École Doctorale : Sciences, ingénierie et environnement (SIE)

Thèse présenté pour l'obtention du titre de

Docteur de l'Université Paris-Est

Spécialité : Science de l'environnement

Beyond Evidence-Based Decision Support: Exploring the Multi-Dimensional Functionality of Environmental Modelling Tools

Comparative Analysis of Tools and Practices in France and Australia in the Context of Water Resources Management

Présentée par

Natalie CHONG

Thèse soutenue le 29 mars 2019 devant le jury composé de :

M. Rémi BARBIER, Professeur, HDR, ENGESS, Université de Strasbourg	Rapporteur
M. Denis SALLES, Directeur de recherche, HDR, IRSTEA Bordeaux	Rapporteur
M. Peter BACH, Research Fellow, Eawag, ETH Zurich/Monash University	Examinateur
Mme. Catherine CARRÉ, Professeur, HDR, Université Paris 1	Examinateur
M. Hadrien COMMENGES, Maître de conférences, Université Paris 1	Examinateur
Mme. Céline BONHOMME, PhD, HDR, Ministère de la transition écologique et solidaire	Directeur de thèse
M. José-Frédéric DEROUBAIX, Chargé de recherche, Université Paris-Est, ENPC	Co-encadrant de thèse

Acknowledgements

I would like to express my deepest gratitude and appreciation to Céline and José, the epitome of interdisciplinary collaboration. It was your unique perspectives and complementary nature that gave this thesis its legs. Thank you for giving me the push I needed to face new challenges, for your continued guidance and support, your candid and insightful feedback, and most of all, your humour, which made it all worthwhile (even if I'm not sure I understood all your jokes!).

To the PIREN-Seine and École des Ponts et Chaussées, who made this all possible, thank you for supporting this incredible and unique opportunity, for which I am extremely grateful. Special thanks to everyone in France and Australia who took the time to speak with me and confide in me their stories, and to the PIREN and CRC for Water Sensitive Cities for opening their doors to critical analysis, which is never an easy thing to do. Catherine, thank you so much for your support and for your kind and welcoming nature. Lara, Tony and Rebekkah, thank you for being such amazing hosts in Australia. Peter, thanks to your great advice and contribution, I was able to successfully publish my first article. I hope the tips you gave me were put to good use in writing this thesis.

To my fellow colleagues – Francesco, Denis, Claire, Saja, Najwa, Kelsey, Damien, Yinghao, Lenora, Momo, Tala, Yi, Sarah, Yujie, Neng, Fabien and Guillerme – thank you for the continued support, and of course, the countless *goûters*. Special thanks to Annick, who keeps the lab warm and is always there to listen to me gripe about my constant and endless struggle with French administration. Francesco, thanks for the stimulating lunchtime convo. Your laid-back nature is a welcome change to the stress of thesis writing. Denis, thanks for the much needed coffee breaks. Special thanks to Claire, Kelsey, and Saja who are always ready to lend a hand (no matter how busy they are!) and to Damien for imparting your scientific wisdom and entertaining stories. Sarah, thank you for giving me a much needed hand with my French and for your moral support.

Finally, I would like to express my love and gratitude for my friends and family who still have no idea what my thesis is about, but continue to support me anyways. Noémie, the BOML, I'm so grateful to have you in my life. Thanks for putting up with me when I was stuck in my writing bubble, for helping me organise my life, and for reminding me that there are other, more important things in life outside of the thesis. Aude, Becca, Julie, and Shandele, thanks for always being available for random conversations when I needed a break and for your love and support from the other side of the world. Simon, my study buddy, thanks for your input and your company, even if we rarely got much work done! Manko, thank you for being the supportive 'mamma bear' that you are. Tuuli, you're next!

Mom, your strong Asian work ethic continues to inspire me every day. Dad, I'm glad to have inherited your love of learning. Craig and Bev, thanks for being the 'okayest' siblings in North America. Russell and Darren, thanks for being the smart, funny, curious and fun-loving kids that you are. Never stop learning or asking questions. And Oreo, thanks for being the best dog in the world.

Abstract

As the sun sets on the age of unlimited growth and consumption, the call for progressively robust, adaptive and integrated solutions to address 'wicked' environmental problems has ushered in a new paradigm that has fundamentally changed the practices of both science and management. Emphasis on collaborative, integrative and participative approaches has given rise to burgeoning science-practice-policy arrangements while necessitating new tools to support the implementation of increasingly demanding regulation.

In the context of water resources, models have emerged as fundamental tools favoured by scientists and practitioners alike, owing to their ability to advance scientific understanding of water systems functioning, while at the same time supporting key decisions in the management, policy and planning of river basins. A wide range of modelling tools have been developed to study the numerous physical, chemical, and biological processes at work, on different spatial and temporal scales, with varying levels of complexity. At the same time, models provide practitioners with a practical tool for supporting 'evidence-based' policy by transposing complex problems into technical, 'manageable' solutions. Yet, their application in practice has proven far from proportional to the amount of time and resources that have been invested in their development.

This thesis aims to elucidate the enduring divide between science, practice and policy in the context of a new paradigm of science and management through the lens of modelling tools and their role at the science-practice-policy interface. Using a qualitative approach, we draw from two empirical examples: the PIREN-Seine in France and the CRC for Water Sensitive Cities in Australia. While both share similar challenges, methods and objectives, the fundamental difference in their strategies and approaches offers a rich foundation for comparison.

In doing so, we explore the driving forces, implications and potential consequences of the parallel paradigm shifts in science and management, focusing on three main aspects: 1/ the use and utility of modelling tools to support water management, policy and planning; 2/ the different modalities of addressing uncertainty in model-based decision support, and; 3/ the role of new science-practice-policy arrangements. By first retracing the history of production and use of modelling tools in both examples, we seek to understand the nuanced relationship between 'use' and 'utility', offering insight into influencing factors. Next, we turn to the question of uncertainty by analysing how researchers practitioners reconcile the fundamental challenge of uncertainty in model-based decision support. Delving deeper into the complex, negotiated social process that comprises the decision-making context, we focus on the social construction of ignorance and its role in decision-making. Finally, we examine the macro-level changes brought about by the paradigm shift in science and management. Amidst these changes, we seek to understand the emergence and functions of 'boundary organisations' in this new epoch, and their role in the quest for robust, adaptive and sustainable solutions.

Keywords: Boundary Organisations, Modelling, Negotiated Ignorance, Science-Practice Interface, Water Resources Management

Résumé

À l'heure où les horizons d'une croissance et d'une consommation infinies sont remis en cause, les appels aux développements de solutions de plus en plus robustes, flexibles et intégrées pour gérer les problèmes environnementaux inédits ont conduit à l'avènement d'un nouveau paradigme, transformant de manière radicale les pratiques de la science et de la gestion. L'importance accrue accordée aux approches collaboratives, intégrées et participatives a soutenu l'essor d'arrangements entre science, pratique et politique, tout en rendant nécessaire la création de nouveaux outils pour accompagner la mise en œuvre d'une réglementation de plus en plus exigeante.

Dans le contexte de la gestion des ressources en eau, les modèles sont apparus comme des outils cruciaux, plébiscités par des scientifiques et des praticiens, pour leur capacité à faire avancer la compréhension scientifique du fonctionnement des systèmes hydrologiques à renseigner les politiques publiques et la planification de l'eau dans les bassins versants. Une grande diversité d'outils de modélisation a été développée pour analyser les processus physiques, chimiques et biologiques à l'œuvre, à des échelles spatiales et temporelles diverses et avec des degrés de complexité variés. Par ailleurs, les modèles sont censés fournir aux praticiens des outils concrets au service de politiques fondées sur des faits scientifiques ('*evidence-based policy*'), en permettant de transposer des problèmes complexes en solutions techniques « gérables ». Pour autant, leur application pratique est loin d'être proportionnelle à l'investissement en temps et en ressources dédié à leur développement.

Cette thèse vise à éclairer le fossé persistant entre science, pratique et politique dans le contexte d'un nouveau paradigme pour la science et la gestion, à travers le prisme des outils de modélisation et de leur rôle à l'interface science-pratique-politique. Nous utilisons une approche qualitative et nous nous appuyons sur deux exemples empiriques : le PIREN-Seine en France et le CRC for Water Sensitive Cities en Australie. Bien que les deux exemples partagent des défis, des méthodes et des objectifs similaires, la richesse de leur comparaison repose sur la différence fondamentale dans leurs approches et leurs stratégies.

Ce faisant, nous explorons les moteurs, implications et conséquences potentielles des changements de paradigme parallèles à l'œuvre de la science et la gestion, en nous concentrant sur trois aspects : 1/ l'utilisation et l'utilité des outils de modélisation pour soutenir la gestion, la planification et les politiques publiques concernant les ressources en eau ; 2/ les différentes modalités qui permettent d'aborder l'incertitude dans l'aide à la décision reposant sur des modèles ; 3/ la signification ou la portée de nouveaux arrangements entre science, pratique et politique. En retraçant l'histoire de la production et de l'utilisation des outils de modélisation dans les deux exemples, nous cherchons tout d'abord à comprendre la relation nuancée entre « utilisation » et « utilité », en offrant un aperçu des facteurs qui les influencent. Nous nous intéressons ensuite à la question de l'incertitude en analysant la manière dont chercheurs et praticiens affrontent le défi fondamental de l'incertitude dans l'aide à la décision fondée sur les modèles. En considérant les processus complexes, socialement négociés, qui s'inscrivent dans le contexte de la prise de décision, nous nous concentrons sur la construction sociale de l'ignorance et sur sa fonction. Nous examinons enfin, à un niveau macro socio-économique, l'évolution des pratiques engendrée par le changement de paradigme dans la science et la gestion. Parmi ces changements, nous proposons une interprétation de l'émergence et des fonctions des « organisations frontières », et le rôle qu'elles sont amenées à jouer dans la recherche de solutions robustes, flexibles et durables.

Mots Clés : gestion des ressources en eau, ignorance négociée, interface science-gestion, modélisation, organisations frontières

Table of Contents

List of Abbreviations

AESN: Agence de l'Eau Seine-Normandie

AI: Artificial Intelligence

BD: Big Data

BO: Boundary Organisation

CRCWSC/CRC for Water Sensitive Cities: Cooperative Research Centre for Water Sensitive Cities

DRIEE: Direction Régionale et Interdépartementale de l'Environnement et de l'Énergie

EPTB Seine Grands Lacs: Établissement Public Territorial de Bassin Seine Grands Lacs)

ERC: European Research Council

GMO: Genetically Modified Organism

IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCC: Intergovernmental Panel on Climate Change

ML: Machine Learning

PIREN/PIREN-Seine: Programme Interdisciplinaire de Recherche sur l'Environnement de la Seine

SIAAP: l'Assainissement de l'Agglomération Parisienne

SDGs: Sustainable Development Goals

STS: Science and Technology Studies

UNFCC: United Nations Framework Convention on Climate Change

WFD: Water Framework Directive

List of Tables and Figures

General Introduction

It is a truth universally acknowledged, that "*all models are wrong, but some are useful*" (Box, 1976). This aphorism, cultivated in an era governed by evidence-based policy and characterised by rapid technological advancement, has contributed to the rise in popularity of modelling tools to address highly complex, interdependent and rapidly changing environmental problems. Models play an increasingly important role in policy processes (Van Egmond and Zeiss, 2010), offering a pragmatic approach for transposing complex problems into more technical, quantifiable and thereby 'manageable' solutions. Across multiple sectors – from water, transport and urban planning to energy and economics – modelling tools have been embraced for their flexible, hybrid nature and multi-dimensional functionality, which has allowed them to simultaneously traverse and unite the boundaries of science, practice and policy. Modelling is now considered "*an essential and inseparable part of all scientific, and indeed all intellectual, activity*" (Silvert, 2001: 261) in a number of domains.

Yet these truths, which we often hold to be self-evident, warrant further examination considering the weight of environmental decisions in the 21st century. As mounting anthropogenic pressure continues to intensify a wide range of social, economic, political and ecological issues worldwide, growing public awareness coupled with more frequent and extreme weather events have prompted a renewed sense of urgency for environmental action and accountability. This is echoed by a greater focus on environmental sustainability in the 2030 Agenda's Sustainable Development Goals (SDGs) (United Nations, 2015) and more recently, in a special report from the Intergovernmental Panel on Climate Change (IPCC) entitled "*Global Warming of 1.5*℃" (IPCC, 2018), which warned of an impending climate change catastrophe in as little as 12 years.

In the context of water resources management, issues of water quality and quantity are inextricably linked as water quality is affected by surface flows and volume (Hattermann and Kundzewicz, 2009). An increase of pollutants (e.g. organic materials and nutrients, synthetic chemicals, heavy metals, micro-plastics and pharmaceuticals, *etc.*) that are affecting water quality are further intensified by water quantity, which is subsequently linked to global issues of water scarcity, food production and the survival of ecosystems (Zehnder *et al.*, 2003). The exponential rate of water use and demand is putting severe strains on freshwater resources (Vörösmarty et al., 2000), which is further exacerbated by conflicting user interests. At the same time, rising sea levels pose an imminent threat to coastal lowlands, leaving them vulnerable to extensive flooding (McGranahan *et al.*, 2007) and threaten to salinize estuaries and groundwater resources (Bates *et al.*, 2008).

To address these concerns, models have emerged as fundamental tools, favoured by scientists and practitioners alike; owing to their ability to advance scientific understanding of water systems functioning, while at the same time supporting key decisions in the management, policy and planning of river basins. The ability of models to encapsulate and transform scientific data and knowledge into simulations offers a unique advantage, allowing the user to explore, test and analyse any number of scenarios in order to gain insight into how an object or phenomenon may behave under a set of predefined conditions (*Systems engineering fundamentals*, 2000). In doing so, they can help characterise and make sense of scientific data which can sometimes be overwhelming or contradictory.

During the latter half of the 20th century, a wide range of modelling tools has been developed to study the various physical, chemical and biological processes at work, on different spatial and temporal scales, with varying levels of complexity. Their role in decision support has ostensibly increased in recent years, based on the amount of literature and references made in policy documents. Yet, the use and adoption of models in practice appears far from proportional to the amount of time and resources that have been invested in their development (Argent, 2004; Bach *et al.*, 2014; Hipel and Ben-Haim, 1999; Liu *et al.*, 2008; Marlow *et al.*, 2013; Riousset, 2012; Uthes *et al.*, 2010). Despite the diversity of tools and approaches that now exist, the persistence of key management issues (e.g. decentralization, sustainability of water projects, cost-effectiveness, flood and drought protection) (Angelakis *et al*, 2012) suggests a continued discrepancy between theoretical solutions and real-life action.

Since the Brundtland Report (1987) placed sustainability at the top of the international agenda, water institutions and policies have undergone significant reform worldwide. But progress continues to be impeded by implementation issues:

> "*In most of the countries of the developing world, water institutions do not function properly, and most of them display fragmented institutional arrangements and overlapping and/or conflicting decision-making structures. […] While some claim that integrated approaches are of fundamental importance to manage water in more efficient ways, the fact remains that their implementation has remained incomplete and unsatisfactory in all countries, developed or developing, after some 60 years of trying*" (Tortajada, 2010: 300).

At the same time, the increasingly blurred lines between science, policy and practice has brought science for policy into "*the core of a perfect storm generated by the insurgence of several concurrent crises: of science, of trust, of sustainability*" (Saltelli and Giampietro, 2016: 31). Ongoing debates over contentious subjects such as Genetically Modified Organisms (GMOs), vaccines and climate change are among the most prominent signs of the erosion of trust in science.

At the heart of this general malaise are concerns over scientific quality: "*There is increasing concern that in modern research, false findings may be the* *majority or even the vast majority of published research claims. However, this should not be surprising. It can be proven that most claimed research findings are false*" (Ioannidis, 2005: 124). In fact, Ioannidis (2014), estimates that as much as 85% of resources are wasted on 'shoddy science'. If accurate, this would call into question the large investment in public expenditure on research funding. When applied in practice, 'shoddy science' can result in significant social, economic and ecological consequences. For example, Stiglitz (2010) traces the recent economic recession back to "*perverse incentives and flawed models*" (92). Other issues include reproducibility (Baker, 2016; Begley, 2013; Ioannidis, 2014, 2005; Saltelli et al., 2016), failing peer-review (Hojat *et al.,* 2003; Jasanoff, 1987; Saltelli *et al.*, 2016; Schroter *et al.*, 2008; Siebert *et al.*, 2015), and the flawed nature of evidence-based policy (Macilwain, 2016; Saltelli and Giampietro, 2017, 2016).

For the time being, science has managed to maintain its foothold as one of the most trusted and respected public institutions: "*Science still commands enormous – if sometimes bemused – respect. But its privileged status is founded on the capacity to be right most of the time and to correct its mistakes when it gets things wrong*" (The Economist, 2013). Ongoing critical analysis of scientific practices and tools is therefore needed to understand the underlying causes of the current crisis and to identify levers of action. This call is particularly urgent for scientific knowledge and tools that are used to support management, policy and planning decisions.

If we continue to adhere to the maxim that "*all models are wrong, but some are useful,*" the ability to discern what is 'useful' from what is 'wrong' becomes a fundamental undertaking. Central to this task is the deconstruction of the social processes behind modelling practices as well as the development and use of the models themselves. However, this task is neither simple nor straightforward, bearing in mind the complex interplay of actors and processes operating at the interface of science, practice and policy at different spatial and temporal scales.

Water in the 21st Century: Evolving Paradigms of Science and Management

The end of the 20th century marked a critical turning point in sustainability, necessitating new tools and approaches to address 'wicked' (Rittel and Webber, 1973) environmental problems. Such problems can be characterised as globalised transterritorial, and cross-sectorial, with desynchronised political and social temporalities, and subject to high scientific and technical uncertainties due to the lack of standard responses from scientific and technical expertise and a multitude of public policies (Salles, 2013: 194; Salles and Leroy, 2013).

As 'wicked problems' require robust, adaptive and integrated solutions, sustainability discourses in the 21st century have subsequently shifted from 'conservation' and 'preservation' to 'resilience' and 'adaption' (Werners *et al.*, 2013), underlined by the concept of 'good governance'. A broad definition of environmental governance "*refers to a normative process of negotiation and decision-making that seeks to fit into the transformations of the general context of collective action, favours interactions negotiated between a plurality of actors (public authorities, organised groups, market actors, civil society) concerned with the regulation of a common problem*" (Salles and Leroy, 2013). Participation has become a standard part of environmental governance, legally recognised by international legislation such as the 1992 Rio Declaration and the 1998 Aarhus Convention (Barbier and Larrue, 2011: 71; Salles, 2013). According to Tortajada (2010), the concept of 'good governance' "*embraces the relationships between governments and societies, including laws, regulations, institutions, and formal and informal interactions […] stressing the importance of involving more voices, responsibilities, transparency and accountability of formal and informal organizations associated in any process*" (298). Not only does this emphasize collaboration, but it also considers the larger socio-ecological context and highlights ethical principles of responsibility, accountability, transparency, equity and equality.

This has given rise to a new paradigm of science and management, which has fundamentally changed the practices of both domains. As collaboration is now widely recognized as the most efficient way to handle complex and, at times, controversial environmental issues (Yankelovich, 1999), the relationship between science and practice is growing more interdependent. Widely adopted regulations such as the European Water Framework Directive (WFD) now advocate for integrated, participative approaches to achieve 'good chemical and ecological status' of European water bodies *(Brack et al., 2017; Everaert et al., 2013; Hering et al.,* 2010; Rekolainen *et al*., 2003).

Participation is considered to be a "*necessary corrective measure to counterbalance the weight of administrative and economic logic by promoting the consideration of social values that are supposed to be more environmentally conscious and oriented towards the long-term*" (Barbier and Larrue, 2011: 67). At the same time, environmental governance has been criticised for its "*ambiguous relationship with participation, in which it is considered more as a means of pacifying exchanges for the sake of managerial efficiency than a contribution to the renewal of democratic legitimacy,*" and has been accused of "*functioning as a quilt capable of quietly silencing the radical alternative and digesting all opposing positions and antagonisms*" (Salles and Leroy, 2013).

According to Bosch *et al.,* (2007), many of the new tools and methodologies that have emerged in recent decades are founded in *Systems Thinking*. Contrary to a traditional approach, where separate elements of a system are broken down and studied independently, *Systems Thinking* is a holistic approach that explores the relationships between a system's constituent parts and how they interact over time within the context of larger systems. Although *Systems Thinking* is quickly becoming more of a necessity than choice, the entrenchment of the 'reductionist' scientific method has fuelled a "*reluctance of science to embrace 'new ways of thinking' to explore the world*" (Bosch *et al.*, 2007: 230). We argue that this resistance is rooted in the difficulty of resolving inherent contradictions in the current paradigm of science and management, which can be characterised as the paradox of complexity and systems thinking, the paradox of evidence-based policy, and the paradox of transboundary collaboration.

The Paradox of Complexity and Systems Thinking

In contrast to the traditional mechanistic model of inputs and outputs of the previous paradigm, a systems approach necessitates understanding the world as a complex and dynamic system, in which learning, feedback and adaptations occur in highly connected, self-organising networks (Connick and Innes, 2003). This shift has already begun to take place at different levels in a number of domains.

Urban water management, for example, has shifted from a primary focus on secure water supply, adequate sanitation and flood protection towards a more integrated perspective of combined management, which takes into account the interactions and non-linear feedbacks of various components of the water system as a whole (Bach *et al.*, 2014; Liu *et al.*, 2008; Mitchell, 2005). More recently, there has been growing interest in integrating concepts of green infrastructure (e.g. Benedict and McMahon, 2006; Gill *et al.*, 2007; Tzoulas *et al.*, 2007) and low impact development (e.g. Ahiablame *et al.*, 2012; Dietz, 2007).

In land management, a systems approach explores "*the complexity of interactions within the 'hard' system (the biophysical components that can be modelled, particularly by simulation) and within the 'soft' system (the interactions* *between the biophysical components, technology and the farm family or village community). It also acknowledges that these systems or whole entities as we might view (or construct) them are embedded in larger systems that provide context and meaning for decisions made at the farm level*" (Bosch *et al.*, 2007: 218).

Addressing environmental issues not only requires the integration of different parts of the system, but also necessitates thinking of the problem within the larger social, economic, political and ecological context. For example, issues in water resources management are not only linked to the hydrological cycle; they are also affected by the agro-food system as well as the larger socio-political context in which problems are framed and decisions made. As contradictory user interests have been a major source of socio-political conflict, a systems approach is vital to addressing issues surrounding the scientific or technical problem: "*In view of the high complexity and the many interests and stakeholders involved, a systematic approach is required when addressing the water issues and challenges, and identifying the need for action*" (Zehnder et al., 2003: 2).

In practice, application of *Systems Thinking* has been slow, due to the paradox of complexity. With the current rate of scientific and technological advancement, the access and abundance of information are unparalleled. At the same time, an overflow of information makes it more difficult to distinguish what is 'good' or 'useful' (e.g. credible, salient and legitimate) (Siebert *et al.*, 2015). Technically speaking, a systems approach necessitates the aggregation of heterogeneous and/or incomplete data that is not always easily compatible. Moreover, the collaboration between multiple actors from different worlds requires the inclusion of various forms of knowledge and perspectives that are not always aligned and often contradictory.

