. These include:

- Competitive / Marginal Cost Pricing and Subsidy
- Cost-of-Service / Rate-of-Return
- Regulatory Asset Base (RAB) / Regulatory Capital Value (RCV)
- Fixed Price / Price Cap
- Benchmark / 'Yardstick' Regulation
- Incentive Regulation

Competitive Price and Subsidy

One approach to setting a regulated price is to set it at the level where a competitive market would. This is where $\mathrm{MC(q)} = \mathrm{D(q)}$. There are two problems with this 'first-best' approach. It does not take into account FC and hence can lead to a loss for the regulated firm. An additional subsidy would then be paid. If this subsidy were to be recovered from consumers at a per unit basis, it would introduce a distortionary tax, shifting the demand curve. A lump sum tax is non-distortionary but not easily deployed in practice. Governments do not usually employ lump sum taxes [*Joskow*, 2007]. Secondly, and more importantly, the regulator may not know the efficient cost structure of the firm and hence would not have the information necessary to set an efficient subsidy. If the regulator relied solely on information from the firm, the regulatory system would result in what would better be characterized as a cost-of-service style regulatory instrument.

Cost-of-Service / Rate-of-Return Regulation

Under a cost-of-service regime, the regulator must determine the total costs at which the service is delivered in order to determine revenue requirements for the firm. This is understood to involve: operating costs, asset base, depreciation, allowed rate of return, tax, and other costs [*Joskow*, 2007]. The asset base is interchangeably called the rate base, Regulatory Asset Base (RAB), Regulatory Asset Value (RAV), and in Ofwat's terminology is referred to as Regulatory Capital Value (RCV). A price is determined which will adequately cover all of these costs in order to finance the firm's operation. In the context of the model used thus far, the price set thereby p_R would be such that:

$$p_R q = TC = FC + \int_0^q MC(q)$$

Eq. 6.7

Clearly, substituting this price into the firm's profit function (Eq 6.1) results in $\Pi = 0$. While this approach prevents profit and loss, it changes the firm's utility function to a constant. Hence the firm is insulated from all cost performance and has no incentive to reduce costs.

Overcoming Hold-up with RAB/RCV/RAV

Regarding solely remuneration for fixed costs of capital expenditure, the Brandeis formula is typically used [*Joskow*, 2007]. This sets net cash flow in a given period as:

$$\Pi_t = D_t + rRAV_t = \frac{K_0}{N} + r\left(K_0 - \sum_0^t D_t\right)$$

Eq. 6.8

Where D_t is capital depreciation, r is a rate of return deemed appropriate by the regulator, K_0 is the cost of the investment required and N is the lifetime of the asset. This rate of return r is set according to the opportunity cost of capital, (i.e. expected returns on other investments). The RCV provides certainty to investors that they will receive a return on their investment and that they will not be 'held up' by regulators after the investment has been made [*Joskow*, 2007; *Stern*, 2014]. A problem recognized with this instrument however is that it creates a capital use bias for the firm [*Averch and Johnson*, 1962; *Joskow*, 2007]. The fact that the firms profit is constrained by the allowed rate of return on the RAV induces a lower effective net cost of capital than would otherwise be the case leading it to substitute capital for operational expenditures.

Benchmarking / "Yardstick" Regulation

Information about cost structure and reduction potential can be gleaned from a benchmarking process among multiple regulated firms as is the case with Ofwat. This simulates competition. If firms could collude to keeping their prices high they could achieve supernormal profits. However as their private benefit is increased by undercutting competitors, they drive down the price over time to marginal costs. Benchmarking amongst disparate monopolists has a comparable effect. Under benchmarking, the regulator sets cost reduction expectations based on an evaluation of costs across companies. Inefficient firms can thereby be identified and penalized while efficient firms can be rewarded [*Joskow*, 2007].

While this mechanism has clear advantages, it may not always be applicable or helpful. The comparative assessment does not however necessarily relate to whether the firm is exerting effort to reduce costs and to innovate. To know this the regulator must form a belief about that firm's specific marginal costs, effort, at least. Although benchmarking imposes a market-like competition between regulated firms, the regulator still faces a series of one-on-one action arenas in evaluating cost reduction. Ofwat employs benchmarking and econometric analysis to inform its baseline estimates of efficient costs while firm-specific variations are then handled through a separate adjustment mechanism [*Ofwat*, 2018a].

Fixed Price Regulation

Under the cost-of-service instrument, the firm is insulated from cost performance. In order to introduce a stronger cost reduction incentive, fixed-price contracts are employed. This entails a fixed revenue regardless of costs. Under a fixed-price contract the firm's costs and revenues are separated. Any cost reduction is kept by the firm.

A simple model of a regulatory decision between fixed-price and cost-of-service regimes [*Laffont and Tirole*, 1993; *Joskow*, 2007] has been defined as:

$$R = a + (1 - b)C$$

Eq. 6.9

where R is the firms regulated revenues; a is a fixed payment to the firm; C are realized costs; $0 \leq b \leq 1$ is the regulatory choice between a fixed-price and a cost-of-service regime.

When $b = 0$, the firm will operate in a cost-of-service regime, again completely insulated from cost performance which are completely compensated for though revenue requirement.

When $b = 1$, the firm's profits are impacted by cost performance as it receives a fixed sum a regardless of cost performance (fixed price). a is then set as a regulatory expectation of efficient costs C^* by the regulator (as determined through a benchmarking exercise for example).

Necessary for this stronger cost reduction incentive is the possibility for the firm to accumulate large profits or losses. For a regulator such as Ofwat which is mandated with both keeping prices low and ensuring the firm maintains financial health, neither profits nor losses are desirable. Large profits would indicate prices could have been lower while losses indicate the firm is losing its financial sustainability.

The RPI-X Price Cap Ratchet

A price cap mechanism sets the price the monopolist can charge. As presented in Chapter 3, the mechanism employed by Ofwat is known as the RPI − X price cap. Under this rule, prices are adjusted on the basis of inflation (using an inflation measure such as the retail prices index or consumer price index as will be adopted for PR19 [*Ofwat*, 2017a]) and cost reduction (efficiency) challenge *X*. The result gives a fixed price which is maintained over the price control period (5 years in Ofwat's case), at the end of which new price determinations are made. Note that another parameter is used to determine investment *Q* required for environmental and drinking water regulation compliance. These investments are reviewed and if approved, added to the firm's RCV. *Q* then includes depreciation and rate of return on the firm's RCV.

Ofwat employs a fixed price instrument of regulation. The core formula [*Ofwat*, 1994; *Joskow*, 2007] used in determining price caps is:

$$P_t = P_{t-1}(1 + RPI - X + Q)$$

Eq. 6.10

Where P_t is the price in the time period *t*, *X* is the efficiency challenge by which prices are reduced (using benchmarking) and *Q* represents the amount by which prices increase due to greater investment required for compliance with quality regulations.

This enacts a differentiation between what the firm does and does not have control over. The firm is insulated against changes in inflation and capital investment requirements imposed by statutory requirements. The firm however is not insulated from all cost performance as these prices are fixed over the 5 year period. Any cost reductions within this period accrue to the firm.

As prices are adjusted every 5 years, this regulatory regime incorporates what is called a 'ratchet' [*Joskow*, 2007]. Prices are fixed within the price control period but cost reductions are passed on to efficiency challenge *X* for the next price control period. The effect of such a ratchet is to strike a balance between cost reduction incentives and cost-of-service profit controls. The firm subsequently faces an incentive to reduce costs within the price control period. However cost reduction measures which would reduce costs beyond the price control period are not incentivized as these cost reductions are passed on to customers in the form of price reductions.

6.2 Cyclicality in the Trustee Model

As noted in Chapter 2, the regulatory action arena involves a two-sided issue of trust. Regulators opportunistically driving down tariffs or expropriating value from investors [*Levy and Spiller*, 1994; *Spiller and Tommasi*, 2005; *Stern*, 2012]. This can happen due to political pressure on regulators or poor institutional design and context [*Levy and Spiller*, 1994; *Ménard and Ghertman*, 2009]. Just as regulators can expropriate value from the regulated firm, the firm can likewise game the regulator by 'gold-plating', extracting additional returns by investing beyond levels necessary to meet environmental and supply requirements [*Averch and Johnson*, 1962; *Joskow*, 2007]. 'Gold plating' has also been noted as an issue due to the asymmetry of information between the regulator and firm in the case of England and Wales [*Ofwat*, 2011]. More generally, the problem of how the regulator knows that the firm is undertaking appropriate levels of effort, if this effort is unobservable by the regulator, creates the issue of moral hazard [*Laffont and Tirole*, 1993; *Stiglitz*, 1994; *Joskow*, 2007].

Here the regulatory action arena is characterized as a trustee game to represent this two sided trust issue. This game has been used to study trust and cooperation in environmental governance [*Ostrom*, 2009b]. The trustee game is characterized by an investor and a trustee. For our purposes the regulated firm can be understood to be the investor and the regulator as the trustee. The firm makes an investment and the trustee pays for the investment. The investor's utility function is written as:

$$u_x(x, p) = xp + (1 - x)\alpha$$

Eq. 6.11

where u_x is the investor's utility; *x* is the investors choice as to where they invest, in the regulated asset or into an alternative asset, hence $0 \leq x \leq 1$; p is the price paid by the regulator (trustee) per unit of investment *x*; and α represents the investor's returns when investing elsewhere (alternative investment).

Now consider the trustee. It receives the investment and determines a value p for how this investment is remunerated (p is also a real number greater than 0). In the original trustee game, this was a share of (the grown) investment returned to the investor. Here p is considered to be the returns on investment as given by the regulatory system.

$$u_p(x, p) = f(x) - xp$$

Eq. 6.12

where $u_p(x, p)$ is the payoff for the regulator which comes as a function of price and investment; *f(x)* defines some benefit from investment that the regulator is pursuing; p is the price the regulator determines.

The Trustee Game with Simultaneous Moves

In the standard trustee model presented in [*Ostrom*, 2009a], the decisions made by investor and trustee are made sequentially. First, the investment is made. Then it grows in value, and then the trustee must decide on what share of the investment to return to the investor. This creates the problem that the trustee will wish to retain all of the investment for themselves. Given investors can expect this to happen, the prediction is that of a hold-up. Investment does not happen because the investor does not trust that the trustee will return any of the investment and hence does not invest at all. Two issues are responsible for this result: sequential moves and bad regulatory incentives.

Sequential moves in this context means that whoever decides last accrues a particular bargaining power. If the investor has made an investment, they can no longer influence the trustee's decision. The utility maximizing trustee will then expropriate the value of the investment. Given that similar games may happen in the future the trustee thereby undermines their reputation and future investments are held up. These sequential move effects on equilibrium analysis are often referred to as Stackelberg equilibria, after the Stackelberg leader-follow model of firm entry into a monopoly market [*Fang et al.*, 1989; *Fudenberg and Tirole*, 1991].

In order to capture both sides of the trust problem but removing the issue of who goes last, the trustee game is modelled as a simultaneous move game instead. Given that both regulator and firm typically work on the basis of plans implemented over the price control period, it is not unreasonable to assume these plans are developed and implemented in parallel. Additionally, simultaneous moves model the core feature of natural monopoly, namely sunk costs. Investors cannot easily adapt their strategy to the regulators price review once the investment has been made. Likewise the regulator cannot change the price within a price control period. Given that neither can adapt their play within a given time instance to the others play, a simultaneous move game is a reasonable action arena characterization.

Equilibrium in the Trustee Game

To find the equilibrium, we first determine the first order conditions (FOC) for optimality for each player by differentiating their utility function with respect to their action variable and setting these equal to 0. Then input each FOC into the other players' FOC to determine the equilibrium strategies.

Given, $\frac{du_x}{dx} = p - \alpha$, the FOC for the investor is:

$$p = \alpha$$

Eq. 6.13

This means that the investor will be indifferent between investment levels where price is equal to the returns on alternative investments.

Given $\frac{du_p}{dp} = -x$, the FOC for the trustee is:

$$x = 0$$

Eq. 6.14

In equilibrium the regulator, will always look to sink prices where investment is happening. If this is the case, the Nash equilibrium will be where prices are equal to alternative investment returns but there is no investment. This is the core of the hold-up problem: because the regulator cannot commit to keeping prices high, the investor will not invest. Clearly, this result is not desirable from the regulatory point of view. This style of reasoning has been used to explain how expropriation due to weak institutions (such as may be found in many developing countries) holds up investment and ultimately leads to environmental and consumer-side problems [*Levy and Spiller*, 1994; *Dassiou and Stern*, 2009].

Given the equilibrium result here is both undesirable to the players and not an accurate reflection of the real world action arena outcomes in the case of Ofwat (investment is made and prices are not driven to 0), this core model of a trustee game must somehow be reviewed. There are two avenues considered here for resolving this: grim trigger strategies and reviewing the regulatory utility function on the basis on its mandate.

A so-called 'grim trigger' strategy can be employed in repeated games for the purposes of making an equilibrium of a pareto-optimal or socially optimal state. Players cooperate to maintain the mutually state initially. If the opponent deviates they switch to the equilibrium strategy worst for the deviator [*Abreu*, 1988]. Disequilibrium cooperative outcomes in a one-shot game can thereby be supported in equilibrium in infinitely repeated games (given low enough discounting of future rewards). This would be applicable to repeated trust games. Such a grim trigger strategy would be beneficial for both sides to adopt as it would ensure neither the regulator expropriates value nor the firm gold-plates. The problem with this approach is that of how feasible such a commitment to permanent non-cooperation post defection is. It may not be reasonable to expect the regulator to be able to sustain a punitive regime in the face of rising investment deficits. Such a sustained punitive regulatory stance would also possibly be open to challenge through the courts and political system for lack of impartiality. Likewise from the investor side, it is infeasible to expect an investor not to return to investing in the regulated asset if the regulatory stance is consistently enticing. Given the problems associated with the grim trigger strategy, the more promising avenue of approach is that of reviewing the regulatory utility function on the basis of its legal mandate.

Regulatory Mandate for Required Investment

As discussed in reviewing the literature on regulatory action arena in Chapter 2 regulators generally are mandated not simply to drive down prices but rather to prevent monopoly price abuse and to provide a proper pricing. Ofwat's regulatory mandate and the legal and pricing instruments as discussed in Chapter 4 are there to ensure the environmental improvements are delivered (in particular those deemed important through the Environment Agency's implementation of environmental laws). To support this function, the RCV (as reviewed in this chapter), reflects how regulatory mandates seek to ensure that investment is valued properly. Ofwat's legal mandate states that firms must offer reasonable rate of return on investment and Ofwat employs the RCV to do this [*Ofwat*, 2018c]. As such then the regulator will not seek to retain all the investment and sink prices to 0 for the regulated company. Instead the regulator will value investment, seek to remunerate adequately in order to ensure that regulated firms can function properly. (Note: both the standard trustee model and this adapted regulator model are employed in Chapter 7). So the utility function should be amended to reflect this. In order to do this, the regulator must have the following FOC for the derivative of their choice variable (price):

$$k = x$$

Eq. 6.15

where k represents the investment level required to meet the environmental and drinking water quality requirements. Integrating this, the regulator's utility can then be written as:

$$U_p = p(k - x) + A$$

Eq. 6.16

where U_p is the regulator's utility function, p is again the price they pay per unit of investment x. A is simply the constant of integration which is ignored subsequently.

The FOC condition implies that the required investment be scaled to the price of the investment. This situation now resembles market demand in that κ becomes an indicator of the willingness to pay of the regulator.

Equilibrium Analysis

Equilibrium analysis proceeds by evaluating the FOCs of both players to find the Nash equilibrium of this game.

As before, for the regulator the FOC is where:

$$\frac{dU_p}{dp} = 0 = k - x$$

Eq. 6.17

$$k = x$$

Eq. 6.18

This means that when investment is at the required level, the regulator will be indifferent across any price it pays and hence no improvements are possible by changing prices.

For the investor is where:

$$\frac{dU_x}{dx} = 0 = p - \alpha$$

Eq. 6.19

$$p = \alpha$$

Eq. 6.20

This means that where regulator prices are equal to alternative returns, the investor will be indifferent between the regulated investment and the alternative. Hence investment levels will not change. Given the regulators FOC, the prices would not change and hence the Nash equilibrium then is where the prices are set equal to returns for alternative investments and where investment is at the level of required investment.

This can be seen to reflect relatively well the situation as found with Ofwat's water regulation. Investor reports from price reviews typically seek to show how regulated returns on RCV closely match returns in other regulated sectors like electricity, civil aviation and others [*Ofwat*, 1994, 2014]. Likewise, in public and official communications environmental and economic regulators laud that investment levels are broadly meeting statutory requirements adequately.

While this provides a good baseline, the CIGA would require the consideration of alternative tools (rather than just Nash equilibrium) in characterizing the decision situation. The analysis is now developed with two further tools to capture two important variations to the decision making characterization: equilibrium stability analysis and secondly fictitious play modelling. In particular both reflect decision making over multiple repetitions of the game.

Equilibrium Stability Analysis

Given that prices over time in the RPI-X system, the regulatory action arena can be considered as a dynamical system rather than a static one as has been presented thus far. This requires a different formal representation using difference equations as drawn from the FOC's employed earlier.

In order to extending the Nash equilibrium analysis employed earlier these difference equations will have to meet the same equilibrium conditions. In other words, a dynamical representation would require $\frac{d}{dt} = 0$ where $\frac{dU}{d} = 0$. By simply setting best response functions equal to time difference equations we get:

$$\frac{dx}{dt} = p - a$$

Eq. 6.21

$$\frac{dp}{dt} = \kappa - x$$

Eq. 6.22

The implication of this assumption is that prices and investment levels will change by the relative utility at that point in time. In other words changes in price will be driven by the difference between required investment and actual investment. Likewise that investment will change proportionally to the difference between alternative investment returns and prices as paid by investments with the regulator.

The fixed points of this system are then where both of these functions equal zero hence the Nash equilibrium point $\{p = \alpha, x = \kappa\}$. For dynamical systems, this equilibrium point can then be evaluated for its stability using the Jacobean matrix [*Katok and Hasselblatt*, 1995]. This matrix shows the first order derivatives of each difference equation for each variable:

$$\boldsymbol{J}(x, y) = \begin{bmatrix} \mathbf{0} & \mathbf{1} \\ \mathbf{-1} & \mathbf{0} \end{bmatrix}$$

Eq. 6.23

The eigenvalues of the Jacobian matrix then determine the stability of this system:

$$\lambda_1 = \mathrm{i}, \qquad \lambda_2 = -\mathrm{i}$$

Eq. 6.24

The fact that both lambdas are imaginary and of differing signs implies that the equilibrium point is elliptical (i.e. an orbit exists around it). Figure 6-1 shows how starting at different locations in the price-investment space the system will tend to fall into a cycle around the equilibrium point. Note that the paths over time are straight at the edges of the figure because constraints were imposed there.

Assuming regulated returns are set at market-returns, the firm will be indifferent in their decision. Likewise for the regulator, if the level of investment is equal to required investment then the regulator will also be indifferent between raising and lowering returns. These conditions are sufficient for Nash equilibrium and a potential conclusion from this is that this state of affairs will be convergent. However, while it is an equilibrium, this state is not an attracting state and perturbations to any of the variables will leave the system in a cycle. The cycle is convergent.

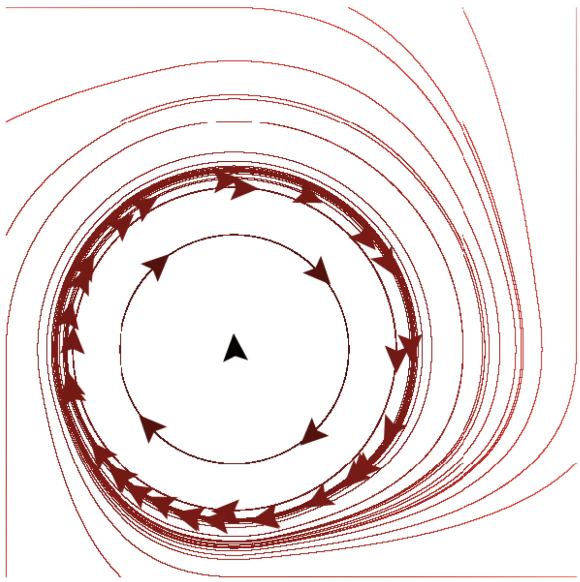


Figure 6-1: Dynamical System Cycle around Equilibrium Point.

Cycles in Fictitious Play

The previous analysis of regulatory price controls as a dynamical system showed cyclicality around an equilibrium point determined by alternative investment returns and investment required for compliance with statutory requirements. It employed difference equations driven by FOCs.

A more accurate characterization of decision making would be to employ fictitious play. As mentioned in Chapter 2, this tool employs an information-constrained characterization of decision making. Players are not aware of the payoff function for the opponent and hence develop expectations based on frequencies of past moves by opponents.

Figure 6-2 shows the results of fictitious play over time for the same utility functions as provided earlier. Each decision variable was constrained to be between 0 and 1 and the external variables were set to be 0.5 (alternative returns and required investment). As with the dynamical system, fictitious play cycles over time. This kind of cyclicality has been discussed in previous game theoretic literature on learning in games using fictitious play [*Shapley*, 1964; *Fudenberg and Levine*, 1998; *Sparrow et al.*, 2008; *Strien and Sparrow*, 2011]. In fact the cycles get longer over time. This is due to the fact that the players accumulate more data each new data point contributes less to the overall expectation on the opponents move. This however does not lead to the cycle moving towards the equilibrium, only to it slowing down over time.

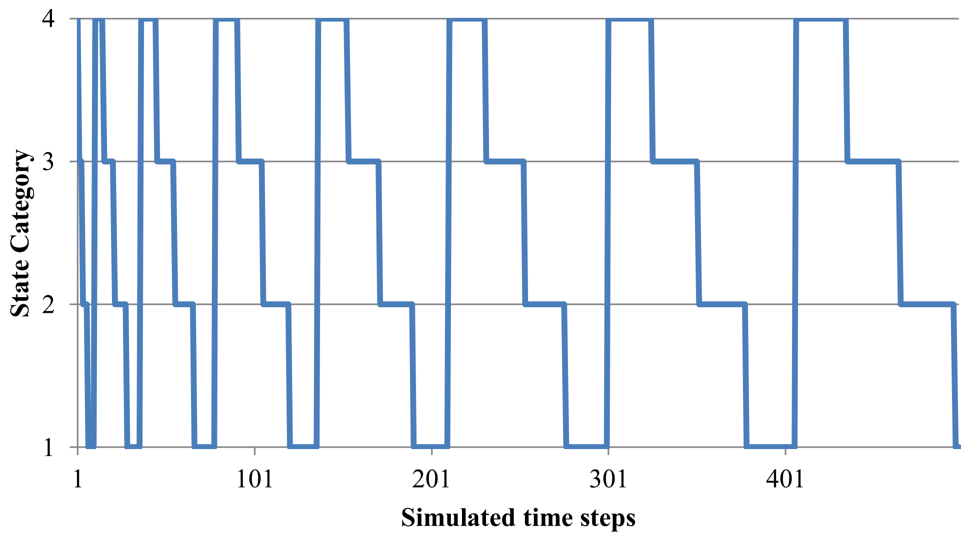


Figure 6-2: States of fictitious play over simulated time.

Fictitious play cycles between four states (1: Low-PI;2: High-P Low-I;3: High-PI;4: Low-P High-I)

6.3 Discussion of the Stages of PI Cycles

This section provides a qualitative interpretation of the stages of the price-investment cycle (PI cycle), associating different stages to key dynamics drawn from the existing utility regulation literature. The theory of price-investment cycles as interpreted here seeks to incorporate these multiple mechanisms to provide a unifying framework for characterizing the regulatory action arena. An overview narrative description of the price-investment cycle can be characterized to move between the following four stages:

1. *Low-PI*: Low prices lead firms to underinvest as they can no longer finance required investments
2. *High-P Low-I*: The perceived inability of utilities to make required investments leads regulators to set prices higher encouraging greater investment.

3. *High-PI*: Generous regulatory incentives induce overinvestment, gold-plating and excessive prices and profits.
4. *Low-P High-I*: High prices place increased public pressure on regulators and governments reduce prices returning the system to the state 1.

While this overview narrative provides a helpful simplification, it does not capture all relevant dynamics. This model and narrative also implies a deterministic movement between the system states. This is not necessarily so as multiple relevant variables can change simultaneously. For example, tightening environmental quality standards leads to a rise in required investment which can move the system to a state of underinvestment without either regulators changing prices or firms changing levels of investment.

The theory of PI cycles should be properly interpreted to mean that unchanging exogenous variables are not sufficient for unchanging prices and investment. Price and investment change is driven not only by changes in quality standards and inflation but also by changes in regulator-firm trust.

Integration of Key Motifs into the PI cycle

These dynamics identified in the literature can be integrated into a single dynamic under the theory of PI cycles. A narrative integration of the way these dynamics are embedded in the PI cycle is show in Figure 6-3. Each entry in the 9 cells in the PI space highlights a mechanism driving investment or returns in the direction given by the arrow pointing away from it. The equilibrium point clearly has no arrows pointing away from it as it is where the two would be in equilibrium.

The interpretation of the PI cycle is not that regulator-firm relationships will always follow a pre-determined path in a cycle, but rather that the PI space creates incentive pressures which drive action in the direction of PI cycles subject to changing market returns and required investment. In a situation of low returns and low investment, policy makers and regulators will encourage a laxer more rewarding environment to attract investment. If the firm takes advantage of this rewarding environment and extracts surplus profits or gold-plates its investments, regulators would respond by driving returns down. Additionally, consumer pressure on government and regulators to drive down prices is stronger when the firms have been found to abuse regulatory trust. It is possible that the firm will persist in low levels of investment even under high returns on offer. The firm and regulator are then in a hold-up problem where they could both be better off if the firm could invest without concern about regulators renegotiating an expropriation afterwards.

The key implication of this model is that the regulatory relationship is not a necessarily stable relationship in the sense that prices and investment will directly reflect the exogenous variables of market returns on investment and the environmentally required level of investment. Rather prices and investment will change also in response to endogenous changes in expectations. As mentioned before, this model and narrative implies a deterministic movement between the system states. This is not necessarily so as multiple relevant variables can change simultaneously. For example, tightening environmental quality standards lead to a rise in required investment which can move the system to a state of underinvestment without either regulators changing prices or firms changing levels of investment.

		Investment		
		Low investment	**Required Investment**	**High investment**
Regulatory Stance	**High returns**	*High expected returns*	*Gold-plating*	*Efficiency Challenge*
	Fair-returns	*Quality Mandate*	*Equilibrium*	*Consumer Capture*
	Low returns	*Financing Mandate*	*Hold-up*	*Low expected returns*

Figure 6-3: Price-Investment Cycle Dynamics

6.4 Evidence for PI cycles in England and Wales

The system of periodic price reviews has been recognized to give rise to a cyclical pattern of investment within price review periods which is deemed disruptive [*HM Treasury*, 2012]. This Treasury report draws on market and supply chain research showing how this pattern creates disruptions in the supply chain as driven by cyclic firm investment. The report argues:

> "The study team consider that a key cause of the late start within each price review period is the lack of effective and timely decisions within the water companies, with decisions around contracts and forward programme delivery not generally being made until after the final determination. Water companies have said that is because they do not have certainty until this time on either investment

or on scheme specific inclusion (particularly with regard to the quality investment programmes)." [*HM Treasury*, 2012]

While the report argues that Ofwat has consistently given only small changes to investment programmes between draft and final determinations, these interview responses highlight that uncertainty around the remuneration for particular projects through RCV is still an issue for water companies. In particular given that investment programmes must be developed well in advance. The report goes on to highlight that:

> "Interviews with company representatives alluded to the situation whereby elements of the business plan which a company submits to Ofwat for the purposes of setting price limits, is superseded by a delivery plan that the company then re-constructs based on its FD. One might perceive this as effectively treating the business plan as a mere 'bid'; Ofwat are aware of the situation and are keen to eliminate such behaviours in future price reviews." [*HM Treasury*, 2012]

Given this situation, it is worth reviewing historical price determinations data as a source of verification and evidence of PI cycles. Figure 6-4 shows the price determinations for the 10 water and wastewater companies in England and Wales.

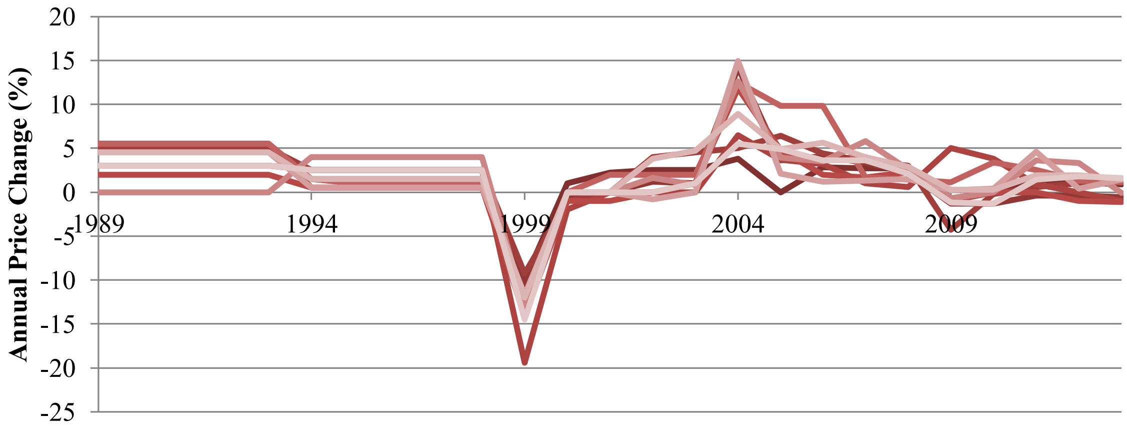


Figure 6-4: K-factors in FDs (annual price increase in %)

Data in Figure 6-4 reflects that water company prices were subject to full period average price increases for the initial period after privatization and PR94. Subsequently prices were adjusted at a year specific level. The data here could go some way to support a cycle theory. After privatization, prices were held high (allowed rate of return in 1989 was at 13%, and investors between 1989 and 1994 made between 25 and 34%! [*Ofwat*, 1994]). Subsequently, this was reduced and then in PR99 reduced again sharply. As reviewed in Chapter 4, by 2004 several important EU directives were begininng to require implementation (UWWTD being the most prominent at the time). These drove new expenditure requirements. However it is hard to isolate these different aspects as FD publications provide simple reporting of the X (efficiency challenge) and Q (quality investments) only for PR94, PR99, and PR04.

Comparable K-factor data that is available for all price reviews is that presenting the difference between the BPs and FDs as shown in Figure 6-5. Given the Treasury report mentioning how companies saw BPs as bids this provides a potential measure of the degree of trust between regulator and firms. A large difference can be seen as either gold-plating by the companies or as unnecessary stringency and potential expropriation by the regulator. One of the interview respondents for this research provides a quote which can serve as a very helpful commentary on the data in Figure 6-5:

> "…PR99, very very little trust. Companies gold plated. PR04 absolutely no trust at all. Ofwat felt quite offended. Since then trust has been building. PR14 the biggest companies were allowed to do more of their own thing. There was a bit more trust there. But I would say there isn't that much trust between Ofwat and the companies. […] I think PR99 we played the game and they realized that it was a very, very generous settlement. A donation. They clamped down beyond what they probably should have in PR04. After that it has been building up. PR09. PR14. Rebuilding of trust or building of maturity perhaps because I think the companies behaved better."

Figure 6-5: Difference between BP and FD K-factors

The data from PR94 and PR99 show that the regulator was cutting down BPs relatively strongly at the time. The fact that the BP-FD difference goes down by 2004 while the interviewee claims "PR04 absolutely no trust at all" and that Ofwat "clamped down beyond what they probably should have in PR04" can be reconciled assuming WCs provided accurate BPs and Ofwat's 1% to 4% challenge was still excessive.

Secondly, the interviewee mentioning learning goes to support a fictitious play interpretation of PI cycles. The regulator and firms are over time learning and adapting to each other's strategies as predicted by the fictitious play model in the trustee game. One important part of this learning has been the way the regulatory system has changed over time.

Increasing and Adapting Incentive Mechanisms

The system of incentives employed by Ofwat has expanded substantially over time. In PR94, the Final Determination argued:

> "When [companies] reduce their operating costs below the level allowed for in the determination, maintain the service capability of their assets more efficiently or are able to raise money in the capital markets more cheaply than assumed by the regulator, they will be rewarded by the additional profits that will accrue. At the subsequent Periodic Reviews, the regulator can ensure that these benefits are, in time, transferred to customers through lower price limits." [*Ofwat*, 1994]

So, other than the incentives inherent to fixed price regulation (which are dampened by the regulatory ratchet), no other incentive mechanism was mentioned. Over the subsequent price reviews a series of additional incentive mechanisms was deployed as shown in Table 6-1.

In particular several instruments have been adopted to manage issues of regulatory gaming. The Opex Incentive Allowance rolls consistent cost reductions over into future price reviews mitigating the ratchet effect by a few years. CIS rewards lower forecast capex, aiming to reduce the capex bias [*Ofwat*, 2011]. ODI's incentivize outcome delivery as against a performance commitment across a series of indicators developed in consultation with Customer Challenge groups, aiming to refocus incentives on outcomes and not on inputs [*Ofwat*, 2017a]. However as mentioned by one interviewee, as long as the RCV remains in place it is likely to remain the overarching incentive maintaining a capex bias.

Table 6-1: Key changes to the system of economic regulation over time

PR99	*Opex incentive allowance*: sustained operational savings are rolled up into the next period extending the 'ratchet'. *Overall Performance Assessment (OPA):* Relative performance across a range of indicators leading to K factor adjustments in the range: [+0.5%, -1%]
PR04	-
PR09 [*Ofwat*, 2010b]	*Capital Expenditure Incentive Scheme (CIS)*: with the aim of mitigating 'gold plating' and the exploitation of information asymmetry [*Ofwat*, 2011] *OPA replaced by Service Incentive Mechanism:* OPAs had converged and SIM provided a better measure of service quality. [+0.5%, -1%]
PR14	*TOTEX Menu regulation:* Firms are offered a menu of total expenditure incentives to address capex bias and strengthen cost reduction incentives. *Performance Commitments (PCs) and Outcome Delivery Incentives (ODIs), Customer Challenge Groups (CCGs)*: Groups of customers are consulted in detail about BPs and have input on key PCs for ODI's. *Enhanced Status:* firms deemed to report good information in a timely manner are streamlined in the regulatory system.
PR19 [*Ofwat*, 2018a]	*SIM replaced by C-MeX and D-Mex:* C-Mex and D-Mex are new measures of customer and developer satisfaction [*Ofwat*, 2017a]. *Menu regulation abandoned*: introduced for PR14 has been abandoned for PR19. This was popular among respondents to the consultation for PR19 [*Ofwat*, 2017b] and partially in order to introduce a simpler cost sharing mechanism [*Ofwat*, 2017a].

Technology Selection in PI Cycles

The theory of PI cycles also has important implications for technological change in the regulated utility. Under the theory of PI cycles, most capital is formed during periods of high-returns when the firm is under strong incentives to develop its asset base. As the theory of PI cycles draws on the literature around gold-plating it broadly indicates that in those phases of capital formation the technology choice will fall in favour of technologies with a larger capital expenditure as opposed to smaller scale technologies which are less capital intensive but have a higher operational expenditure.

This has been recognized by Ofwat and hence in PR14 the regulator moved away from a differentiated approach between CAPEX and OPEX towards one focusing on TOTEX. This way it is hoped that the regulatory framework would not induce distortions to technology decisions giving each equal regulatory support. In terms of the theory of PI cycles this change can be understood to be part of the reaction to a period of high-returns and high-prices where capital formation is no longer the priority and the regulator is more stringent and drives prices down.

Political Pressure

> "What cannot be changed is the current form of privatization; legally, there could be deprivatization but the practical difficulties are so great that no government is likely to feel the costs worth the change, or that it is a sufficiently high priority for reform." [*Green and Anton*, 2012] p209

Today the prospect of renationalization is not nearly as far removed as this quote states. A set of reports and academic publications have contributed to a mounting political pressure on the regulator and companies to reduce profits. The most recent of these is a report by PSIRU [*Yearwood*, 2018] shows how almost all of the debt taken out by water companies has gone not to finance new investment but rather to pay dividends in England, while for Scottish Water which is under a different regulator and is majority owned by the Scottish government, this is not the case. Motivated in large part by a critique of profits being made by the water companies, the UK Labour Party recently adopted nationalization of the water sector as part of its policy manifesto [*Labour Party*, 2017]. Likewise, the Conservative Party Secretary of State for Defra, has publically criticised water sector profits and dividends [*Gove*, 2018]. At the same conference, the Ofwat CEO reiterated the issue of profits and dividends [*Cox*, 2018].

Clearly, there is pressure on the regulatory system to drive down profits and hence prices. This goes further to support the claim that at this point in time, the PI cycle is likely to move into lower price states. Accordingly there will likely be greater pressure on affordability and hence cheaper technological solutions.

6.5 Conclusions

Trust is a core issue in economic regulation. The trustee game was used to represent two-sided issues of trust in the regulatory action arena. Under dynamic systems models and fictitious play, decision makers in the trustee model will fall into a cyclical pattern. This can be interpreted through the Theory of Price-Investment Cycles.

Evidence from data and interviews show that trust issues exist and that a cyclicality to this dynamic can be seen within and across price reviews. Evidence from interviews and changes to PR methodology indicate that Ofwat and the companies are learning and adapting their practices to mitigate these issues. This can be seen to be part of the long term cycle which has implications for technology change in the sector. As the PR methodology moves more heavily into incentive based regulation and the role of RCV is adapted within this, it can be expected that technology in the sector will more towards less centralized systems.

Recent political pressure and the increased potential for renationalization are placing renewed pressure on regulation, prices and returns in the water sector. This could have far reaching implications for investment and technological choice although characterizing this potential alternative institutional configuration is outside the scope of this research.

Chapter 7: Trust and transitions in trustee and coordination models

Key Points:

- Variants on the Coordination Game and the Trust Game are used to model technological change and regulatory commitment.
- Nash, GMCR, and reinforcement-learning are employed as part of a CIGA to modelling the focal action arenas
- Less informed decision-makers may achieve better outcomes in transitioning to better technologies.
- While all decision methods struggle with lock-in in Coordination Games, outcomes in trust games vary much more for different decision-methods.

Research in water governance and resource management is increasingly reliant on models of human choice. How decision-making is understood is a fundamental assumption underpinning much contemporary environmental research. Archetypal game-theoretic models of the Prisoners Dilemma, Chicken, and the Stagg Hunt have been reviewed as models for generic water resource management conflicts [*Madani*, 2010].

This chapter employs the CIGA to two issues pertinent in water governance: 1) Coordination Game: Firms and regulators need to coordinate in changing technological or regulatory regimes. 2) Trustee Game: Regulating water companies requires trust between firm and regulator. The CIGA highlights the need for a comparative approach to modelling SESs which this chapter does through the use of multiple decision making characterizations as well as variations in game structure reflecting different possible preferences the actors involved face. In terms of an Information-Graded approach this chapter takes a more abstracted view than the Chapter 6 which delved into more depth on SES characterization.

Water governance can be defined as: "the range of political, social, economic and administrative systems that are in place to develop and manage water resources, and the delivery of water services, at different levels of society." [*Rogers et al.*, 2003] Governance is the process by which technological and institutional configurations are adopted by a set of actors with potentially diverging preferences over these configurations. As shown in Chapter 2, participants in socio-technical regime coordinate in the adoption of new and innovative technologies or regulations [*Geels*, 2011]. The Coordination Game (CG) has been used to model the emergence of technological change under increasing returns [*Arthur*, 1989; *Zeppini* *et al.*, 2014]. The resultant 'lock-in' dynamics can also be observed in institutional change generally [*North*, 1990] and as such, lock-in has also been observed in greenhouse gas [*Unruh*, 2000] as well as water governance [*Saleth and Dinar*, 2004].

The CG has been used to model the emergence of technological change [*Arthur*, 1989]. For some technologies, increasing returns to adoption generate positive network effects, meaning that the benefits of adopting grow with the number of adopting actors. The above discussion of water sector peculiarities highlighted the tendencies towards monopoly and other instances of increasing returns in the water sector. 5 of 17 companies in the UK water sector identify innovation as including the adoption of technologies and techniques successfully adopted by others [*London Economics*, 2009]. While learning from others and adopting techniques with a proven track record is an important part of technological progress, the resultant dynamics generate a tendency towards lock-in. As more companies adopt a technology further improvements in that technology are likely. This further increases the relative performance of this technological path against that of others which may have been better alternatives in the longer term.

One of the key insights of this view is the threshold nature of technological change. Once a given share of the population has adopted a technology, it is likely to diffuse rapidly. However, getting to and breaching this threshold can be difficult if no actors are willing to incur the associated first-mover disadvantages. These dynamics aim to explain lock-in or path-dependent continuity in sub-optimal technologies. [*Arthur*, 1989] shows that under rational expectations with full information, starting from a position of equal shares, the expectation of lock-in actually works to expedite the lock-in to a single technology. For a critical review of mechanisms leading to path-dependent continuity see [*Beyer*, 2010]. For a review of other threshold models of technological change, in particular a further variant on the CG which involves asymmetric penalties for misalignment see [*Zeppini et al.*, 2014]. Variations on the CG will be the basis for the technological transition model here.

The Multi-level Perspective literature understands the process of technological change as an interaction between protected niches where innovations develop, established socio-technical 'regimes', and macroscopic 'landscape' tendencies and pressures [*Geels*, 2002]. Regulation plays an important part in the path-dependent nature of socio-technical co-evolution [*Unruh*, 2000]. Institutional standards themselves can exhibit tendencies towards lock-in, and institutional change has been found among other things to depend on the institutions history [*Bhat and Blomquist*, 2004]. In a case study on the transition from surface water to piped water in the Netherlands, [*Geels*, 2005b] argues that technological change can at times only happen as part of a broader social change because the established governance configuration is unable to find a solution within its current form. While lock-in can happen in the space of technological options, essentially the same dynamic happens among institutional and regulatory options.

As argued in Chapter 2, investments in water infrastructure needed for supply and environmental quality improvements require trust in the regulatory authority. As the regulator often has the authority to expropriate value from them through price controls or other powers [*OECD*, 2015], how it commits to not abusing its statutory tools is a prevalent concern in its governance [*Levy and Spiller*, 1994; *Rogers et al.*, 2003; *Stern*, 2014]. The trustee model is at the core of other game-theoretic analyses of regulatory commitment [*Dassiou and Stern*, 2009] where contracts between government and investors are made while the investor updates its belief in the trustworthiness of the government to honour its contractual agreement.

However this model ignores the potential for the firm to game the regulatory system by gold plating or employing low-effort (see Chapter 2 and Chapter 6 for further detail on this issue). The trustee model [*Ostrom*, 2009b] used here, allows for this two-sided trust issue to be modelled: a regulator able to set prices (an thereby expropriate value) and the firm with the ability invest (or expend effort finding the most efficient technology or practice).

Three variants of the CG (reflecting different possible technology performances) and two variants of the trust game, as found in [*Ostrom*, 2009b], are analysed here. In line with the CIGA, these models are analysed with Nash equilibria, the Graph Model for Conflict Resolution (GMCR), and reinforcement learning.