A classic example of the complexity paradox is illustrated by modelling environmental systems, which seeks to represent complex, unbounded, open systems in bounded representations (Bouleau, 2014). Increasing regulatory pressure and a turn to *Systems Thinking* are giving rise to more complex models that integrate a larger number of environmental processes. In theory, this would allow for a better representation of the system, thereby reducing uncertainty and contributing to better decision-making.

In practice, however, complex models are not necessarily more informative or useful. For example, Petrucci and Bonhomme (2014) found that the inclusion of basic geographical data, such as land use, was sufficient to improve model performance after using varying amounts of geographical information to test different configurations and structures of the popular stormwater management model SWMM5. They concluded that while some spatial distribution improves model performance, there is a tipping point where too much geographical data can lead to issues of over-parameterisation.

More complex models also require a higher level of expertise, vast amounts of data, and are often found to be too difficult to employ in an operational context where time and resources are limited. Producing models that are both useful and usable would likely necessitate striking a balance between having sufficient complexity to adequately represent the system, while still being accessible to non-expert users, or developing a user-friendly model that may be less robust.

The Paradox of Evidence-Based Policy

A systems approach recognises the complex and dynamic nature of environmental systems which, "*unlike a machine, cannot be controlled by any* *agency, person or institution, regardless of how clever and well informed"* (Connick and Innes, 2003: 8). Nevertheless, the ability to manage environmental systems is paramount. The present paradigm of evidence-based policy requires decisions to be grounded in scientific evidence, with current practices relying heavily on data, indicators and mathematical modelling to help navigate complexity. In this context, models can serve as effective policy instruments.

In the Netherlands, for example, rising costs in the health care sector prompted the Dutch government to adopt the 'care model' to help shift health care policy towards a more economic approach (Van Egmond and Zeiss, 2010). Incorporating a market-oriented policy program into the model helped to articulate as well as reinforce the policy: "*Once a policy approach has permeated many governmental institutions, it becomes more difficult to argue against such a policy approach. As such, the model has served to legitimate new governmental policy directions regarding the health care system*" (Van Egmond and Zeiss, 2010: 71).

At the same time, Saltelli and Funtowicz (2014) identify several issues that can arise when scientific models are used in practice, including the intentional use of disproportionate models to impress or obfuscate; the dependence on assumptions that are often tacit and unverified; uncertainties that are strategically inflated or deflated, and; the reduction of complexity through instrumental compression and linearization to give the impression of production and control.

Prominent cases of misuse, whether wilful or unintentional, can fundamentally undermine the credibility and legitimacy that scientific evidence lends to management and policy decisions (Saltelli and Funtowicz, 2014; Saltelli and Giampietro, 2016). This was the case in 2011, when the claim that renewable energy could provide more than 80% of the world's energy needs by 2050 dominated international news headlines. The scientific basis for this claim was founded in an IPCC report on global energy supply strategies based on a 10-region energy system model (Teske *et al.*, 2011). However, after the report was published, it was discovered that the 'Energy [R]evolution' scenario on which the claim was based was derived from the unrealistic assumption that global energy consumption would drastically decrease by the year 2050 (Teske *et al.*, 2011). It also came to light that the lead author of the report was a prominent energy campaigner for Greenpeace International who effectively used the authority of the IPCC to advocate for policies that support renewable energy. The report itself was based on an earlier report developed by Greenpeace International and the European Renewable Energy Council, both of whom have a vested interest in a transition to renewable energy.

Modelling is the epitome of an approach that attempts to manage an increasingly complex and interdependent world by transposing management decisions and actions to computer algorithms and technological systems. In the context of evidence-based policy, mathematical models are often used to evaluate and quantify risk in order to address uncertainty. However, transferring human agency to machines for the sake of efficiency and predictability may, in fact, be undermining our capacity to adapt to uncertainty (Benessia *et al.*, 2016). To understand the gravity of this concern, one needs only to look at how the reliance on flawed computer models left us woefully unprepared for the 2008 economic crisis (Saltelli and Giampietro, 2016).

Evidence-based policy is considered a modern positivistic model based on dramatic simplifications and compressions of available perceptions of the state of affairs and possible explanations ('hypercognition') (Saltelli and Giampietro, 2017). In practice, a single reductionist frame is used to filter scientific knowledge, often due to limitations in time and resources. Science for policy, therefore, requires scientists to *"reduce complex, unpredictable problems to much simpler, manageable models by leaving out important factors, which allows scientists to come up with neat solutions – often to the wrong problems,"* (Sarewitz, 2016: v) which can potentially lead to unsound management and policy recommendations (Saltelli and Giampietro, 2017).

While simplification is necessary to comprehend and manage complex systems, the process of reductionism is rarely transparent and typically involves select individuals. In their seminal work, *Laboratory Life*, Latour and Woolgar (1979) found that knowing which data to keep and which to disregard is deeply embedded in scientific training and activity. The subjectivity implied by these processes leaves science vulnerable to manipulation and overstated claims of certainty and legitimacy, which can quickly lead to a crisis of trust, such as we are experiencing at present.

Thus, the paradox of evidence-based policy is that it necessitates scientific evidence to manage highly complex and dynamic environmental systems, but doing so requires scientific knowledge to be simplified and compressed, often to the point that it is virtually meaningless. Whereas from a scientific point of view, models are useful in the analysis of complex systems, they are still not considered to be reliable enough to be used for practical or predictive purposes (Beven, 2007, 2001, 1993; Knutti, 2008; Tassin *et al.*, 2003). Yet, models continue to be at the centre of global policy issues such as climate change, despite the fact that they offer little to no reliable information (Benessia *et al.*, 2016; Pindyck, 2013; Stern, 2016). This is not to say that science has no place in policy, but in order to be effective, the social processes underlying science for policy must be critically reassessed.

The Paradox of Transboundary Collaboration

The paradox of transboundary collaboration is that actors from different worlds are obligated to work together while at the same time, they are expected to maintain the boundaries that separate them. However, in practice, these boundaries are constantly evolving and increasingly blurred through myriad science-practice-policy arrangements.

Greater emphasis on evidence-based policy has served as a catalyst for more interdependent relationships between science, practice and policy. On one hand, practitioners are required to justify decisions using best available evidence. On the other, more and more scientists feel compelled to make their work relevant to real-world issues, often through financial incentives. This trend is reflected in numerous research schemes. For example, the Horizon 2020 program of the European Commission encourages public-private and public-public partnerships as a tool for promoting growth and innovation to tackle societal challenges (European Commission).

The effective management, policy and planning of water resources demands not only a nuanced understanding of the complexity of the issues at hand but also the capacity to negotiate trade-offs between social, economic, political and ecological aspects among competing interests. Jasanoff (1990) uses the term 'regulatory science' to describe the "*hybrid activity that combines elements of scientific evidence and reasoning with broad doses of social and political judgement*" (229). As decisions take place in these complex, negotiated social processes, some authors warn that this new relationship can produce 'policy-based evidence' rather than 'evidence-based policy' (Benessia *et al.*, 2016), raising concerns over credibility and legitimacy.

While science is assumed to be objective and neutral, this thesis takes the position that the use of science in policy is an inherently political act, since policies seek to promote a specific objective. According to Lascoumes and Le Gales (2007), the use of policy instruments in the decision-making process is a reflection of the socio-political space in which they are used and constructed. As such, they are neither neutral nor are they purely technical, but should be understood as a device that is both social and technical, used to enforce power relationships through legitimacy and politisation or de-politisation (Lascoumes and Le Gales, 2007). Similarly, models are not only abstract representations of reality based on scientific knowledge and empirical data. How the problem is framed *in* or *by* the model is a product of social construction based on agreed upon realities reflecting the values, norms and biases of the actors involved (Dewulf *et al.*, 2005; Intemann, 2015; Isendahl *et al.*, 2009; Pahl-Wostl *et al.*, 2007; Sanders and Miller, 2010; Voinov *et al.*, 2014).

Broadly speaking, models have multi-dimensional functionalities (Alliance ATHENA, 2013). The cognitive dimension helps to determine *what we know*, while the normative dimension helps to establish *what should be*. For example, the cognitive dimension of water quality models deepens scientific understanding by simulating various processes and interactions. The normative dimension comes into play when the results of the models are used to quantify, negotiate, establish and maintain rules (e.g. regulatory standards, indicators, norms, and targets). Models also serve a performative function, actively shaping the social worlds they coordinate (Van Egmond and Zeiss, 2010). Analysing these multi-dimensional functions could offer further insight into the role that models play in facilitating transboundary collaboration.

Continued Challenges at the Interface of Science, Practice and Policy

Modelling tools offer several advantages in science for policy. For example, models can serve as a common framework, orienting knowledge and resources towards mutual objectives. They can also be a way of reconciling the concurrent demands in transboundary collaboration, *Systems Thinking*, and evidence-based policy. Using models to mediate interactions and exchanges between different actors can ease tensions in transboundary collaboration. They can respond to the demands of *Systems Thinking* by integrating different aspects or representations of the system. Their ability to transform complex environmental issues to conform to the demands of evidence-based policy makes them an effective policy instrument. Yet, the use and utility of modelling tools in practice continues to be hindered by a number of fundamental challenges.

This thesis seeks to deconstruct these challenges in an effort to better understand the role of modelling tools in water resources management. Although some may seem apparent, unravelling the underlying causes may lead to deeper insights. For example, a number of authors (e.g. Liu *et al.*, 2008; Marlow *et al.*, 2013; McNie, 2007; Sarewitz and Pielke, 2007) point to the issue of communication as a major barrier to the use and adoption of modelling tools. Researchers and practitioners often come from different academic backgrounds, work in different contexts and speak different languages, making communication and understanding difficult. However, empirical examples of successful transboundary collaboration suggest the contrary. *Were they able to overcome this barrier? If so, how? Or was communication never a problem in the first place?*

Other challenges include the difference in time and objectives between research and practice. Practitioners are governed by specific deadlines, often requiring punctual information and efficient tools, which do not always align with the timeline of scientific research. Whereas science is meant to be objective, management and policy decisions are inherently political as practitioners represent different and sometimes contradictory interests.

Technical challenges include issues of complexity (Argent, 2004; Bach e*t al.*, 2014; Marlow e*t al.*, 2013; Muschalla, 2008), and data availability or reliability

(Ascough *et al.*, 2008; Beven, 1993; Brugnach *et al.*, 2007a; Refsgaard *et al.*, 2007; Walker *et al.*, 2003). The challenge of complexity refers to the difficulty of capturing and adequately representing a complex environmental system. Empirical data remains difficult and costly to acquire, while data that is collected can be unreliable and highly uncertain. The availability and reliability of data also have implications on the calibration and validation of a model, which greatly influences its use and utility.

Further challenges include institutional barriers and paradigm shifts (Hipel and Ben-Haim, 1999; Liu e*t al.*, 2008; Marlow *et al.*, 2013). For example, political and administrative fragmentation may lead to a diffusion of responsibilities, impeding fruitful collaboration. The political fragmentation characteristic of existing institutions is counteractive to collaboration, thus hindering concerted effort on a shared issue (Connick and Innes, 2003). This challenge is amplified by the fact that governance issues are distributed among actors and institutions at different levels, whose relationships are themselves complex, heterogeneous and constantly evolving (Tortajada, 2010; Zehnder *et al.*, 2003).

Context of the Thesis

A Call for (Restrained) Introspection

This thesis was co-financed by ENPC (*École Nationale des Ponts et Chaussées*) and the PIREN-Seine (*Programme Interdisciplinaire de Recherche sur l'Environnement de la Seine*). Specifically, it was part of Axe 3 of the PIREN-Seine (PIREN), which seeks to enhance and reflect on the knowledge and tools produced by PIREN in an effort to better understand the qualitative and quantitative elements involved in the management of aquatic environments. While this implied general expectations for the thesis, specific demands were never explicitly expressed, leaving the door open to explore different research questions. This ambiguity was due in part to an internal conflict between a desire to reflect on the past and future role of models on one hand, and resistance to exposure to critical reflection on the other.

This study took place during a significant period of transformation within PIREN, characterised by a number of important landmarks. First, the 3-year study was conducted during a transitional period from Phase 7 to Phase 8 of the program, offering the unique opportunity to directly observe the processes involved in planning a new research agenda. Second, the advent of PIREN's 30th anniversary prompted questions concerning the future direction of modelling as well as a desire to evaluate its impact over the past 30 years. Growing emphasis on impact stems from a parallel demand from researchers, who wish to enhance the value of their work, and operational partners, who are required to justify their investment. This thesis also contributes to an ongoing debate within PIREN over the question of science transfer: *do scientific knowledge and tools need to be 'useable' (i.e. directly appropriated) in order to be useful?*

While this type of reflection was originally proposed in the early stages of the program, it was not accepted until Phase 7, suggesting a change in mentality. Previously, there were only a handful of studies (e.g. Bouleau, 2007; Carré *et al.*, 2014; De Coninck, 2015) that reflected on the work of PIREN from a social science perspective. Therefore, this period also marks a significant transition not only towards greater inclusion of social sciences but also an acceptance of reflexive approaches.

Challenges and Limitations

As mentioned above, this thesis marked one of the first reflexive studies within PIREN, attempting to analyse something that has previously only been experienced but never formally documented. Whereas the exploratory nature of this study allowed for a large amount of freedom and flexibility to formulate and analyse research questions, it was also constrained by a number of challenges.

The first challenge was dealing with the taboo undertones of the subject itself. Although internal interest was a driving factor for this study, the critical nature of investigation generated some resistance, particularly at the beginning. That is not to say that PIREN has been entirely exempt from criticism. Similar to other research programs, PIREN comprises a heterogeneous group of actors with perspectives and opinions that are not always aligned, resulting in instances of debate and disagreement. However, whereas those interactions have remained, for the most part, anecdotal or informal, this study would produce an official record of these differences. Although researchers are posing the same questions internally, the act of publicising these inquiries engenders feelings of vulnerability, since bringing to light these disparities can fuel debate as well as conflict, which have the potential to help or hinder the PIREN's work.

In the early stages of my research, my initial findings were presented at the annual PIREN symposium in 2016. My intention was not to criticise the models or the PIREN's approach but rather to highlight the fact that there seemed to be no consensus on a modelling strategy, the role of models, the 'ownership' of a model, or even on the definition of what a model is. However, this sparked a contentious debate within the audience, namely among a number of model developers. As a result, an internal meeting was organised in early 2017, for model developers to collectively reflect on PIREN modelling tools. After numerous disagreements eventually resulted in an impasse, it became clear that there was indeed a lack of consensus, even among model developers themselves, which eventually eased some of the tension that this study may have initially triggered.

For the most part, interview participants were relatively open, recounting stories that were usually hidden or kept behind closed doors. The personal histories of the ProSe and Seneque models, for example, revealed a sort of unspoken 'rivalry' between the two, which resulted in the development of each model reflecting two different philosophies. Whereas ProSe gives a more detailed description, focusing on a specific section of a watercourse, Seneque takes a more holistic approach at the catchment scale. While both models simulate similar processes, their contrasting approaches have inevitably resulted in each model having different uses and utilities.

Another major challenge was dealing with my dual status as an observer and participant. As the study necessitates a critical reflection of a research program that also funded it, I am considered a participant of a program, which also happens to be my object of study. In this context, criticism was permitted, but only to a certain extent. This dual status put me in an uncomfortable situation, which often made it difficult to discern when it was appropriate to participate and when I should simply observe, as active engagement would influence my object of study.

In an effort to quantify the principal findings of this study, an online questionnaire was disseminated to PIREN actors in August of 2018. Unfortunately, the response rate was not high enough to be considered useful or representative (only 9 respondents out of more than 200 people). This could be attributed to poor timing (it took place during summer holidays), relevance (many interview participants felt that they had nothing to do with modelling) or institutional barriers (some actors felt that it did not go through the proper channels).

At the same time, a lack of response illustrates the paradoxical status of models in PIREN and highlights the nuanced relationship between use and utility. Although only a handful of examples exist where operational partners have directly appropriated a PIREN model, modelling remains emblematic of the program. The low response rate could also suggest that the domain of competence in modelling stays among a select few. Even if modelling results can serve a wide audience, modelling is considered by most to be a closed process involving a small number of specialised participants. In parallel, the low frequency of appropriation juxtaposed against the high rate of satisfaction among PIREN actors suggested that models can be useful even if they are not used 'directly'.

Thesis Objectives

It was British statistician George E.P. Box (1976) who famously quipped *"all models are wrong, but some are useful"*. But *what exactly makes a model useful and in what context is this true? Who are they useful for and what exactly are they used to do?* Following this line of questioning, this thesis positions itself at the axis of two emerging trends: the increasing role of modelling tools at the science-practice-policy interface and the concurrent crises of science, trust and sustainability.

Using a qualitative based on two empirical examples in France and Australia, this study seeks to explore the driving forces, implications and potential consequences of these emerging trends, focusing on three main aspects: 1/ the use and utility of modelling tools to support water management, policy and planning; 2/ the different modalities of addressing uncertainty in model-based decision support, and; 3/ the purpose and functions of partnerships between science, practice and policy.

Two Contrasting Cases: Examples from France and Australia

The growing importance of modelling to support decision processes has given rise to underlying questions of how models function in practice. This study draws from two exemplary cases from which we intended to gain insight: The PIREN-Seine in France and the CRC for Water Sensitive Cities (Cooperative Research Centre for Water Sensitive Cities) in Australia. The water management contexts in France and Australia are decidedly different, for example, in terms of priority issues, climate and land use. Identifying the parallels between these examples also highlighted significant distinctions, both of which were helpful in elucidating the role of modelling tools in water resources management.

PIREN and the CRC for Water Sensitive Cities (CRCWSC) are both examples of interdisciplinary research programs that bring together researchers and practitioners with the aim of achieving shared objectives in water resources management. Epistemic communities are a prominent feature of both cases, while modelling is at the centre of a considerable portion of research activity. Specifically, the development of modelling tools can be considered a product and a catalyst of research in each case. They also face similar challenges, as they position themselves at the interface of science, practice and policy.

Notwithstanding the many similarities, there are fundamental differences, for example, in funding structures and the types of models that have been developed and used. Whereas PIREN's funding is a joint investment between research and public institutions, the funding of CRCWSC is shared among various partners in government, research and industry. As a result, these research programs have evolved according to two different philosophies. On one hand, PIREN is more oriented towards fundamental research as a priority objective, making a stronger distinction between research and practice. On the other, CRCWSC aims to narrow the gap between research, policy and practice, by orienting scientific knowledge and tools towards industry needs.

A juxtaposition of the two cases offers a unique opportunity to explore the parallels between these distinct philosophies and their effect on use and utility in terms of the scientific knowledge and tools that are produced. PIREN's research models aim to be useful for practitioners, despite a more indirect link with policy processes compared to CRCWSC. Whereas CRCWSC actively engages with local and national governments to promote its modelling tools as a way of supporting and implementing 'water sensitive' policies[1], PIREN operational partners are not explicitly instructed on how models are to be used in the decision process. This would suggest that identifying model use in PIREN would be more difficult than in CRCWSC.

A general overview of the two cases is presented and further detailed in Chapter 1, in the article entitled *Use and Utility: Exploring the Diversity and Design of Water Models at the Science-Policy Interface*. Interview guide questions can also be found in the annex of the article, as well as a more detailed description of the methods and materials used.

Comparative analysis between the two cases was asymmetrical; the case of CRCWSC being used to gain insight into hypotheses formulated by analysis of the primary case study of PIREN. As a result, the CRCWSC field study was much shorter than that of the PIREN (26 interviews over a 3-month period for the former; 49 interviews in a 3-year period for the latter). Therefore, we opted to focus on the practices and structures centred on modelling activities with the objective of elucidating the *use and utility of modelling tools* and the *functions of hybrid*

[1] Water Sensitive Cities is a holistic concept that not only involves technical elements to optimize water resources but also a change in societal behaviour and practices (Wong and Brown, 2009)

organisations. It should be noted that while questions of uncertainty were posed in both cases, this thesis focuses primarily on uncertainty in the case of PIREN, since the process of trust building needed to explore such a sensitive topic occurs over a longer period of time, which was not possible in the case of Australia. Nevertheless, these examples made for a fruitful comparison, uncovering key factors and subtle perspectives that might otherwise have been overlooked (e.g. the nuanced relationship between use and utility, interest in collaboration, issues in funding, etc.).

Evolution of Analysis

This study progressed in a way that was as logical and natural as it was ambiguous. It began with a seemingly straightforward question: *How have PIREN modelling tools impacted the management of water resources in the Seine River basin in the past 30 years of PIREN?*

To obtain a foundational background, it was necessary to obtain a history of the PIREN and the models in question. Specifically: Which actors and institutions were involved in their development and how (e.g. *what did they contribute*)? Why were they developed (e.g. *what was the context, the need/drive for its development*)? What questions do they answer (e.g. *what processes are taken or not taken into account*)? Who and what are they developed for (e.g. *for researchers to conduct research or for water managers to support decisions*)? However, as the analysis evolved, the complexity behind this line of questioning became overwhelmingly apparent.

First, there was the issue of ownership. As the case of PIREN was the primary study context, it was necessary to define the scope by first characterising its modelling tools. In other words, *how and when does a modelling tool acquire the PIREN 'label'?* Moreover, *how do 'PIREN' modelling tools differ from other modelling tools?* Despite numerous attempts, we were unable to arrive at a clear consensus. For some, ownership was a question of licensing and intellectual property rights. For others, ownership was the right of the model developers, since they have creative control over the code, while some defined ownership in terms of financing.

Further complicating this issue is the difficulty of isolating models from their constituent parts. For example, models can comprise sub-models or models, and can be coupled to or integrated with other models that may have been developed elsewhere. Moreover, the development of a model or its constituent parts could be the product of collaboration between multiple actors and institutions involved in various ways and at different stages of development.

The sum of these factors made it difficult to arrive at a definition that is both satisfying and inclusive. To capture the breadth and diversity of our findings, we propose our own definition of PIREN modelling tools, which can also be applied to CRCWSC tools. While we recognise that it can be perceived as ambiguous and may not align with other definitions, our definition was left intentionally broad in order to maximise the scope of our study.

Our definition is as follows: *a PIREN/CRCWSC modelling tool is considered to be any model, modelling tool, model-based support tool or its constituent part, that was developed, used and/or supported by PIREN/CRCWSC, whether or not it holds legal authority over it. This includes any association of a PIREN/CRCWSC actor who has contributed to its use and development. Under this definition, a modelling tool can refer to a sub-model or module that can simulate biophysical or chemical processes using mathematical equations and numerical calculations. Any subsequent references to this will henceforth be referred to as PIREN/CRCWSC models or modelling tools.*

The difficulty in characterising a PIREN/CRCWSC modelling tool highlighted a second key point of ambiguity: the diversity of models. While some models have a more prominent legacy due to long-term mutual investment and strategic interests (e.g. ProSe, Seneque, MUSIC), others have come and gone without garnering much attention. In some cases, models were specifically designed or adapted for practitioners. In other cases, models were intended solely for research purposes. Although this type of model often has a limited number of model users, the outputs of the model can still have multiple uses in a research and operational context. This led to the need to distinguish between *use*, *usage* and *utility*. First, *use* can be understood as the technical or physical act, practice or activity (*what is done in or to the model*). This is differentiated from *usage*, which is considered as the strategy employed (*what is done with the model*). Finally, there is *utility*, which is measured by performance (*what the model allows*).