The CIGA is applied to these models with a particular view towards prescriptive outputs, namely analysis based on the assumption of a choice between different tools and hence the ability to prescribe which will yield the best outcomes for the participants in the relevant action arenas (see Chapter 2). The implications of the analysis outputs here are twofold: 1) Which tools are effective in different game structures? In other words, which kinds of tools are better at coordinating and trusting? 2) Are the problems of coordination and trust resistant to the selection of tools? In other words, if we could choose the tool, would we be able to overcome these issues or are they intractable under every tool considered?

The outcomes of the analysis are twofold: 1) Which tools deliver good outcomes across different games? The caution that allows some GMCR tools to cooperate in the PD and Trust games prevent effective alignment in Coordination Games. Without awareness of the others' action, reinforcement learning yields better outcomes in both coordination and trust games. 2) Which outcomes are consistent across different tools? While all tools struggle with lock-in in Coordination Games, outcomes in trust games vary much more across tools.

7.1 Coordination Game (Transitions)

The actions available to players in CG are the same set of technologies. The models used here deploy a set T of two technologies; $T := \{a, b\}$. The CG is here modelled in three variants: "Choosing Sides" (Figure 7-1a shows this in strategic form and 7-1b shows this game in graph form), "Battle of the Sexes" (Figures 7-1c and 7-1d), and "Pure" Coordination (Figures 7-1e and 7-1f). The common dynamic in these games is that both players have a preference to be *aligned* on one option. The utility functions for all players, given the network effects of the technology are such that

$$u_i(t_i, t_j) > u_i(t_i, t'_j), \ \ \forall i$$

Eq. 7.1

where u_i is the payoff to player *i* which is a function of the technology choices t_i; j is a different player; *t* is one of the technology options $(t \in T)$ and *t'* is a different technology option. The variants reflect potential differences in the preferences actors have over the aligned states. Variants of the CG where coordination is simply a matter of aligning on one choice ("Choosing Sides") set;

$$u_i(t_i, t_j) = u_i(t'_i, t'_j), \ \ \forall i$$

Eq. 7.2

The variant of the CG where preferences over the technological configuration are divergent "Battle of the Sexes");

$$u_i(t_i, t_j) > u_i(t'_i, t'_j), \qquad u_j(t_i, t_j) < u_j(t'_i, t'_j)$$

Eq. 7.3

and those where both sides agree that one technology is better than the other ("Pure Coordination").

$$u_i(t_i, t_j) > u_i(t'_i, t'_j), \ \forall i$$

Eq. 7.4

In “Choosing Sides” the agents do not have a preference for one technology over the other. The name comes from the question of choosing the side of the road to drive on: we do not really care which side, as long as we all agree on one side. It is rare to find that there is no significant difference among a set of choices, however it does happen that a reference standard, language, or other institution must be chosen. Technological or institutional choices may have differences but with such performance uncertainties that they are essentially of equal value. This can be the case when considering options with impacts very far into the future such as different climate change adaptation measures. Performance uncertainty can also be high if the past performance of a policy is not consistent. Alternatively, the performance in one assessment criterion may be offset by another roughly equally so that the options, when aggregated across criteria, perform roughly the same.

Figure 7-1 shows that in all three settings, alignment of both players on any technology, if adopted by both players are Nash equilibria. A mixed strategy equilibrium also exists in each game. In “Choosing Sides”, misalignment can be expected half of the time. In “Battle of the Sexes”, each player assigns a higher probability to their more preferred technology generating a higher probability of misalignment (5/9). In “Pure Coordination” both players play the less preferred technology with a probability of 2/3 meaning misalignment is expected 4/9. It is counterintuitive that if both agree on the preferred option, they would be less likely to achieve it and more likely to remain in the initial state than if they are ambivalent between options.

The GMCR analysis shows that alignment is a convergent condition for all tools. It also finds the misaligned condition to be convergent for all tools which consider disimprovements without knowledge of the others’ preference. Only those tools which include knowledge of the others’ preference do not find misalignment to be convergent. One important point to note is that the GMCR has the same results for all three variants, reflecting the fact that the relative preferences between the different technologies do not come into play – only the improvements from moving from misalignment to alignment are taken into account.

Regulator

Investor	Tech a	Tech b
Tech a	1 , 1	0 , 0
Tech b	0 , 0	1 , 1

Figure 7-1a: “Choosing Sides”

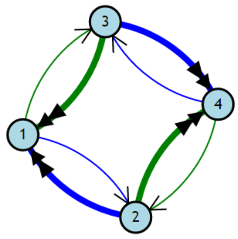


Figure 7-1b: “Choosing Sides” in graph form

Regulator

Investor	Tech a	Tech b
Tech a	1 , 2	0 , 0
Tech b	0 , 0	2 , 1

Figure 7-1c: The “Battle of the Sexes”

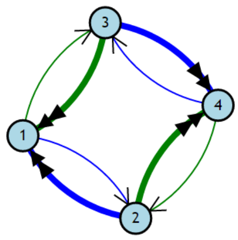


Figure 7-1d: “Battle of the Sexes” in graph form

Regulator

Investor	Tech a	Tech b
Tech a	1 , 1	0 , 0
Tech b	0 , 0	2 , 2

Figure 7-1e: “Pure” Coordination

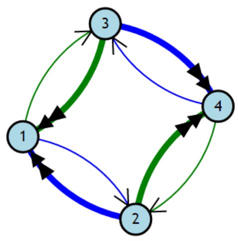


Figure 7-1f: “Pure” Coordination in Graph form

Figure 7-1: Coordination Game Variants

Table 7-1: Comparative modelling applied to CG variants

Coordination Variant		Choosing sides				Battle of the Sexes				Pure Coordination			
firm	transition	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
regulator	transition	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
Payoff For:	firm	4	3	3	4	4	2	2	3	3	2	2	4
Payoff For:	regulator	4	3	3	4	3	2	2	4	3	2	2	4
	Ignorant	0.9	0	0	0.1	0.9	0	0	0.1	0.75	0	0	0.25
	Adaptive	0.4	0.2	0.2	0.2	0.4	0.2	0.2	0.2	0.4	0.2	0.2	0.2
	Mixed-S.	0.25	0.25	0.25	0.25	0.22	0.44	0.11	0.22	0.44	0.22	0.22	0.11
	Nash	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y
	GMR	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	SEQ	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y
	SIM	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	SEQ & SIM	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	SMR	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y

Figure 7-2 shows the results for agent based simulations of the three CG variants for the two variants of reinforcement learning. The 100 simulations are ordered top-to-bottom and time steps from left-to-right. Each figure depicts the state the game is in at a given time-step via coloured blocks. Each state is assigned an index number and colour coded. White (index value 1) is alignment on initial state, grey (2) and blue (3) are misaligned states. Black (4) is alignment on the non-status quo technology. Runs are sorted top to bottom by the index value of the state in the final time step and subsequently by sum of index values over time steps. Simulations were all started from a status quo position of alignment on non-transition (i.e. Tech a).

By considering the state pattern over time, convergent states and rates of convergence to the different states can be seen. Where a row's colours stop changing after a given time, a convergent state can be identified.

Ignorant agents find technology alignment convergent in all three variants. In both "Battle of the Sexes" and "Choosing Sides" agents were largely locked in to the initial state with only a very small share transitioning to the other technological alignment. Under "Pure

Coordination" they are able to transition slightly more often although most runs return to the initial state. It is noteworthy that with much higher ε-greedy values all runs converge to the preferred technology but this is not often achieved under the ε-greedy value calibrated in the PD. Random attempts at transition do not likely coincide, hence the option of transition retains a low value.

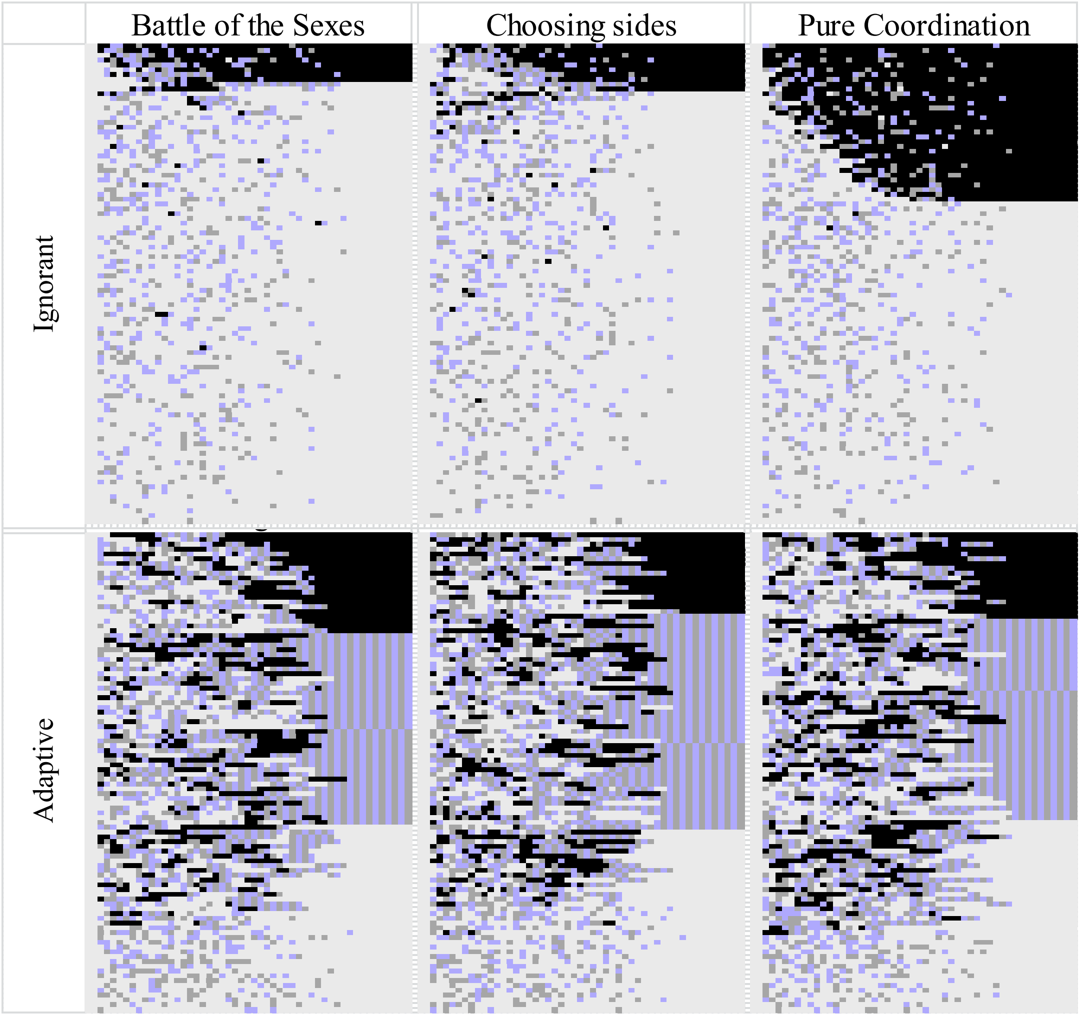


Figure 7-2: CG variants for the states of 100 runs of ignorant and adaptive agents over 50 simulated time steps.

0 to 50 steps left to right. Each state is assigned an index number and color coded (1) is alignment on initial state, grey (2) and blue (3) are misaligned states. Black (4) is alignment on the non-status quo technology. Runs are sorted top to bottom by the index value of the state in the final time step and subsequently by sum of index values over time steps.

Adaptive myopic agents yield the same pattern of outcomes across the three variations. A share of runs never transition at the same time and remain in the status quo for this reason. Another share does have simultaneous transition and remains there or returns to converge at the initial alignment. Finally, a substantial share of runs fall into a cyclical misalignment with each attempting to adjust to the other, leading to each changing the strategy each turn and never aligning, instead converging to incessant switching.

In summary, the CG, when analysed with the GMCR yielded the same outcomes for each variant. Reinforcement learning also found identical outcome patterns across game variants with the exception of ignorant myopic agents who were able to transition slightly more often under "Pure Coordination". Ignorant myopic players exhibit a stronger tendency lock-in than the adaptive agents. Adaptive players often converge to a cycle of misalignment. Adaptive players also had a share of runs simply remain in the initial state and never discover the option of an alternative alignment. Adaptive agents also did not change the pattern of outcomes under different preferences over the technologies indicating that lock-in is further compounded by better information of the game structure.

7.2 Trustee game (Cooperative Investment)

The Trust Game, as found in [*Ostrom*, 2009b], is a two-step, two-player game involving an investor (*x*) choosing whether to make an investment with a trustee (*p*). If the investment is made, it is multiplied by 3 to give the added value of the investment having been done. The trustee then chooses how much of the now tripled sum to return to the investor. Figure 7-3a and 7-3b below represent a simplification of this game as used to model the action arena here. Instead of functions used in the original characterization, here the investor can choose between investing or not $\{x_1, x_0\}$. The regulator chooses between yielding high returns and low returns $\{p_1, p_0\}$. Utility values u_i in the cells represent both cardinal and ordinal values for player *i* as before.

It is assumed that when the trustee reciprocates they give the investor a share of the winnings such that the investor is better off than if they had kept the investment to themselves:

$$u_x(x_1, p_1) > u_x(x_0)$$

Eq. 7.5

If the investor does not invest, it is ambivalent as to where the regulator sets prices. This untrusting outcome is better than if investment is made and the regulator sets a low price which reflects expropriation.

$$u_x(x_0) > u_x(x_1, p_0)$$

Eq. 7.6

The two variants on the game are the “Trust Game” and “Predator-Prey”. The “Trust Game” simply translates the two-step Trust Game into a one-step strategic form game. Given a choice by the investor not to invest, the regulators decision has no effect on either players performance.

$$u_p(x_0, p_0) = u_p(x_1, p_1)$$

Eq. 7.7

Given the fact that many regulators seek to attract investment in the sector they are regulating and are often mandated to do so, the “Predator-Prey” variant (Figure 7-3c) adds a preference for the regulator to raise water prices in order to attract investment if none is there.

$$u_p(x_0, p_1) > u_p(x_0, p_0)$$

Eq. 7.8

The name is taken from biological models of predation where the predator (regulator) depends on the survival of its prey (investor) which in certain models are understood to exhibit equilibrium points around which they cycle [*May*, 2001].

There are two Nash equilibria: one with no investment and low prices as the regulator has no preference for raising prices without investment. The second is a mixed strategy with no investment but the regulator chooses between high and low prices with equal probability. The only Nash equilibrium in this game is a mixed strategy equilibrium where each option for each player is played with a 50% likelihood. As there is no pure strategy Nash equilibrium the GMCR does not identify one. The non-investment (state 1) and the investment *with high prices* (state 2) are both convergent under GMR, SEQ, SMR, but not under SIM. A risk of low prices deters the desired investment to make state 1 convergent. State 2 is convergent as the regulator recognizes that the investor can sanction a low price by withdrawing further investment. The risk for the regulator to lose the trust of the investor and to fall into a mutually suboptimal state is clearly at the forefront of the GMR analysis.

Trustee

Investor	Reciprocate	Do Not Reciprocate
Invest	**2** , 1	**0** , 2
Do not Trust	**1** , 0	**1** , 0

Figure 7-3a Trust game in strategic form

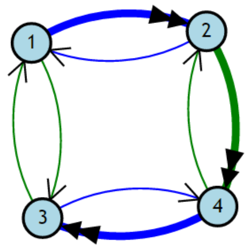


Figure 7-3b. Trust Game in Graph form

Regulator

Investor	High Prices	Low Prices
Invest	**2** , 2	**0** , 3
Withdraw	**1** , 1	**1** , 0

Figure 7-3c. "Predator-Prey" in strategic form

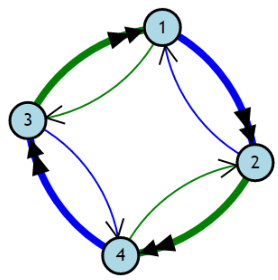


Figure 7-3d. "Predator-Prey" in Graph form

Figure 7-3: Trust Games

Most ignorant agents were not able to maintain investor confidence in the Trust game, with the regulator subsequently randomly choosing between price levels. Adaptive investors learned to invest when prices are high and so the states with investment happened far more often as part of a randomly delayed cycle. The random delay occurs when the regulator does not raise prices.

Table 7-2 shows the results for these two games. As before the first two rows indicate which actions (or strategies) are being taken. The combination of actions defines the outcome or strategy profile. So the outcome in the first row is where the investor does not invest and the regulator does not set low prices.

Table 7-2: Comparative game modelling as applied to the two variants of the Trust Game.

		Strategic Form Trust				Predator Prey			
investor	Invest	N	Y	N	Y	N	Y	N	Y
regulator	Low prices	N	N	Y	Y	N	N	Y	Y
Payoff For:	investor	2	3	2	1	3	4	3	2
Payoff For:	regulator	2	3	2	4	2	3	1	4
	Ignorant	0.33	0.33	0.33	0.01	0.50	0.50	0.01	0
	Adaptive	0.2	0.2	0.35	0.25	0.25	0.25	0.25	0.25
	Mixed-S.	0.5	0	0.5	0	0.25	0.25	0.25	0.25
	Nash	N	N	Y	N	N	N	N	N
	GMR	Y	Y	Y	N	Y	Y	N	N
	SEQ	Y	Y	Y	N	Y	Y	N	N
	SIM	N	N	Y	N	N	N	N	N
	SEQ & SIM	Y	Y	Y	N	Y	Y	N	N
	SMR	Y	Y	Y	N	Y	Y	N	N

As can be seen in Table 7-2, the addition of a regulatory preference for high prices under low investment in the "Predator Prey" game led to very different outcomes.

Figure 7-4 shows the results for reinforcement learning variants applied to the trust game variants. Note that the starting state has investment with a high price which is highlighted in grey in the first two rows defining the state move configuration.

Ignorant agents now manage to maintain investment in half of the cases and stabilize in a state of no investment and high prices otherwise. For adaptive agents, the distribution of state counts is equal among the states just as it is in the mixed strategy equilibrium however for different reasons. Adaptive agents consistently converge to a cyclic pattern: invest, lower prices, withdraw, raise prices, then invest again, and so on. This can be seen by the regularity of the pulses in Figure 7-4. It is noteworthy that in this context convergence does not mean remaining in a single state but rather a pattern of change between states.

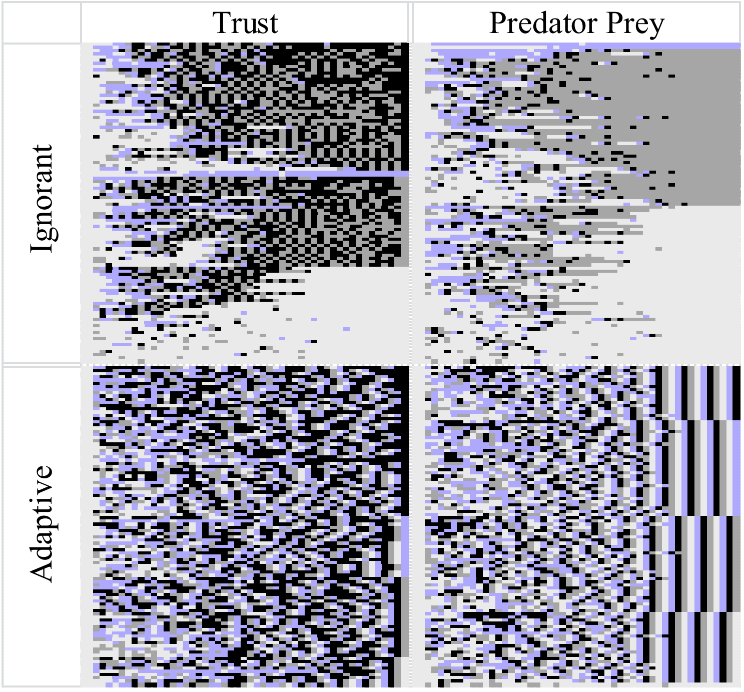


Figure 7-4: 100 runs of 50 step repetitions in the Trust games.

Sorted by state index in final state then state index sum: 1) the initial state is investment and reciprocation (white), 2) investment high price (grey), 3) no investment high price (blue), 4) no investment low price (black)

The probability distribution in the mixed strategy equilibrium is a function of the cardinal utility values for each player, while the distribution of state-counts in the adaptive agent simulation is a result of cycling through the states. Each run has its last random move at a random time step and hence runs are at different states in the cycle in the final step.

In summary, the variation between the “Trust Game” and “Predator Prey” game changes outcomes for each tool. The smallest change is for the adaptive agents who cycle through the states in both variations, but do so in a regular pattern under the “Predator Prey”. Adaptive agents find stability in the same states as all the GMCR tools except Simultaneous Stability (SIM).

7.3 Discussion

The discussion will first briefly review the results and subsequently address the two sets of implications of these analyses: 1) which decision-making methods yield good outcomes? 2) which outcomes are consistent across decision-making methods?

GMCR solutions enable cooperation in the PD while reinforcement learning can do this only when the algorithm does not look for an alternative to a cooperative status quo. GMCR concepts which allowed convergence to cooperation in the PD, fail to reach coordinated outcomes in the Coordination game. Variants on the coordination game show that differentiated preferences over options do not affect outcomes greatly. Reinforcement learning simulations are able to converge to coordination and do so at a higher rate when an alternative technology is preferred by both agents although generally transition fails and the agents are locked in to the suboptimal state. If agents are aware of the others' action a dynamic pattern of alternating between states of technological misalignment emerges as convergent and the fact that one technology is preferred over the other by both players becomes irrelevant. Ignorant agents are then better able to transition than agents aware of others' actions.

GMCR analysis of the trust game shows that investment is inhibited by the risk of non-reciprocation by the trustee. Trustees with a preference for supporting investment when it is absent, reduce the convergence of non-investment outcomes. Under reinforcement learning, ignorant agents show this preference to relatively effectively induce investment. Agents aware of others' actions commonly converge to a cyclical pattern (invest, lower prices, withdraw, raise prices, invest, etc). With no preference for inducing investment when it is absent, agents are actually more likely to remain in an investment state and not to enter this cycle, whereas with the preference adaptive agents consistently enter the cyclic pattern. As with the coordination game, increased agent sophistication can be counterproductive to reaching desirable outcomes.

Which decision-making methods yield good outcomes in all games?

Broadly, the ignorant agents were best able to deal with the issues presented. Reinforcement-learning allowed these agents to align in coordination games, transition more often when the transition is in both players' interest, and develop some degree of trust in the trust games, particularly when regulators have a preference for high prices under no investment. The GMCR concepts are however able to find convergence in a cooperative state in the prisoner's dilemma which the reinforcement learning agents were not able to. Adaptive agents and Nash equilibria often found someone counterintuitive results: cyclical misalignment and no- or counterproductive effects of common preference for transition. SEQ and SMR were effective in coordination and trust both successfully avoiding misalignment and finding trusting outcomes convergent, however both also suffer from finding Nash equilibria convergent, hence being further locked-in in coordination and converging to states of distrust.

Which game problems are difficult for many different decision-making methods?

From the above analysis that as long as the general structure of the coordination game holds, the issue of coordination will persistently lead to sub-optimal technological or institutional alignment. The only way out of this problem is that agents must accept a higher cost incurred by exploration. The higher ε-greedy value means that more random moves will be made. The crucial issue being that it is important to make sure these costs are incurred at the same time. In the water sector, where public health concerns are primary involved actors are generally not willing to incur the potential costs of experimentation. Having arrived at a workable technological and institutional co-configuration they will not easily find another feasible configuration better than the status quo.

The variation between the "Trust Game" and "Predator Prey" game changes outcomes for each decision-making method. This is an important part of real-world water governance where regulators or procuring public authorities must be able to effectively commit to the private involvement. One of the problems of water governance in countries with weak instruments of institutional commitment is that investment will not happen or will require a much higher guaranteed rate of return in order to cover the regulatory risk. If this is possible however, it will likely deliver better results, the only exception being to adaptive agents where the difference is not substantial in that the cycling happens in a more regular pattern.

7.4 Conclusions

Comparative game modelling yields insights into different aspects of a multi-decision-maker situations. While Nash equilibria analysis is often considered a benchmark, its limitations have led to the widespread consideration of alternative tools. The use of a comparative approach allows for exploratory modelling efforts to consider which tools are better than others in a given situation or across multiple different decision situations. It also allows for understanding which kinds of problems may be difficult to solve for many different kinds of agents and hence pose substantial challenges regardless of tool employed.

Better informed decision-makers such as those aware of others' decisions (adaptive agents) or Nash equilibria often do not deliver better outcomes than less informed agents. This is not necessarily the case as being aware of whether a counter-move will be in the interest of the other player is important and therefore GMR and SMR find technological misalignment convergent. The exact nature of the bound on information will determine the effectiveness of the tool in a given situation.

Coordination problems are an issue for most tools. The lock-in to suboptimal technologies is a problem for every tool reviewed here. Importantly, differences over technological preference do not change outcomes at all except in the case of mixed strategies where they can create perverse effects and in the case of ignorant reinforcement learning where the preference for an alternative technology will help in the transition especially with high rates of random explorations.

Future directions in this research are plentiful. Alternative games can also be analysed with this approach and alternative tools can be employed. This chapter has taken some popular games and tools from the literature and applied these. An empirical basis for the possible tools is important to develop in their application, however some heterogeneity will likely persist and this comparative approach can be used in developing effective policies for such situations. The key difficulty of this approach is to bring a common framework to understanding patterns of convergence and transition to the integration and comparison of the different tools.

Chapter 8: Myopia and Foresight in Water Technology Public Goods

Key Points:

- Water technology adoption is modelled as a public goods problem.
- Myopic stakeholders under-invest despite rising costs of inaction.
- With foresight decision making develops innovation earlier through strategic loss.
- The incentive for foresight is ambiguous, depending on differentiation between players.

8.1 Introduction

Sustainable management of water resources requires the involvement of the multiple decision-makers. If they do not consider long-term outcomes of short-sighted strategies, it is likely that technology adoption will be postponed. This delay may mean that more expensive measures may have to be undertaken later as water stresses accumulate. The focus on regulator firm relationships in Chapter 6 and 7 is here turned to the action arena involving multiple users interacting over a public good problem. The application of CIGA's approach to rationality in this context focusses on the role of foresight.

These types of problems have been understood under the umbrella term of social dilemmas, such as common-pool resource (CPR) use or the provision of public goods [*Hardin*, 1968; *Ostrom*, 1990]. Variations on these models have been used to explain problems across a range of social and environmental problems, such as climate change mitigation [*Madani*, 2013], irrigation maintenance [*Podimata and Yannopoulos*, 2015], and fisheries [*Bailey et al.*, 2010].

This chapter is an adapted version of a paper in Water Resources Research which formally explores the role of foresight in a model of a public good [*Ristić and Madani*, 2019]. That paper considered the role of foresight contextualized to an irrigation system. Here this model is applied to the adoption of water technologies in the face of rising water stress and demand. The model presented here employs only the continuous time variant of the model and presents a more sophisticated approach to interconnection across time, taking into account cumulative risks showing also how the core result is essentially the same as that in the simpler model presented in [*Ristić and Madani*, 2019].

Earlier models evaluated in this thesis developed a model of the regulator-firm relationship which can be seen as involving a certain hierarchy or asymmetry. Chapter 6 considered a regulator setting a price for a monopolists investment. This same hierarchy was considered in the trust games evaluated in Chapter 7. This chapter considers a different angle on water technology adoption. Instead of this asymmetry we consider players who are in a sense symmetric as each can make an investment in and is affected by a public good both players participate in. This is similar to the coordination games considered in Chapter 7. For the purposes of this chapter we will exemplify on the relationship between a water company and a large industrial user.

Assume WC *a* implements a technology to increase water supply such as a water recycling or desalination plant. This has the effect of reducing the need for another user to implement a measure in their practice. For example a large industrial (*b*) user can implement a water recycling system which would reduce the need for the local water company to develop a new reservoir or their own water recycling system. This creates a public goods problem as user *b* benefits from *a*'s innovation without contributing to it. Given symmetric reasoning about this from both *a* and *b,* the prediction is that public goods will be under-provided as users will free-ride each other's contributions.

As users free-ride however, the public good problem can become worse as water demand continues to rise and water supply remains at the given level. This changing game structure has been noted previously for other similar situations, from what appeared not to be a conflict, through a prisoner's dilemma to a game of chicken [*Madani*, 2013]. It has been argued [*Madani and Lund*, 2012] that the changing benefit, or utility, accruing to users due to the changing conditions over time have been overlooked in modelling natural resource management. The concept of "evolving game structure" was proposed in [*Madani*, 2010] and used to show how players' optimal choices can change over time due to these changing conditions. This was followed by the evaluation of the effect of evolving game structures on optimal choices in different natural resource management games [*Madani*, 2010, 2013; *Madani and Lund*, 2012; *Hui et al.*, 2016]. Relating to water supply options, as the water availability falls over time, there comes a point when one or a group of users are better off investing even if others continue to free-ride.

Remedial and preventative measures are often delayed due to uncertainty about changes in the underlying resource or the possibility that other actors will take on responsibility. As risks become more apparent one or more parties may eventually take on costs and responsibilities of more sustainable water management.

In characterizing the decision-making of resource users, interconnecting across temporally evolving games has already been explored in [*Madani*, 2011]. There, the concept of "strategic loss" was introduced in the context of temporally interconnected games. The term 'strategic loss' is used to denote when a player's loss in some subgame results in their increased gain in some larger game which that subgame is a part of. Strategic loss may appear as suboptimal play in the subgame. However given the larger game, strategic loss is part of optimal play. Accepting costs and responsibilities of contributing to a public good early on despite others' free riding is just such a strategic loss.

Strategic loss in interconnected games has been introduced and analysed using the tools of cooperative game theory in [*Madani*, 2011]. Here, the Nash equilibrium tool from non-cooperative game theory is applied. While cooperative game theory assumes players coordinate their actions when mutually beneficial and provides axiomatic formulae for how gains from cooperation are divided [*Stefano et al.*, 2006], non-cooperative game theory makes no such assumption . Instead each decision is modelled solely on the basis of individual utility maximization where mutual optimal responses generate equilibrium points (see [*Madani and Hipel*, 2011] for more detail).

In this chapter, a model of a two users investing in water supply options conceived of as a public good is analysed (as based on [*Madani*, 2010; *Madani and Lund*, 2012; *Madani and Zarezadeh*, 2014]). Myopic play is analysed as a series of games played independently over time [*Madani and Hipel*, 2011; *Madani and Dinar*, 2012]. Under myopia, opportunities for strategic loss are not identified by the players. Under Nash equilibrium, users allow the problem to worsen over time. With foresight however, temporally changing games are interconnected across, and opportunities for strategic loss become part of Nash equilibria. The decision makers are no longer blind to future changes and invest to ensure its sustainability, incurring strategic losses.

8.2 Model Characterization

To characterize a simple model of this issue consider first a one decision-maker situation for a water company. At any given time it has the option to invest in a water innovation or not to do so. If it pays immediately for investment it incurs the costs of that investment M. Making this investment is also considered to end the game. The justification for this is that the new investment resolves the issue of water supply-demand imbalance.

If the company does not invest it incurs the risk of failure F. This is understood as the costs of a failure to deliver water to customers. This can be interpreted as the incentive penalties associated with hosepipe bans, lost revenues, reputational damage and other costs. Additionally, if the investment is not made, the costs of the investment will go up because the issue of water supply-demand balance is now worse than it was initially and a larger investment is needed. $M(t)$ is then a function of time and this rising investment cost is denoted as:

$$\frac{dM(t)}{dt} > 0$$

Eq. 8.1

Second, if the investment is not made immediately, the risk of failure $F(t)$ also rises as a function of time. Since no investment was made the likelihood and magnitude of costs of failure rise likewise. This risk of failure however rises more rapidly than the cost of the investment needed to resolve the supply-demand imbalance, denoted as:

$$\frac{dF(t)}{dt} > \frac{dM(t)}{dt}$$

Eq. 8.2

A second user

The single decision maker situation is now extended to include another user. Given our initial decision maker was the water company, consider the second user as a large industrial user which has the potential to significantly affect water demand in the area of the water company. This is a simplified model with alternatives, including multiple other decision makers, considered in the discussion after the model is presented and analysed. The costs of this user are modelled with the same parameters as that of the water company (investment cost and risk of failure). The user can invest in their own water reuse system or incur the risks of failure for adequate water for production. If both users were to invest simultaneously they could share the investment burden. Given these two decision makers strategic interaction, the following cost function is used for each decision maker *i*:

$$C_{i,t} = (p_{i,t})\frac{M(t)}{1+p_{j,t}} + (1 - p_{i,t})F(t)$$

Eq. 8.3

where $C_{i,t}$ is the cost to decision maker *i* at time *t*; $p_{i,t} \in \{0,1\}$ is decision maker *i*'s payment at time *t*; $M(t)$ is the investment cost as a rising function of time *t*; $F(t)$ is the cost of failure which also rises as a function of t. As before, players have an option to invest or not, the choice being between the two terms of the equation: either incur investment costs or incur risk of failure.

If both the water company (denoted as *a*) and the industrial user (denoted as *b*) were to invest in a coordinated plan, the total investment cost would be split between them. After either or both make the investment the game ends so no payment for any time $q < t$ is assumed:

$$\int_0^{q<t} (p_{a,q} + p_{b,q}) = 0$$

Eq. 8.4

Assuming that even when split, initial investment costs are higher than initial cost of system failure $\frac{M(0)}{2} > F(0)$.

Equilibrium under myopia

Myopic players consider each time in isolation. While the risk of failure for a given time is below the cost of investment neither will pay moving the game to the subsequent stage. However, when risk of failure rises above required investment, the game structure changes to a game of chicken. The payoff matrix for this decision is shown in Figure 8-1.

		Industrial User	
		$p_{b,t}$	$\neg p_{b,t}$
Water Company	$p_{a,t}$	$\frac{M(t)}{2}, \frac{M(t)}{2}$	$\underline{M(t)}, \underline{0}$
	$\neg p_{a,t}$	$\underline{0}, \underline{M(t)}$	$F(t), F(t)$

Figure 8-1: The payoff matrix for myopic decision makers for where $F(t) > M(t)$.

Best responses are underlined and Nash equilibria are shown with thick outlines.

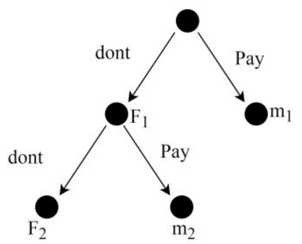
The two equilibria in this game reflect the fact that each player's best response depends on the opponents move. If the water company makes the investment, then the industrial user will not bear any more risk of failure and hence will not need to invest. Vice versa the same logic applies. If the industrial user invests, then the water company will not need to make the investment.

A third equilibrium involves mixed strategies where players assign probabilities to their strategies instead of playing one or another. However, mixed strategy equilibria are ignored here for two main reasons. First, no mix of strategies can give a higher expected value than a pure strategy response to any strategy (pure or mixed) by the opponent in our games. This would be one practical application of randomization [*Perea*, 2012]. Second, randomization does not provide a reasonable strategy recommendation to players in a non-repeated one-shot game with complete information. This applies to our later interconnected game for players with foresight also as that is also just a one-shot game.

Equilibrium under foresight

For continuous time with foresight, decision makers consider the cost of a strategy as the net present value of that course of action as shown in Figure 8-2.

Decision Tree



Choice

Strategy	*Cost*
Pay	m_1
Don’t, pay	F_1+m_2
Don’t, don’t	F_1+F_2

Figure 8-2: The decision-tree and strategy-cost pairs for a single decision-maker

The options the decision maker *a* faces can then be characterized as paying at a given time *t* ($p_{a,t}$) or not paying at all ($\neg p_a$).

a strategy s_i would be costed as $C_i(s_i) = \int_0^t C_{i,t}$. So for paying immediately:

$$C_i(p_{i,0}) = \frac{M(0)}{1 + p_{j,t}}$$

Eq. 8.5

For both players never paying $s_i = \neg p_i$

$$C_i(\neg p_i, \neg p_j) = \int_0^{t=\infty} \mathrm{F(t)}$$

Eq. 8.6

Finally, the costs of a strategy of making an investment at some intermediate time can be defined. As risks cumulate over time but investment is made at some intermediate point (so that cost of failure at that time is 0), current cost of failure must be subtracted. Hence, for paying at some intermediate point ($s_i = p_{i,t}$)

$$C_i(p_{i,0}) = \frac{M(0)}{1 + p_{j,t}} + \int_0^t \mathrm{F(t)} - \mathrm{F(t)}$$

Eq. 8.7

There are times when the cumulative risk of failure is below the initial investment costs and times when cumulative cost of failure is above initial investment cost. For clarity, these cumulative costs are denoted as:

$$\boldsymbol{X = \int_0^t F(t) - F(t) < M(0),\ Y = \int_0^t F(t) - F(t) > M(0)}$$

Eq. 8.8

Taking these cost functions for the two decision makers together, a payoff matrix of the game interconnected across time for the two players can be written down and is shown in Figure 8-3.

Industrial User

Water Company	$p_{b,0}$	$p_{a,t'}$	$p_{a,t''}$	$\neg p_b$
$p_{a,0}$	$\frac{M(0)}{2}, \frac{M(0)}{2}$	$M(0), \underline{0}$	$\underline{M(0)}, \underline{0}$	$\underline{M(0)}, \underline{0}$
$p_{a,t'}$	$\underline{0}, M(0)$	$\frac{M(t')}{2} + X, \frac{M(t')}{2} + X$	$M(t') + X, X$	$M(t') + X, X$
$p_{a,t''}$	$\underline{0}, \underline{M(0)}$	$\underline{X}, M(t') + X$	$\frac{M(t'')}{2} + Y, \frac{M(t'')}{2} + Y$	$\frac{M(t')}{2} + Y, Y$
$\neg p_a$	$\underline{0}, \underline{M(0)}$	$\underline{X}, M(t') + X$	$Y, M(t'') + Y$	$\int_0^\infty F(t), \int_0^\infty F(t)$

Figure 8-3: the Interconnected Game with parametric cost values.

Best responses are underlined. Nash equilibria are the cells with the thick outline. With foresight to beyond time t'' the game becomes a game of chicken.

The 'chicken' payoff structure holds across the interconnected game as a whole. Nash equilibria are in states where one or the other side pays the full amount immediately and the other plans on investing at any point subsequent to t'' including never paying. The core result is the same as for myopic players where $F(t) > M(t)$. One side invests as it expects the other not to. With foresight, however the side that will pay will prefer to do so in the first instance to avoid the rising investment costs. This is the core benefit of strategic loss.

Graphical Representation of Strategic Loss due to Foresight

Figure 8-4 shows the changing game structure over continuous time. The phase where the red line is above the yellow line but below the green line is a set of prisoner's dilemma games for myopic agents. There, paying together the players would have a lower total cost. However, the $\neg p$ strategy is strictly dominant. This ensures that myopic players continue not paying, extending the game. They only stop the game once the cost of inaction for one individual becomes higher than if that single player simply pays everything. When they reach the point where the red line reaches and surpasses the dark green one, the expected cost of system failure is higher than the investment cost borne by one decision maker. s_1^* is then where

$$F(t) = M(t)$$

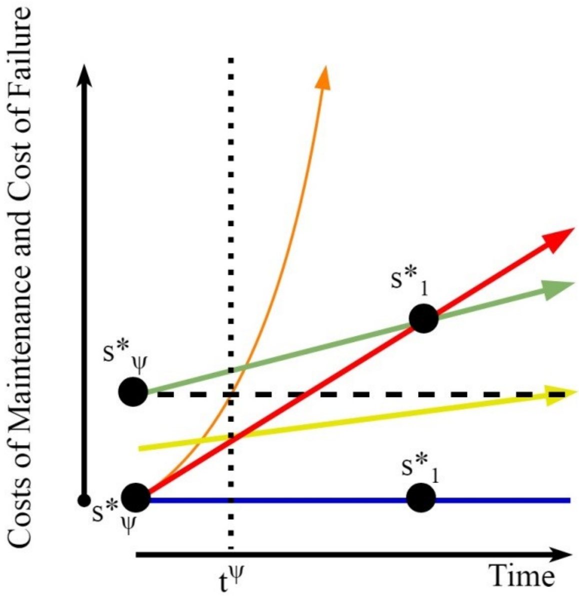


Figure 8-4: Cost functions in the temporally interconnected game from the view of one of the decision makers (*i*).

Green shows *i* investing while *j* does not; yellow shows equally split investment costs; and blue shows *i* not investing with *j* investing instead. Red is the cost of system failure. The dashed line indicates initial costs of investment which later costs can be compared against under foresight. The orange line indicates the cumulative risk of failure. The dotted line indicates where the cumulative cost of failure exceeds the initial investment cost, hence the extent of foresight required to support strategic loss at the start of the game. The points labelled s_{ψ}^{*} denote equilibrium under foresight to time t^{ψ}. Points labeled s_{1}^{*} denote equilibrium under myopia.

Players with foresight can compare their initial costs to the costs incurred by delaying across all the games they have foresight to. If foresight reaches to where cumulative risk of failure rises above costs of cooperative payment, the game becomes a prisoner's dilemma. With foresight to the point t^{ψ} where cost exceeds costs for a sole payer at the beginning of the game, players gain an opportunity for strategic loss. Strategic loss here involves losing the initial game $t = 0$ (i.e. paying immediately) in order to avoid future costs – yielding the equilibrium strategy s_{ψ}^{*}.

The horizontal dotted lines in Figure 8-4 show how players with foresight compare future costs to the current cost of investment. The cumulative risk of failure due to inaction rise above the initial costs of investment after t^{ψ} where

$$\int_0^{t^{\psi}} F(t) - F(t^{\psi}) = M(0)$$

Eq. 8.9

Foresight to the point at which myopic players pay (t^1) is not necessary because costs of inaction will necessarily rise above initial costs of action earlier. When comparing equations equilibrium under foresight with equilibrium under myopia, the following inequality results:

$$\int_0^{t^{\psi}} F(t) - F(t^{\psi}) = M(0) < M(t^1) = F(t^1)$$

Eq. 8.10

This will necessarily hold because investment costs at t^1 will be greater than at $t = 0$ and hence that $t^{\psi} < t^1$. In other words, players with foresight will necessarily pay earlier and hence that the costs will necessarily be lower. The size of this inequality (as determined by the rate of growth in investment costs over time) represents the size of cost savings due to strategic loss.

8.3 Discounting

Linking games across time involves comparing future to the present values. Future costs and benefits are typically discounted relative to contemporary costs. Discounting is expressed with the following function:

$$PV = \frac{v}{(1+\delta)^t}$$

Eq. 8.11

where PV is the present value of some cost; v is the cost being discounted; t is how far into the future v is; and δ is the discount rate. Figure 8-5 depicts the same functions used earlier in thin lines and the discounted values in thick lines. Note an arbitrary discount value was chosen for illustrative purposes and that different discount rates would induce different discounted curves.

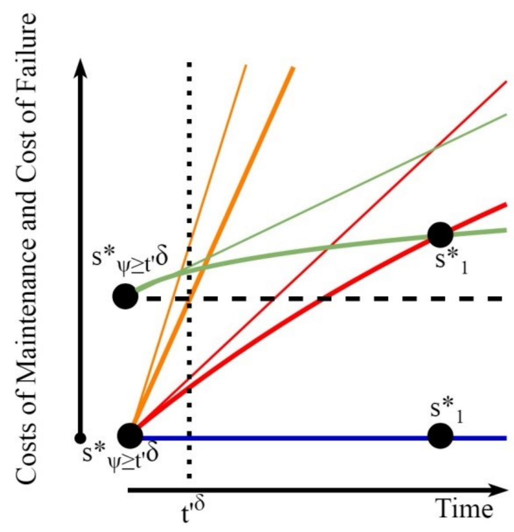


Figure 8-5: Cost functions over time without discounting and with an illustrative discount rate (represented in thick lines).