Underlying the use and utility of modelling tools is the issue of uncertainty and how it was reconciled in practice. Specifically, *if models are characterised by uncertainty, why and how do they continue to support management, policy and planning decisions?* Moreover, *what methods are used to reconcile knowledge gaps in model-based decision support?* Finally, *what are the consequences and implications of applying different modalities to reconcile uncertainty?*

This led us to the final set of questions concerning the role of hybrid or 'boundary organisations'. Specifically, *how do different science-practice-policy configurations influence the use and utility of modelling tools?* Moreover, *how do they help address issues of uncertainty?* Finally, *what role do/can they play in what are the context of model-based decision support?*

Thesis Structure

The present thesis is structured in three main chapters, which offer insight into the role of modelling tools from different perspectives.

Chapter 1 focuses on questions of use and utility, retracing the history of production and use of modelling tools in examples of the PIREN-Seine in France and CRC for Water Sensitive Cities in Australia. Specific questions for investigation are as follows: *What factors contribute to the 'usefulness' of a model? Who are they useful for and what can they be used to do?* Exploring these questions through empirical examples aims to elucidate the relationship between use and utility, while at the same time giving insight into the role of modelling tools in water resources management, policy and planning.

Chapter 2 focuses on the challenge of uncertainty, outlining the different modalities employed by various actors to reconcile between knowledge and ignorance in the context of model-based decision support. Delving deeper into the complex, negotiated social practices that characterise decision-making processes, this section highlights the social construction of ignorance and its subsequent role in decision-making.

Chapter 3 focuses on the emergence and role of 'boundary organisations', exploring their functions and limitations within the context of macro-level socio-economic changes underlying a parallel shift in the paradigms of science and management.

Finally, a general conclusion summarises the knowledge gleaned from the analysis, ending with final thoughts and perspectives.

Chapter 1

The Use and Utility of Modelling Tools in Water Resources Management

Modelling tools are now a common part of water resources management and planning. But *what exactly makes a model useful? Who are they useful to and what are they useful for?* While interest and investment in modelling tools have increased in recent decades, their specific role in the decision-making process in practice remains somewhat ambiguous. This chapter attempts to explore these questions by analysing the diversity and design of water models in the examples of the PIREN-Seine in France and the CRC for Water Sensitive Cities in Australia.

"Error 404: User Not Found"

Major advances in computing power coupled with an emphasis on evidence-based policy have largely contributed to the popularity of modelling tools across major sectors. The rise of public policy tools in general – from simple checklists and decision trees to cost-benefit analysis and computer models of varying complexity – has been motivated by mounting pressure to ground decisions in best available evidence to address increasingly wicked environmental policy problems (Nilsson *et al.*, 2008). In Europe, the systematic collection and use of evidence are perceived as 'Better Governance' (European Commission, 2003), while recent policy assessment systems specifically require the use of policy tools, favouring those that employ a quantitative approach (e.g. models) (Radaelli, 2004).

The advantage of modelling tools is that they help make sense of complex processes, while at the same time, transposing wicked problems into technical, 'manageable' solutions. This has led to large-scale investments in a wide range of modelling tools. For example, the European Commission's 6th and 7th Framework Programmes have funded a number of research projects on policy assessment methods and tools, investing heavily in computer-based tools such as models (European Commission, 2003). From a scientific perspective, models are still one of the only tools available capable of analysing, evaluating and predicting the behaviour of environmental systems. From a management perspective, the exploratory and predictive capacities of models coupled with their basis in scientific evidence make them efficient policy instruments.

Despite increasing interest and potential advantages that modelling tools can offer and the wide range of tools that now exists to meet a multitude of needs, the use and adoption of models in practice continues to lag behind (Argent, 2004; Bach *et al.*, 2014; Hipel and Ben-Haim, 1999; Liu *et al.*, 2008; Marlow *et al.*, 2013). This suggests that there is a mismatch between the growing supply of modelling tools and the demand in practice.

In a review of integrated urban water models, Bach *et al.*, (2014) summarised current barriers as: 1/ model complexity, 2/ user friendliness, 3/ administrative fragmentation, and 4/ communication. In an assessment of participatory modelling, Carré *et al.*, (2014) highlighted issues related to "*institutional capacities and constraints*", described as differences in professional cultures as well as financial and political constraints (Turnpenny *et al.*, 2008), a mismatch in perspectives between modellers and stakeholders (Radaelli, 2004), and the inability of models to meet the expectations of its end-users (Riousset, 2012).

In the case of PIREN, a diversity of modelling tools has been developed over the past 30 years. Yet, much like a computer will display a '*404 Error*' code when the server is unable to find the requested resources, a search for examples of model uses in practice often returned the same response: '*Error 404: User Not Found*'. At the same time, PIREN practitioners reported a high level of satisfaction when it came to modelling, referring to models as 'useful' tools that were integral to their work. *How then, can this inconsistency be explained?*

The source of the error came down to a problem of binary thinking. To understand this discrepancy, it was necessary to first explore the common dichotomies of *use* vs. *utility* and *research* vs. *operational* models. Throughout the interviews, it became apparent that there was no clear distinction between these terms among participants. While for some, 'using' a model referred to physical manipulation of the model itself, others considered 'use' as making use of its results, sometimes without understanding the inner workings of the model. Conversely, some actors felt that they had "*nothing to do with models*" even if later they cited examples of how models have played a role in their work or of contributing to their development (e.g. providing input data). Sometimes, this was due to a distinction between their individual involvement and that of the institution they represent. There also appeared to be ambiguity around *who uses what* and *to what extent*, as there was often a mismatch between how one actor described another's involvement and how the individual described their own involvement in the modelling process.

In terms of *research* vs. *operational* models, some made the distinction between the two according to application (i.e. the same model but applied in different contexts), while others perceived the difference as a matter of design (i.e. operational models are typically more 'user-friendly' and adapted to the needs of practitioners). Participants with the latter perspective often felt that *research* models tended to be more scientifically sound, since they were developed by researchers, whereas *operational* models were more adapted to answer management questions, since they were typically tailor-made by consultancies according to a design brief (‘*cahier des charges*’).

Distinguishing Between Use, Usage and Utility

In general terms, *use* is understood as *“a method or manner of employing or applying something”,* whereas *utility* is defined as *“the quality or state of being useful”* (Merriam-Webster Dictionary), which suggests an underlying motivation. For example, a model developer designs a model with a specific *use* in mind (e.g. to simulate stormwater runoff). However, its *utility* is determined not only by *how* it is used but also *by whom* it is used. Whereas the model may have been developed for its perceived *utility* in estimating the amount of water that is infiltrated and the amount of water that flows into the catchment during a rainfall event, an elected government official may in fact, *use* the model to estimate sanitation needs or justify a large budget, and understand its *utility* as a way of pushing through a political agenda and satisfying constituents (Commenges and Deroubaix, 2017).

In the context of this analysis, we further distinguish between *use*, *utility* and *usage.* Whereas *use* is understood as the technical or physical *act, practice* or *activity* of those developing or employing the model or its results, *utility* can be seen as the *performance* or *outcome*, while *usage* is considered the *strategy* employed by the user regarding the model. In other words, *use* is what is done in or to the model itself (e.g. entering lines of code or data, making a simulation, changing the parameters, retrieving results); *usage* is what the user intends to do with the model or its outputs (e.g. participating in the development of the model or justifying and action or decision), and; *utility* is what the model allows the user to do and has more of an impact on decision processes (e.g. understand or explain biological, chemical or physical processes, justify an action or decision, communicate to different audiences).

This thesis focuses primarily on the *use* and *utility* of modelling tools in the context of water resources management, while *usage* is evaluated more indirectly. The main reason is due to time constraints. Since this was the first analysis of this nature, it was necessary to begin with retracing the history of how and why models were developed before we could delve into the strategies of different actors, which requires a more in-depth analysis into the motivations of each actor and institution. Another constraint was that *usage* is difficult to characterise and quantify without first understanding use and utility, as it was seldom explicitly articulated. Even if several interviewees considered that models were useful or that they were used frequently, they were often unable to cite specific examples. This could also be due to the fragmentation of roles and responsibilities within institutions, which separated the individuals doing the modelling from those taking decisions, who may have been outside of the study context.

Research Models vs. Operational Models: Two Sides of the Same Coin?

This study initially followed the hypothesis that models can be divided into two general categories: *research* and *operational* models. *Operational* modelling was distinguished by a practical application or purpose, particularly in the context of decision-making (Hipel and Ben-Haim, 1999; Makropoulos *et al.*, 2008; Tomasoni, 2014). *Operational* models can be explanatory or predictive, enhancing understanding of management or policy problems by allowing practitioners to explore multiple scenarios, evaluate and assess risk, and make forecasts based on scientific knowledge and empirical data. The results of these models are applied to address real problems and are used by decision-makers to develop, evaluate and assess public policies, regulatory standards, public works or urban projects.

In contrast, *research* models were characterised by a primary objective of deepening scientific understanding and can be used to test scientific hypothesis. Whereas *operational* models may be more accessible to non-expert users, *research* models tend to be highly academic, necessitating scientific expertise to operate and understand. In this sense, *operational* models are more in line with the idea of decision support tools (e.g., Argent *et al.*, 2009; Giupponi, 2007; Matthies *et al.*, 2007; Shim *et al.*, 2002; Willuweit and O'Sullivan, 2013), as opposed to *research* models, which are typically not designed specifically for practitioners to use themselves. *Research* model outputs as well as the model itself often stay within the academic realm and may not have a direct link to practical applications.

In practice, however, the distinction between the two may not be so clear-cut. First, PIREN models were developed by researchers to deepen scientific understanding, while also aiming to (directly or indirectly) support management and planning decisions within a designated water basin. This suggested that the two categories are not necessarily mutually exclusive. Second, there was no consensus among actors on what differentiates a *research* model from an *operational* model. Whereas some actors made the distinction according to usability (e.g. *operational* models are more user-friendly), others considered the context of application to be the distinguishing factor.

The diversity of responses among interview participants suggested that this distinction was more a question of perspective than design. In other words, the difference between a *research* and an *operational* model was dependent on context. Specifically, *where and how the model was applied, by whom, and for what purposes*? At the same time, model design – what processes were taken into account, which actors were included in its development and to what extent, its ‘user-friendliness’, *etc*. – were all found to have an influence on a model’s *use* and *utility*.

Exploring the Use and Utility of Modelling Tools at the Science-Practice Interface

The ambiguity surrounding the terms above has largely contributed to the confusion over what makes a model ‘useful’. This has led to the common view that models must be used ‘directly’ and adopted by practitioners in order to be useful. This would partially explain why some authors continue to report that models are rarely used as decision support tools in water resources management (Carré et al., 2014; Riousset, 2012; Uthes et al., 2010).

Current literature follows this perspective (Makropoulos et al., 2008; Willuweit and O’Sullivan, 2013), which can be explained in terms of *substantive rationality* and *procedural rationality*, the former supposing that better technology leads to better decisions, while the latter supposes that better technology enhances the decision-making process itself (Commenges *et al.*, 2014). Whereas *substantive reality* sees the function of a model as directing decision-makers towards a rational decision by identifying specific policies that can produce optimal outcomes (Ascher, 1981), *procedural rationality* sees the role of modeling to support the decision-making process by reducing the effort required to make decisions (Todd and Benbasat, 1992).

However, the lack of use and adoption by practitioners does not necessarily negate its utility. Our empirical examples show that models are perceived to be useful even in cases where they are not directly adopted. In PIREN, for example, the majority of actors believe that models are useful despite the fact that there are only two examples of models being fully adopted by practitioners. The example of the

CRC for Water Sensitive Cities also shows that different types of models have different uses and utilities. For example, while earlier models were intended to serve more short- to medium-term management and planning purposes, a number of new modelling tools are designed for long-term scenario planning under *deep uncertainty*. Both purposes may be useful, depending on the stage of the decision-making process.

The complexity of the decision-making process itself should also be considered as it comprises a web of interactions among heterogeneous actors and forms of knowledge that takes place at different stages in the decision-making process and at different levels of governance. In this context, modelling tools provide one form of knowledge and decision support among many others. Modelling can provide guidance to practitioners by allowing them to explore a range of different options. However, they are often confronted with contradictory results, which require expertise to interpret and translate into information that is readily accessible and applicable to non-experts.

Some authors argue that models have no intrinsic value (Commenges *et al.*, 2014; Owens *et al.*, 2004), but like most policy tools, their value is socially constructed by the actors involved (Lascoumes and Le Gales, 2007). In a decision-making context, public policy tools such as models are a reflection of the socio-political space in which they are constructed and used. They are not neutral nor are they purely technical, and instead should be understood as a device that is both technical and social, that can be used to enforce relationships of power between politics and society through forms of legitimacy, politicization or de-politicization (Lascoumes and Le Gales, 2007). This suggests that the *utility* of models can also be attributed to its social value, for example, in fostering trust or enforcing legitimacy and credibility. In other words, the performance of the model and its results are not necessarily as important as the perceived validity of the model and the expertise behind it being viewed as credible and reliable.

In the following article entitled *Use and Utility: Exploring the Diversity and Design of Water Models at the Science-Policy Interface*, we analyse the production and use of seven water models: four PIREN models (ProSe, Seneque, MODCOU, STICS) and three CRCWSC modelling tools (MUSIC, Water Sensitive Toolkit, DAnCE4Water).

PIREN is focused on issues of water quality, flooding, and the large water cycle at the watershed scale, whereas CRCWSC's priority is water quantity, drought and the small water cycle at the scale of cities. They also have distinct funding structures: PIREN is funded by the public sector (research and public institutions), whereas CRCWSC is funded from public-private partnerships (government, research and industry partners). These contrasting cases enable us to explore the diversity of uses and utilities and shed light on the nuanced relationship between the two. Highlighting the heterogeneity of perspectives in each case, we aim to move beyond the strict dichotomy of *research* vs. *operational* model, while also considering that models have different degrees of *use* and *utility*, depending on the context. By elucidating the factors that may influence the *use* and *utility* of modelling tools, we also aim to better understand their role at the science-practice-policy interface.

Article

Use And Utility: Exploring The Diversity And Design Of Water Models At The Science-Policy Interface

Natalie CHONG, Peter M. BACH, Régis MOILLERON, Céline BONHOMME, José-Frédéric DEROUBAIX

Published in Water, December 2017

Article

Use and Utility: Exploring the Diversity and Design of Water Models at the Science-Policy Interface

Natalie Chong[1]*, Peter M. Bach[2, 3, 4], Régis Moilleron[1], Céline Bonhomme[1] and José-Frédéric Deroubaix[1]

1 Laboratoire Eau Environnement et Systèmes Urbains (LEESU), École Nationale des Ponts et Chaussées, University of Paris East, 6-8 Avenue Blaise Pascal 77455 Champs-sur-Marne, France; regis.moilleron@enpc.fr (R.M.); celine.bonhomme@enpc.fr (C.B.); j.deroubaix@enpc.fr (J.-F.D.)
2 Swiss Federal Institute of Aquatic Science & Technology (Eawag), Überlandstrasse 133, 8600 Dübendorf, Switzerland; peter.bach@monash.edu
3 Institute of Environmental Engineering, ETH Zürich, 8093, Zürich, Switzerland
4 Monash Infrastructure, Department of Civil Engineering, 23 College Walk, Monash University, Clayton VIC 3800, Australia
* Correspondence: natalie.chong@enpc.fr; Tel.: +33 01 64 15 39 50

Received: 31 October 2017; Accepted: 4 December 2017; Published: 19 December 2017

Abstract

Effort to narrow the gap between the production and use of scientific knowledge for environmental decision-making is gaining traction, yet in practice, supply and demand remains largely unbalanced. A qualitative study based on empirical analysis offers a novel approach to exploring key factors, focussing on seven water models in the context of two organisations at the science-policy interface: the PIREN-Seine in France and the CRC for Water Sensitive Cities in Australia. Tentative linkages drawn from these examples identify: (1) objective and expertise; (2) knowledge and tools; and (3) support structures as main drivers influencing the production of scientific knowledge which, in turn, affect the use and utility of modelling tools. Further insight is gained by highlighting the wide spectrum of uses and utilities existing in practice, suggesting that such 'boundary organisations' facilitate interactions and exchanges that give added value to scientific knowledge. Coordinated strategies that integrate inter-, extra- and intra-boundary activities, framed through collaborative scenario building and the use of interactive modelling platforms, may offer ways to enhance the use and utility of scientific knowledge (and its tools) to better support water resources management, policy and planning decisions, thus promoting a more cohesive relationship between science and policy.

Keywords: boundary organisation; environmental decision-making; integrated modelling; knowledge brokering; model usability; strategic planning

1. Introduction

The trade-off between scientific complexity and 'usability' of scientific knowledge and tools to support management, policy and planning decisions is a fundamental question at the heart of the science-policy interface. Similar to all areas of environmental decision-making, water resources managers must make decisions under high system complexity and uncertainty, which demands effective integration of useful and relevant scientific information [1]. In this context, 'useful' scientific knowledge possesses a utilitarian function by clarifying and expanding different options for decision makers to achieve desired outcomes [2,3], and must also be perceived as credible (reliable and of high quality), relevant (context-specific) and legitimate (transparent and objective) [4-8].

The myriad of challenges and opportunities affecting usability have been well documented in the literature, summarized by Lemos *et al*. [9] as a function of the interconnected factors of fit, interplay and interaction. Elucidating the complexity of these dynamics requires a departure from the traditional 'linear' model of research use, where scientists produce scientific information, viewed as objective or neutral facts, which are then transmitted to a passive audience [10]. Instead, use and utility should be understood as the product of a complex and nuanced relationship comprised of mediated interactions between the various actors involved. Accordingly, the science-policy interface represents a set of social processes between scientists and decision makers, which facilitates the exchange and co-construction of knowledge to support decision-making [11], while also taking into account the complex, iterative, and selective nature of the decision making process [12].

A growing body of work dedicated to the subject defines the science-policy interface in terms of 'boundaries' [6,13,14], which 'demarcate the socially constructed and negotiated borders between science and policy, between disciplines, across nations, and across multiple levels' [5] (p.1). 'Boundary organisations', are intermediary organisations straddling the frontiers of science and policy through the co-production of shared interests, knowledge and tools [6], that can facilitate and/or hinder communication, collaboration, and collective action [5]. Touted by some as promoting the best of both worlds, others remain cautious of how we distinguish 'science' from 'non-science' within these arrangements, otherwise known as the 'boundary problem' [14]. In the same vein, Jasanoff [13,15] argues that scientific claims are socially constructed through various social influences and constraints, which can place unusual strains on science when applied to real-world situations. While concerns over the bureaucratisation or standardisation of science are certainly valid, Guston [6] maintains that boundary organisations can help to avoid these issues, by having one foot in science and the other in policy, thereby keeping one another in check.

Within this discourse, modelling tools can be considered 'boundary objects' [16,17], which serve to deepen scientific understanding, while concurrently supporting key management, policy and planning decisions [1,18]. Their dual function as a research and an operational tool has enabled practitioners to navigate the complexities of water resources management and planning, which demands not only a nuanced understanding of dynamic environmental processes, but also the ability to negotiate trade-offs between a multitude of social, economic, political and ecological interests among competing stakeholders. On the other hand, models have different forms and functions, not all of which are equal in terms of: (1) their *use*, i.e. 'the method or manner of employing or applying something', and (2) their *utility*, i.e. its ‘fitness for some purpose or worth to some end’ or ‘something useful or designed for use’ [19].

While considerable efforts have been made to bridge the gap between the production and use of scientific knowledge in decision making [5,9,20-26], many authors continue to highlight a mismatch between supply and demand [1,2,10,12,20,27-29], suggesting the need for further insight into the production as well as the use and utility of such knowledge and tools in practice. Much of the existing literature on creating ‘usable’ science focuses on opportunities and challenges without delving into what exactly this information is *used* or *useful for* in the context of environmental decision making. To date, discussion on model complexity vs. usability has been largely based on the notion that a model’s use and utility is contingent upon its ‘usability’ (e.g. user-friendly interface, simplified processes and outputs, etc.). However, this overlooks the multitude of uses (ranging from direct to indirect), which exists in practice. Here, we distinguish ‘utility’ from what others have referred to as ‘usability’ [9] in an effort to incorporate this diversity. Within this literature, boundary organisations have been identified as an effective strategy for producing knowledge that is both useful and usable for decision making [9,27,30-32], yet there is still a lack of empirical data to reinforce this hypothesis.

In an effort to address these gaps, this paper aims to provide further insight by using a novel approach based on empirical analysis to explore the boundary organisation hypothesis: the way an organisation or a (set of) tools is structured can help or hinder the production of scientific knowledge that is perceived as valuable for the implementation (or elaboration) of public policies. We explore this hypothesis, focussing on the use and utility of modelling tools within the context of two interdisciplinary research programs whose core activities are rooted in research-industry collaboration (public or private): the PIREN-Seine *(Programme Interdisciplinaire de Recherche sur l'Environnement de la Seine)* in France and the CRC (Cooperative Research Centre) for Water Sensitive Cities in Australia.

The choice of these examples derived from a desire to compare two exemplary experiences, which share the overall objective of improving collaboration and exchange at the science-policy interface. Specifically, both aim to address challenges of water resources management, policy and planning through the advancement of scientific knowledge and the development of modelling tools in partnership with various stakeholders. These challenges include technical factors, such as model complexity, uncertainty, and the availability and reliability of data, as well as socio-economic factors such as institutional barriers and paradigms, competing objectives, time and resource constraints, and lack of effective communication and understanding. However, they approach these challenges using strategies that are fundamentally different: one being more 'research-oriented', while the other is more 'industry-oriented'. On one hand, the PIREN-Seine in France favours models with more scientific rigour at the cost of usability for industry partners. On the other, the CRC for Water Sensitive Cities in Australia is developing modelling tools designed for industry use, though it remains to be seen whether they will be readily adopted.

The breadth and diversity of modelling tools represented in both examples provides a sufficient dataset with which to draw from, while the openness and transparency of these programs allowed for the collection of empirical data, which can be considered an adequate representation of reality. As both programs use modelling tools developed (or partially developed) outside of their defined 'boundaries', we are also able to go beyond the two case studies to explore the legacy of seven water models across two countries. Finally, the diversity of modelling tools found in both examples represents different stages of model development and use, thereby giving further insight into current and potential use and utility.

Through an empirical analysis of the PIREN-Seine in France and the CRC for Water Sensitive Cities in Australia, this paper aims to narrow the gap between the production and use of scientific knowledge by exploring the nuanced relationship between the use and utility of modelling tools within boundary organisations at the science-policy interface. Section 2 presents the methods and materials used to inform this analysis, as well as the framework for discussion. Based on Grounded Theory (GT) [33], our approach is an exploration of the factors influencing the use and utility of modelling tools, using empirical data as a starting point. Through an historical perspective, Section 3 offers a comprehensive characterisation of the different strategies implemented by the two organisations in order to enhance utility. Brief descriptions of the seven models will be presented to provide context for the discussion that follows. Section 4 explores the links between the respective strategies and their effect on the use and utility of these models for decision-making. We deepen this discussion in Section 5, by characterising the different types of use and utility represented in the two examples.