The further into the future a cost is, the less its present value. Hence linearly rising costs become curves.

The result of discounting is to lower the future costs relative to the present ones. For myopic players discounting does not change the game because they only consider current costs. Also, since all values at a given point in time are discounted equally, the curves cross at the same point time regardless of the discount rate. Discounting does however dim foresight by extending the foresight required to see the point at which cumulative risk of failure rises above initial investment costs. This is shown by the difference between where the thin and thick orange lines intersect the dotted line. This effect is noted by the fact that the equilibrium that supports strategic loss at the beginning of the game now requires foresight $\psi \geq t'^{\delta}$.

8.4 Heterogeneous Decision Makers: Who Invests?

Our models have considered two perfectly identical decision makers. This meant that the equilibria are the same (either a or b pays). Hence, thus far the question of which of the decision makers ends up investing has been left unanswered.

In practice, such a strong symmetry is unlikely. Discount rates are not always the same across different decision makers. Different decision makers may also be differently affected by rising risk of failure. Industrial users may be more or less exposed, having fewer opportunities to adapt their production or source water elsewhere. They may hold different beliefs about changes in the cost of system failure. Their expected valuations also depend on their risk tolerance. For example, for different institutional stakeholders such risk tolerance may be mandated differently by different regulations on which return period droughts or floods they must consider in planning and system design. This is particularly the case when considering the second decision maker to be the local council with responsibilities partially overlapping with water companies around flood protection. All of these differences can be in play at the same time, constituting differences in their understanding of the game.

Figure 8-6 shows the changing expected costs of non-payment relative to the initial investment costs in a situation where b's risk of failure rises more rapidly than a's. The x and y axes indicate the costs to decision maker a and b respectively. They then strive for nodes closer to the origin on their scale. As the games are interconnected over time, the cost of failure $F_i(t)$ can be plotted as moving through the cost space in the direction indicated by the arrow, indicating b's risk of failure is rising more rapidly than a's.

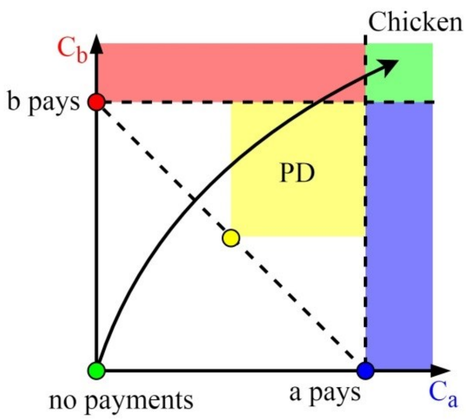


Figure 8-6: A scenario where the cost of failure rises faster for b.

The diagonal dashed line represents initial investment cost $M(0)$; the yellow node represents initial investment costs shared equally, the blue and red nodes indicate $p_{a,0}$ and $p_{b,0}$, respectively. The green node indicates the expected costs of neither player paying $F_i(t=0)$ with the arrow showing how the risk of failure grows faster for b than for a over time.

In order for the game structure to enter a game of chicken, cost of failure must rise equally for both. Figure 8-6 shows a scenario where this is not the case. Costs pass through the prisoner's dilemma phase before entering the region marked in red where b can reduce costs by paying while this is still not the case for farmer a. If such a difference exists between a and b, the game of chicken will not come about because b cannot commit to not paying in the red region. With foresight to this, a will free-ride player b's payment.

8.5 The Ambiguous Incentive for Developing Foresight

There are several countervailing incentives for foresight. The first incentive rewards foresight with opportunities for lower costs through strategic loss. In the model this involved 'chickening out' earlier to avoid higher future costs. However, there are also disincentives for foresight.

Developing foresight by estimating future changes through acquiring information, research, and modelling can be costly even if these costs are small relative to the other costs in the model. Costs of foresight may involve costly actions undertaken on the basis of incorrect expectations, but uncertainty induces a more complex game structure involving imperfect and incomplete information (see the subsection on Risk and Uncertainty in the discussion). It is optimal to develop foresight where the equilibrium state under foresight offers a greater cost reduction than the costs of acquiring the foresight itself:

$$C_i(\psi) < C_i(s_1^*) - C_i(s_\psi^*)$$

Eq. 8.12

where $C_i(\psi)$ is the cost of foresight to player i (assume $C_i(\psi) > 0$); $C_i(s_\psi^*)$ and $C_i(s_1^*)$ are costs in equilibrium with and without foresight respectively.

Based on the earlier analysis of asymmetric costs, three cases for costs under myopia $C_i(s_1^*)$ can be defined:

1) ***a* pays**: $C_a(s_1^*) = F(t^1)$ and $C_b(s_1^*) = 0$;
2) ***b* pays**: $C_a(s_1^*) = 0$ and $C_b(s_1^*) = F(t^1)$; or
3) ***a* and *b* enter a game of chicken**.

In Case 1, developing foresight for a would be optimal since the cost savings would exceed the cost of developing foresight. Here, a is able to exploit the opportunity for strategic loss.

In Case 2, since $C_a(s_1^*) = 0$, the right-hand side of equation 9 will be less than or equal to 0 and so the inequality will not hold and it will not be optimal for *a* to develop foresight. Since *b* would have paid first, *a* could have reduced costs by not developing foresight. Additionally, assuming the difference in costs between *a* and *b* is not large, *a* will be the one to pay because cumulative risks of failure will exceed initial investment costs before myopic players pay. If the difference in costs is large then it is possible that b's cumulative risk of failure rises so rapidly that they reach future investment costs before a's cumulative risk of failure reaches initial investment costs. In this case of large cost differences, *a*'s cost will only be the cost of foresight. By developing foresight, *a* has incurred the costs of foresight as well as potentially ensuring *a* is the one that will invest (if cost differences are small).

In Case 3, costs rise symmetrically for *a* and *b*. This is the same case as when small cost differences were considered in Case 2. It is optimal for *a* to invest immediately if it develops foresight, even as *a* would have delayed under myopia with the possibility *b* would have paid in the end.

The incentive for developing foresight is dependent on whether the game has strongly asymmetric costs and who it is that will end up investing. If *a* would have invested anyway (Case 1), then *a* will be able to reduce costs under foresight, whereas if *a* would have been the one not to pay (Case 2 and one of the equilibria in Case 3), developing foresight will raise its costs. The value of developing foresight then depends on prior assumptions about the size and likelihood of cost differences. A model exploring strategic choice over investment *as well as* the development of foresight would involve a more complex game structure with incomplete information (see subsection on Risk and Uncertainty in the discussion).

8.6 Discussion

This model was based on two users investing in water technologies (such as water reuse) with the effect of increasing supply or decreasing demand. It showed how foresight enables strategic losses, how discounting increased the necessary foresight for strategic loss, how differentiation drove who pays, and how incentives to develop foresight are ambiguous.

The discussion in [*Ristić and Madani*, 2019] explores 4 themes in the context of irrigation: extensions and alternative modelling approaches, the issue of how myopia can be reduced in practice, the application of interconnection across water use sectors, and the role of risk and uncertainty. Here these are some of these issues are reviewed only briefly with greater emphasis given to relating this model to the specifics of UK water innovation stakeholders.

Extensions and alternative modelling approaches:

The model presented is simplified in many ways so it is worth reviewing alternative approaches to evaluate the model's generalizability and possible future developments. Note that each extension or alternative is discussed separately. Incorporating multiple changes simultaneously involves greater complexity which is scoped out of this discussion.

The discussion in [*Ristić and Madani*, 2019]considered models bargaining and repeated games as extensions which are only briefly mentioned here. Bargaining games (based on [*Roth*, 1985]) can give more nuance on how investment costs would be split among users. The discussion in [*Ristić and Madani*, 2019], concluded that differential discounting and differentiated risk of failure more generally drove results comparable to those in repeated bargaining games. This model of bargaining however still assumed a fixed maintenance cost without providing alternative levels of maintenance as may be available. Users would then pay the amount that minimizes their costs given their level of foresight. Evaluating this requires defining benefits from different levels of maintenance for a net cost to be calculable.

Regarding repeated games: In this model, once one player pays the game is over. In practice, after payment, users might face the same strategic choices once again. A so-called 'grim trigger' strategy in repeated games, would see players cooperate initially but if the opponent deviates they switch to the equilibrium worst for the deviator [*Abreu*, 1988]. Disequilibrium cooperative outcomes in a one-shot game can thereby be supported in equilibrium in infinitely repeated games (given low enough discounting of future rewards).

Additional users

As has been shown in Part 2, a characterization of the UK water sector involves more than two users. It should then be discussed what modelling additional players would entail. With three or more decision-makers in this model, splitting costs would still not be an equilibrium as decision maker *i* would still be able to cut their costs by free-riding the remaining contributor(s). Assuming a homogeneous risk of failure, an N number of decision makers would mean an N number of equilibria, each involving only one payer.

Benefits

Our model ignores the benefits of production due to water supply for industrial water users or the revenues from water supply for the water company. Without investment, such benefits could diminish over time. To include this, assume benefit b_t is earned each period. For foresighted players, these benefits cumulate, forming a downward sloping curve (on our cost figures), flattening over time as declining supply reduces per period benefits. Adding this function to the risk of failure and investment cost functions would not change points of intersection but would decrease future costs against current costs, increasing the foresight necessary for early strategic loss (as with discounting). A high enough b could induce a new minimum cost point on the maintenance costs curve at $t > 0$. Foresighted players would prefer to pay there and would compare future costs against this point. Depending on the function used for b_t other possible strategic dynamics could emerge and future models could explore such alternatives. The function characterizing b_t could also take into account how different levels of investment affect benefits differently. Players would pay wherever post-investment benefits exceed maintenance costs.

Myopia in the context of water technology

What then can be understood as foresight and myopia in the context of innovative water technologies? Myopia applies to relatively certain prospects ignored by decision makers. This is not that same as difficulties with uncertainty (see subsection on risk and uncertainty below). In practice, all decision makers (implicitly or explicitly) employ a planning horizon for strategic decisions, setting how far into the future outcomes considered in assessing different courses of action.

Water sector planning horizons vary considerably between 15 years in Pennsylvania, 50 years in Australia, and 100 years for flooding and coastal erosion planning in the UK [*Baker et al.*, 2016]. Setting appropriate planning horizons for Water Resources Management Plans should initiate at around 40-60 years but should be adjusted according to the ability to forecast scenarios, the size of net costs, typical asset life-spans, the availability of flexible solutions, and concerns about low-probability high-impact events beyond the planning horizon [*Baker et al.*, 2016].

Foresight in this context is driven by formal institutions. Company bonuses linked to quarterly earnings encourage myopia while longer-term incentives may promote it. UK water companies, are mandated to consider long-term supply-demand balance and their price controls include expenditure for investment to support this [*Ofwat*, 2014]. Likewise, governments and regulatory authorities can be mandated to think long-term. The Climate Change Act 2008 established the independent Climate Change Commission to monitor and evaluate UK governments on climate change targets and the same has been proposed to enshrine 25-year environmental planning in law [*Environmental Audit Committee*, 2018]. The EU Water Framework Directive (WFD) mandates member states to develop 25-year River Basin Management Plans [*European Commission*, 2000], which encourage planners and stakeholders to think ahead and undertake timely investments.

Drawing on [*Micklin*, 1988, 2016; *FAO*, 2013], [*Ristić and Madani*, 2019], consider the cases of the Aral sea, Lake Urmia [*AghaKouchak et al.*, 2015] and the San Joaquin River Delta [*Madani and Lund*, 2012] as examples of myopic decision making in the context of irrigation and water resource development. Arguing these to be cases where a myopic dash for development using inefficient irrigation led to environmental and health costs being borne by those most exposed to the risks regardless of their participation in the benefits of development.

Investments, Risk of Failure, and Myopia for Key UK Stakeholders

Key stakeholders involved in the adoption of water technology innovations were identified in Part 2. Each can be reviewed for how they could be represented in this model along the key parameters of investment option, risk of failure, and foresight. Not all however fit into the hierarchy of this model (namely the symmetry in terms of investment opportunities). Above the horizontal relationship that exists between different investors in the public good are the national government and regulators (EA and Ofwat). None of these typically make direct investments into water technologies in the UK. (The case of the Thames Tideway tunnel however showed that the government is ultimately prepared to provide a government support package for large scale infrastructure interventions to avoid litigation under EU law.) Additionally, suppliers are below the level of water technology investments as they largely react to the decisions made above them, simply providing the technologies as procured by the participants in the public good problem.

The players centrally located in the public good problem are the water companies, developers, industrial users and local councils. These are presented along the core model parameters in Table 8-1.

Water Companies: Water companies make investment proposals as driven by EA requirements and their own assessments of their local water and wastewater needs. These are approved through Ofwat final determinations. Water companies are also at the forefront of exposure to risk of failure given that their reputation and costs are most directly associated with these. There is however a question of what degree water companies are insulated from risk of failure by the regulatory regime as explored in Chapter 6. Results from stakeholder interviews in Chapter 5 showed support that water companies' foresight usually extends to not much more than the coming price review.

Developers: Developers can make investment decisions about installing household water technologies. Interviews from Chapter 5 highlighted that developers however are not exposed to the risks of water stress as they typically sell the property soon after. Some developers with an ongoing interest in their area may be concerned about local water issues and would then be willing to make the investment.

Local Councils: Local councils must make expenditure decisions regarding some types of water technologies in particular regarding SuDS and flood defences. Local councils can also impose stricter water efficiency requirements for developers.

Table 8-1: Water stakeholders by investment, exposure, and foresight

Stakeholder	**Investment Costs**	**Exposure to Failure**	**Myopia/Foresight**
Water Companies	**Direct** technology implementation. Regulatory cost **insulation**.	**Direct** impacts from resource stressors. Regulatory cost **insulation**.	Price Review periods, WRMPs, and RBMPs.
Local Councils	**Direct** adoption of SuDS and household efficiency standards.	**Externalized** to WC and national water management duties.	Elections and budget planning.
Developers	**Direct** implementation SuDS and distributed technologies.	**Direct** impacts from stricter standards. **Insulated** by cost to buyer.	**No foresight** to water issues.
Industrial Users	**Direct** implementation of distributed technologies.	**Direct** impact from availability constraints. **Insulated** by WC water management.	**Short term** (1-5 years) business planning.

Overall a discrepancy generally exists between some of those making water technology investment decisions (developers and suppliers) and those exposed to the costs of water stress and with the foresight to take it into account in their decision making (EA, national government). The key locus is at the regulatory level which mediates between risks of failure and investments in water technologies.

Myopia across sectors

This chapter showed how interconnection across time creates opportunities for strategic loss. Linkage across issues are also discussed in [*Ristić and Madani*, 2019]. International policy measures such as the Sustainable Development Goals (SDGs) [*United Nations General Assembly*, 2018] and WFD [*European Commission*, 2000] promote integration across sectors to advance sustainable water management. Yet, as with inter-temporal myopia, institutional design can often drive myopia in cross-issue interconnection. Literature reviewed and interviews reported on in Part 2 of this thesis, highlighted that catchment-based approaches and Blue Green solutions have the potential to deliver cheaper solutions than those delivered by a single actor. In particular if multiple different aspects are taken into account (including flood defence, amenities, wastewater treatment and water supply).

Risk and uncertainty

The model developed in this chapter is deterministic for the sake of simplicity around strategic aspects of decision-making in this context. That being said, it can be reinterpreted to deal in expected value for the risk of failure. The discussion in [*Ristić and Madani*, 2019] considers issues of risk and uncertainty in detail relating these to the two types of information constraints typically considered in game theory: imperfect information (what moves the opponent has played) and incomplete information (the structure of the game including the strategies of the opponents, their payoffs and/or other aspects) [*Harsanyi*, 1967]. A core issue is that of the distinction between risk and uncertainty. Uncertainties around technical and environmental variables can be expressed in terms of expected value and risk only if the probability density functions are known [*Knight*, 2012]. In water resource management, some key uncertainties may include future precipitation and temperature changes, magnitude of floods and droughts. For some of these uncertainties good historical data may allow reliable probability estimates for design and operation. For other uncertainties, such as runaway global warming, commodity prices, technological advances, and socio-political changes estimating expected values can be even more problematic.

One major problem is that of estimating expected value of low-probability high-impact events (so-called black swans) [*Taleb*, 2007]. Black swans have a large impact but may never have happened or happen very rarely. Hence, estimating their probability is problematic with small errors generating large changes to expected value. For example, even a small change in assessed likelihood of a dramatic drought could mandate large investment in a new reservoir or costly policy reforms.

Related is the concept of 'deep uncertainty' which highlights poorly defined probability values and system understanding more generally [*Walker et al.*, 2010]. For these kinds of uncertainties, alternatives to expected value have been suggested, such as the precautionary principle, scenario analysis, or dynamic adaptive policy pathways to improve robustness and resilience [*Biggs et al.*, 2011; *Haasnoot et al.*, 2013; *Herman et al.*, 2015]. Regardless of the approach taken, decision makers must assign probabilities (even if only implicitly by including or excluding certain possibilities) and such probability estimates are unlikely to be accurate [*Babovic et al.*, 2018].

Relating back to the present model, where differentiation in risk of failure drives who invests, difficulties with deep uncertainty and black swan valuation may become key drivers of expected cost of failure differentiation. Does i, for example, expect a dramatic drought and is therefore willing to pay for a new wastewater recycling plant? j's optimal decision on contributing to investment depends on i's type but an i with either high or low costs would however, want to signal to that they have low costs to induce j to pay (so-called pooling equilibria [*Fudenberg and Tirole*, 1991]). In the game of chicken, signals about player type offer no information about the player's *real* type due to this incentive. If i were to develop a precautionary valuation of that dramatic drought, this would drive up i's expected cost of failure and the likelihood of i paying. Hence, it is not in i's interest to adopt a precautionary valuation of the cost. As with foresight itself, uncertainty creates a perverse incentive against taking on strategic loss. However, if i were to be the one to take on costs later, deploying measures mandated by a precautionary valuation or as part of a dynamic adaptive pathway, can be an effective way to incur strategic loss.

8.7 Conclusion

This chapter showed how the lack of foresight can cause underinvestment in innovative water technologies. A myopic view of the future and uncertainty over changes over time leads to postponing necessary investments. The chapter showed how interconnecting games over time helps promote innovation investments via strategic losses. Foresight means decision makers do not need to have foresight to where myopic decision makers would invest. They only need to see the risk of failure cumulate to above the costs of early investment.

The problem of myopia is exacerbated when discounting is high which further extends the foresight required to prompt investment. Finally, incentives for developing foresight are ambiguous. If a decision maker can remain credibly myopic, others with a longer view are more likely to take up the costs. Promoting foresight through research can reduce the cost of foresight, inducing strategic losses, and reducing the credibility of myopic strategies.

This model as applied to the institutional setting of water technology adoption in the UK showed how investment and risk of failure is dispersed between water companies and regulators. The degree of foresight is largely driven by legislative requirements for WRMPs, RBMPs, and the system of periodic price reviews. While other actors such as developers, industrial users, and suppliers have investment options, they are not exposed to the risks of failure which lie largely with water companies. The water companies themselves are however partially insulated from investment and failure costs through price controls which transfer these to regulators as representatives of consumers. Ultimately, this means that the decision makers with the greatest control over investment, greatest exposure to risks of failure and the greatest foresight are the regulatory authorities. The degree of foresight regulators have driven strategic losses incurred and hence the pace and style of water technology innovation in the UK.

Part 4: Conclusion

Chapter 9: Summary and Conclusions

Key Points:

- CIGA outputs provide the basis for policy recommendations.
- Tools for establishing trust in the regulatory action arena can create problems for innovation.
- Regulatory interactions may pass through cycles of trust and mistrust which are unhelpful to consistent drive for innovation.
- Institutional and technical factors lead to lock-in which only very exploratory tools can overcome, and even then, they do so with great difficulty.
- Myopia is a key barrier to innovation and given multiple users there is an ambiguous incentive to develop it.
- Directions for future research in approach, tools, and alternative governance systems are noted.

This chapter summarizes the outputs of the research, reciting key findings, discussion, policy recommendations and directions for future research.

This thesis examined regulation and innovation in the water sector in England and Wales. Social-Ecological Systems (SES) theory, the Multi-Level Perspective and a morphology of tools were brought together as part of a Comparative Information-Graded Approach (CIGA) for this purpose.

7 mechanisms by which regulation affects innovation: Direct regulatory funding for R&D, regulatory requirements as drivers of demand, regulation as a signal to the suppliers, regulatory review and approval of technologies, economic regulation shaping water company decision making, economic regulation securing or precluding water company funding for technologies, and the promotion of competition where desirable.

Lack of trust was identified in 5 key areas where the mechanisms for overcoming this problem can act as barriers to innovation. As stakeholders establish certainty through these mechanisms, some opportunities for innovation are sacrificed. Underemployment of outcomes-based procurement due to mistrust leading to input based procurement, non-collaborative environmental regulation, the guarantee of public trust in water quality acts as a barrier to experimentation, investor confidence in economic regulation leads to commitment mechanisms which slow change, and mutual distrust between, the economic regulator

(Ofwat) and the water companies leads to tighter scrutiny and stymied firm independence. The issue of trust create problems for the adoption of distributed interventions specifically and it is worth highlighting two of these areas more directly. The instrument of Regulatory Capital Value (RCV) supports a system of regulatory commitment ensuring capital investments are remunerated adequately. The RCV creates a bias towards capital intensive solutions and it is difficult to move away from the use of RCV due to its central role in ensuring regulatory commitment. Another important example is that mistrust in water company-supplier procurement is overcome by Framework Agreements and Tier 1 consultants. While these again work to resolve issues of trust by establishing commitment they are not always seen as efficient promoters of innovation, transition and the distributed interventions underutilized across the water sector.

Three groups of models were analysed. The trustee game models the two sided issue of trust between Ofwat and the water companies. Analysis of this model exhibits a convergent cycle for dynamical systems and fictitious play providing an explanation for observed cycles in trust and mistrust which create an inconsistent drive for innovation. In evaluating trustee and coordination models by multiple tools considered in the CIGA, it was possible to show how most tools struggle with the issue of technological lock-in. A final model of multiple innovators in a public good water technology, showed how the role of foresight in this context is important for driving early investments and innovations but that there is an ambiguous incentive to develop foresight. Ultimately, the environmental and economic regulators are the decision makers best placed in terms of foresight and exposure to risks to drive investment and innovation in the sector.

9.1 Predictive CIGA Outputs

CIGA outputs come in the form of predictive and prescriptive outputs as resulting from the literature, interviews and modelling. Predictive outputs highlight the key conditions of the action arenas. These are characteristics which are relatively fixed and cannot be expected to change easily. Hence policy recommendations made as part of prescriptive outputs will have to work within these constraints.

CIGA Predictive Outputs – (Conditions and Expectations)

Decision making in the sector is poorly characterized by alternative decision influences while decision making morphologically similar to Nash equilibrium analysis, the family of tools employed in the Graph Model for Conflict Resolution (GMCR) and bounded information tools are more accurate characterizations of water sector decision making.

Novel regulatory instruments like competition in the bioresources (sludge) market and Outcome Delivery Incentives (ODIs) are seen by interviewees to provide a helpful boost to innovation. Competition for non-household retail is seen to be less helpful in this regard while competition for household retail is often seen negatively by interviewees.

Issues of trust are central to regulation and can lead to cyclical patterns of trust and mistrust and will likely continue to do so. This forms part of how the regulatory system changes and adapts and will continue to do so. RCV however, will not likely change substantially in the future meaning the capital bias arising from it is also likely to stay unless suitable adjustments can be found.

Foresighted decision makers in the sector are those driving investments and innovations. This is largely in the hands of regulators who thereby play a leading role in promoting investments and shaping technological change. However smaller actors with foresight such as some classes of developers also play an important role in the early adoption of distributed systems such as water reuse technologies.

9.2 Prescriptive CIGA Outputs and Policy Recommendations

Prescriptive outputs are the set of policy recommendations arising from modelling and interviews. These must be considered within the constraints imposed by the predictive findings.

Potential changes to game structure in the three core model structures that were analysed (trustee models in Chapters 6 and 7, coordination games in Chapter 7, and foresight in public goods games in Chapter 8) can be reviewed to highlight which changes are possible, how these lead to improved outcomes, and what the resulting policy recommendations are.

Trustee and Predator Prey Models

The trustee model highlights the issue of trust and regulatory commitment for ensuring adequate investment. The variation on this model to the predator-prey model showed how clear regulatory mandates for delivering required investment improve outcomes in this setting.

Potential changes to Predator-Prey Models

It is not really possible to change the investor's utility function, meaning the only variables would be the regulatory utility function. This was already shown with the change from the simple trustee model to the predator prey model of regulation.

One potential aspect that could be explored is the speed of price adjustment in the context of the dynamical systems representation of the game. If price adjustments were to be made more slowly, than as given in the model, this could work to stabilize system to the equilibrium point. The representation given shows a stable orbit around the equilibrium point. In order for this to be changed the rate of price adjustment should simply be slower than the rate of investment adjustment.

While this would work to stabilize the system, this approach would have to be able to bear the resulting pressures of slower price adjustments. A longer period spent in a state with high prices and over investment would be undesirable. Ultimately the predator prey model does not yield a very hopeful picture for changes along the lines of changing speeds for price adjustments. A more hopeful picture is instead gleaned from the comparison of different tools for decision making characterization in this context as given in Chapter 7.

The core result from that chapter was that the best tools to use were those which considered disimprovements and punishments such as those of the GMCR family of models. These yielded convergence to states with investment even in the simple trustee model without a regulatory mandate as given by the changed utility function of the predator-prey model. The fact that the GMCR family of tools yielded convergence while the dynamical systems, reinforcement learning and fictitious play concepts typically converged to cycles indicates which tools would be better at avoiding the inconsistency associated with PI cycles.

Resulting Policy Recommendation: Minimize Cycles

PI cycles are problematic in that they create inconsistent incentives for innovation. As far as possible price and investment swings over the course of the cycles should then be minimized. Reducing as far a possible the drivers of these cycles should be pursued: Regulatory expropriation under consumer pressure, investor uncertainty, gold-plating opportunities. As shown with the comparison across different tools these are largely driven by historical perceptions and in so far as possible there must be certainty and consistency in regulatory and firm behaviour.

Resulting Policy Recommendation: Disaggregate Price Controls

The core argument of the theory of PI cycles however is that these cycles are difficult to eradicate given the uncertainties of the different parties involved. If different parts of the system can however be disaggregated it may be possible for the different cycles to overlap and hence smooth out total price and investment across the corresponding parts of the system. There is already some movement in this direction with the increased use of targeted incentives and performance commitments. Also the disaggregation of price controls across water and wastewater as well as the splitting off of different parts of the water system such as the bioresources market and retail competition. Such disaggregation must however be carefully balanced against opportunities for coordinated activity in the pursuit of pooled learning by doing for enabling transitions.

Resulting Policy Recommendation: Harness Residual Cycles

Given that the cycles are not likely to be completely minimized and that large parts of the water system will still require an aggregated price control, the theory of PI cycles would argue that cycles are likely to persist. If this is the case, the best should be made of a problematic situation. In this direction opportunities for harness PI cycles should be taken. In particular, periods of high investment should be used to move the socio-technical regime in the best possible direction while periods of low investment should be used for critical evaluation of the regulatory and technological system. These low investment periods ultimately create the driver for higher future prices and investments and hence are critical to future technological change. In this sense, low prices and investment should be taken as an opportunity for additional pressure for exploration in smaller scale distributed technologies.

Despite the need for constancy and certainty in the regulatory system, Ofwat has found ways to gradually adapt the system to problematic incentives and external pressures. This has been particularly the case with the adoption of incentives to try to reduce the capital bias of the RCV and the dampened incentive for cost reduction under the regulatory cost sharing over price control periods. These incentive systems could further work to promote a more balanced approach to the tension between centralized and distributed technologies. Such incentives and tighter price conditions may offer opportunities to rethink the technological regime and explore potential for transitioning to alternative technologies at the next phase of higher prices and investments.

Coordination Games

To model technology selection under spillover effects, coordination games were employed. These reflect spillovers through the preferences players have for technological alignment. 'miscoordination' yields lower payoffs for the players than coordination. Three variants of this game considered different conditions where technologies are equally preferred by the players, of different preferences between players, and finally, where one technology is preferred over another by both players.

Potential Changes to Coordination Game Models

The core problem faced in the coordination games are that players do not wish to deviate from a given technology once it is established, regardless of the variants used. A unilateral deviation to a different technology results in lower payoff to all players. If this issue could somehow be addressed transitions from one to another technological alignment could be made easier.

This would in effect require the improvement in payoffs for technological exploration. The costs of a failed deviation to an alternative technology is the core driver here. If these costs could be reduced such technological exploration would be encouraged. Of course it is not possible to change the knowledge spillovers themselves, however in the context of price controls the allocation of costs could be changed so as to make exploration less costly to the water company, with these costs instead being borne by consumers through price increases. The hope being that ultimately, net costs would be lower as better technologies are more readily adopted.

Resulting Policy Recommendation: Encourage exploration to discover transition options

Models of technological transition in a coordination game showed how difficult it is for most tools considered to transition from a coordination around a particular technological configuration to a new one even when this new configuration would yield improvements for all decision makers. The tools that most successfully did this were those with a high rate of exploration.

This exploration should be encouraged by Ofwat and other decision makers through a common innovation fund for example. It was noted in interviews that such a fund has not been developed thus far because of issues of trust between regulators and the firms that stand to benefit from such a fund. Appropriate governance structures for the establishment of a sector wide fund reasonably dealing with trust issues should be a matter of priority for the sector.

Resulting Policy Recommendation: Encourage coordinated transitions

It was shown that tools which consider moves and responses by other players found even technological misalignment a convergent state. This is a very undesirable outcome. Technological selection and change should be coordinated as far as possible between involved parties so that when a novel approach is attempted this is coordinated with other parties to reap co-benefits and yield the best possible outcomes. The multiple actors working together can also pool their technological learning and cost reductions. This way knowledge spillovers can be harnessed for transition rather than being allowed to simply work to sustain technological lock-in.

Resulting Policy Recommendations: Transition to Distributed Systems:

Centralized technology will likely remain the main approach due to economies of scale and institutional lock-in. Government Support Packages and Direct Procurement (competitive financing tenders) as developed in the case of the Thames Tideway Tunnel offer further institutional support in this direction of capital intensity.

Efforts seeking to promote distributed interventions as part of a portfolio of solutions will require improved systems of governance and funding for SuDS, reuse and other technologies. In particular, reform of drainage charges, natural capital accounting, ecosystem services were given by interviewees as ways in which more efficient uptake of distributed interventions could be promoted. The adoption of incentives specific to distributed technologies, while going against regulatory technology neutrality) offer another policy instrument supportive of technological transition. Broader adoption of ODIs targeting areas where distributed solutions can deliver would likely work to support these and provide coordinating signals to the involved decision makers.

Foresight in Public Goods Games

Chapter 8 analysed a model of myopia and foresight in public goods games over water technology investments. Early investments in public good maintenance was shown to only be adopted by foresighted players, but the incentive to develop foresight however was shown to be ambiguous.

Potential Changes to the Model

The changes to the model revolved around a comparative approach to differing levels of foresight. Greater levels of foresight allowed for early investments reducing overall costs. The policy implication is then which players are foresighted (hence well placed to make investments) and how foresight in general can be developed.

Resulting Policy Recommendation: Promote foresight with policy instruments

It is possible to boost foresight through policy and regulatory instruments. Regulatory tools such as the River Basin Management Plans and Water Resources Management Plans (WRMPs) all play an important part in this and government and regulators should ensure continued application of similar institutional drivers of foresight. Establishment of appropriate rules for governments to develop and employ foresight should also be explored such as through a statutory foundation for National Environmental Plans which as for 25 years of foresight in developing environmental policy. Given that many assets in the water sector are of longer lifetimes (sometimes as long as 50 years), these time horizons should further be extended. Measures to this effect should be employed at government, regulatory, and firm levels.

Resulting Policy Recommendation: Focus on players with foresight

While foresight should be encouraged, it is not always the case that all involved decision makers will have the ability to develop long time horizons and extended foresight. Developers of housing and industrial sites are a big challenge as their activities have a direct impact on the water environment however these are completely external to their interest. If it is not possible to change this, local councils or other entities more permanently invested and associated with such site are better placed to apply foresighted decision making to technology selection. The system of regulation and policy should consider ways in which foresight can be promoted among key participants focussing on those which are well placed to employ it given their exposure to the water environment and ability to make relevant investments. This would support functional integration among the different aspects affecting the water environment.

9.3 Integrating Discussion

Theory and Approach

The study of SESs requires a selection of among potential tools for representing decision makers within an action arena. Multiple decision making characterizations exist drawing on different understandings of the drivers of decision making for individuals and organizations. As shown with multi-criteria tools, a comparative approach to tools yields an insightful series of alternative perspectives on the action arena under study – namely the interaction between Ofwat and water companies in the regulatory action area. Selection of a predictive decision making characterization is possible at different levels of abstraction given the grade of information available on real-world decision making.

Higher-Order Conditions (HOCs), Landscape Pressures, and the Environmental System

HOCs are driven by EU environmental law and the laws establishing the mandate of the economic and other regulators. In characterizing the environmental system, it was shown that the water sector plays an important role as both a source of problems and solutions for the water environment. Further political pressure in the form of both critiques of profits as well as renationalization placing is being exerted on the regulatory arena.

Regulatory Action Arena: Preferences, Options, and Decision Making

Ofwat's mandate is understood here to drive the regulator's preferences. Ofwat's system of regulation in turn shapes the preferences of the water companies. This was shown through the discussion of the capital expenditure bias which distorts efficient selection between centralized and distributed technologies. In reviewing carbon intensity, it was shown that centralized technologies do not consistently outperform distributed systems and hence that these technologies should be considered in parallel.

Interviews highlighted a wider set of interactions between regulators, water companies, and technology suppliers, noting the need for better integration of WRMPs, water company plans, the Building Code, Local Authority permitting, Environment Agency (EA) licensing and consents and the supply chain involved in the adoption of distributed systems.

Interview response support a decision making characterization as one of optimizing agents with good information on their own costs but incomplete information on the costs and preferences of others. Regulatory decision making characterization includes disimprovements of the GMCR tools. Among the most agreed upon claims made by interviewees was the claim that WCs are risk averse and that the system of regulation exacerbates this.

The Theory of Price-Investment Cycles

The trustee game was used to represent two-sided issues of trust in the regulatory action arena. Under dynamic systems models and fictitious play, decision makers in the trustee model follow a cycle. Evidence from data and interviews show that trust issues contribute to this cyclicality within and across price reviews (PRs). Evidence from interviews and changes to PR methodology indicate that Ofwat and the companies are learning and adapting their practices to mitigate these issues. This can be seen to be part of the long term cycle which has implications for technology change in the sector. As the PR methodology moves more heavily into incentive based regulation and the role of RCV is adapted within this, it can be expected that technology in the sector will more towards less centralized systems.

Archetypal Games of trust and transition

Coordination problems are an issue for most tools. The lock-in to suboptimal technologies is a problem for every tool reviewed here. Reinforcement learning with high rates of random explorations is the most successful tool in transition where the preference for an alternative technology is present for both decision makers.

Foresight in Public Goods

Lack of foresight can cause underinvestment in innovative water technologies. A myopic view of the future and uncertainty over changes over time leads to postponing necessary investments while foresighted players interconnect over time and 'strategically loose' by being the ones to take on the costs of investment early on in order to reduce long-run costs. Incentives for developing foresight however are ambiguous. If a decision maker can remain credibly myopic, other's with a longer view are more likely to take up the costs.

As applied to the institutional setting of water technology adoption in the UK showed how investment and risk of failure is dispersed between water companies and regulators. The degree of foresight is largely driven by legislative requirements for WRMPs, RBMPs, and the system of periodic price reviews. While other actors such as developers, industrial users, and suppliers have investment options, they are not exposed to the risks of failure which lie largely with water companies. The water companies themselves are however partially insulated from investment and failure costs through price controls which transfer these to regulators as representatives of consumers. Ultimately, this means that the decision makers with the greatest control over investment, greatest exposure to risks of failure and the greatest foresight are the regulatory authorities. The degree of foresight regulators have driven strategic losses incurred and hence the pace and style of water technology innovation in the UK.

9.4 Limitations and directions for further research

Key limitations and directions for future research of this kind can be grouped into 3 categories: method, model, governance.

Methodological Issues:

SoS and data driven approach to water technology selection. The comparison of different technologies conducted in this thesis was limited to considering EA data on carbon intensity. A further expansion of the relevant data set to include multiple criteria, multiple technology outputs (in terms of quality and quantity parameters), in combination with data on environmental requirements could yield a more specific understanding of technology selection issues. However this is not directly relevant to the operation of the system of economic regulation which maintains an "arms-length" from particularities of technology selection.

More interviews for more reliable outputs. Further development of the CIGA method in relation to more effective means of bridging tools and interviewees needs to be done. This will enable better tool selection and outputs.

Models:

The application of CIGA to *more specific models* of environment, assets, and financial models. Ofwat and others publish models which can be used to determine more specific functions for characterizing the exact incentives and relative importance of different aspects of the regulatory regime. A comparative approach to these could delve deeper into predictive and prescriptive exploration of incentives and the regulatory system.

The *inclusion of the supply chain* in formal models is important and was not in the scope of this research. This is a very important area as most technological change is driven in this part of the sector. These models should explore supply chain decision making in the face of regulatory decision and signals, WC procurement policies, mutual competition.

A final modelling note would be to explore *heterogeneous tools*. In particular given that it was identified that WC and regulators differ by some important aspects of the characterization of decision making.

Examination of different systems of governance

Two important potential changes to governance face the water sector in England and Wales: *Brexit and renationalization*. While at the time of writing, there seems little doubt that the UK will leave the EU, it is not nearly as clear what the environmental laws after Brexit will look like. Secondly, if the Labour party do win the next general election and pursue (as they claim to) a policy of water sector renationalization, it is unclear how this will affect the regulatory system and technology choice in the sector. Both of these issues are worthy of study and have garnered much attention but were not in the scope of this research.

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Appendix I: Interview Invitation Letter

Centre for Environmental Policy
Imperial College London
14 Princes Gardens
South Kensington Campus
London SW72AZ
Tel: +44 (0)20 7594 9334
Fax: +44 (0)20 7594 9334
www.imperial.ac.uk/environmental-policy
Bora Ristic
PhD student in Centre for Environmental Policy
Elzavira Effendi
MSc student in Centre for Environmental Policy

<date>

[Address]
Dear (Participant's name)

We are a team of doctoral and masters students from Centre of Environmental Policy at Imperial College London. We would like to invite you to participate as an interviewee in our study of regulation and sustainable technologies in the UK water sector.

We aim to analyse the effects of water regulation on the adoption of sustainable technologies. The information we hope to obtain revolves around technologies, water reuse and sector governance. We want to elicit expert opinions on barriers and enablers to technological change and actors' decision-making. The results will be qualitatively interpreted and potential game-theoretic modelling will be developed from these insights. Your participation and expert judgement on this subject are very valuable to us due to your active involvement in the field.

The interview is approximately one hour in length and will happen at a location and time of your convenience. More information on the interview is provided in the information sheet. If you have any questions regarding this study or would like further information to assist you in reaching a decision about participation, please contact us at:

Bora Ristic : +447903592612/ bora.ristic13@imperial.ac.uk

Elzavira Effendi :+447456310650/elzavira.effendi16@imperial.ac.uk

We very much look forward to speaking with you and thank you in advance for your assistance in this project.

Yours sincerely,

Bora Ristic Elzavira Effendi Dr. Kaveh Madani

Appendix II: Participant Information Sheet

Participant information sheet

“Adoption of water reuse technologies in the UK: a game theory approach to modelling stakeholder interactions”

We are a team of doctoral and masters students from Centre of Environmental Policy Department at Imperial College London. Our team consists of the following:

1. Bora Ristic (PhD student, Centre for Environmental Policy, Imperial College London)
2. Elzavira Effendi (MSc student in Environmental Technology course, Centre for Environmental Policy, Imperial College London)

Centre for Environmental Policy department at Imperial College London is a department under Faculty of Natural Sciences which provides a unique research interface between science, technology, economic and policy context. The focus of the studies in this department is on environmental and development issues which includes energy, pollution, conservation of natural resources, food security and poverty reduction. The Centre produces interdisciplinary research programs which aims to create solutions for sustainable environment.

This study is carried out under the Hydro-Environment and Energy Systems Analysis (HEESA) research group, under supervision of Dr. Kaveh Madani, whom is a Reader in Systems Analysis and Policy in Centre for Environmental Policy, Imperial College London.

This research is funded by the following bodies:

1. NERC studentships for Bora Ristic
2. Indonesia Endowment Fund for Education for Elzavira Effendi

The study aims to contribute in developing understanding of the effects of regulation and governing institutions on promoting or slowing the adoption of sustainable technologies in the water sector. Due to its strategic and political significance, the water sector is subject to a series of regulations and law covering the sector’s economic, operational and environmental performance. It is therefore necessary to have an understanding on how the water regulation will affect the adoption of sustainable technologies. Since the water sector is currently facing challenges in limited supply and meeting the increasing demand, sustainable technologies is necessary to answer the challenges. Hence, this study is required to produce a policy recommendation for improvement of the adoption of these technologies in the UK.

The information which will be needed from the interview are perspectives from various stakeholders on the innovations in the water sector, the development, barriers and enablers, followed by the questions on game theory context to observe the importance of each actors on the innovation system, their options and preferences, followed by the interaction among these actors. The questions will cover innovation in general, water reuse technologies and innovation in the governance. The interview will take approximately one hour to complete. Since the study is focused on stakeholder interaction, the information from several stakeholders which are regulator, water company, supplier, policy maker, consultant

and academic is critical. Therefore, your participation and perspectives on this matter is very valuable to us, due to your active involvement in the sector.
Participation in this study is voluntary. It will take place in a mutually agreed upon location. You may decline to answer any of the interview question if you wish. You may also decide to withdraw from this study at any time. Participant will not be identifiable in the final data since we only consider the aggregated data to develop the model. The interview will be recorded with your permission to support the collection of information that will later be used for analysis. After the interview is completed, we will send you a copy of the transcript to give you opportunity to confirm the accuracy of the conversation and clarify point if you wish. This study will not require any commercially sensitive or confidential information and if you have any concerns about this we will happy to delete anything from the record.

If you have any questions before we begin, feel free to ask. You can ask clarifying questions at any point during the interview or after it is finished.

Researchers' contact details

Bora Ristic

PhD student

Centre for Environmental Policy

Imperial College London, 14 Princes Garden South Kensington Campus

London SW72AZ

Email: bora.ristic13@imperial.ac.uk

Elzavira Effendi

MSc student

Centre for Environmental Policy

Imperial College London, 14 Princes Garden South Kensington Campus

London SW72AZ

Email: elzavira.effendi16@imperial.ac.uk

Appendix III: Interview Question Sheet

About you	
1. Name	
2. Which describes the organisation you belong to best?	☐Regulator ☐Water company ☐Supplier ☐Policy maker ☐Consultancy ☐Academic ☐Other:
3. What position describes your role in your organisation best?	☐Junior ☐Middle management ☐Senior ☐Director/board member
4. How long have you been working in the water sector?	☐0-2 years ☐3-5 years ☐6-10 years ☐11-20 years ☐more than 20 years
5. Training/discipline. *Tick all that apply*	☐Civil/environmental engineering ☐Business/management ☐Accounting/finance ☐Economics ☐Computer science ☐Physics ☐Biology ☐Chemistry ☐Social sciences ☐Environmental research ☐Other
Introduction to water reuse *We define water reuse as treating wastewater for potable or non-potable use. Potable is defined as safe for drinking. Non-potable covers non-drinking usage of water, such as washing, toilet flushing, landscape irrigation, street cleaning and vehicle washing.*	
6. Are you currently involved in the adoption or promotion of water reuse technologies?	☐Yes ☐No ***(go to question 10)***
Your experiences with water reuse	
7. Please give an identification label or the name on the specific case of water reuse project or technology you are involved in.	