By delving into these specificities, we highlight the influence of model use (direct or indirect) on its utility, and vice versa. Moving past the assumption that knowledge is *useful* only when it is *used*, we posit that the social value of this knowledge is also derived from the different types of interactions and exchanges, existing between the complex, dynamic web of science-policy boundaries. Finally, we arrive at the conclusion that the use and utility of scientific knowledge (and its tools) could be enhanced through coordinated strategies which frame these inter-, intra- and extra-boundary exchanges and interactions through the co-construction of scenarios and the use of interactive modelling platforms.

2. Materials and Methods

We conducted a qualitative study using an approach based on Grounded Theory (GT), a general research methodology that derives theory through the systematic collection and analysis of data [33-35]. Rather than having an established framework or theory from the outset with which to test against research data, this method offers a more flexible, adaptive approach through an iterative process that involves: raising generative (but not static or confining) questions to guide research, identifying core theoretical concepts through the systematic collection and analysis of data, and developing tentative linkages between core concepts and data [35]. This approach allows for an exploration (and subsequent identification) of the factors influencing the use and utility of modelling tools through:

1. A characterisation of the strategies implemented by the two organisations and a description of the different types of modelling tools, which is used to explore the influence of these strategies and the potential use and utility embedded in the structure of the model (Section 3);
2. Systematic observation and analysis of the interactions and perceptions of the different producers and users of modelling tools, which allows us to form tentative linkages (Section 4), and;
3. A characterisation of the different model uses (ranging from direct to indirect), which is shown to inform their utility (and vice versa) (Section 5).

Our analysis draw primarily on systematic document analysis (e.g. activity reports, of the scientific literature produced by both programs), formal semi-structured interviews with researchers and practitioners from both countries, and observations during science-practice engagement activities. This provided a rich data set for comparing the PIREN-Seine in France and the CRC for Water Sensitive Cities in Australia.

2.1. Document Analysis

Document analysis focused on the work produced by the PIREN-Seine and the CRC for Water Sensitive Cities throughout the duration of each program, which included hundreds of peer-reviewed journal articles as well as grey literature such as periodic activity reports (over 700 reports from the PIREN-Seine and over 150 from the CRC for Water Sensitive Cities), synthesis documents, and other communications. As a lot of the modelling in the Australian urban water sector also emerged from a long legacy of research and industry collaboration dating back to the 1990s, we were also cognisant of older documents prior to the commencement of the CRC for Water Sensitive Cities research program including those from its predecessors, the CRC for Catchment Hydrology, the CRC for Freshwater Ecology and the eWater CRC.

Pertinent documents were identified by searching different combinations of the following keywords: 'decision making'; 'exploratory modelling'; 'management'; 'model'; 'modelling'; 'planning'; 'policy'; 'strategic planning'; 'water sensitive cities', and; 'water sensitive urban design' on each program's website in addition to the major search engines (Scopus, Web of Science, Google Scholar). Keywords were selected and narrowed down from initial searches based on relevance to the respective research program and included the names of specific 'operational' or industry partners (practitioners) and known modelling tools in order to obtain information about their use and application in practice.

Though this process was systematic, the permeable nature of the 'boundaries' between science and policy limited our ability to adequately define the models represented in this study. First, there is no clear consensus regarding ownership. While for some, it is a question of licencing and rights, for others, the model developer is considered the 'owner', since they have the ability to change the code. Second, model development is typically a long process, where different actors may be involved in some capacity at various stages, contributing to its overall development and evolution. This work can be carried out under the auspices of the boundary organisation or it can be done through external contracts or exchanges. Third, these models are not entirely independent. That is to say, they often include modules or sub-modules that were developed outside of the program. In some instances, models were created in other research contexts and were subsequently developed, further elaborated and maintained by the program.

With these limitations in mind, we refer to 'PIREN support tools' or 'Water Sensitive City (WSC) tools' to distinguish modelling tools that were developed, used and supported within these two contexts to conduct research associated with the respective program. To capture (as much as possible) the breadth and diversity of modelling tools represented in both cases, we took a broad definition of 'model' to mean any model, modelling tool, or part of a modelling tool mentioned in the documents produced by either program, that was either developed or used at one time or another by a researcher of that program. Under this definition, a model can also refer to a sub-model or module that can simulate biophysical or chemical processes using mathematical equations and numeric calculations.

2.2. Semi-Structured Interviews and Observation of Engagement

Since what is written and officially communicated is not necessarily what is said and done in practice; observation and semi-structured exploratory interviews were implemented to support initial findings in both France and Australia.

A total of 36 and 21 interviews were conducted in France and Australia respectively with researchers (including modellers and non-modellers) and practitioners (including modellers, water authorities, consultants, regulating authorities and government officials) who were either previously or are currently involved (both directly or indirectly) with modelling activities within these two contexts. Interviews were semi-structured, based on a general question guide (provided in Annex A) that focussed on themes relating to: (1) the development and use of modelling tools, (2) the relationship between researchers and partners, (3) the regional context; as well as (4) the objectives and themes of the respective research program. Questions were adapted to the individual participant according to their role and involvement in modelling activities, the program, or their position. Interviews were open-ended and lasted anywhere from 1 to 4 hours with an average duration of 1.5 hours. Interviews were transcribed and coded according to the four themes listed above.

Anecdotal observations were used as secondary data, which were collected throughout 2015-2017, during numerous meetings, seminars, and conferences organised by the PIREN-Seine in France. This included two general assembly and annual planning meetings organised to reflect on the year's work and co-define upcoming program objectives. In Australia, anecdotal observation was limited to seminars and conferences organized by the CRC for Water Sensitive Cities from May to August 2017, which included one major national conference in Perth and two workshops.

3. Retracing the History of (Co-) production in France and Australia

The PIREN-Seine and the CRC for Water Sensitive Cities provide a platform for researchers and practitioners to collectively address some of the key issues of water resources management, policy and planning, using different strategies to achieve a common objective. As its name suggests, the PIREN-Seine focuses on the Seine River basin in France, while the CRC for Water Sensitive Cities extends its focus across cities to include the Yarra, Swan-Canning and Brisbane river basins in Australia, which represent notable examples of historically significant catchments facing serious issues of water quality and quantity due to increasing anthropogenic pressures caused by rapid urbanisation, population growth, and climate change.

The PIREN-Seine has adopted a territorial perspective of the Seine River basin, with a desire to understand the ecological functioning of the entire watershed in relation to human activities [36,37]. Most of the research is centred on issues of water quality, though water quantity concerns are also explored (mostly from a quality perspective), particularly in light of recent major flood events. While industry collaboration is considered an essential part of the program, the intrinsic desire to maintain scientific integrity is reflected in the knowledge and tools produced, which have traditionally leaned towards academic pursuits as a primary function and responding to operational demands as secondary. As a result, modelling tools are primarily seen as 'research tools', which have been used to support management and planning decisions, though the tools themselves have only been adopted by industry partners in exceptional cases of mutual interest and investment.

In contrast, the CRC for Water Sensitive Cities focuses on issues of urban water management in cities throughout Australia and abroad in pursuit of sustainability, resilience and liveability [38,39]. This has been partially motivated by extreme weather conditions experienced within the region, such as the Millennium Drought [40-42], which lasted more than a decade and has shifted the primary focus towards issues of water supply security (e.g. seawater desalination, rain water harvesting) even though water quality remains a serious concern, particularly for recreation and consumption [43,44]. Direct uptake of research into practice being the main objective, a large part of this work has been devoted to adoption pathways and socio-technical transitions, resulting in tools that lean towards practical application as a primary function. While this has proved successful in some cases, leading to wide-scale adoption of one example (i.e. the MUSIC model) that we feature in this study, it remains to be seen whether the new generation of modelling tools will be able to generate the same appeal.

The contrasting strategies and diversity of models at different stages of development represented by these examples makes for a fruitful comparison for exploring how organisational configurations and context-specific drivers may influence the production of knowledge and tools within these spaces, and what that means in terms of use and utility. A summary of the two research programs is presented in Table 1 below.

Table 1. Summary of Research Programs

	PIREN-Seine	**CRC for Water Sensitive Cities**
Duration	(1989-)	(2012-2021)
Level / Scale	Territory; Basin	Urban; City
Interest	Seine River basin	Cities in Australia and abroad
Research Priority	Quality/Quantity	Quantity/Quality
Main Objective	To produce research to better understand river system functioning that can also support decisions	To produce research and tools for industry use to achieve water sensitive cities
Types of Actors	National research institutes, universities, mixed research groups, research laboratories, public institutions, regulating authorities	Universities, public utilities, governments (local, state), regulating authorities, capacity-building organisations, consulting companies, software companies

As the PIREN-Seine and the CRC for Water Sensitive Cities both position themselves at the science-policy interface, a comparison between the two presents a mutual learning opportunity: the CRC for Water Sensitive Cities can benefit from the nearly 30 years of experience from the PIREN-Seine, while the PIREN-Seine can gain insight from an international perspective. Additionally, this analysis can provide guidance for similar examples on a wider scale: the Seine River basin is facing strong anthropogenic pressures that are characteristic of many large watersheds, while Australia can be considered a 'litmus test' for other countries as it continues to face extreme weather conditions that may soon become the norm under climate change.

3.1. The PIREN-Seine, France

Established in 1989, the PIREN-Seine (PIREN) is an interdisciplinary research program in France comprised of 22 research teams and 140 researchers from a range of academic backgrounds. The majority are rooted in the fields of hydrology, biology, chemistry, or engineering, while a growing number of geographers, agronomists, political economists, political scientists, and sociologists have become involved. The main types of actors in relation to modelling activities are represented in Table 1. Notable industry partners include the *Syndicat Interdépartemental pour l'Assainissement de l'Agglomération Parisienne* (SIAAP), a public institution responsible for wastewater treatment and sanitation in the Paris region, and the *Agence de l'Eau Seine-Normandie* (AESN), a public institution responsible for the management of water resources in the Seine-Normandy watershed, both of whom, are heavily involved in modelling activities within the PIREN-Seine.

Partnerships between universities, research units and research institutions not only provide a pool of expertise, they can also provide a source of funding, either through specific projects that directly or indirectly contribute to the work of the PIREN-Seine or through in-kind contributions in the form of researchers who are paid by their own institutions or doctoral students and post-doctoral researchers who support them. As for industry partners, relationships are largely financial, allowing them direct access to the knowledge and tools produced by the PIREN-Seine. They also play an active role in the elaboration of the program's research objectives and, in some cases, the modelling tools as well. In the case of the regulating authority – the *Direction Régionale et Interdépartementale de l'Environnement et de l'Énergie (DRIEE*) – the relationship has an added regulatory element.

While each organisation has a defined role within the basin, individual relationships are not clearly defined, as many researchers and industry partners have formal and informal relationships that extend beyond the 'borders' of the program. For example, several individuals who have previously obtained their doctoral degree under the supervision of PIREN-Seine researchers now represent industry partners. Furthermore, a model that may have been developed within the context of the PIREN-Seine may see further development outside of the program through external contracts with individual researchers, research teams or even external consultancies.

Over the past three decades, the objectives and research themes of PIREN have evolved in response to changing research and operational needs and emerging trends, while gradually incorporating new disciplines and perspectives [45], which also went hand-in-hand with the development and evolution of modelling tools. Phase 1 (1989-1992), emerged from the need to create dialogue and fundamental partnerships between researchers and water actors as a prerequisite for mobilising research that could address specific water quality concerns at a territorial scale.

Initial objectives soon evolved towards obtaining a more global vision that encompasses the entire river basin, a mentality that echoed the 1992 Water Act [46] and the Master Plan for Water Development and Management (SDAGE) [47]. Whereas Phase 1 looked at the longitudinal dimension of the aquatic continuum (upstream-downstream), Phase 2 (1992-1996) turned its attention to transverse interactions between watercourses and riparian zones such as wetlands, as well as the urban water cycle and the fate of pollutants in the river system. It is within this phase where the perception of models began to change from being seen as strictly research tools to their consideration for decision support.

From 1998-2006, work in Phases 3 and 4 aimed to contextualize the hydrographic network within the different interactions and anthropogenic influences occurring within the watershed. A retrospective outlook was used to consider the historic and dynamic nature of the hydrological system, which in turn increased the capability of models to simulate and test prospective management and planning scenarios. Phase 5 (2007-2010) integrated public health risks posed by emerging micropollutants such as new molecules with little known effects, pharmaceuticals and pathogens. Territorial studies also investigated the impact of ecological engineering and the reform of the Common Agricultural Policy (CAP).

Phase 6 (2011-2014) further expanded into 5 main research axes, which reflected the concerns and challenges jointly identified by researchers and industry partners. These include: (1) creation of agricultural scenarios according to water quality requirements; (2) identification of the role of wetlands; (3) a deepened understanding of water quality in the current climate; (4) a better understanding of the relationships between chemical pressures and ecological states; and (5) understanding dynamics of chemical pressure over a long duration.

The current phase, Phase 7 (2015-2020), focuses on gaining an in-depth understanding of the mechanisms that regulate water resources and climate change scenarios to support management strategies that are more adapted to the agricultural, environmental and urban issues facing the region. Scenario building has become increasingly popular, allowing researchers and industry partners to collectively envision and anticipate possible futures. This outlook is reflected in official discourse, which promotes a science-policy transfer through a newly dedicated transfer unit (‘*cellule de transfert*’). At the same time, a shared mentality insists upon its foundation in research, aiming to provide knowledge and expertise that helps inform management and policy decisions without directly implicating itself in the role of a policy maker.

3.2. PIREN-Seine Models: From Aggregation to Integration

PIREN-Seine modelling tools have evolved in parallel to its research objectives, adapting to suit changing demands and/or being used with other models to answer specific questions or to provide a more global view of the functioning of the system. This has produced a variety of models, including hydrologic models, biogeochemical models, hydraulic models, agronomic models, economic models and a model that simulates the environmental impact on fish populations. The majority of these models address issues of water quality, particularly the transfer of nutrients or pollutants through different parts of the system. However, within a large river system such as the Seine, individual models are only capable of telling 'part of the story', limited to a specific temporal and spatial scale.

At the same time, increasingly strict requirements from regulations such as the European Water Framework Directive (EU-WFD) [48] are place increasing pressure on researchers and decision makers to restore water bodies to 'good ecological status' [49-51], which demands a global vision of the system. These trends have resulted in a change in trajectory from individual models responding to specific questions, to the adaptation or coupling of models to answer bigger questions, towards modelling chains and/or platforms that can be applied to the entire Seine system. Here, we present four main models (see Table 2) based on their history of development and use (directly and indirectly) by industry partners: ProSe, Seneque, MODCOU, and STICS.

Table 2. Overview of PIREN-Seine Support Tools*

Model	Type	Key References
ProSe	River quality model	Even *et al* [52]; Garnier and Mouchel [53]
Seneque	Catchment quality model	Garnier and Mouchel [53]; Billen *et al.* [54]
MODCOU	Surface-groundwater model	Ledoux [55]; Ledoux *et al.* [56]
STICS	Agronomic model	Brisson *et al.* [57,58]

* Limited to the models presented in this paper

3.2.1. ProSe

Short for *'Projet Seine'*, the model ProSe was developed by researchers at *École des Mines ParisTech* in collaboration with PIREN-Seine research teams, research institutions, universities and industry partners [52,59] within the context of the PIREN-Seine. Originally designed to study problems of water quality and chronic deoxygenation related to effluent discharges from wastewater treatment plants on downstream sectors of the river and accidental overflow of sewage networks during rainy events [60,61], it has also been applied to hydraulic problems and questions associated with the transport of particles [60].

The modular structure of ProSe allows for greater adaptability in simulating different scenarios, therefore its applicability is widespread. In recent years, ProSe has undergone several revisions (producing versions 1 to 4), increasing previous functionality in terms of knowledge gained as well as the ability to be coupled with other models. Although it is neither a standardized nor commercial model, simulations using ProSe are being requested and sometimes required by regulating authorities such as the DRIEE to justify project proposals (SIAAP representative, 27 June 2016), and it is now widely considered a reference model for the water quality of the Seine.

The development and evolution of ProSe has been partially motivated by special interest from the SIAAP, who uses ProSe as a medium- to long-term management and planning tool (SIAAP representative, 29 November 2016). This has resulted in additional investment (time and resources), which extends outside of PIREN-Seine, either through ARMINES, a consultancy arm of *École des Mines* engineering school, or through a working group involving researchers and practitioners interested in adapting ProSe to meet operational demands (PIREN researcher, 28 April 2016). As such, ProSe is considered both a research and operational tool, even though the tool itself is one and the same (PIREN researcher, 16 June 2016).

However, despite being frequently cited as an example of this dual functionality, the future of ProSe remains uncertain. Many original developers have either retired or expressed interest in moving on to other research projects (PIREN researcher, 16 June 2016), while its only current operational user (SIAAP) is moving towards artificial intelligence and real-time control methods and is considering replacing the model with statistical techniques for daily operations (SIAAP representative, 10 March 2016).

3.2.2. Seneque

Seneque, which stands for '*Seine en equation*', was developed by the research team METIS – an interdisciplinary research unit at the University of Pierre and Marie Curie (UPMC) – in the context of the PIREN-Seine, though some of its components (i.e. RIVE) were developed outside of the program. Based on the concept of stream-order, Seneque simulates the transport of nutrients and the biogeochemical functioning of the hydrographic network using a simplified and idealised conceptualisation of the drainage network of large regional basins with a refined representation of in stream microbiological processes using the RIVE model [62,63]. Also referred to as Riverstrahler, Seneque is essentially the same model applied to the Seine River basin and coupled with a GIS interface [64]. The added functionality of a user-friendly interface has enhanced the user's ability to visualise and explore results in a way that is more accessible to non-specialist users. Since its creation, Seneque has undergone several revisions and has been applied to different situations in combination with other models [52,62,65,66].

Also considered to be an 'operational' model, Seneque has been appropriated directly by the AESN as a medium- to long-term planning tool, used for example, to evaluate the ecological state of the basin by amalgamating different datasets to construct 'snapshots' at different spatial and temporal scales. The model has since reverted back to a 'research' tool mostly due to a loss in internal expertise at the AESN (AESN representative, 8 June 2016). The most recent incarnation of the model, Pynuts, has allowed researchers more flexibility in terms of model development, to explore new research questions using updated technology without having to invest time and resources on interfacing.

3.2.3. MODCOU

The MODCOU model was developed by researchers at *École des Mines ParisTech* [55,56,67,68] to simulate the movement and circulation of surface and groundwater. MODCOU describes surface and groundwater flow at a daily time step: the surface model calculates the water balance between evaporation, runoff and infiltration, while the underground model calculates the transfer of water in aquifers and surface-groundwater exchanges [67,69].

Much of the work on MODCOU is concentrated on its integration with other models. For example, it is often coupled with the model STICS [67,70] (presented next) in order to obtain a more complete understanding of nitrate contamination and the influence of agricultural activity on surface and groundwater. To date, MODCOU has been effectively applied to predict surface and groundwater flows in many French basins with varying scales and hydrogeological settings [67,71]. Though it has remained as a research tool, studies requested by partners such as the AESN to assess the impact of climate change on water resources have used MODCOU to evaluate groundwater levels and monitor trends in nitrate and pesticide content.

3.2.4 STICS

The model STICS has been developed by the *Institut National de Recherche Agronomique* (INRA) since 1996 [57] in collaboration with large research and professional institutes [58]. It was not developed in the context of the PIREN-Seine but is considered here as a PIREN support tool since it is often used to conduct research within the context of the program. STICS (*Simulateur mulTIdisciplinaire pour les Cultures Standard)* is an agronomic model that simulates crop growth, soil water and nitrogen balances driven by daily climatic data [57,58,72]. Intended to simulate the evolution of water, carbon, and nitrogen in the soil-plant system over one or more years successively [57,73], STICS was designed and developed with the dual objective of calculating agronomic variables (e.g. plant biomass, harvested yield, protein content of the grain, nitrogen balances of the crop) and environmental variables (e.g. flow of water and nitrate out of the root zone) [58,72]. Crop generality allows for adaptation to various crops, whereas robustness in the model allows the user to simulate various soil-climate conditions without considerable bias in the outputs.

Development of the model has focused on usability through collaboration between model developers and users in a way that allows users to participate in its evolution. Mostly considered a research tool, its conceptual modularity has allowed STICS to be chained with other models in order to understand the transfer of nitrates and pesticides into surface and groundwater [74]. These types of studies are often requested by partners such as the AESN, who are interested in monitoring the impact of agriculture on water quality. In this way, it can also be considered a decision-support tool, although researchers are charged with running the model and scenarios.

3.3. The CRC for Water Sensitive Cities, Australia

Established in 2012, the CRC for Water Sensitive Cities (CRCWSC) [75] is one of many Cooperative Research Centres in Australia, which are part of a government initiative to fund innovative research that can directly meet the needs of industry. CRCWSC involves over 200 researchers from various backgrounds (hydrology, biology, chemistry, engineering, economics, and social sciences), from national and international universities and research institutions. Setting itself apart from other on-going CRCs, the CRC for Water Sensitive Cities builds upon the research base of previous CRCs (the CRC for Catchment Hydrology from 1992-2005, CRC for Freshwater Ecology from 1993-2005 and eWater CRC from 2005–2008) and focuses specifically on creating water sensitive cities [76,77], or sponge cities [78-80], guided primarily by three main principles: (1) Cities as water supply catchments; (2) Cities providing ecosystem services; and (3) Cities comprising water sensitive communities [77].

Main actors in relation to modelling activities are represented in Table 1. Some of these partnerships are financial in nature, either through direct funding to the program, funding for specific projects which contributes to the work of the CRC for Water Sensitive Cities, or through in-kind contributions of researchers paid by their home institutions. Most partners are directly involved in research support, either as researchers themselves, or 'beta-testers', who test, apply, provide feedback, and play an essential role in disseminating the knowledge and tools on the ground. This network also includes associate partners, who may access the knowledge or tools and help test, apply and disseminate this research without direct investment, and may also contribute to capacity-building activities.

Whilst PIREN is a research program that is renegotiated every 4-5 years, CRCWSC runs for 9 years (2012-2021), as opposed to the average 5 years of other CRCs. Its research program comprises two parts: Tranche 1 (2012-2016), focused on research and Tranche 2 (2016-2021), focuses on adoption pathways and implementation of the research produced in addition to building new knowledge. Within the first tranche, four diverse programs in the areas of Society (Program A), Water Sensitive Urbanism (Program B), Future Technologies (Program C), and

Adoption Pathways (Program D), have produced research outputs that have either fed directly into the development of new modelling tools or have applied, adopted, and expanded existing industry standard models in new contexts. In particular, Program D focussed on developing partnerships between relevant actors at all levels (from community to government), capacity building, and holistic decision-support tools. With the first tranche completed, this program has continued in an evolved form in Tranche 2.

3.4. Water Sensitive City (WSC) Models: New Tools for New Strategies

WSC (models or tools) have moved away from decision support based on deterministic or stochastic models towards integrated modelling platforms and visualisation – an evolution in strategic planning within a new era of 'deep uncertainty' [81,82] and greater collaboration [83,84]. Whereas running models individually can support management and policy decisions on a short- to medium-term, an integrated modelling approach allows for exploratory modelling and adaptive planning for an uncertain future [81]. In the context of CRCWSC research, models are complementary, meant for use at different parts of the workflow. Here, we focus on three models (see Table 3): MUSIC, WSC Toolkit, and DAnCE4Water. Two of these models began development well before the CRC for Water Sensitive City program, but have since been extended or upgraded based on latest research that has resulted from Tranche 1 and are currently used – or intend to be used – by industry partners.

Table 3. Overview of WSC Tools*

Model	Type	Key References
MUSIC	Stormwater quality model	Wong *et al.* [85]; http://www.ewater.org.au/products/music/
Water Sensitive Toolkit	Infrastructure planning tool	https://watersensitivecities.org.au/solutions/water-sensitive-cities-toolkit/
DAnCE4Water	Cloud-based city modelling platform	Rauch *et al.* [86]; www.dance4water.org

* Limited to the models presented in this paper

3.4.1. MUSIC

The Model for Urban Stormwater Improvement Conceptualisation (MUSIC) was developed in 2001 by the CRC for Catchment Hydrology (1992-2005), involving many past and current researchers of CRCWSC. This work continued after it merged with the CRC for Freshwater Ecology (1993-2005) to eventually form eWater, a government owned non-profit organisation (and CRCWSC industry partner) offering capacity building, technical support services, and modelling tools to support integrated water resources management and governance.

Developed with the objective of synthesizing research into an easy-to-use tool, MUSIC is a decision support system that allows water managers to evaluate stormwater management systems based on specific water quality objectives, as well as determine appropriate sizing of stormwater treatment facilities and associated infrastructure [85]. Its core feature is how it describes water quality behaviour through a first-order kinetic decay model (K-C* Model) of three key pollutants (suspended solids, phosphorus, nitrogen), as well as the hydrodynamic behaviour within a stormwater treatment device through the continuously stirred tank reactor (CSTR) concept [85,87]. The current version of MUSIC (v6) has expanded and updated initial capabilities to a wider range of stormwater treatment devices and new performance indicators [88]. Through on-going research efforts and communication between eWater and CRCWSC, many improvements to MUSIC's capabilities and functionality have been made and its applicability to non-Australian cities like Singapore is being assessed.

As one of eWater's most widely adopted models, MUSIC has since become the industry standard across Australia for stormwater quality management and Water Sensitive Urban Design (WSUD). Early endorsement from two key industry partners in Melbourne and Brisbane, who were investigating ways of protecting receiving waters from urban stormwater pollution, heavily contributed to rapid adoption across many municipalities in Australian's east, particularly in the states of Victoria and Queensland [89]. Practitioners use MUSIC to design integrated stormwater management plans based on a specific catchment and to demonstrate compliance to local standards. It has also been used for CRCWSC research, contributing to the development of other tools such as the WSC Toolkit.

3.4.3 Water Sensitive Cities (WSC) Toolkit

Developed in Tranche 1 of the CRCWSC program, the WSC Toolkit synthesises key research outcomes into easy-to-use modules for assessing the benefits of WSUD. The model aims at supporting strategic planning, by focussing on evidence-based quantification of the benefits of urban green infrastructure (GI) initiatives in order to develop business cases that are both robust and water sensitive [90]. The model is capable of: (1) improving stream health impacts based on the effectiveness of WSUD in mitigating runoff volumes, frequency and pollutant concentrations [91-94]; (2) assessing changes in flow frequency and reduction of geomorphic impact on streams based on the stream erosion index [95]; and (3) mitigating the urban heat island effect through urban greening and retaining water in the landscape [96]. Other modules are still under development including a future climate module, which will draw from a database of future rainfall projections for major Australian cities and can be used independently or as input data for future climate scenarios [97,98]. An economic valuation module is also planned, to consider the likely willingness-to-pay of community members based on various improvements made to liveability and sustainability of the catchment.

The WSC Toolkit is currently in closed 'beta-testing' mode, with its adoption slowly taking place in select municipalities across Australia. Much of its momentum is currently driven by the need for quick and easy microclimate assessment tools that enable local municipalities to formulate a business case for funding more WSUD and green infrastructure projects. The ability of the WSC Toolkit to communicate directly with MUSIC is also a strategic choice and leverages the familiarity of an existing large user base.

3.4.2. DAnCE4Water

The DAnCE4Water model (Dynamic Adaptation for eNabling City Evolution for Water) began as part of the European Framework Program 7 – 'PREPARED enabling change' (www.prepared-fp7.eu) prior to the CRC for Water Sensitive Cities [86,99]. It was then adopted within Program A (Society) of the CRC for Water Sensitive Cities, where it evolved into a cloud-based city modelling platform. Aspiring to be an interactive, 'user-friendly' decision support tool for different water actors to explore future scenarios and evaluate different policy and action strategies, DAnCE4Water takes into account the interactions between urban water infrastructure, the urban environment, as well as social dynamics [86]. This is represented in three modules rooted in a central unit, or 'conductor', which runs each scenario by storing, managing and providing required data to the relevant modules [100]. Formerly driven by a societal transitions model [101], DAnCE4Water now relies on the interplay between urban development and societal dynamics influenced by an economic willingness-to-pay framework. The urban development module, in particular, projects the changes of the urban environment down to the household level [102]. Various biophysical modules are used to simulate the impact that urban development has on the infrastructure and include well-known hydraulic models such as EPANET [103] and EPA SWMM [104], as well as a link with MIKE URBAN for flood risk assessment [105].

While this modelling tool has great potential for strategic planning and adaption, its use and utility remain undetermined for the moment, as (at the time of writing) it is still under development and not yet fully operational due to its scale and broad city-scale scope. The underlying computational and web-based framework has, however, paved the way for smaller tools that are currently being trailled across Australia, such as the Water Sensitive Cities Index, which enables municipalities to benchmark how 'water sensitive' their local area is compared to their peers and the overarching vision of CRCWSC [106].

4. Influence of Organisational Configurations and Context-Specific Drivers

Our exploration of the strategies and modelling tools in the context of the PIREN-Seine in France and the CRC for Water Sensitive Cities in Australia provides insight into their effect on the use and utility of modelling tools in each example. Both PIREN and CRCWSC fit the criteria for 'boundary organisations': they straddle the boundary between two distinct worlds (i.e. science and policy) but are accountable to both, provide opportunity and sometimes incentives for the development and use of shared objects or 'boundary objects' [6,16,17] (e.g. modelling tools), and involve participation of actors from both sides of the boundary, as well as actors who play a mediating role [6]. In this way, they not only mobilise various stakeholders but also orient research and available tools towards achieving common goals, which in turn, informs the potential and/or intended use and utility of their scientific knowledge and tools. Here, we draw from systematic observation and analysis to explore tentative linkages, highlighting the role of organisational configurations and context-specific drivers on model use and utility in practice. These can be classified into three main categories: (1) objectives and expertise; (2) knowledge and tools; and (3) supporting structures.

4.1. Objective and Expertise

Empirical data suggests that the objective(s) of the program and the expertise of the individuals involved have a large influence on the scientific knowledge that is produced and subsequently, how that knowledge is used (if at all). On one hand, PIREN has a territorial focus with expertise on the Seine River basin, although some of the knowledge and tools have been applied to other basins (PIREN researcher, 2 May 2016). On the other, CRCWSC has an urban focus, which began in Australia in the early days of its Melbourne-based predecessor (the 'Cities as Water Supply Catchments' Project) and has now expanded abroad through the involvement of international partners. Although PIREN engages researchers from different disciplines, most have a background in natural sciences or engineering with a focus on water quality. Other than annual conferences and planning sessions, research teams mostly keep to themselves (PIREN researcher, 1 December 2016). The representation of social sciences is small, but growing, moving from quantitative studies to more qualitative studies, which include historical trends, social dynamics and the production of science. Likewise, CRCWSC involves an interdisciplinary team, though there is a greater balance between the natural and social sciences, which is seen as both necessary and inseparable (CRCWSC researcher, 22 June 2017).

Differing perspectives on the relationship between science and policy is perhaps the biggest difference between the two programs: PIREN tends to favour research over policy, while CRCWSC specifically orients its research towards use and adoption. On one hand, PIREN prefers a more marked distinction, with the objective of providing expertise and support without taking an active role in policy (PIREN researcher, 29 June 2016), although this perspective is not necessarily shared among all individuals and the mentality is generally becoming more open. Even if researchers would like their work to be applicable in practice, policy issues are commonly perceived as something beyond their role and responsibility (PIREN researcher, 12 January 2017). While this allows them to maintain scientific objectivity, it also may limit their impact in terms of knowledge dissemination and practical application, or at least render it more difficult to ascertain. On the other hand, CRCWSC has a clear objective: to promote sustainability, resilience and liveability through WSUD and the water sensitive cities by directly engaging with local councils, regional and national governments and citizens. Taking an active role in connecting science and policy and specifically organising its research around its use and transfer in practice has resulted in direct impacts on policy and planning (e.g. regulation standards set by MUSIC) (CRCWSC researcher, 9 June 2017).

Increasingly blurred borders and long collaborative relationships (official and unofficial) have likely contributed to building trust, credibility and legitimacy; a sentiment that was expressed in some form or another by all interview participants. In both examples, the science-policy interface resembled the web of interactions described by Vogel *et al.* [107]: in PIREN, many practitioners came from the same academic training as researchers (AESN representative, 8 June 2016), while in CRCWSC, it was common for researchers and practitioners to have held positions on both sides of the boundary at different stages in their career (CRCWSC researcher/industry partner representative, 21 June 2017). While this also occurs in PIREN (some industry partners were previous students of PIREN researchers), the lines between research and practice in this example have traditionally been more distinct.

Collaboration, co-production and co-development resulting from the multitude of official and unofficial interactions and exchanges (inter-, intra- and extra-boundary) create mutual understanding and communication, which subsequently promote feelings of trust among the different actors. In both examples, all interview participants expressed 'trust' in the models, as far as models can be trusted, knowing they are only a representation of reality. Confidence is fostered through official interactions such as conferences, working groups, planning sessions, and workshops, as well as unofficial interactions where practitioners can consult researchers even when they are 'off-the-clock' (SIAAP representative, 10 March 2017).

Whereas blurring the borders may foster collaboration, understanding and trust, maintaining legitimacy may, in some cases, require the borders to be restored (even if only temporarily) in order to clearly distinguish science from policy. This allows scientific knowledge (e.g. model outputs) to maintain scientific objectivity, since it produced by researchers using scientific tools, and is therefore presumed to be free from political bias (SIAAP representative, 29 November 2016).

4.2. Knowledge and Tools

One of the biggest differences between the knowledge and tools that have emerged in the two examples is their definition of purpose. Whereas PIREN support tools tend to place research as their primary objective and (indirectly) policy and planning as secondary, WSC tools are designed to make the underpinning research available and actionable for practitioners to demonstrate compliance and show the multiple benefits of local water sensitive solutions to regulators, authorities and communities. On one hand, a wide range of PIREN support tools are considered useful for practitioners, yet these tools tend to be highly academic and difficult to translate directly into action. On the other, the 'user-friendly' design of WSC tools is meant to promote adoption by industry partners, though some are still too new to be fully evaluated for use and utility.

In some cases, models may be improperly used or stretched beyond their capabilities to answer questions that they were not designed to answer (Australian water utility representative, 8 August 2017). While this is a general concern among model developers (CRCWSC researcher, 20 June 2017), there is a general feeling of trust among water actors that models will not be intentionally abused (CRCWSC researcher, 25 July 2017). For PIREN, a higher level of trust is felt among practitioners who have modelling expertise or who were involved in the development process, owing to a better understanding of the objectives and limitations of the model (AESN representative, 8 June 2016).

For the most part, uncertainties were not explicitly discussed between researchers and industry partners in either case; the onus is therefore placed on experts and technicians to transmit relevant information (PIREN industry partner representative, 7 March 2017). Industry partners who have internal modelling expertise may also run their own uncertainty analyses, motivated by the direct consequences of such uncertainties on their work (SIAAP representative, 3 March 2017). 'Acceptance' or explicit concerns over uncertainty is therefore linked to potential consequences (social, economic, environmental) of management and planning decisions that were based on modelling results.

Other tools might have to be simplified to enhance its use and utility. For example the Water Sensitive Cities Index [106], which is less of a model and more of a benchmarking tool (CRCWSC researcher, 20 June 2017), has found opportunities for application due to its simplicity. Conversely, a more critical view was expressed for some of the larger-scale strategic planning tools, which may be considered 'helpful but unnecessary', as it was opined that conventional methods such as cost-benefit analyses or SWOT analyses could deliver the same results (Government Representative, 31 July 2017). It is important to highlight that this view may stem from previous controversial experience that the state of Victoria has had with the use of such large-scale 'black box' models [108]. Although this case was frequently cited, interview participants in Australia still generally expressed high levels of trust in models due to the demand for greater transparency and communication following this incident (CRCWSC researcher, 20 June 2017).

In the case of PIREN, the lack of 'operational' models that partners can use themselves is a strategic choice, not only for reasons of objectivity but also due to time and resource constraints:

"Tools are available if [partners] want to use them as is but they don't have the human resources and they don't finance the interfacing either…We think more in terms of services, where the user defines what they want to do or what they want to evaluate and we [researchers] will perform the simulations and deliver the results"

(PIREN researcher, 29 June 2017)

In this way, providing services are considered to be a more efficient use of resources for both researchers and industry partners, none of whom are prepared to invest time and human resources for a model they only require on occasion. However, there may be less of an incentive in cases where industry demand does not pique scientific interest.

4.3. Support Structures

Support structures refer to the different configurations that can promote or reinforce scientific knowledge or tools. This includes financial structures, organisational configurations, technical support, and regulatory measures. Lemos *et al.* [9] suggest that usability can be improved through strategies of value-adding, retailing, wholesaling and customisation. While these may exist to some extent in both examples, the limitations posed by their respective 'boundaries' (in objectives and expertise, knowledge and tools and support structures) may not leave enough room to fully incorporate these strategies unless it is made to be a deliberate aim.

For PIREN, this necessitated external contracts and support structures through the creation of ARMINES, the consulting arm of the engineering school, *École des Mines ParisTech* (PIREN researcher, 29 June 2016). While ARMINES provides a lucrative sideline activity, which tailors research to specific industry demands, it is usually the research (scientific knowledge) itself that is customised, rather than the tools. For example, an industry partner such as AESN may request a specific study to be conducted and only require the results. In France, retailing, wholesaling and customisation of modelling tools is often perceived as the work of consultants, not researchers. For CRCWSC, modelling work was also outsourced with the MUSIC model through support from eWater (CRCWSC researcher, 9 June 2017). The structure of eWater is more aligned to strategies of retailing, wholesaling and customisation of tools, resulting in higher adoption of their tools.

On one hand, boundary organisations play an important role in putting key players together with support and tools oriented towards a common objective and on a much wider scale than other science-policy partnerships. On the other, their 'boundaries' may limit their ability to fully support effective strategies that promote use and utility alone. The 'best of both worlds' may, in fact, be found in coordinated strategies that combine interactions and exchanges both inside and outside of these 'boundaries'.

Within these structures, financing often plays a large role on what is or can be done. On one hand, PIREN benefits from an extended and, for the moment, indefinite duration, allowing them more freedom to explore a wider range of research questions over a longer period of time. However, their research actions are limited by a fixed amount of public funding from industry partners, an amount that has not seen much increase over the years despite a growing number of researchers involved in the program. Additionally, the autonomy of researchers is also subject to external funding sources that may come from universities, national research projects, or European projects, which allows certain freedom while posing other constraints. On the other hand, CRCWSC is working on a 9-year timeline with a fixed budget of public and private funding from industry partners, governments, and companies. Compared to PIREN, they are working with a bigger budget on a smaller time frame, which has allowed them to focus on specific goals and meet targeted objectives. In-kind support is also a major contributor in both examples, by way of researchers and doctoral students.

At the same time, CRCWSC could face major challenges on the impact and sustainability of their work, particularly regarding the refinement, maintenance and adoption of modelling tools once the program ends. This can partly be addressed with technical support structures, which include user guidelines, technical manuals, training workshops, capacity building, and user support in the form of collaboration between researchers and industry partners, which fosters mutual understanding, transparency, and trust. The WSC Toolkit, for example, has initiated some of these structures including a user manual and a series of national training workshops for some of its operational features, building upon the experience learnt in the development and adoption of MUSIC (CRCWSC researcher, 20 June 2017). Technical support also exists in the PIREN, though more through official or unofficial collaboration between researchers and partners. In the case of ProSe, for example, a technical working group was created in parallel to PIREN, involving some of the same researchers and partners while remaining outside of its boundaries.

Another important supporting structure is regulation, as illustrated by the examples of MUSIC in Australia and ProSe in France, both of which are required (even if unofficially) by regulating authorities. As an industry recognised tool, MUSIC has helped standardize regulations (e.g. [109,110]) across different territories with shared water networks (Government representative, 26 June 2017). The use of

MUSIC as a compliance tool has also supported its legitimacy, since it 'helps speed up the process' for project proposals (Australian water utility representative, 8 August 2017). Additionally, models that are used nation-wide undergo a government-recognised accreditation process, which enhances the perception of its validity (Government representative, 26 June 2017).

However, despite accreditation and validity, cost can be a limiting factor, with licences ranging from AU$0 for a 21-day limited trial version to prices starting at AU$5000 for a multiple user licence [111]. In the case of ProSe, the fact that the SIAAP is the only operating partner with the capability of running the model independently gives them a better bargaining position, however; the requirement to use ProSe also limits their ability to explore other models that may be more adapted to their needs (SIAAP representative, 3 March 2017). Regulations and the demand for evidence-based decisions may also place pressure on science to answer non-scientific questions. For example, since Paris won the bid to host the summer Olympics in 2024, there has been increased pressure for scientists to improve the water quality in the Seine to make it swimmable. Although issues of water quality are of scientific interest, particularly for PIREN, some may consider specific requirements for recreational use (e.g. faecal contamination levels) to be outside of the interest or expertise of the PIREN researchers.

5. Moving Beyond the 'Usability Approach'

Technological advancement coupled with the production of expertise has led to the development of a large number of modelling tools [1,49,112], which aim to address specific environmental questions at different temporal and spatial scales. In parallel, practitioners face increasing pressure to base management and policy decisions on scientific evidence and data [18,113,114]. In this context, it would seem natural for modelling tools to be adopted by managers and decision makers, yet this is still far from the norm [115]. While challenges posed by the lack of communication or expertise are often cited among the main driving factors influencing the adoption of models [1,49,112,116,117], much of the literature is based on the dichotomy of ‘use’ vs. ‘non-use’.

However, tentative linkages explored in the previous section using our examples suggest a more complex and nuanced relationship between use and utility that stretch beyond the common understanding of ‘usability’, where the value of scientific knowledge and tools is tied to its ability to be applied (or directly used) in practice [9]. Proponents of, what we refer to as the ‘usability approach’, often speak about ‘usability’ without detailing *how* scientific knowledge is actually used and *what* it is used for in practice, which we argue, have consequences on its use and utility. Building on previous research and aiming to deepen ‘usability approach’ thinking, this section explores the myriad of uses and utilities representative of our two cases.

5.1. Use vs. Utility

The major utilities for WSC tools and PIREN-Seine support tools generally fall under three main categories: (1) Enlightenment, (2) Decision support, and (3) Negotiation support, which reinforces previous findings [113,118,119]. Enlightenment can refer to a general contribution to overall understanding, specific information used for daily management or medium to long-term planning, or to monitor trends and emerging issues. Decision support refers to daily management, medium to long-term planning, or evaluation of actions taken, as well as to anticipate future trends. Negotiation support can refer to justification for a project or proposal, a way of asserting of a certain role or position among a network of actors, or a way of acquiring or maintaining bargaining power. These categories are typically not independent and often coincide.

The utility of a model is further influenced by three factors: objective, relevance and knowledge/expertise [120]. Objective refers to the set of priorities that the user seeks to be satisfied by the model. In other words, what is asked of the model, what purpose will it serve, and what can be done with the model or its results? Relevance refers to how closely the model simulations correspond to the issues at stake for the user. In other words, the capability of the model to respond to the specific needs of the user, as well as the importance given to what is modelled. Finally, knowledge/expertise relates to the background or training of the user and their experience with modelling activities. This includes their capability to run the model independently, add or modify components, understand its functions and limitations, know what data are required, and effectively translate and/or interpret the results.

5.2. User Involvement

In addition to the various utilities listed above, models use was found to be better represented as a spectrum based on four levels of user involvement [120] ranging from:

- **Direct++,** which indicates total mastery of the model;
- **Direct+,** which refers to independent model use without being able to change the model itself;

- **Direct**, which refers to a good understanding of what is being modelled while retaining limited involvement in the modelling process; to
- **Indirect**, which refers to complete detachment from modelling activities.

In **Direct++**, users can run the model independently, have access to input data, run simulations and are capable of making changes to the model itself (to the code, parameters, etc.). Next, **Direct+** users understand how the model works; they can run simulations by themselves and may participate in the development of a model but are not able to make changes to it themselves. **Direct** use refers to users who have a good understanding of what is modelled and may participate in the elaboration of scenarios but are not involved in the modelling process itself. This type of user typically requests studies from experts and prefers to use the results instead of investing in in-house modelling expertise. Finally, there is **Indirect** use, where users are removed from the modelling process but can still benefit indirectly, as the knowledge produced by models is diffused into the global domain. A general framework outlining the relationships between use and utility from our two examples is found in Figure 1 below.

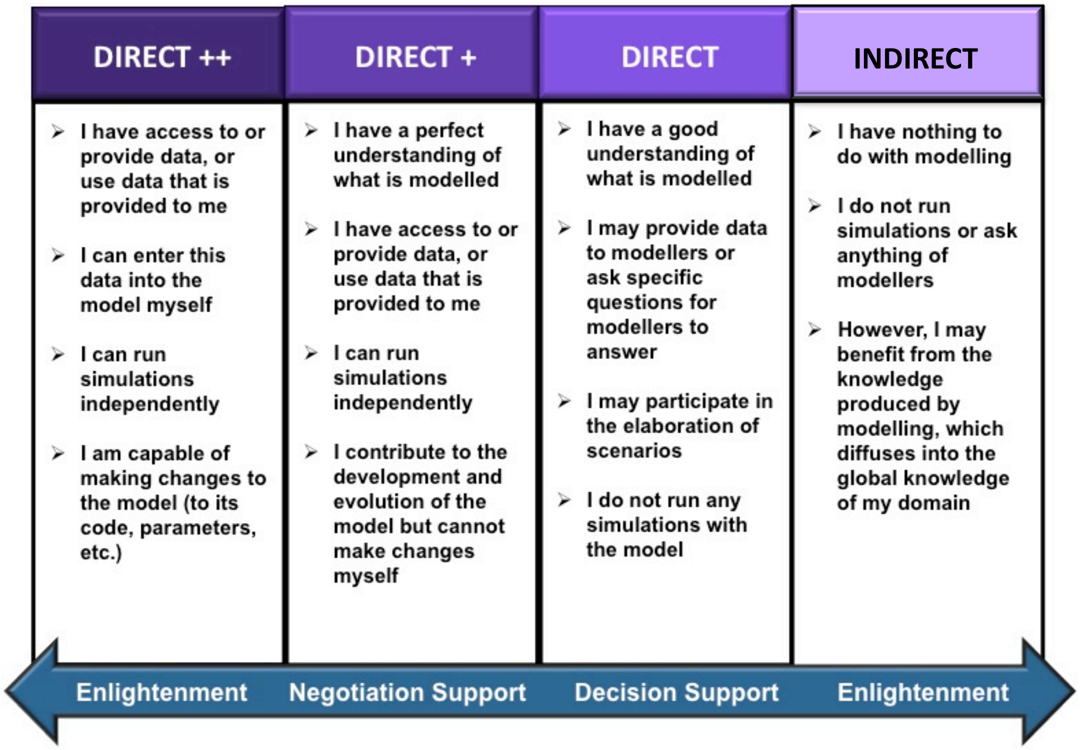

Figure 1. General Framework for Use and Utility Integrating User Involvement

5.3. Integration and Application of Concepts

Of the numerous modelling tools that were either developed and/or used by PIREN over the past few decades, only two models (Seneque and ProSe) were identified as being used directly (at one time or another) by an operational partner, while one of the two (ProSe) is still in regular use today, suggesting greater 'non-use' of PIREN support tools. In retrospect, we could say that this is due to the fact that PIREN models are too academic and not 'user-friendly', rendering them less usable and therefore less useful. However, while this may be true in some cases, many of the partners interviewed maintained that the knowledge and tools produced by PIREN were integral to their work.