8. Who are the stakeholders involved in this process and at which stages are they involved in?
9. How do these stakeholders interact during the innovation and adoption process and what problems arise during this process?
(Only if responding "No" to Question 1) **Reasons for not adopting**
10. Why are you not involved with the adoption or promotion of water reuse technologies?
11. What changes do you think are necessary to make you more inclined towards the adoption of water reuse technologies or practices?
12. Who are the stakeholders you think should be involved in the adoption of water reuse technologies and at which stages should they be involved?
Regulation and Stakeholder interactions in the adoption of water reuse technologies
13. In your opinion, how does the current regulation in the UK affect the development and adoption of water reuse technologies?
14. Based on these measures, which is your most and least preferred measure relating to the adoption of water reuse in the UK and why?

Measures
Do nothing (maintain *status quo*: enhanced capital allowance)
Non-binding guidelines for potable water reuse
Non-binding guidelines for non- potable water reuse
National target on water reuse
National standard for non-potable water reuse quality
Awareness-raising action
Research and development, impact assessment

15. How do you expect **water companies** to respond to your most and least preferred measures?
16. How do you expect **suppliers** to respond to your most and least preferred measures? *By 'suppliers' we are referring to the firms supplying goods and services to water companies.*
17. How do you expect **the public** to respond to your most and least preferred measures?
18. What are the conflicting issues that may arise between stakeholders in carrying out the most and least preferred measures?
19. Which stakeholder do you think is the main enabler in the adoption of water reuse and why?
20. Which stakeholder do you think is the main barrier in the adoption of water reuse and

why?
Selected Issues in Water Technology and Governance In this section, we will ask for your comments three groups of questions: 1. Technological change and innovation 2. Changes to governance and institutional arrangements For each of these I will ask you to consider the effects on water prices, innovation, and environmental outcomes. Please let me know if you would like to skip a question because you are not familiar with the area.
21. Which technological innovations are likely to have the biggest impact on household freshwater prices?
22. Which technological innovations are likely to have the biggest impact on environmental outcomes?
23. In transitioning to a new technology, what conflicts are most likely to emerge between stakeholders?
24. Do these stakeholders coordinate or cooperate? If so, how effective is this? If not, why not?
25. Which changes to water sector governance are likely to have the biggest impact on environmental outcomes and what are they?
26. Which changes to water sector governance are likely to have the biggest impact on water prices?
27. Which changes to water sector governance are likely to have the biggest impact on innovation and technological change in the water sector?
28. In transitioning to new rules and institutional arrangements, what conflicts are most likely to emerge between stakeholders?
29. How do the actors involved in such transitions coordinate or cooperate? How effective is this?
30. Does the price control process encourage the adoption of new technologies, if so how?
31. In setting price controls, how do the firms, investors, and OFWAT ensure trust between each other?
32. Does the process of technological change and innovation create conflicts with commitments made as part of the process of economic regulation?

Selected Stakeholder Decision-Making In this section we will ask you to identify two stakeholders you have experience with in water sector innovation and subsequently to answer questions about the decision-making of each.	
33. Which two stakeholders or stakeholder groups are you most familiar with in the water sector? We encourage you to choose yourself or your organization as the first.	S1: S2:

Decision-Making of Stakeholder 1
34. Stakeholder Name/ID
35. What information do they have on their own costs and preferences?
36. How do they collect this information?
37. Which information do they lack and why?
38. What information do they have on costs and preferences of other stakeholders?
39. How do they collect this information?
40. Which information do they lack and why?
41. How do they discover new options or actions available to them?
42. How do they form expectations about the future prices, market conditions and regulations?
43. Do they use a single criterion or multiple criteria to make decisions? If so, what are they?
44. Please give any general comments on how this stakeholder's decision-making contributes or detracts from water sector innovation and technological change.
Decision-Making of Stakeholder 2
45. Stakeholder Name/ID
46. What information do they have on their own costs and preferences?
47. How do they collect this information?
48. Which information do they lack and why?
49. What information do they have on costs and preferences of other stakeholders?
50. How do they collect this information?
51. Which information do they lack and why?
52. How do they discover new options or actions available to them?
53. How do they form expectations about the future?
54. Do they use a single criterion or multiple criteria to make decisions? If so, what are they?
55. Please give any general comments on how this stakeholder's decision-making contributes or detracts from water sector innovation and technological change.

Final Comments

We discussed water reuse and the decision-making of relevant stakeholders. Please give any other general comments you may have on any of the material covered in this interview.

Thank you very much for your time! Do you have any questions for me?

Appendix IV: Grouped Interviewee Key Claims

Drivers of Innovation, the Innovation System and Innovation Dynamics

System design and optimization relies heavily on the expertise of in-house staff with problem solving (68), a breadth of experience (71) and consultation with external experts (69) such as universities (75, 76), often looking internationally (80). System design is a process of trial and error (70) involving different combination of existing and new technologies for the given water stream (72, 73). The entry of new actors into the water space and engaging with customers can generate new ideas and partnerships for solutions (78, 79).

Costs of novel technologies are driven by: health risks (2), water quality risks (5), performance risks (3) and the costs of retraining staff (6). The high costs of novel technology which come down (4) through learning and scale (34, 35). The evidence base for these takes time to develop (11) and prices are negotiated in the market (9,10).

Water shortages and need to develop resources do drive innovation however (116). Current prices have not prevented the development of innovative treatment technologies (14) including membrane systems (15) and understanding of microbiology and biological treatment (77) which drive down costs.

Technical standards support confidence in novel technologies (17,18, 20) but must be sensitive to different applications (19) and should only be adopted carefully so as to not lock in a bad standard (21).

Novel technologies are not adopted without a pilot scheme (22) however none of the key actors drive these (23,24). A technology must be proven and have references and good examples (26, 27, 28) however not all actors accept external piloting and may require their own pilot project (29, 30,31, 32). WCs in water stressed areas will however do uneconomical projects for learning and reputation (117).

Procurement and Specifications

Procurement is no substitute for in house innovation (45) and delivering one's own projects provides a better understanding of cost (49), but purchasers can discover new options through broad tenders (43). The WC-supplier coordination often does not provide enough opportunities for supply chain to provide innovative solutions, technologies and creativity (40, 41). WC procurement is slow, deferred to top management (46), subject to EU tendering rules requiring at least 3 competitive bids (47).

In procuring technologies, the supplier often engages with the user to challenge the brief and co-shape specifications (36). While some WCs offer open procurement some provide very detailed specifications (42) because open specifications leave open the potential for cutting quality (44). Outcomes based approaches and open innovation require a serendipitous meeting of suppliers for a useful combination or outcome (55) meaning not all such processes as successful (56)

Trust is important in the customer-supplier relationship (38). WCs and suppliers usually enter into framework agreements governing the relationship (37) and suppliers can offer long-term support to ensure trust (39). The core tension is around who bears the risk of cost overruns (51, 57). Typically suppliers are paid a fixed price for the project (50), thereby bearing the risk of cost overruns. One type of contract will provide the supplier with an 'engineering phase' where they are paid to design and cost the project (52). Without this their quote will be higher to reduce the risk of cost overruns (53).

In managing the purchaser-supplier relationship the purchaser will often employ consultants to bring together users and suppliers so everyone can understand each other's requirements (58, 62). Suppliers and purchasers trust the consultants' technical knowledge (59,60) although at times there is concern that consultants may lack practical expertise (61). The WCs employ Tier 1 contractors for interfacing with the supply chain (67). Tier 1's do not drive innovative solutions (64) and are mostly concerned with maintaining relationships with large WCs (65).

General Claims about Distributed Systems

Distributed systems should be explored (81) as they could reduce costs (83) and water efficient technologies will improve environmental outcomes (82). Rainwater and reuse systems are being considered by WCs in water stressed areas (115).

Their challenges involve disrupting existing WC businesses (84), potential intermittency and greater metering requirements for rainwater harvesting for example (85), distributed risks to quality and resilience (89). Such distributed risks would require a reconfiguration of the governance of these systems (99, 166), potentially involving local authorities more closely (100). This issue was raised for WRTs, RWH and SuDS. Finally, having distributed systems also connected to the existing infrastructure to ensure security of supply dramatically hampers their cost savings (90).

Two concerns with the interplay between distributed and centralized systems are: First, the possibility that capital projects have come at the expense of cheaper but less proven distributed systems (91). Before the introduction of the TOTEX reform, WCs had a bias towards capital solutions (97) and they may still retain that tendency (98). Secondly, concerns around stranding existing assets under a transition to distributed systems (86). For example, the deployment of WRT will reduce burden on sewerage (122) and a fall in revenues from water supply (147). A phased approach, allowing existing assets to retire naturally could mitigate this (87) but may involve running parallel systems for a time (88).

As with the earlier discussion of the innovation system, costs for distributed systems and their suppliers follow economies of scale for water reuse technologies (92), rainwater harvesting (93) and for suppliers of treatment technologies (94). A further economy of scale is that regarding governance of distributed systems where the establishment of dedicated authorities reviewing this would only be worthwhile with a widespread enough adoption of such distributed systems (101). One instance where economies of scale may not hold is in the case of using food waste which decomposes less over shorter distances and hence introduces a diseconomy of scale (95, 96).

As an example in the centralized versus distributed systems discussion the example of the Thames Tideway Tunnel was mentioned by 3 respondents two of whom agreed that it was the right solution for London's problem with combined sewer overflows (102). It was noted that there is insufficient space for SuDS based solutions in London (104). Some resistance to the project was largely locally based and NIMBYist (103). The project also garnered a government support package due to the large size of the project and risks (105).

Water Reuse Technologies (WRTs) and Rainwater harvesting (RWH)

WRTs are available (111) and have been used for toilets and irrigation by WCs (146). Agriculture and industry are promising areas for WRT (112, 145, 170). Some WC are willing to support RWH with additional meter installation (119) and consider WRTs as part of their WRMPs (143). However uptake of WRT and RWH is low (92, 118).

Barriers to WRTs adoption are that systems of dual reticulation are more expensive (154), create risks of misconnections and related health and legal risks (106, 137), and the high cost and difficulties of retrofitting (109, 110). Additionally, there is low driver and need for potable water reuse (138, 139) which is more expensive than alternative sources (136) such as desalination in London (140). Potable reuse would also require Defra inquiries and consultations (142) and promotion by WCs (151).

Developers see no benefit in WRTs (155), additional costs leading to higher prices for property buyers (160). Developers prefer demand reduction over WRT (157). Developers do install if it means saving money on connection to mains (156), when big clients want high voluntary standards (161), as an additional sale point (163) or environmentally aware self-builders (162). It is largely only under a long-term view that occupiers would see savings with WRTs (164) and developers sell and move on so do not have such a view (165).

There is a question regarding operation and ownership of WRTs (166). Developers are further deterred by having to return to the development when systems fail (159). Such failures can happen when home-owners do not maintain WRTs properly (168). There are WCs who own and operate the WRTs taking on their risks (167) when these are at community scale with a dedicated team (169).

WRT research and development is important (107) and the costs and benefits of domestic reuse are not proven (108). Suppliers, working with academia, play an important role in building the evidence base for these technologies (123) but some suppliers are reluctant to participate in developing the evidence base (126). This may be partly due to the potential for awareness raising to attract new entrants into the market (114). Another difficulty in developing evidence is in assessing the post-handover performance as the supplier is no longer involved (125). Lastly, awareness raising will not affect supplier investment decisions (113).

There was some disagreement over the overall environmental burden of WRT/RWH between respondents. WRT and RWH is more energy intensive than mains water and sewerage (120, 121). 3 respondents referred to an EA evaluation report on WRT and RWH which found that rainwater harvesting and greywater recycling are more energy and carbon intensive than mains water and sewerage systems [*Parkes et al.*, 2010]. While one respondent agreed with the findings, two challenged the conclusions arguing the report did not take a broad enough view of the benefits regarding flood and water management as the report focussed only on relative energy and carbon intensities of the technologies.

WCs would be the main enabler of WRTs (152) but would consult with customer views on WRT acceptability (153). WRTs trade off against other solution on costs, savings, and customer views in WC decisions (144) who are generally against WRTs (149). WCs also faced revenue falls from WRT adoption (147) and must discount non-potable tariffs (148). Adoption of WRTs also require integration between water and wastewater departments in WCs which may not coordinate well (150).

WRT awareness raising is important (130), particularly for informing customers (131) and persuading the public (134) and developers (158). Without public support for it trust in water would be undermined (132). The public has an instinctive negative reaction to WRTs (135) which negative media portrayals of WRTs have contributed to (133). The public also prefers leakage reduction to reuse (141).

Industrial or commercial users are also enablers of WRTs (170), where these reduce their costs (172) relative to wastewater charges (174, 175) and other alternative cost saving measures (173).

Other Areas of Technology and Practice Innovation

Innovations likely to improve environmental outcomes include (in order of number of respondents mentioning them: network optimization (177), cross sector collaboration (178), water efficient technologies (179), zero water discharge technologies (180), SuDS (181, 182), RHW and WRT (182, 183).

The use of Smart Systems, data, and internet of things (184, 185, 186) would allow for further optimizations, and the smoother integration and enabling of distributed systems (186), as well as monitoring and metering water use for leak detection (188, 189). Such technologies exist but ready-made standardized solutions are missing (187). In particular 4 respondents highlighted the role of IoT networks in monitoring and optimizing at a catchment level (445). Barriers to this technology involve risks and uncertainties around data security (190), consent (192), and ownership under the separation of retail from wholesale (193).

Regulatory, Legislative, and Governance Relation To Innovation

At national level, government policy making must be sensitive to local water conditions (196). Broadly, regulation and policy only changes when there is a failure (198) otherwise the system of water governance does not change much (197). While government does fund research (205), neither government nor regulators seek to promote particular technologies (203, 204, 261, 262).

Current legislation does not inhibit innovation (202). Current regulation promotes only incremental efficiency rather than radical innovation (201).

Coordination among regulators and with the government is important under the current system (230, 231, 232, 234). Respondents disagreed to some extent over how effective this coordination is. One claim is that there is a lack of coordination in and out of government around novel technologies (199) and no single body is responsible for water issues making progress slow (206). A general issue in governmental coordination was the tensions over allocation of duties (244, 245, 249).

A core tension exists between EA seeking to get environmental interventions delivered through WCs Ofwat is looking to keep company expenditure and prices under control (233). 2 respondents said that EA, WC, Ofwat coordination works well (235). 2 however disagreed, claiming EA Ofwat coordination is ineffective (236) and barrier to innovation (239). The system of coordination involves EA determining the NEP which WCs then implement through WRMPs and AMPs scrutinized by the respective regulators (250, 251, 253), however Ofwat may challenge elements of the WRMP (254) and it would be helpful if AMPs and WRMPs were integrated (255). AMP-WRMP integration would be beneficial to innovation and long term planning (616, 617, 618).

Regarding flood risk, WC-local authority coordination is hard due to different duties / risk preferences (238), while central and local government have a conflict over it (243). More generally, local authorities are not always aware of catchment-wide measures (269). Legislative reforms to this end could involve reform for greater legislative and regulatory coherence (213, 214), an independent authority reporting NEP implementation to Parliament (212).

Some respondents indicated possible high-level reforms around exploring the role of government and societal direction plays in water innovation (207); government setting more interventionist direction (208); the supply chain being involved in planning (211); Ofwat being given a technology policy mandate (209). Ofwat does not consider or know what an alternative model of water governance may look like (210) so presumably at least some way for it or some other authority to explore such alternatives. Natural Capital Accounting was also mentioned as a possible reform that would drive eco-innovation (435) and that monetary valuation of biodiversity benefits would also promote SuDS and related distributed interventions (436).

Regarding reuse, regulators setting reuse adoption as a goal would be a major driver (259), however national targets reduce flexibility of future governments (260), UK government and regulators do not make technology targets (261, 262). As such it is possible the government acts as a barrier to WRT adoption (263). Additionally, while planning conditions could also drive WRT (265), the Building Code and Planning permission are too weak to do so (264) and the Code for Sustainable Homes which used to be a driver has been abandoned (266). Local authorities face a trade-off promoting WRT vs driving development (268) and the developer lobby has prevented tighter building code and planning conditions (267).

Renationalization was broadly seen negatively: a mistake (226), too expensive (227), and an uncertain impact (228). Scottish Water as an alternative model of a more cooperative relationship with SEPA (241), is more social but cutting costs less (229). Welsh water coordinates better with Welsh government than in England (240).

Although respondents disagreed on whether or not environmental standards would fall after Brexit (216, 217, 218, 219), the most respondents mentioning Brexit supported the claim that there is a high degree of uncertainty around what changes will take place after Brexit (215). Two potential benefits of Brexit were identified: a slower and cheaper approach to implementation (220), laxer winter licensing without WFD non-deterioration requirements (221). Brexit may however negatively affect the supply chain in importing from the EU and using EU references (224).

Drinking Water Quality Regulation

DWI aims to maintain public trust in water (270). WC and suppliers must convince DWI a novel technology will deliver to legislative standards (271). WRT require DWI support and regulation (272). These regulatory instruments could function to constrain WRT (274) and other innovations however only one responded indicated this. The DWI pursues risk based regulation and reviews technologies cautious of and seeking to avoid the potential it constrains innovation.

Economic Regulation

The current system was established to deliver investments needed for water and sewerage (275). The periodic nature of the price review means Ofwat staffing rises and falls around the PR (278), as capital investment dips around the PR (279).

The relationship can be understood as a negotiation (276) over the cost of equity vs the maintenance of assets (284) or investor expectations and affordable bills (285). Ofwat is generally looking to keep prices down (307, 308).

The role investors play is important here as Ofwat sets the investor returns (293, 294, 295, 297). Ofwat generally set a 'fair' rate of return at 6% (294) and that return is low risk (295). Ofwat has pushed WCs to be more transparent in their structure, ownership and returns (296) and wins against shareholders leading to a change in owners at times (297). The role of personalities is important and at times not recognized by investors (280, 281).

6 respondents said there is little trust between Ofwat and the WCs (283) while 3 said there is good trust between Ofwat and WCs (although it is noteworthy that these 3 are not involved with price reviews). WC and Ofwat seek to develop and ensure trust and avoid surprises through consultations, dialogue (298), transparency (299, 300), early warning (301), incremental changes (302), auditing and assurance (304, 305, 206).

Key problems are that Ofwat does not trust WCs not to abuse looser controls (286), and companies exert effort to work around economic regulation to extract profits (287, 288). WCs try to argue on the basis of customer outcomes (277) and hide expected profits from sale of land for example (290). One respondent highlighted changes in trust over the course of the price reviews as companies abused the trust and Ofwat clamped down and then trust has slowly been rebuilt (289) and is relatively good in PR14 (289, 292).

As noted earlier there was some disagreement over the role regulation plays in innovation with respondents as a group seeming to lean more towards claiming regulation to be a barrier. Key mechanisms of this barrier identified were that there is no funding for failed innovations (317), outperformance of innovation is shared with customers (318, 319), and that AMP cycles mean that capital asset innovations are delayed until the next AMP (321). 5 year cycle means technologies with returns beyond these are not selected (611, 612).

That being said, 6 respondents highlighted that recent moves towards an outcomes approach and the adoption of the innovation pillar in the PR mean regulation is now more supportive (315, 316, 613).

Ofwat has not provided a sector wide innovation fund such as exists in the energy sector (328, 329) and prevents WCs from pooling money except through UKWIR (332). The reason for this is that Ofwat does not trust that the incumbents receiving more money is the solution (330).

Existing Instruments of Economic Regulation

Regulatory Capital Value – Incentivizes building capital assets (333, 336), guarantees stranded assets are borne by customers (334). Changing the RCV would drive innovation (335), but could reduce investor confidence (338), could drive up cost of capital (337), strand assets (339), and could break the whole regulatory system (340).

Comparative Efficiency – drives cost reduction (341) and squeezes supplier margins (344), has been softened (342), and is in conflict with customer nominated improvements (343).

New Appointments and Variations (NAVs) – require new appointee to be cheaper than incumbent (346) and enable new entrants, pressuring incumbents' efficiencies (351). NAVs competition difficult and unsuccessful (345) with little activity for the first 10 years (348) although picking up lately (349).

Recent Reforms to Instruments of Economic Regulation

TOTEX – 4 respondents agreed that the move to TOTEX is helpful for innovation (354). It removes the bias towards capital projects (355) encouraging catchment interventions (356).

Outcome Delivery Incentives (ODIs) – 3 respondents agreed ODI's support innovation. ODI's help to put monetary value to performance improvements (360), inform the supply chain about WC priorities (361). While some companies forgo incentive price grants to keep prices down for customers (363), penalties from ODI's will reduce prices (364).

Competition Reforms

Ofwat has recently moved to introducing competition in some areas. 5 respondents agreed that opening the market for bioresources will drive innovation (370)

5 respondents agreed that retail competition will reduce prices (379) particularly for large consumers (380). There was concern that poorer customers would end up paying more under retail competition (384) as savings for large customers are transferred to households for example. There is however concern that the retail market will become oligarchic (381, 382) although it was mentioned that WCs broadly are not in favour of losing monopolies to competition reform (383). An unintended consequence of competition reforms, are that if they drive down prices this will reduce the conservation incentive for consumers (378), and make raising environmental tariffs by WCs (376).