We can explain this discrepancy by combining use, utility and user involvement into a general framework (Figure 1), which represents empirical findings from both examples. Within this framework, most users tend to fall on opposite ends of the spectrum: the majority of researchers involved in modelling activities are considered **Direct++** users, while most operational partners are considered **Indirect** users, with the exception of the SIAAP who is a **Direct+** user of the model ProSe.

Although enlightenment is a fundamental utility of all types of uses, more prominent examples are found at the opposite ends of the spectrum in **Direct++** and **Indirect** uses. For example, researchers can make simulations with models (**Direct++**) to gain a deeper understanding of the transfer of micropollutants in the basin. While this information is relevant to operational partners, the science may not be at the point where it can be translated into action, or, similarly, the regulations may not have caught up with the science. Monitoring these research activities (**Indirect**) in the meantime will help to guide future planning by anticipating emerging trends.

On the flipside, CRCWSC aims to produce modelling tools that are adopted (directly) by water managers and decision makers. Using the general framework, we can say that most of the researchers are **Direct++** users, while the most industry partners are (or aim to be) **Direct+** or **Direct** users. While some models, such as MUSIC have achieved this objective, it is too early to say whether newer tools such as DAnCE4Water or the WSC Toolkit will share the same success.

Compared to the CRCWSC, the uses and utilities found within PIREN appear to be more varied. In both examples, **Direct++** users tend to be researchers or model developers, while the knowledge they produce can be useful for researchers and industry partners of all user types for enlightenment. For example, in the case of PIREN, MODCOU is considered a research model (mostly **Direct++** and **Direct+** uses), yet the results are used by the AESN (mostly **Direct** or **Indirect** uses) to monitor and identify trends, which allows them to develop more adaptive climate change strategies (AESN representative, 8 June 2016).

While most of the WSC models are aimed at **Direct** and **Direct+** uses by industry partners, there is only one current instance of a **Direct+** use within PIREN (case of the SIAAP who uses ProSe for enlightenment, decision support and negotiation support). While most models serve an enlightenment function, the SIAAP also uses ProSe to support decisions (e.g. when sizing infrastructure and implementing new projects) as well as negotiation support, since they are required to justify proposals to the regulating authority using ProSe (SIAAP representative, 27 June 2016). Despite having the in-house capacity to run the model independently and contribute to model development and data collection, practitioners are not able to change the code and must turn to researchers for specific requests (PIREN-Seine researcher, 28 April 2016). In Australia, MUSIC is a similar example of a **Direct+** use by industry partners. As it has become the industry standard, using MUSIC to support decisions and justify proposals, though not always required, is beneficial (CRCWSC researcher, 9 June 2017). **Direct** uses are also common within the PIREN, in cases where partners ask for a specific study to be conducted. For example, when the AESN uses STICS-MODCOU to evaluate nitrates and pesticide flows in a specific aquifer (AESN representative, 8 June 2016).

While uncertainty related to modelling was rarely discussed explicitly, findings in both examples suggested that the 'acceptability' of uncertainty was implicitly informed by its use and utility. **Direct** and **Direct+** users in PIREN were more concerned with quantifying uncertainty, as the stakes were relatively higher. As an underestimation of pipe sizing by the SIAAP could directly contribute to major flooding in dense urban areas resulting in high economic, social and environmental costs. Failure to account for model uncertainty in these cases could also undermine project proposals based on modelling results, which also undermines negotiating power as it calls into question the expertise. On the other hand, the technical expertise required of these user types allows them to maintain trust in the model, by knowing what you can and cannot trust (SIAAP representative, 29 November 2016). Conversely, **Indirect** users may also maintain a high level of trust in the models despite a lack of technical expertise. In this case, trust is not in knowing *what* to trust (in the model) but rather, *whom* you can trust (experts) (DRIEE representative, 12 May 2016). For CRCWSC, uncertainty was considered 'more acceptable' (implicitly) in strategic planning tools such as DAnCE4Wate. Since its intended use is to explore a range of possible future scenarios, the high level of associated uncertainty is a given (CRCWSC researcher, 14 June 2017).

Despite research and practice becoming increasingly collaborative processes, several studies continue to highlight the weak correlation between scientific production and use in practice. For example, through an empirical analysis of 20 scientific assessments co-produced by researchers and decision makers, Weichselgartner and Kasperson [27] revealed that decision makers did not sufficiently draw from available research-based knowledge, while at the same time, the knowledge produced by researchers was not sufficiently usable (directly). In another example, Holmes and Clark [28] analysed the studies conducted by the Environment Research Funders' Forum (ERFF) in the United Kingdom, pointing out that there was still significant lag time between current practice and guidance. Similarly, in their assessment of management practices in the Columbia River Basin, Callahan *et al.* [29] found that climate forecasts were significantly underutilised by managers despite their potential to support their ability to manage water resources in the face of increased climate variability.

The general framework of use and utility provided in Figure 1 extends the concept of use and utility from a strict dichotomy common to 'usability approach' thinking to a spectrum of uses and utilities that are found in examples such as PIREN and CRCWSC. Maintaining this dichotomy could lead some to develop solutions that are counteractive to their objective of increasing the adoption of modelling tools by practitioners and decision-makers. For example, a simplified model with a user-friendly interface may seem like a logical solution to overcome issues of communication and lack of expertise between researchers and practitioners. However, it may be of little use to a practitioner who requires a complex model to answer specific questions but does not want to invest the time and resources towards in-house expertise. A better understanding of the nuanced relationship between use and utility can therefore support the development of tools that are more adapted to the needs of practitioners and decision-makers, according to what is needed (the model itself or the results), how they are used (level of user involvement), and what they are used for (to justify proposals, monitor trends, etc.). While there is no one-size-fits-all solution (nor do we advocate for one), our analysis may help identify key points to consider when assessing the use and utility of modelling tools to better support water resources management, policy, and planning decisions.

Furthermore, discussion on how to produce 'usable' science could benefit from more in-depth analysis of empirical examples. The fundamental difference between the CRC for Water Sensitive Cities and the PIREN-Seine is their objective and approach, which has resulted in different tools with different purposes. On one hand, the CRC for Water Sensitive Cities has taken a more market or policy driven approach, resulting in the production of 'operational' tools and active involvement from developers, water actors, local councils, and state governments (CRCWSC researcher, 9 June 2017). Not only does this promote research that is directly 'usable' for policy, it also establishes a target audience and built-in user base (Australian water utility representative, 27 July 2017).

In addition to decision support, WSC tools are designed with the specific (and arguably political) objective of achieving water sensitive cities in mind. In the case of MUSIC, its development and use as a compliance tool further entrenches the intimate relationship between science and policy, by creating both supply and demand (CRCWSC researcher, 9 June 2017). On the other hand, the PIREN-Seine has traditionally focused on the production of research and research tools as a primary objective to enlighten policy and planning decisions (PIREN researcher, 29 June 2016). Whereas CRCWSC takes an active role in policy, PIREN prefers the role of policy supporter rather than direct advisor, resulting in mostly 'research' tools and knowledge that is often difficult to translate to action and with an impact on policy that is not as easily quantifiable. However, the example of ProSe illustrates how a 'research' tool can also be 'operational' when mutual interest and supporting structures are strategically aligned (SIAAP representative, 27 June 2016).

While some commonalities can be extrapolated, our analysis of the specific organisational configurations and context-dependent drivers supports the findings of previous authors [10,12] who stress the importance of moving beyond traditional 'linear' models of research use, and advocate for a better account of the complex and nuanced interactions which take place at the science-policy interface. Vogel *et al.* [107] suggest we can begin by reimagining these relationships in terms of 'spider webs', which are 'composed of nodes and a multitude of ephemeral linkages' [p.360]. Commonly held perceptions concerning the production of 'usable' knowledge and tools for management and policy tends to oversimplify the problem [2,10,12,107], which, in turn, limits opportunities for overcoming this fundamental challenge.

Attempts to tackle this issue would therefore benefit from reframing the discussion to include and embrace the diversity that exists in modelling, which will not only provide a more informed understanding, but also help guide the development of knowledge and tools that are more adapted to different user needs. While the debate over scientific complexity vs. usability is still valid for specific models, it does not always need to be a trade-off. Instead, we can think of models as having different forms and functions, which can be used to complement one another or at different stages of the workflow to support different levels of planning and action (CRCWSC researcher, 6 June 2017; CRCWSC researcher, 20 June 2017). For example, deterministic models or real-time control for short to medium term management and planning, and modelling platforms for longer-term planning and strategic thinking.

While each program uses a different approach, both are moving towards the idea of co-construction through collaborative scenario building and the use of modelling chains and/or integrated modelling platforms to address industry demands. On one hand, this is a logical choice, as scenario building and strategic modelling can support more robust and adaptive strategies (CRCWSC researcher, 14 June 2017). On the other, focus on 'co-construction' over 'co-production' may be considered a strategic choice, since a strict focus on the co-production of modelling tools requires researchers and practitioners to invest heavily in time and resources, may not end up being very productive (PIREN researcher, 29 June 2016). Therefore, changing the discourse to the concept of co-construction of scenarios rather than co-production of models may allow for a more effective collaborative exchange as well as a more efficient use of resources. Partners may still be involved in the development of modelling tools, by providing feedback or as 'beta-testers' but the technical development (e.g. changing the code, adding parameters) resides with the researchers, who have the technical expertise. This way, each side plays to its strengths, while enhanced communication and understanding can be facilitated through interactive spaces such as workshops, seminars and working groups [10,107].

Finally, a more efficient science-policy relationship may benefit from a shifted focus from knowledge transfer to knowledge brokering [121-123], which helps ensure appropriate translation of research findings and facilitates the creation, sharing, and use of knowledge [124]. Knowledge brokers have played a key role in the dissemination of the work of the CRC for Water Sensitive Cities, helping to bring together different stakeholders towards the same objectives and increasing their impact on policy (CRCWSC researcher, 25 June 2017). In both cases, knowledge brokering would enhance the use and utility of modelling tools by helping developers understand user needs, and helping users understand the objectives and limitations of the model.

Modelling chains and platforms may be considered effective 'boundary objects', by linking different modules together to tackle questions that are relevant to both research and policy. The same can be said of scenario building through strategic thinking exercises facilitated by these tools. In this context, the use and utility of the model itself is less of a concern, since the purpose is not to produce a specific outcome but rather to co-conceptualize and envision a range of possible outcomes. This allows different actors to come together and explore different strategies in a more neutral setting. Whether it is used directly or indirectly, collaborative scenario building and the use of modelling chains and/or platforms may prove to be a more effective path to the use and usability of scientific knowledge in practice.

6. Conclusions

Science and policy have become increasingly interdependent and science-policy collaborations more common, yet clear pathways for producing 'usable' scientific knowledge and tools remain uncertain. A novel approach based on an empirical analysis was used in the context of two boundary organisations in France and Australia to explore the tentative links between program strategy and the use and utility of modelling tools. Organisational configurations and context-specific drivers of: (1) objective and expertise; (2) knowledge and tools and; (3) support structures were identified as primary factors. Empirical findings highlighted a complex and nuanced relationship between use and utility, which suggests the need to go beyond 'usability approach' thinking. Further insight was also given into the role played by boundary organisations in bringing together relevant actors, facilitating formal and informal exchanges and building capacity, credibility, salience and legitimacy, suggesting that knowledge brokering and coordinated strategies which effectively integrate inter-, extra- and intra-boundary activities would likely enhance use and utility. An exploration of the layered complexities between use and utility also suggests that added social value is created through mediated interactions and exchanges, which are facilitated by boundary organisations. The trend towards collaborative scenario building and the use of modelling chains and/or interactive modelling platforms offers ways of framing these interactions to better support management, policy and planning decisions. In this way, models may become a tool for communication and mediation between various actors, serving as a common reference point for co-conceptualising robust and adaptive strategies towards a shared vision of water resources management.

Acknowledgments: This study was co-funded by the PIREN-Seine program, École Nationale des Ponts et Chaussées, University of Paris East, and LABEX Futurs Urbains in France, in cooperation with the Cooperative Research Centre for Water Sensitive Cities in Australia. The authors would like to extend their gratitude to all researchers and partners who graciously contributed valuable time, insight and knowledge to this research.

Author Contributions: N.C. and P.M.B drafted and edited the manuscript, with P.M.B. contributing heavily to the data and analysis on the Australian side. N.C. conducted interviews and provided anecdotal observation; R.M., C.B., and J.F.D. helped to formulate the theories and frameworks used and contributed to the analysis of the data on the French side.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A: Interview Question Guide

BACKGROUND/HISTORY
What is your involvement in the PIREN-Seine/CRC for Water Sensitive Cities? How did you get involved? How long have you been involved?
How did the program get started? (Ex. Demand from researchers, industry or government?)
What is your background/training/experience?
How would you describe the relationship between researchers and partners in the program?
Do you think science should play a role in influencing policy?
How is the program funded? Who finances it? How much funding does the program have in total? How much does each partner contribute? What are the financial obligations from both sides?
In general, do you think there's a large gap between research and policy? How does the program help to overcome this? What could be improved?

MODELS: DEVELOPMENT, EVOLUTION, USE
Were you involved in the development of any modelling tools? Which ones? How were you involved? (Ex. did you develop the code, a module, provide feedback, etc.)
Who was involved in the development? (Ex. research teams, universities, institutions, partners, etc.) How were the different actors involved? (Ex. funding, feedback, research, etc.)
What was the reason/need for developing this model?

Were there other models that existed at the time that could have done the same thing? If so, why develop a new model instead of using the existing one?
What were the main challenges in developing this model?
How has the model evolved? (Ex. different modules, more functionality, etc.)
What are the advantages/limits of the model?
Who uses the model? Which actors? (Ex. Specific researchers, partners)
How do you use the model? What does the model allow you to do, that you could not do (or not as easily do) without? Do you run the model yourself or do you use the results?
What are some of the challenges in using this model? Would you say it is easy to use for someone without training/expertise in modelling?
Would you prefer to be able to use the model yourself or just use the results?
Is the model used outside of the context of this program?
Do the outputs of the model meet the needs/demands of the user? If not, what could be improved?
Would you say it's more of a research model or an operational model? What do you consider to be a 'research' or 'operational' model?
What type of user is the model designed for?
What type of use is the model designed for?
Can you think of any models that were developed within the context of the program but were not used or forgotten over time?
Would you say there's a big industry demand for modelling tools? What types of tools are they looking for? (Ex. deterministic models, planning and visualisation tools, etc.)
TRUST/UNCERTAINTY
What do you need in order to 'trust' a model?
How is uncertainty taken into account in the modelling process/decision-making process?
Do partners ask for specific information on uncertainty?
What is considered to be an 'acceptable' level of uncertainty and how is this determined?
Can you think of a time where modelling results or the model itself were put into question?
Does the lack of available/reliable data pose a problem for you in trusting the model?
Would you say there is generally a lot of trust in modelling?
Would you prefer to have a model with a high level of associated uncertainty or to not have a model at all?
SCENARIOS
What simulations/scenarios were made with this model?
Who is involved in the construction of a scenario?
How do you determine which scenarios to test? Out of an infinite number of possible future scenarios, how do you decide on the plausible scenarios to test?

ROLE OF MODELLING IN DECISION-MAKING
When are models used/their results taken into account in the decision-making process?
Besides modelling, what other factors influence the final decision?
Do you use this model more for daily management, or long-term planning?
Is it required by the regulating authority to use this model?
Can you give me specific examples of when the model (or its results) was used to make a decision? Do you think that the knowledge/tools produced by this program have a big influence on policy in the country?

References

1. Liu, Y.; Gupta, H.; Springer, E.; Wagener, T. Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management. *Environ. Model. Softw.* **2008**, *23*, 846–858, doi:10.1016/j.envsoft.2007.10.007.

2. McNie, E. C. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. *Environ. Sci. Policy* **2007**, *10*, 17–38, doi:10.1016/j.envsci.2006.10.004.

3. Haas, P. When does power listen to truth? A constructivist approach to the policy process. Available online:

   http://www.ingentaconnect.com/content/routledg/rjpp/2004/00000011/00000004/art00001 (accessed on Oct 30, 2017).

4. Cash, D.; Clark, W. C. From science to policy: Assessing the assessment process. *John F Kennedy School of Government Faculty Research Working Papers Series RWP01-045* **2001**.

5. Cash, D.; Clark, W. C.; Alcock, F.; Dickson, N.; Eckley, N.; J�ger, J. Salience, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making. *SSRN Electron. J.* **2003**, doi:10.2139/ssrn.372280.

6. Guston, D. Boundary Organizations in Environmental Policy and Science: An Introduction. *Sci. Technol. Hum. Values* **2001**, *26*, 399–408.

7. Sarkki, S.; Niemela, J.; Tinch, R.; van den Hove, S.; Watt, A.; Young, J. Balancing credibility, relevance and legitimacy: A critical assessment of trade-offs in science-policy interfaces. *Sci. Public Policy* **2014**, *41*, 194–206, doi:10.1093/scipol/sct046.

8. White, D. D.; Wutich, A.; Larson, K. L.; Gober, P.; Lant, T.; Senneville, C. Credibility, salience, and legitimacy of boundary objects: Water managers' assessment of a simulation model in an immersive decision theater. *Sci. Public Policy* **2010**, *37*, 219–232.

9. Lemos, M. C.; Kirchhoff, C.; Ramprasad, V. Narrowing the Climate Information Usability Gap. *Nat. Clim. Chang.* **2012**, *2*, 789–794, doi:10.1038/NCLIMATE1614.

10. Nutley, S. M.; Walter, I.; Davies, H. T. O. *Using Evidence: How Research Can Inform Public Services*; Policy Press: Bristol, England, 2007; ISBN 978-1-86134-664-3.

11. van den Hove, S. A rationale for science–policy interfaces. *Futures* **2007**, *39*, 807–826, doi:10.1016/j.futures.2006.12.004.

12. Young, J. C.; Waylen, K. A.; Sarkki, S.; Albon, S.; Bainbridge, I.; Balian, E.; Davidson, J.; Edwards, D.; Fairley, R.; Margerison, C.; McCracken, D.; Owen, R.; Quine, C. P.; Stewart-Roper, C.; Thompson, D.; Tinch, R.; Van den Hove, S.; Watt, A. Improving the science-policy dialogue to meet the challenges of biodiversity conservation: having conversations rather than talking at one-another. *Biodivers. Conserv.* **2014**, *23*, 387–404, doi:10.1007/s10531-013-0607-0.

13. Jasanoff, S. S. Contested Boundaries in Policy-Relevant Science. *Soc. Stud. Sci.* **1987**, *17*, 195–230, doi:10.1177/030631287017002001.

14. Gieryn, T. F. *Boundaries of Science*; Springer: Berlin, Germany, **1995**, 293–332, doi:10.1007/978-1-349-25249-7_12.

15. Jasanoff, S. Procedural choices in regulatory science. *Technol. Soc.* **1995**, *17*, 279–293.

16. Star, S. L.; Griesemer, J. R. Institutional Ecology, "Translations" and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Soc. Stud. Sci.* **1989**, *19*, 387–420.

17. Leigh Star, S. This is Not a Boundary Object: Reflections on the Origin of a Concept. *Sci. Technol. Hum. Values* **2010**, *35*, 601–617, doi:10.1177/0162243910377624.

18. Argent, R. M.; Perraud, J.-M.; Rahman, J. M.; Grayson, R. B.; Podger, G. M. A new approach to water quality modelling and environmental decision support systems. *Environ. Model. Softw.* **2009**, *24*, 809–818, doi:10.1016/j.envsoft.2008.12.010.

19. Dictionary by Merriam-Webster: America's most-trusted online dictionary Available online: https://www.merriam-webster.com/ (accessed on Oct 30, 2017).

20. Sarewitz, D.; Pielke, R. A. The neglected heart of science policy: reconciling supply of and demand for science. *Environ. Sci. Policy* **2007**, *10*, 5–16, doi:10.1016/j.envsci.2006.10.001.

21. Jacobs, K. *Connecting Science, Policy, and Decision-making: A Handbook for Researchers and Science Agencies*; National Oceanic and Atmospheric Administration, Office of Global Programs: Silver Spring, MD, USA, 2002.

22. Xu, Y.-P.; Booij, M. J.; Mynett, A. E. An appropriateness framework for the Dutch Meuse decision support system. *Environ. Model. Softw.* **2007**, *22*, 1667–1678, doi:10.1016/j.envsoft.2007.01.002.

23. Castelletti, A.; Soncini-Sessa, R. A procedural approach to strengthening integration and participation in water resource planning. *Environ. Model. Softw.* **2006**, *21*, 1455–1470, doi:10.1016/j.envsoft.2005.07.013.

24. Brown Gaddis, E. J.; Vladich, H.; Voinov, A. Participatory modeling and the dilemma of diffuse nitrogen management in a residential watershed. *Environ. Model. Softw.* **2007**, *22*, 619–629, doi:10.1016/j.envsoft.2005.12.027.

25. Dilling, L.; Lemos, M. C. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Glob. Environ. Chang.* **2011**, *21*, 680–689, doi:10.1016/j.gloenvcha.2010.11.006.

26. Jacobs, K.; Garfin, G.; Lenart, M. More Than Just Talk: Connecting Science and Decision Making. *Environ. Sci. Policy Sustain. Dev.* **2005**, *47*, 6–21, doi:10.3200/ENVT.47.9.6-21.

27. Weichselgartner, J.; Kasperson, R. Barriers in the science-policy-practice interface: Toward a knowledge-action-system in global environmental change research. *Glob. Environ. Change* **2010**, *20*, 266–277, doi:10.1016/j.gloenvcha.2009.11.006.

28. Holmes, J.; Clark, R. Enhancing the use of science in environmental policy-making and regulation. *Environ. Sci. Policy* **2008**, *11*, 702–711, doi:10.1016/j.envsci.2008.08.004.

29. Callahan, B.; Miles, E.; Fluharty, D. Policy implications of climate forecasts for water resources management in the Pacific Northwest. *Policy Sci.* **1999**, *32*, 269–293, doi:10.1023/A:1004604805647.

30. Buizer, J.; Jacobs, K.; Cash, D. Making short-term climate forecasts useful: Linking science and action. *Proc. Natl. Acad. Sci.* **2016**, *113*, 4597–4602, doi:10.1073/pnas.0900518107.

31. Cash, D. W.; Clark, W. C.; Alcock, F.; Dickson, N. M.; Eckley, N.; Guston, D. H.; Jäger, J.; Mitchell, R. B. Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci.* **2003**, *100*, 8086–8091.

32. Boezeman, D.; Vink, M.; Leroy, P. The Dutch Delta Committee as a Boundary Organization. *Environ. Sci. Policy* **2013**, *27*, 162–171, doi:10.1016/j.envsci.2012.12.016.

33. Glaser, B. G.; Strauss, A. L.; Strutzel, E. The Discovery of Grounded Theory; Strategies for Qualitative Research. *Nurs. Res.* **1968**, *17*, 364.

34. Glaser, B. G.; Holton, J. Remodeling Grounded Theory. *Forum Qual. Sozialforschung Forum Qual. Soc. Res.* **2004**, *5*.

35. Corbin, J.; Strauss, A. *Basics of qualitative research: Techniques and procedures for developing grounded theory,* 3rd ed.; SAGE Publications, Inc.: Thousand Oaks, CA, USA, **2008**.

36. Billen, G. *Le PIREN-Seine : un programme de recherche né du dialogue entre scientifiques et gestionnaires;* CNRS Éditions; La Revue pour l'histoire du CNRS: Paris, France, **2001**, doi:10.4000/histoire-cnrs.3182.

37. Conseil scientifique du Comité de Bassin Seine-Normandie *Evaluation du Programme de recherche PIREN-Seine*; Agence de l'Eau Seine-Normandie: Nanterre, France, 2008.

38. Wong, T.; Allen, R.; Beringer, J.; R. Brown, R.; Deletic, A.; Fletcher, T.; Gangadharan, L.; Gernjak, W.; Jakob, C.; O'Loan, T.; Reeder, M.; Tapper, N.; Walsh, C. *Blueprint 2013 - Stormwater Management in a Water Sensitive City*; Cooperative Research Centre for Water Sensitive Cities: Melbourne, Australia, 2013; ISBN 978-1-921912-01-6.

39. de Haan, F. J.; Ferguson, B. C.; Adamowicz, R. C.; Johnstone, P.; Brown, R. R.; Wong, T. H. F. The needs of society: A new understanding of transitions, sustainability and liveability. *Technol. Forecast. Soc. Chang.* **2014**, *85*, 121–132, doi:10.1016/j.techfore.2013.09.005.

40. Low, K. G.; Grant, S. B.; Hamilton, A. J.; Gan, K.; Saphores, J.-D.; Arora, M.; Feldman, D. L. Fighting drought with innovation: Melbourne's response to the Millennium Drought in Southeast Australia: Fighting drought with innovation. *Wiley Interdiscip. Rev. Water* **2015**, *2*, 315–328, doi:10.1002/wat2.1087.

41. Grant, S. B.; Fletcher, T. D.; Feldman, D.; Saphores, J.-D.; Cook, P. L. M.; Stewardson, M.; Low, K.; Burry, K.; Hamilton, A. J. Adapting Urban Water Systems to a Changing Climate: Lessons from the Millennium Drought in Southeast Australia. *Environ. Sci. Technol.* **2013**, *47*, 10727–10734, doi:10.1021/es400618z.

42. Heberger, M. Australia's Millennium Drought: Impacts and Responses. In *The World's Water*; Island Press: Washington, DC, USA, 2012; 97–125 ISBN 978-1-61091-048-4.

43. Brown, R. R.; Keath, N.; Wong, T. H. F. Urban water management in cities: Historical, current and future regimes. *Water Sci. Technol. J.* **2009**, *59*, 847–855, doi:10.2166/wst.2009.029.

44. Ferguson, B. C.; Brown, R. R.; Frantzeskaki, N.; de Haan, F. J.; Deletic, A. The enabling institutional context for integrated water management: Lessons from Melbourne. *Water Res.* **2013**, *47*, 7300–7314, doi:10.1016/j.watres.2013.09.045.

45. Qu’est-ce que le PIREN Seine ? | Programme Interdisciplinaire de Recherche sur l’Environnement de la Seine Available online:

http://www.metis.upmc.fr/piren/?q=presentation_PIREN-Seine (accessed on Mar 6, 2017).

46. *Loi n° 92-3 du 3 janvier 1992 sur l’eau*; Assemblée Nationale: Paris, France.

47. *Le SDAGE 2010-2015 du Bassin de la Seine et des Cours d’Eau Côtiers Normands*; Agence de l'Eau Seine-Normandie: Nanterre, France, 2010.

48. European Union. *Water Framework Directive*; European Commission: Brussels, Belgium, 2000.

49. Bach, P. M.; Rauch, W.; Mikkelsen, P. S.; McCarthy, D. T.; Deletic, A. A critical review of integrated urban water modelling – Urban drainage and beyond. *Environ. Model. Softw.* **2014**, *54*, 88–107, doi:10.1016/j.envsoft.2013.12.018.

50. Carre, C.; Haghe, J. P.; De Coninck, A.; Becu, N.; Deroubaix, J.; Pivano, C.; Flipo, N.; Le Pichon, C.; Tallec, G. How to integrate scientific models in order to switch from, flood control river management to multifunctional river management? *Int. J. River Basin Manag.* 2014, *12*, 231-249.

52. Mouchel, J.-M. *Rapport de synthèse 2007-2010 - Introduction Générale*; PIREN-Seine: Paris, France, 2010.

52. Even, S.; Poulin, M.; Billen, G.; Garnier, J. *Modèles PROSE et SENEQUE : établissement de versions de référence applicables aux études de gestion*; PIREN-Seine: Paris, France, 1998.

53. Garnier, J.; Mouchel, J.-M. *Man and River Systems: The Functioning of River Systems at the Basin Scale*; Springer: Cham, The Netherlands, 1999; ISBN 978-94-017-2163-9.

54. Billen, G.; Garnier, J.; Mariotti, A. *Bilan des transferts d’azote dans le bassin de la Seine: l’approche du modèle SENEQUE*; PIREN-Seine: Paris, France, 1998.

55. Ledoux, E. Modélisation intégrée des écoulements de surface et des écoulements souterrains sur un bassin hydrologique. Doctoral Dissertation, École des Mines, Paris, France, 1980.

56. Ledoux, E.; Girard, G.; Marsily, G. de; Villeneuve, J. P.; Deschenes, J. Spatially Distributed Modeling: Conceptual Approach, Coupling Surface Water And Groundwater. In *Unsaturated Flow in Hydrologic Modeling*; Morel-Seytoux, H. J., Ed.; NATO ASI Series; Springer: Cham, The Netherlands, 1989; 435–454 ISBN 978-94-010-7559-6.

57. Brisson, N.; Mary, B.; Ripoche, D.; Jeuffroy, M. H.; Ruget, F.; Nicoullaud, B.; Gate, P.; Devienne-Barret, F.; Antonioletti, R.; Durr, C.; Richard, G.; Beaudoin, N.; Recous, S.; Tayot, X.; Plenet, D.; Cellier, P.; Machet, J.-M.; Meynard, J. M.; Delécolle, R. STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. *Agron. Sustain. Dev.* **1998**, *18*, 36, doi:10.1051/agro:19980501.

58. Brisson, N.; Gary, C.; Justes, E.; Roche, R.; Mary, B.; Ripoche, D.; Zimmer, D.; Sierra, J.; Bertuzzi, P.; Burger, P.; Bussière, F.; Cabidoche, Y. .; Cellier, P.; Debaeke, P.; Gaudillère, J. .; Hénault, C.; Maraux, F.; Seguin, B.; Sinoquet, H. An overview of the crop model stics. *Eur. J. Agron.* **2003**, *18*, 309–332, doi:10.1016/S1161-0301(02)00110-7.

59. Billen, G.; Garnier, J.; Mouchel, J.-M.; Silvestre, M. The Seine system: Introduction to a multidisciplinary approach of the functioning of a regional river system. *Sci. Total Environ.* **2007**, *375*, 1–12, doi:10.1016/j.scitotenv.2006.12.001.

60. Even, S. *Description du logiciel ProSe, version 4.1 - Logiciel de simulation de l'hydrodynamique, du transport et du fonctionnement biochimique d'un écosystème fluvial*; PIREN-Seine: Paris, France, 2007.

61. Even, S.; Poulin, M.; Garnier, J.; Billen, G.; Servais, P.; Chesterikoff, A.; Coste, M. River ecosystem modelling: application of the PROSE model to the Seine river (France). *Hydrobiologia* 1998, *373*, 27–45.

62. Ruelland, D.; Billen, G. Riverstrahler, SENEQUE and SENECAM: modelling tools for water resources management from regional to local scales. In Proceedings of the 6th International Conference of EWRA, France, Menton, 7-10 September 2005.

63. Thouvenot, M.; Billen, G.; Garnier, J. *Denitrification in the Riverstrahler Model*. In Proceedings of the Denitrification Modeling Workshop Agenda, New York, NY, USA, 28-30 November 2006.

64. Ruelland, D.; Billen, G.; Brunstein, D.; Garnier, J. SENEQUE: A multi-scaling GIS interface to the Riverstrahler model of the biogeochemical functioning of river systems. *Sci. Total Environ.* **2007**, *375*, 257–273, doi:10.1016/j.scitotenv.2006.12.014.

65. Ruelland, D.; Silvestre, M.; Thieu, V.; Billen, G. *Applicatif SENEQUE 3.4: notice d'utilisation*; PIREN-Seine: Paris, France, 2007.

66. Thieu, V.; Billen, G.; Silvestre, M.; Garnier, J. *SENEQUE and Co: Développements logiciels et améliorations des outils;* Rapport PIREN-Seine; PIREN-Seine: Paris, France, **2006**.

67. Ledoux, E.; Gomez, E.; Monget, J. M.; Viavattene, C.; Viennot, P.; Ducharne, A.; Benoit, M.; Mignolet, C.; Schott, C.; Mary, B. Agriculture and groundwater nitrate contamination in the Seine basin. The STICS–MODCOU modelling chain. *Sci. Total Environ.* **2007**, *375*, 33–47, doi:10.1016/j.scitotenv.2006.12.002.

68. Viennot, P.; Ledoux, E. *Influence de l'augmentation des prélèvements anthropiques en formations aquifères sur le fonctionnement hydrodynamique du bassin de la Seine*; PIREN-Seine: Paris, France, 2007.

69. Viennot, P.; Monget, J.-M.; Ledoux, E.; Schott, C. *Modélisation de la pollution nitrique des aquifères du bassin de la Seine : intégration des bases de données actualisées des practiques agricoles, validation des simulations sur la période 1971-2004, simulations prospectives de measures agro-environnementales*; PIREN-Seine: Paris, France, 2006.

70. Habets, F.; Flipo, N.; Goblet, P.; Ledoux, E.; Monteil, C.; Philippe, E.; Querel, W.; Saleh, F.; Souhar, O.; Stouls, A.; Viennot, P.; David, C.; Bacchi, A.; Blanchoud, H.; Moreau-Guigon, E.; Launay, M.; Ripoche, D.; Mary, B.; Jayet, P.-A.; Martin, E.; Morel, T.; Tournebize, J. *Le développement du modèle intégré des hydrosystèmes Eau-dyssée*; PIREN-Seine: Paris, France, 2009.

71. Saleh, F.; Ducharne, A.; Oudin, L.; Flipo, N.; Ledoux, E. *Hydraulic modeling of flow, water levels and inundations: Serein River case study*; PIREN-Seine: Paris, France, 2009.

72. Coucheney, E.; Buis, S.; Launay, M.; Constantin, J.; Mary, B.; García de Cortázar-Atauri, I.; Ripoche, D.; Beaudoin, N.; Ruget, F.; Andrianarisoa, K. S.; Le Bas, C.; Justes, E.; Léonard, J. Accuracy, robustness and behavior of the STICS soil–crop model for plant, water and nitrogen outputs: Evaluation over a wide range of agro-environmental conditions in France. *Environ. Model. Softw.* **2015**, *64*, 177–190, doi:10.1016/j.envsoft.2014.11.024.

73. Gomez, E.; Ledoux, E.; Mary, B. *La démarche de modélisation régionale des écoulements d'eau, de la production et du transfert d'azote sure le bassin de la Seine, structure du modèle d'écoulement*; PIREN-Seine: Paris, France, 1998.

74. Gomez, E.; Ledoux, E.; Monget, J.-M.; De Marsily, G. Distributed surface-groundwater coupled model applied to climate or long term water management impacts at basin scale. *Eur. Water* 2003, *1*, 3–8.

75. About the CRCWSC. CRC Water Sensitive Cities. Available online: https://watersensitivecities.org.au/about-the-crcwsc/ (accessed on 2 August 2017).

76. Howe, C.; Mitchell, C. *Water Sensitive Cities*; International Water Association (IWA) Publishing: London, UK, 2011; ISBN 978-1-84339-364-1.

77. Wong, T. H. F.; Brown, R. R. The water sensitive city: Principles for practice. *Water Sci. Technol.* **2009**, *60*, 673–682, doi:10.2166/wst.2009.436.

78. Geiger, W. F. Sponge city and lid technology--vision and tradition. *Landsc. Archit. Front.* **2015**, *3*, 10–22.

79. Li, X.; Li, J.; Fang, X.; Gong, Y.; Wang, W. *Case Studies of the Sponge City Program in China*. In Proceedings of the World Environmental and Water Resources Congress 2016, West Palm Beach, FL, USA, 22-26 May 2016.

80. Xia, J.; Zhang, Y.; Xiong, L.; He, S.; Wang, L.; Yu, Z. Opportunities and challenges of the Sponge City construction related to urban water issues in China. *Sci. China Earth Sci.* **2017**, *60*, 652–658, doi:10.1007/s11430-016-0111-8.

81. Malekpour, S.; de Haan, F. J.; Brown, R. R. Marrying Exploratory Modelling to Strategic Planning: Towards Participatory Model Use. In Proceedings of the 20th International Congress on Modelling and Simulation (MODSIM2013), Adelaide, Australia, 1-6 December 2013.

82. Walker, W. E.; Haasnoot, M.; Kwakkel, J. H. Adapt or Perish: A Review of Planning Approaches for Adaptation under Deep Uncertainty. *Sustainability* **2013**, *5*, 955–979, doi:10.3390/su5030955.

83. Tewdwr-Jones, M.; Allmendinger, P. Deconstructing Communicative Rationality: A Critique of Habermasian Collaborative Planning. *Environ. Plan. A* **1998**, *30*, 1975–1989, doi:10.1068/a301975.

84. Klosterman, R. E. Planning Support Systems: A New Perspective on Computer-Aided Planning. *J. Plan. Educ. Res.* **1997**, *17*, 45–54, doi:10.1177/0739456X9701700105.

85. Wong, T. H.; Fletcher, T. D.; Duncan, H. P.; Coleman, J. R.; Jenkins, G. A. A Model for Urban Stormwater Improvement: Conceptualization. In *Global Solutions for Urban Drainage*; American Society of Civil Engineers: Reston, VA, USA, 2002; 1–14.

86. Rauch, W.; Urich, C.; Bach, P. M.; Rogers, B. C.; de Haan, F. J.; Brown, R. R.; Mair, M.; McCarthy, D. T.; Kleidorfer, M.; Sitzenfrei, R.; Deletic, A. Modelling transitions in urban water systems. *Water Res.* **2017**, *126*, 501–514, doi:10.1016/j.watres.2017.09.039.

87. Wong, T.; Fletcher, T.; P. Duncan, H.; Jenkins, G. Modelling Urban Stormwater Treatment – A Unified Approach. *Ecol. Eng.* **2006**, *27*, 58–70, doi:10.1016/j.ecoleng.2005.10.014.

88. eWater Water Quality Objectives - MUSIC Version 6 Documentation and Help - eWater Wiki Available online: https://wiki.ewater.org.au/display/MD6/Water+Quality+Objectives (accessed on 16 May 2017).

89. *eWater Annual Report 2011-12*; eWater: Canberra, Australia, 2012.

90. Water Sensitive Cities Modelling Toolkit Factsheet; CRC for Water Sensitive Cities. Available online: https://watersensitivecities.org.au/wp-content/uploads/2017/06/Fact-Sheet_Water-Se nsitive-Cities-modellingtoolkit_Project-D1.5_V3.pdf (accessed on 2 August 2017).

91. Fletcher, T. D.; Walsh, C. J.; Bos, D.; Nemes, V.; RossRakesh, S.; Prosser, T.; Hatt, B.; Birch, R. Restoration of stormwater retention capacity at the allotment-scale through a novel economic instrument. *Water Sci. Technol.* **2011**, *64*, 494–502, doi:10.2166/wst.2011.184.

92. Fletcher, T. D.; Mitchell, V. G.; Deletic, A.; Ladson, T. R.; Séven, A. Is stormwater harvesting beneficial to urban waterway environmental flows? *Water Sci. Technol.* **2007**, *55*, 265–272, doi:10.2166/wst.2007.117.

93. Walsh, C. J.; Fletcher, T. D.; Bos, D.; Nemes, V.; Edwards, D.; A., O. K. *Little Stringybark Creek: Environmental benefit calculator technical notes*; Melbourne Water, Department of Water and Environment (Victoria), University of Melbourne: Melbourne, Australia, 2012.

94. Walsh, C. J.; Fletcher, T. D.; Ladson, A. R. Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. *J. North Am. Benthol. Soc.* **2005**, *24*, 690–705.

95. Brookes, K.; Wong, T. H. F. The adequacy of stream erosion index as an alternate indicator of geomorphic stability in urban waterways. In Proceedings of the 6th Water Sensitive Urban Design Conferene and Hydropolis, Perth, Australia, 5-8 May 2009.

96. Coutts, A.; Harris, R. *A multi-scale assessment of urban heating in Melbourne during an extreme heat event: policy approaches for adaptation*; Monash University: Clayton, Australia, 2013.

97. Raut, B.; de la Fuente, L.; Seed, A.; Jakob, C.; Reeder, M. Application of a space-time stochastic model for downscaling future rainfall projections. In *Hydrology and Water Resources Symposium*; Engineers Australia: Barton, Australia, 2012; pp. 579–586.

98. Zhang, K.; Manuelpillai, D.; Raut, B.; Jakob, C.; Reeder, M.; Deletic, A.; Bach, P. M. Impact of future rainfall projections from ensemble GCMs on stormwater management. In Proceedings of the 14th International Conference on Urban Drainage (14ICUD), Prague, Czech Republic, 10-15 September 2017.

99. Rauch, W.; Bach, P. M.; Brown, R.; Rogers, B.; de Haan, F. J.; McCarthy, D. T.; Kleidorfer, M.; Mair, M.; Sitzenfrei, R.; Urich, C.; Deletic, A. Enabling change: Institutional adaptation. In *Climate Change, Water Supply and Sanitation*; IWA Publishing: London, U.K., 2015.

100. Urich, C.; Bach, P.; Sitzenfrei, R.; Kleidorfer, M.; Mccarthy, D.; Deletic, A.; Rauch, W. Modelling cities and water infrastructure dynamics. *Proc. Inst. Civ. Eng. Eng. Sustain.* 2013, *166*, 301-308.

101. de Haan, F. J.; Rogers, B. C.; Brown, R. R.; Deletic, A. Many roads to Rome: The emergence of pathways from patterns of change through exploratory modelling of sustainability transitions. *Environ. Model. Softw.* **2016**, *85*, 279–292, doi:10.1016/j.envsoft.2016.05.019.

102. Urich, C.; Rauch, W. Exploring critical pathways for urban water management to identify robust strategies under deep uncertainties. *Water Res.* **2014**, *66*, 374–389.

103. Rossman, L. A. *EPANET 2 User Manual*; US Environmental Protection Agency: Cincinnati, OH, USA, 2000.

104. Rossman, L. A. *Storm Water Management Model - User's Manual Version 5.1*; US Environmental Protection Agency: Cincinnati, OH, USA, 2004.

105. Löwe, R.; Urich, C.; Domingo, N. S.; Mark, O.; Deletic, A.; Arnbjerg-Nielsen, K. Assessment of urban pluvial flood risk and efficiency of adaptation options

through simulations - A new generation of urban planning tools. *J. Hydrol.* **2017**, *550*, 355–367.

106. Chesterfield, C.; Urich, C.; Beck, L.; Berge, K.; Charette-Castonguay, A.; Brown, R.; Dunn, G.; De Haan, F.; Lloyd, S.; Rogers, B. A Water Sensitive Cities Index - Benchmarking cities in developed and developing countries. In Proceedings of the International Low Impact Development Conference, Beijing, China, 26-29 June 2016.

107. Vogel, C.; Moser, S. C.; Kasperson, R. E.; Dabelko, G. D. Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. *Glob. Environ. Change* **2007**, *17*, 349–364, doi:10.1016/j.gloenvcha.2007.05.002.

108. Baker, R.; McKenzie, N. Troubled waters: What is the Office of Living Victoria up to? *The Age*, 28 February 2014.

109. Department of Environmental and Resource Management (DERM) *Urban Stormwater Quality Planning Guidlines 2010*; Queensland Government: Brisbane, Australia, 2010.

110. Department of Environment, Land, Water, and Planning (DELWP). *Victoria Planning Provisions*; Department of Environment, Land, Water, and Planning: Melbourne, Australia, 2017.

111. Evolving water management - eWater. Available online: http://ewater.org.au/ (accessed on 24 November 2017).

112. Argent, R. M. An overview of model integration for environmental applications—components, frameworks and semantics. *Environ. Model. Softw.* **2004**, *19*, 219–234, doi:10.1016/S1364-8152(03)00150-6.

113. Nilsson, M.; Jordan, A.; Turnpenny, J.; Hertin, J.; Nykvist, B.; Russel, D. The use and non-use of policy appraisal tools in public policy making: an analysis of three European countries and the European Union. *Policy Sci.* **2008**, *41*, 335–355, doi:10.1007/s11077-008-9071-1.

114. Fletcher, T. D.; Andrieu, H.; Hamel, P. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Adv. Water Resour.* **2013**, *51*, 261–279, doi:10.1016/j.advwatres.2012.09.001.

115. Brugnach, M.; Tagg, A.; Keil, F.; de Lange, W. J. Uncertainty Matters: Computer Models at the Science–Policy Interface. *Water Resour. Manag.* **2007**, *21*, 1075–1090, doi:10.1007/s11269-006-9099-y.

116. Hipel, K. W.; Ben-Haim, Y. Decision making in an uncertain world: Information-gap modeling in water resources management. *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.* **1999**, *29*, 506–517.

117. Marlow, D. R.; Moglia, M.; Cook, S.; Beale, D. J. Towards sustainable urban water management: A critical reassessment. *Water Res.* **2013**, *47*, 7150–7161, doi:10.1016/j.watres.2013.07.046.