Retail competition will make innovation expenditure more justifiable in WC planning and decision making (374) and introduce an incentive for alternative sources and WRT (375), but will not drive major changes which only happen with major asset upgrades (372, 373). Adding a retailer in between the WC and the consumer however may make coordination around novel technology more challenging (385, 386) for example with regards to data ownership (387).

Household retail opening meanwhile had a much less positive response. 5 respondents believed it was either not going to happen or not likely to happen or should be discouraged (389, 390, 393) . Household retail competition will not drive innovation (388), would not likely reduce prices for customers (392) and wrongly places cost liability on customers (391).

Upstream market opening will introduce more competition in abstraction sources. Upstream reform will reduce prices (394). Other claims were contested. Upstream reform will have a positive environmental impact (395), but this will be limited (396). It could encourage innovation for small abstractors (398) but it is not likely to promote large scale investments (397).

Environmental Regulation

The most agreed upon claim (4 respondents) for environmental regulation generally was that collaboration and cross-sector work can deliver environmental outcomes (399). 4 respondents highlighted that regional groups already emerged to consider strategic options (455), for example to consider a regional reservoir (459). Integrated catchment management (ICM) was highlighted by 4 respondents to allow for integrated solutions to drainage, flooding, pollution, and resource management (437). WRT, RWH, and SuDS would play a part in ICM and help to deal with combined sewer overflows (442). The key tension in this comes over who will pay for interventions (439, 443) with constrained local authorities unwilling to take on commitments such as SuDS maintenance (444). Effective cost sharing mechanisms were not in place (449), meaning works with co-benefits were not being delivered (447), poor coordination among WC and local authorities (448). Another tension in ICM is the allocation of water among competing users and uses (440).

The Environment Agency (EA) talks with WCs (401, 402). It scrutinizes WC WRMPs (404), and WC regularly challenge EA assessments of what needs to be done (403). The EA works with stakeholder to ensure changes are acceptable (400), although there are conflicts over what level of regulatory tightening is achievable (405). The EA generally tries to work collaboratively (406), and actors have learned to collaborate over time (407). However legal action and enforcement are regularly undertaken in parallel (408) which can end in public enquiry and be time consuming for all involved (409).

Environmental regulation is generally only tightening (411), due to environmental stressors (413), detectability (414) and health studies (415). The EA focuses efforts and consents based on past performance and risks (410) as well as experience from past droughts and expected population growth (419). In particular local authorities with water related industry are more concerned with tighter consents (416). Likewise abstraction licensing is tightening (460), due to climate change (461) and water stress (463), although this was difficult for the EA because it meant changing property rights (464), and managing conflict between green groups and abstractors (465).

Environmental regulation relates to innovation in a number of ways. 6 respondents agreed that tighter parameters and consents drive development of new processes (428). Differentiated consents mean it is difficult to optimize standardized technologies or solutions (426) but encourage exploring different solutions in different contexts (425). The EA itself supports research programmes into treatment processes for emerging pollutants (421). While EA head office is supportive of WRT (430), local EA procedures are a barrier to WRT (431).

Drivers of Water Price

Water prices are largely driven by required investment in assets (467) such as reservoirs (469), innovative treatment processes (471), and the cost of capital (468). Relatedly, the price is driven by environmental improvements (486), the WFD (487), priority substances in particular (494) and UWWTD on CSOs (419), tighter consents (488), pesticide removal (489), nutrient removal (490).

The largest operating cost for WCs was electricity (474), and most water innovations are energy intensive (475). Sludge and energy recovery technologies are able to reduce prices (477). Leakage reduction could also reduce prices (484) except where developing alternative sources is cheaper (485). Cheaper treatment technologies require large space which is not available (476) and increased use of chemicals can reduce energy consumption (481).

Another driver of costs and hence prices is water scarcity. 2 respondents claimed diminishing sources under population growth will drive up prices (497). 3 participants claimed alternative sources like WRT can drive down prices (496) while 2 disagreed, claiming new alternative sources drive up prices (499).

The clearest downward pressure on prices is from customers (504), particularly low income households (500), and this is also supported by CCWater the consumer representation body (501). Closer engagement with customers through CCGs will contribute to this (501). There is also political pressure on WC regarding the amount of profit being generated (502).

Regarding the role price has in consumption it was claimed that water prices are too low to encourage use reduction (505), flat rates do not encourage conservation (506) while metering can help reduce consumption (507) and innovation (508). In particular shifting consumption to non-peak electricity hours would save on costs (509). While changing customer behaviour could reduce prices (510), demand reduction typically doesn't last (511).

General Claims about Collaboration

A complicated set of interactions take place between all the stakeholders (521) and complex legal frameworks underpin some of these (522) but there is a general lack of effective coordination among all actors around novel technologies (199).

Coordination around transitions is helped by a phased approach (518). Regular engagement with stakeholders helps with coordination (519). Trust is important in facilitating coordination (514) and such trust is built up in relationships over time (515). Regarding regulator firm relationships, the EA does not trust WCs to maintain assets and not pollute given greater regulatory flexibility (516, 517). The effectiveness of cooperation also relies on the expertise of the personalities involved (520).

Appendix V: Statistical Addendum to Stakeholder Interviews

This addendum collates data and tables drawn from the responses to the supplementary survey.

Questions on Foresight

Taking together supplementary survey responses for primary and secondary stakeholder, descriptive statistics of responses relating to WCs are:

Table A2.1: Responses to question on time horizons for respondents indicating WC as the primary or secondary stakeholder

Statistics			**Frequency Distribution (years)**		
Responses (n)	**Mean (years)**	**Sample standard deviation (years)**	**5-6**	**20-25**	**≥40**
10	20.6	14.94	4	4	2

These responses corroborate the results from the interviews which highlighted that although WCs focus on the 5 year AMP through WRMPs and some other more forward looking aspects, the companies sometimes do have longer time horizons.

Responses regarding time horizons of other stakeholder categories are provided below:

Table A2.2: Responses for Planning Horizon not indicating WC as stakeholder category

Stakeholder Category	**Planning Horizon**
Supplier	5
Supplier	1
Supplier	5
Regulator	Not clear
Regulator	varies
Regulator	50
Consumer	Varies
Consumer	5

One point that could be raised it that the suppliers' time horizons are typically either shorter than or equal to those of relatively short-sighted WCs namely around 5 years.

Questions on Discount rates

The combined responses to the survey question: "What discount rate do they use?" for both primary and secondary stakeholder are given below.

Table A.3: Responses for question about stakeholder discount rate

Stakeholder Category	Response
Consumer	no idea
Consumer	
Consumer	?
Regulator	N/A
Regulator	
Regulator	
Supplier	12%
Supplier	
WC	
WC	Green Book
WC	
WC	complicated
WC	
WC	
WC	Estimation of WACC
WC	?
WC	12%
WC	?

Clearly, this question was poorly designed in that most respondents did not respond or indicated that the question was unclear to them. No meaningful result can be drawn from this data other than the indicators that the Green Book methodology is used or the cost of capital is used.

It is however possible to substitute some values for some of the methodology. The Green Book recommends a 3.5% discount rate for the first 30 years of a project [*Lowe*, 2008]. The WACC in PR 14 Final Determinations was 3.6% [*Ofwat*, 2014]. Therefore we have at least for the water companies 3 values of 3.5%, 3.6% and 12% giving a mean of 6.36%. Again unfortunately this is not a result based on abundant data.

Data from Supplementary Survey Responses to Statements on Decision Making

Table A2.4: Supplementary survey responses on decision making for all stakeholders.

	Scale Responses						Weight factor								
	Always	Most of the time	About Half the time	Sometimes	Never	Response Count	1.00	0.75	0.50	0.25	0.00	Quantified Sum	Average Response	Standard Deviation	Confidence: Response over total
CBA	6	10	1	4	1	22	6	7.5	0.5	1	0	15	0.68	0.13	1
Deliberate	3	12	3	4		22	3	9	1.5	1	0	14.5	0.66	0.11	1
Selfish	1	10	1	6	3	21	1	7.5	0.5	1.5	0	10.5	0.50	0.17	0.954545455
Satisfice	1	5	2	10	1	19	1	3.75	1	2.5	0	8.25	0.43	0.14	0.863636364
Rule	1	1	4	11	2	19	1	0.75	2	2.75	0	6.5	0.34	0.09	0.863636364
Response	3	11	1	5	1	21	3	8.25	0.5	1.25	0	13	0.62	0.13	0.954545455
Punish	3	8	1	2	2	16	3	6	0.5	0.5	0	10	0.63	0.14	0.727272727
Punish+	1	7		6	2	16	1	5.25	0	1.5	0	7.75	0.48	0.17	0.727272727
RiskAverse		8	3	9		20	0	6	1.5	2.25	0	9.75	0.49	0.16	0.909090909
Altruist	1	2	2	13	4	22	1	1.5	1	3.25	0	6.75	0.31	0.09	1
Emotion		1	1	13	7	22	0	0.75	0.5	3.25	0	4.5	0.20	0.08	1
Culture		4	1	12	3	20	0	3	0.5	3	0	6.5	0.33	0.11	0.909090909
Ideology		2		3	13	18	0	1.5	0	0.75	0	2.25	0.13	0.12	0.818181818

Table A2.5: Supplementary survey responses on decision making for WCs.

	Scale Responses						Weight factor								
	Always	Most of the time	About Half the time	Sometimes	Never	Response Count	1.00	0.75	0.50	0.25	0.00	Quantified Sum	Average Response	Variance	Confidence: Response over total
CBA	2	6		2		10	2	4.5	0	0.5	0	7	0.70	1.26	1
Deliberate	2	5	1	1		9	2	3.75	0.5	0.25	0	6.5	0.72	0.60	0.9
Selfish		5	1	3		9	0	3.75	0.5	0.75	0	5	0.56	1.79	0.9
Satisfice		2		5	1	8	0	1.5	0	1.25	0	2.75	0.34	1.00	0.8
Rule			2	7	1	10	0	0	1	1.75	0	2.75	0.28	0.31	1
Response	3	5			1	9	3	3.75	0	0	0	6.75	0.75	1.13	0.9
Punish		4			2	6	0	3	0	0	0	3	0.50	2.00	0.6
Punish+		2		2	2	6	0	1.5	0	0.5	0	2	0.33	1.17	0.6
RiskAverse		3	1	5		9	0	2.25	0.5	1.25	0	4	0.44	1.79	0.9
Altruist		1	2		2	5	0	0.75	1	0	0	1.75	0.35	0.74	0.5
Emotion			1	5	4	10	0	0	0.5	1.25	0	1.75	0.18	0.74	1
Culture		1		7	2	10	0	0.75	0	1.75	0	2.5	0.25	0.50	1
Ideology				1	8	9	0	0	0	0.25	0	0.25	0.03	0.10	0.9

Table A2.6: Supplementary survey responses on decision making for regulators.

	Scale Responses						Weight factor								
	Always	Most of the time	About Half the time	Sometimes	Never	Response Count	1.00	0.75	0.50	0.25	0.00	Quantified Sum	Average Response	Standard Deviation	Confidence: Response over total
CBA	1	3		1	1	6	1	2.25	0	0.25	0	3.5	0.58	0.19	1
Deliberate	1	4		1		6	1	3	0	0.25	0	4.25	0.71	0.11	1
Selfish		2		1	3	6	0	1.5	0	0.25	0	1.75	0.29	0.25	1
Satisfice	1		2	2		5	1	0	1	0.5	0	2.5	0.50	0.18	0.833333333
Rule	1	1	2	2		6	1	0.75	1	0.5	0	3.25	0.54	0.16	1
Response		5		1		6	0	3.75	0	0.25	0	4	0.67	0.12	1
Punish	3	3				6	3	2.25	0	0	0	5.25	0.88	0.11	1
Punish+	1	4		1		6	1	3	0	0.25	0	4.25	0.71	0.11	1
RiskAverse		3		3		6	0	2.25	0	0.75	0	3	0.50	0.21	1
Altruist	1			4	1	6	1	0	0	1	0	2	0.33	0.16	1
Emotion		1		3	2	6	0	0.75	0	0.75	0	1.5	0.25	0.14	1
Culture		3		3		6	0	2.25	0	0.75	0	3	0.50	0.21	1
Ideology		1		2	3	6	0	0.75	0	0.5	0	1.25	0.21	0.17	1

Testing for primary and secondary stakeholder differences in decision making statements

It is useful to compare responses between primary and secondary stakeholders to see if there are any trends in the data due to how stakeholders evaluate their own organization versus the counterpart stakeholder regardless of stakeholder category. Two key tests were conducted to this end. 1) a t-test for differences in means between primary and secondary stakeholder for each statement. This would test whether there are trends in the mean response due to primary/secondary stakeholder. The expectation would be that the data not likely to reject a null hypothesis here due to stakeholders answering for many difference stakeholder categories for each. 2) the second set of tests (Pratt's tests) were conducted to test whether differences in responses between primary and secondary are symmetrically distributed around 0 meaning they were essentially random. The expectation here is that these differences would reject the null hypothesis indicating that the differences were not essentially due to chance but rather due to actual differences in the stakeholders' perceptions of the decision making of the primary and secondary stakeholder.

Difference in Means

The strongest difference in means was for Deliberate where respondents indicated the largest difference in mean values for the secondary as opposed to primary stakeholder – a negative difference considering the secondary stakeholder to be less Deliberative (mean difference = -0.03). The hypotheses needing testing here is whether this difference is due to the difference in primary or secondary stakeholder. This would mean that regardless of stakeholder category respondents would rate the primary as more deliberative than the secondary. This test is conducted for each statement.

T-tests are used for testing differences in means. One important condition for t-test applicability is that variances are not correlated. F tests were conducted to indicate whether differences in variances between the responses for primary and secondary stakeholders substantially different than expected if these were driven by chance alone. As shown in Table A2.7, F tests rejected null hypotheses in only two of the statements. This means variances are not correlated and the t test is applicable.

Table A2.7: F tests for differences in variances between primary and secondary stakeholder

	CBA	Deliberate	Selfish	Satisfice	Rule	Response	Punish	Punish+	RiskAverse	Altruist	Emotion	Culture	Ideology
variance 1	0.11180556	0.025	0.10347222	0.06423611	0.02013889	0.11388889	0.15066964	0.08482143	0.05277778	0.11388889	0.04166667	0.0625	0.0078125
variance 2	0.09791667	0.05555556	0.08958333	0.08506944	0.08333333	0.07986111	0.0297619	0.08035714	0.05245536	0.02013889	0.02847222	0.06423611	0.10714286
f values	1.14184397	2.22222222	1.15503876	1.32432432	4.13793103	1.42608696	5.0625	1.05555556	1.00614657	5.65517241	1.46341463	1.02777778	13.7142857
df1	9	9	9	8	9	9	7	7	9	9	9	8	7
df2	9	9	9	8	6	8	6	6	7	9	9	8	7
1 is numerator?	1	2	1	2	2	1	1	1	1	1	1	2	2
t table value	4.026	4.026	4.026	4.4333	5.5234	4.102	5.1186	5.1186	4.197	4.026	4.026	4.4333	4.9949
a = 0.025	fail	fail	fail	fail	fail	fail	fail	fail	fail	reject H0	fail	fail	reject H0

As shown in Table A2.8 paired t-tests did not show that with this data it is possible with any substantial degree of confidence to conclude that these differences are not due to chance alone. In other words, differences in means were not driven by the primary-secondary stakeholder distinction. This helps to verify that the results reflect perceptions of stakeholder category rather than whether a stakeholder is the primary or secondary stakeholder.

Table A2.8: Paired t-tests for primary vs secondary stakeholder for each statement.

	CBA	Deliberate	Selfish	Satisfice	Rule	Response	Punish	Punish+	RiskAverse	Altruist	Emotion	Culture	Ideology
sum d	0	-0.3	0	0.125	0.25	-0.02777778	0.41666667	0.41666667	0.125	-0.175	-0.075	0.02777778	0.21875
n	10	10	10	8	7	9	6	6	8	10	10	9	8
mean d	0	-0.03	0	0.015625	0.03571429	-0.00308642	0.06944444	0.06944444	0.015625	-0.0175	-0.0075	0.00308642	0.02734375
sd	0.5	0.26925824	0.47434165	0.21650635	0.23145502	0.3808697	0.372678	0.23570226	0.25	0.275	0.16007811	0.248452	0.26331718
se	0.15811388	0.08514693	0.15	0.07654655	0.08748178	0.12695657	0.15214515	0.09622504	0.08838835	0.08696264	0.05062114	0.08281733	0.09309668
T	**0**	**-0.35233213**	**0**	**0.20412415**	**0.40824829**	**-0.02431083**	**0.45643546**	**0.72168784**	**0.1767767**	**-0.20123585**	**-0.14815944**	**0.0372678**	**0.29371348**
df	9	9	9	7	6	8	5	5	7	9	9	8	7
crit 0.5	0.703	0.703	0.703	0.711	0.718	0.706	0.727	0.727	0.711	0.703	0.703	0.706	0.711
0.4	0.883	0.883	0.883	0.896	0.906	0.889	0.92	0.92	0.896	0.883	0.883	0.889	0.896
0.3	1.1	1.1	1.1	1.119	1.134	1.108	1.156	1.156	1.119	1.1	1.1	1.108	1.119
0.2	1.383	1.383	1.383	1.415	1.44	1.397	1.476	1.476	1.415	1.383	1.383	1.397	1.415
0.1	1.833	1.833	1.833	1.895	1.943	1.86	2.015	2.015	1.895	1.833	1.833	1.86	1.895
0.05	2.262	2.262	2.262	2.365	2.447	2.306	2.571	2.571	2.365	2.262	2.262	2.306	2.365
0.02	2.821	2.821	2.821	2.998	3.143	2.896	3.365	3.365	2.998	2.821	2.821	2.896	2.998
crit 0.5	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail
0.4	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail
0.3	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail
0.2	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail
0.1	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail
0.05	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail
0.02	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail	fail

Distribution of Pair Differences

Pratt's test (a modification of the Wilcoxon signed-rank test) is a robust test when applied to paired Lykert scale data [*Pratt*, 1959; *Derrick and White*, 2017]. This test was used also because it is suitable to a data scarce setting where normal distributions of that data cannot be assumed but where paired information is available. Pratt's modification allows for the inclusion of 0 within-pair differences which are common to Lykert scale paired data. The null hypothesis of this test is that the difference in responses for primary and secondary stakeholder will have a symmetric distribution around 0. Correspondingly the alternative hypothesis is that these differences are not symmetrically distributed around 0. Pratt's tests were conducted on each statement to identify which statements the respondents tended to differentiate themselves from their counterparts more strongly in.

It would be reasonable to expect that the differences between responses for primary and secondary stakeholder would be driven by more than chance alone. As such it would be reasonable to expect to reject the null hypothesis for most of these tests. The results are given in Table A2.9 and confirm that expectation for 7 of the statements at the 95% confidence level. Results do however indicate that for some statements it is not possible to make that conclusion. This seems largely driven by the low data count for where participants indicated 'don't know'. Broadly the conclusion drawn from this set of results is that the sample set was too small, with 6 of the statements only receiving 8 or less responses.

Table A2.9: Results for Pratt's tests for primary vs secondary stakeholder for each statement

	CBA	Deliberate	Selfish	Satisfice	Rule	Response	Punish	Punish+	RiskAverse	Altruist	Emotion	Culture	Ideology
Nr	10	10	10	8	7	9	6	6	8	10	10	9	8
correlation	-0.325	0.000	-0.296	0.671	0.500	0.147	-0.231	0.250	0.374	0.522	0.605	0.452	0.617
Mean Diff.	0	-0.3	0	0.166666667	0.275	0.011111111	0.316964	0.33035714	0.14375	-0.175	-0.075	0.02777778	0.21875
W	0.5	-23	0	9.5	12.5	0	9	10	7.5	-16	-12	3.5	13
critical0.1	11	11	11	6	4	8	2	2	6	11	11	8	6
critical0.05	8	8	8	4	2	6	0	0	4	8	8	6	4
critical0.02	5	5	5	2	0	3	#NV	#NV	2	5	5	3	2
critical0.01	3	3	3	0	#NV	2	#NV	#NV	0	3	3	2	0
result 0.1	Reject H0	Reject H0	Reject H0	Fail	Fail	Reject H0	Fail	Fail	Fail	Reject H0	Reject H0	Reject H0	Fail
result 0.05	Reject H0	Reject H0	Reject H0	Fail	Fail	Reject H0	Fail	Fail	Fail	Reject H0	Reject H0	Reject H0	Fail
result 0.02	Reject H0	Reject H0	Reject H0	Fail	Fail	Reject H0	#NV	#NV	Fail	Reject H0	Reject H0	Fail	Fail
result 0.01	Reject H0	Reject H0	Reject H0	Fail	#NV	Reject H0	#NV	#NV	Fail	Reject H0	Reject H0	Fail	Fail

Conclusion on Statistical Tests for Primary-Secondary Stakeholder Difference

Differences in means between primary and secondary reject the claim that primary-secondary distinction drove differences in means. Regarding distribution of differences, it is unlikely that the perceptions stakeholders have of primary and secondary stakeholders' decision making are randomly distributed. Although the data should be considered with caution as the sample set was very small and Pratt's tests did not reject null hypotheses for all statements. Use of supplementary survey data should proceed in the knowledge that these results are not well characterized by a random distribution and hence bear information about stakeholder decision-making perceptions.

Appendix VI: Permission Letter

22 November 2018

To whom it may concern,

By this letter I hereby give my permission to:

Name : Bora Ristic

Department : Centre for Environmental Policy, Imperial College London

To use the data collected from the interviews for my MSc thesis on "Adoption of water reuse in the UK: a game theory approach to modelling stakeholder interaction" which was submitted for academic year 2016/17 in Centre for Environmental Policy, Imperial College London. I acknowledged and granted this permission on the use of the data for the purpose of his PhD dissertation.

If you require any additional information, please do not hesitate to contact me at

Sincerely,

Elzavira Felaza Effendi
Graduate of MSc Environmental Technology
Centre for Environmental Policy, Imperial College London