118. Clark, W. C.; Tomich, T. P.; van Noordwijk, M.; Guston, D.; Catacutan, D.; Dickson, N. M.; McNie, E. Boundary work for sustainable development: Natural resource management at the Consultative Group on International Agricultural Research (CGIAR). *Proc. Natl. Acad. Sci.* **2011**, *113*, 4615–4622, doi:10.1073/pnas.0900231108.

119. O'Mahony, S.; Bechky, B. A. Boundary organizations: Enabling collaboration among unexpected allies. *Adm. Sci. Q.* **2008**, *53*, 422–459.

120. Chong, N.; Bonhomme, C.; Deroubaix, J.-F.; Moilleron, R. *Production et usages des modèles dans le cadre du PIREN-Seine*; PIREN-Seine: Paris, France, 2016.

121. Johri, A. Boundary spanning knowledge broker: An emerging role in global engineering firms. In Proceedings of the 38th Annual Frontiers in Education Conference (FIE 2008), Saratoga Springs, NY, USA, 22-25 October 2008; p. S2E–7.

122. Turnhout, E.; Stuiver, M.; Klostermann, J.; Harms, B.; Leeuwis, C. New roles of science in society: Different repertoires of knowledge brokering. *Sci. Public Policy* **2013**, *40*, 354–365, doi:10.1093/scipol/scs114.

123. Sverrisson, Á. Translation Networks, Knowledge Brokers and Novelty Construction: Pragmatic Environmentalism in Sweden. *Acta Sociol.* **2016**, *44,* 313-327, doi:10.1177/000169930104400403.

124. Meyer, M. The Rise of the Knowledge Broker. *Sci. Commun.* **2010**, *32*, 118–127.

Chapter 2

Reconciling Uncertainty in the Modelling Process

Chapter 1 illustrated the nuanced relationship between use and utility. For example, a model can be considered 'useful' even if it is not used 'directly'. In many cases, the utility of a model is in its outputs. At the same time, it is commonly acknowledged that a model is only as good as its inputs ("*garbage in, garbage out*"). Issues of quality, access and reliability of input data remain a fundamental challenge in modelling. This inevitably leads to questions of trust, credibility, and legitimacy. Therefore, this chapter aims to elucidate the following question: *how do modelling results, which are characterised by a high level of uncertainty, turn into decisive action?*

Uncertainty remains a major challenge in water resources management: hydrological systems are made up of dynamic processes and non-linear interactions, requiring solutions that are reinforced by knowledge and empirical data that are not always adequate or available (Sigel *et al.*, 2010). Van der Sluijs (2005) describes uncertainty as a 'monster', i.e. "*a phenomenon that at the same moment fits into two categories that were considered mutually excluding, such as knowledge versus ignorance, objective versus subjective, facts versus values, prediction versus speculation, science versus policy*" (87). Though it is generally accepted that models are imperfect representations of reality, an under or overestimation of error can lead to significant socio-economic or ecological consequences. For example, under-sizing drainage pipes can lead to failure of the system to support an extreme rainfall event, causing more pollutants to infiltrate natural waterways. In recent decades, increasing attention is being paid to uncertainty surrounding models, but there is still a reluctance towards uncertainty estimation in hydrological and hydraulic modelling (Pappenberger and Beven, 2006).

While uncertainty may be one factor hindering the use and utility of modelling tools, participatory modelling exercises conducted by Carré *et al.*, (2014) found that the use of modelling tools helped stakeholders better understand the uncertainty surrounding the consequences of removing dams, which was eventually taken into account in the creation of a new action plan. Similarly, Juston *et al.*, (2013) advocate for 'positive uncertainty' a term borrowed from psychology that *"urges moving beyond deterministic frameworks of the past, but doing so not just by regrettably accepting that uncertainties are inevitable, but by positively thriving in the new perspectives that accompany this recognition"* (Gelatt, 1989). Acknowledging and deepening our knowledge of uncertainties – their nature, sources and implications –can help to reduce or manage them by improving our models and data. They go on to cite seven reasons to be positive about uncertainty estimation, including learning about data and models, producing more reliable and robust predictions, engendering trust, deepening academic understanding and the fact that technological advances are making it easier (Juston *et al.*, 2013).

In this chapter, the case of PIREN is used to explore the different modalities of dealing with uncertainty in the modelling process, from the development and design of a model to the application of the model and/or its results in the decision process. Specifically, we seek to understand the apparent reluctance towards uncertainty assessment, despite its potential to enhance decision-making. By examining some of the most common strategies to dealing with uncertainty in the context of PIREN, we aim to elucidate the following question: *if formal uncertainty assessments are infrequently used, how then, is uncertainty addressed and subsequently taken into account in the modelling process?*

Part 1 focuses on the different strategies and perspectives of PIREN researchers and operational partners, highlighting the heterogeneity within each group. This analysis illustrates the gap between the fragmented and highly academic methods of PIREN researchers and the more pragmatic field-oriented approaches of practitioners.

Part 2 further investigates the gap between the academic-oriented approach of researchers and the field-oriented approach of practitioners, exploring the ways in which different actors navigate the limitations of knowledge and ignorance when scientific knowledge and tools fail to provide information that is readily comprehensible, accessible and applicable to practitioners.

PART 1

EXPLORING PERSPECTIVES AND APPROACHES TO UNCERTAINTY

Uncertainty is a growing concern for researchers and practitioners alike. But *how exactly is it addressed in the modelling process?* This section aims to shed light on this question by exploring the different perspectives and approaches that exist in the example of the PIREN-Seine in France.

Understanding Uncertainty

One of the central difficulties of understanding uncertainty is that it does not belong to one single discipline, resulting in a wide range of interpretations and perceptions based on different academic traditions (Refsgaard *et al.*, 2007; Smithson, 2008; Walker *et al.*, 2003). Whereas Funtowicz and Ravetz (1990) describe uncertainty as a state of having inadequate information in the form of inexactness, unreliability and bordering with ignorance, Walker *et al.* (2003) point out that this definition neglects situations where new information may, in fact, increase uncertainty by uncovering new uncertainties that were previously unknown or understated.

According to Sigel *et al.* (2010), uncertainty should be understood as a continuous spectrum ranging from 'very high uncertainty' to 'very low uncertainty', rather than a strict dichotomy between having knowledge and a lack of knowledge. Adding another layer to our understanding of uncertainty, Klauer and Brown

(2004) define uncertainty in terms of a lack of confidence due to a belief that the information is ambiguous, inadequate, inaccurate, or unreliable. Sigel *et al.* (2010) take this idea a step further by suggesting that uncertainty is not only subjective, but also multi-layered: confidence is not only in the knowledge itself but also in an individual's ability to evaluate the reliability of his/her own knowledge.

Drawing from these definitions, uncertainty in the context of this analysis is understood as:

- A spectrum ranging from 'very low uncertainty' to 'very high uncertainty', recognizing that absolute certainty is not possible
- The extent to which reality can be adequately represented
- A reflection of confidence, whether it be confidence in the knowledge itself or the individual's knowledge, and is often subjective

General Framework

Attempting to address the challenge of understanding and communicating uncertainty, some authors (e.g. Refsgaard *et al.*, 2007; van der Keur *et al.*, 2010; Walker *et al.*, 2003) have outlined a classification of uncertainty in relation to modelling and its use and environmental policy and planning. Within these classifications, uncertainty is represented in three main dimensions: (i) *source*, (ii) *level or type*, and (iii) *nature*. These categories are not mutually exclusive and often coincide.

Source of Uncertainty

Within the literature, four main sources of uncertainty have been identified (Refsgaard *et al.*, 2007; Walker *et al.*, 2003):

- Context and framing uncertainty
- Input uncertainty
- Model uncertainty
- Parameter uncertainty

Context and framing uncertainty are typically found when the model context and system boundaries are defined. *Context uncertainty* includes external economic, environmental, political, social, and technological aspects involved with the problem at hand, while also taking into account different spatial and temporal scales. *Framing uncertainty* refers to uncertainty about the objectivity of the problem, questioning whether it has been framed in a way that accommodates personal values, objectives or the choice of a model.

Input uncertainty is found in input data resulting from a lack of knowledge of the deterministic and stochastic properties of the system, or an insufficient description of the variability inherent in certain phenomena (van der Keur *et al.*, 2010). Uncertainties in the external driving forces include the changes they produce within the system as well as their magnitude.

Model uncertainty can be subcategorized into *model structure uncertainty*, and *model technical uncertainty*. Whereas *model structure uncertainty* refers to the ability of a model to produce an adequate representation of the real system, *model technical uncertainty* refers to errors in the hardware such as software bugs or design errors in algorithms or typing errors in source code.

Parameter uncertainty is related to the data and methods used in the calibration of model parameters. Although parameter uncertainty can be reduced when all parameters are well calibrated, residual uncertainty is unavoidable and is usually treated as its own parameter.

Although *model outcome uncertainty* is described as a fifth source, here we consider it to be the total uncertainty accrued, rather than a separate source in and of itself. Also known as *prediction error*, it refers to the difference between the true value of an outcome and the predicted value of the model.

Level or Type of Uncertainty

In addition to the source, there is the *level* or *type* of uncertainty, which ranges from what we *can know* to what we *cannot know* (Walker *et al.*, 2003). At one end of the spectrum we have *statistical uncertainty*, which is closer to determinism, then we have *scenario uncertainty*, followed by *recognised* and *total ignorance,* at the opposite end.

Statistical uncertainty is uncertainty that can be adequately described in statistical terms and can apply to any location in the model or to model structure uncertainties (Walker *et al.*, 2003). An example is *measurement uncertainty*, as no measurement can precisely represent the 'true' value of what is being measured. This can be a result of sampling error, inaccuracy, or imprecision in measurements. For example, *measurement uncertainty* can stem from errors related to using the tool itself, such as poor calibration or ageing components in the equipment (ISO 1995). This inherent inaccuracy can also result from rounding up, or specific sampling locations which can be highly variable (Cladière, 2012).

Scenario uncertainty is based in the reality that many possible outcomes exist, and the mechanisms which lead to these outcomes are not understood well enough to formulate the probability of one outcome occurring over another (Walker *et al.*, 2003). Examples of scenario uncertainty include the range of outcomes resulting from different underlying assumptions, uncertainty over which changes or external driving forces are relevant for the outcome of interest, or uncertainty about the levels of relevant changes.

All remaining types of uncertainty that cannot easily be identified are placed under the category of *recognised* and *total ignorance*. *Recognised ignorance* describes a situation with high uncertainty, of which the actors are all conscious, and can be further divided into *reducible ignorance* and *irreducible ignorance* (Klauer and Brown, 2004). Whereas *reducible ignorance* can be minimized with further research, *irreducible ignorance* describes a situation in which neither research nor development can provide adequate knowledge concerning the essential relationships (Walker *et al.*, 2003).

At the far end of the spectrum is *total ignorance*, which describes the level of uncertainty where we do not know what we do not know, and we have no way of knowing the full extent of our ignorance.

Nature of Uncertainty

The nature of uncertainty is separated into two extremes: *epistemic uncertainty* and *stochastic* or *variability uncertainty* (ISO, 1995; Refsgaard *et al.*, 2007; van der Keur *et al.*, 2010; Walker *et al.*, 2003). *Epistemic uncertainty* refers to uncertainty resulting from imperfect knowledge, while *stochastic uncertainty* stems from inherent variability. *Epistemic uncertainty* is associated with limited or inaccurate data, measurement error, incomplete knowledge, limited understanding, imperfect models, subjective judgement, and ambiguities.

Stochastic or *variability uncertainty* is associated with the inherent randomness related to variations in external input data, input functions, parameters, and certain model structures. It is common for both *epistemic* and *stochastic uncertainty* to occur simultaneously, however, whereas epistemic *uncertainty* can be reduced with more research and data collection, a certain level of *stochastic uncertainty* will always be present, as its chaotic and unpredictable nature is characteristic of natural phenomena such as weather.

Perspectives and Approaches to Uncertainty in the PIREN-Seine

Armed with a general framework for understanding uncertainty in the context of water resources modelling and management, we examine the different perspectives and approaches to reconciling uncertainty, using the example of the PIREN-Seine in France. Since 1989, PIREN has worked to create an environment that fosters collaboration between researchers and practitioners around issues of water resources management in the Seine River basin. Decades of research, experimentation and data collection have resulted in specialised knowledge and expertise within the region, which has contributed to an overall feeling of confidence and satisfaction within the program. However, with uncertainty assessment being relatively new to the field, an analysis of the different perspectives and approaches within PIREN suggests that a shared understanding and approach to reconciling uncertainty that is able to meet the concomitant demands of research and practice is still difficult to achieve.

In the following article entitled *Reconciling uncertainty in the hydroinformatic process: Exploring approaches, perspectives and the spaces between*, we draw from scientific literature produced by PIREN actors and interview material to outline the various perspectives and approaches to reconcile uncertainty in practice. In doing so, we aim to highlight important gaps in the production and transformation of scientific knowledge and its subsequent use in the decision-making process.

Article

RECONCILING UNCERTAINTY IN THE HYDROINFORMATIC PROCESS: Exploring approaches, perspectives and the spaces between

Natalie CHONG, Céline BONHOMME, José-Frédéric DEROUBAIX

Submitted to Journal of Hydroinformatics, October 2018

Reconciling uncertainty in the hydroinformatic process: Exploring approaches, perspectives and the spaces between

Natalie Chong[1*], Céline Bonhomme[1], José-Frédéric Deroubaix[1]

[1]LEESU, École Nationale des Ponts et Chaussées, University of Paris East, 6-8 Avenue Blaise Pascal, 77455 Champs-sur-Marne, France
*Email: natalie.chong@enpc.fr; Tel: +33 01 64 15 39 50

Abstract

Ambiguity, complexity and ubiquity epitomize the difficulty of dealing with uncertainties embedded in the hydroinformatic process. Growing awareness coupled with scientific advancement has given rise to formalised methods to address uncertainty in hydrological modelling. Yet, they remain fragmented and highly academic, thus difficult to translate into information that is easily comprehensible, accessible and applicable for practitioners. Drawing primarily from interview material and scientific production in the empirical example of the PIREN-Seine in France, this paper employs a qualitative approach to explore the ways in which different actors attempt to reconcile uncertainty at the science-practice interface. The juxtaposition of an 'academic-oriented' approach of researchers against the more 'field-oriented' approach of practitioners reveals a number of key gaps; opening the door for the dilution of scientific knowledge in practice, with the potential for serious social, economic and ecological implications. As research and practice are becoming increasingly intertwined, this study highlights the need for more comprehensive approaches to address uncertainty, taking into account the diversity of methods, perceptions and types of knowledge that exist in such science-practice spaces, and advocate for the use of existing frameworks and guidelines in practice.

Keywords: hydrological modelling; hydroinformatic process; science-practice interface; uncertainty assessment

1. Introduction

In the pursuit of effective solutions to 'wicked' environmental problems, knowledge and ignorance often go hand-in-hand, with uncertainty occupying the spaces between. Generally attributed to Benjamin Franklin, playwright Christopher Bullock was first to quip, "*'tis impossible to be sure of anything but death and taxes!*" (1716), while French philosopher Blaise Pascal mused that "*it is not certain that everything is uncertain*" in his seminal work *Pensées* (1669). Despite its pervasiveness, uncertainty can evoke feelings of anxiety and vulnerability, particularly in matters that have a direct impact on our daily lives, such as the economy, healthcare and the environment.

In the hydroinformatic process, uncertainty is a fundamental concern for researchers and practitioners alike. Models are favoured tools, used to encapsulate and apply the best available scientific knowledge to support a wide range of basin management and planning decisions (McIntyre *et al*., 2003). At the same time, they represent selective abstractions of reality, often based on incomplete and/or unreliable data (Hall, 2003) and scientific assumptions. While uncertainty is inherent to the hydroinformatic process, a failure to acknowledge and adequately address uncertainty can quickly lead to poor decision making (Mishra, 2009), with potentially serious social, economic and ecological implications. Uncertainties in water quality modelling for example, can have a direct impact on the ability to properly manage and control pollutants (Radwan *et al.*, 2004). Yet, in practice, the systematic analysis of uncertainty is still far from the norm.

Growing concern has led to the development of more formalised methods to address uncertainty in hydrological modelling. Among the most commonly used are sensitivity analysis and uncertainty analysis, which can be used to highlight areas requiring more attention and resources, and provide guidance on how these uncertainties should be weighed in the decision making process (Radwan *et al*., 2004). However, these methods often remain fragmented and highly academic, making it difficult to translate into information that is easily comprehensible, accessible and applicable for practitioners (Isendahl *et al*., 2009; Vezzaro *et al*., 2013).

In an effort to bridge the gap between science and practice, some authors are advocating for the use of common frameworks and guidelines that have been developed to enhance communication and understanding (e.g. Brugnach *et al*., 2009; Kwakkel *et al*., 2010; Mishra, 2009; Van Der Sluijs *et al*., 2005; Van Der Sluijs *et al*., 2005). However, implementation of these tools in practice remains marginal at best. Similarly, a growing body of literature incorporates different perspectives in their analysis of uncertainty in the hydroinformatic process (e.g. Ascough, Maier, *et al*., 2008; Isendahl, Dewulf, *et al*., 2009; Vezzaro, Mikkelsen, *et al*., 2013; Brugnach, Henriksen, *et al*., 2009), but there are still few empirical examples that incorporate the practitioner's point of view.

Drawing from the empirical example of the PIREN-Seine program (*Programme Interdisciplinaire de Recherches sur l'Environnement*) in France, this paper uses a qualitative approach to explore how different actors attempt to reconcile uncertainty at the science-practice interface. Rather than attempting to provide a comprehensive analysis of the methods used or of the effectiveness of the methods themselves, the aim is to highlight how the priorities, perspectives, and approaches of different actors may impact the treatment of uncertainty and what implications this may bring.

First, we attempt to outline and classify the diverse methods and approaches used by the PIREN-Seine (PIREN) researchers, illustrated by a number of key studies from the scientific production. Next, we examine how PIREN operational partners reconcile uncertainty when modelling tools are used to support management and planning decisions in practice. A juxtaposition of the 'academic-oriented' approach of researchers against the 'field-oriented approach' of practitioners highlights the diversity of methods and approaches used in different contexts, while at the same time revealing significant gaps that remain in the spaces between.

2. Methods and Materials

This study was based on Grounded Theory, (Glaser *et al.*, 1968; Strauss and Corbin, 1997), an iterative research methodology guided by generative questions to identify core theoretical concepts through the systematic collection and analysis of empirical data. The PIREN-Seine program in France served as the basis for a qualitative empirical analysis, drawing primarily from documentary analysis, exploratory interviews and observation. The long duration of the program allows for a more in-depth analysis of how established science-practice relationships can influence the reconciliation of uncertainty, while internal interest for a review of the program has allowed for open dialogue and introspection.

2.1 Documentary Analysis

Documentary analysis centered on scientific production of the PIREN since its creation in 1989, which included hundreds of peer-reviewed journal articles and books as well as grey literature (over 700 reports, synthesis documents and other communications). A series of iterative searches was conducted to identify pertinent documents that satisfied the following criteria:

- It involved research that was supported by the PIREN – identified by any mention of contribution (financial or otherwise) – and/or involved researchers and operational partners of the PIREN without any direct reference to the PIREN;
- It involved modelling within the context of the Seine River basin;
- It had some reference to uncertainty (either explicit or implicit).

2.2. Exploratory Interviews and Observation

As the nature of this study requires a level of critical reflection that is not evident from official communication alone, semi-structured exploratory interviews and observation were used to support documentary analysis. A total of 40 interviews were conducted throughout 2015-2017 with researchers (modellers and non-modellers) and operational partners (modellers, public institutions, and regulating authorities) of the PIREN. Interviews were semi-structured and based on a question guide (*see supplementary material*) which was adapted to each interview participant depending on their role and involvement in modelling activities. Each interview was recorded, transcribed and coded according to relevant subjects, perspectives and ideas. They ranged from 1 to 4 hours, with an average duration of 1.5 hours. Observation served as secondary data during various meetings, seminars, and conferences organised by the PIREN, which included three general assembly and annual planning meetings organised to reflect on and co-define current and future program objectives.

3. Results

The PIREN-Seine is an interdisciplinary research program that brings together researchers from various academic backgrounds (e.g. hydrology, biology, chemistry, agronomy, engineering, geography, sociology) and operational partners with a vested interest in the water quality of the Seine River basin. While a collaborative environment is fostered within the PIREN itself, researchers and practitioners ultimately operate in different contexts, resulting in a diversity of methods and approaches used to reconcile uncertainties.

3.1 The Academic-Oriented Approach of PIREN Researchers

Researchers involved in modelling activities were typically focused on model-related uncertainties that were identifiable, quantifiable and mostly technical. The uncertainties that were addressed and the extent to which they were addressed often depended on the objective and scope of the study in question, as well as the academic background and objective of the individual themselves and the institutions they serve. This resulted in a fragmentation of methods employed on an *ad hoc* basis. As the methods used were not always consistent, they were organised into two categories – *explicit* and *implicit* approaches – in order to present them in a coherent manner. *Explicit* approaches are those that directly address uncertainty using formal, standardised methods; whereas *implicit* approaches address uncertainty indirectly, without necessarily mentioning uncertainty, detailing which uncertainties were addressed (and which were not) and/or outlining the specific methods used.

3.1.1 Explicit Approaches

Several examples of explicit approaches were found in the scientific literature. The primary objective being to further scientific research, these approaches mainly focused on model-related uncertainties from an academic perspective. Although these methods are highly fragmented, addressing specific uncertainties to varying degrees, sensitivity analysis, uncertainty analysis and comparison to empirical data appeared to be among the most common.

Cladière *et al.* (2014) focused on *input uncertainty*, *measurement uncertainty*, *parameter uncertainty* and *model uncertainty* in their study of the fate of the endocrine disrupting compounds (EDCs) 4-nonylphenol (4-NP), nonylphenol monoethoxylate (NP_1EO) and nonylphenolic acetic acid (NP_1EC) in the Seine River. *In-situ* sampling and measurements were taken since the fate constants of NPnEO have mostly been mainly determined through laboratory experiments that '*fail to represent the complexity of freshwater ecosystems, including spatial, temporal heterogeneity and numerous biological, physical and chemical parameters which may interfere with the dynamics of the NPnEO degredation*' (Cladière, Bonhomme, *et al.*, 2014: p. 1051). Taking samples from three different points on the same study site (left bank, middle and right bank) and three samples from the same spot within a 10-minute interval, they identified quantification errors in the sampling protocol due to *measurement uncertainty*, which suggested the need to address uncertainty in environmental variability as well as the sampling protocol itself. Finally, '*uncertainties on measurements and on the calibration parameters [were] estimated through a sensitivity analysis*' (Cladière, Bonhomme, *et al.*, 2014: p. 1050). The sensitivity analysis was used to identify the impact of each process on biodegradation, which resulted in a ±10% change for each optimised value. *Model uncertainty* and *parameter uncertainty* were also assessed using *in-situ* measurements were used to calibrate and validate parameters, which indirectly validated the model that was used.

Model-related uncertainties were also the focus of Thouvenot, *et al*. (2007) in their study of the fate of nitrogen (N), phosphorus (P) and silica (SiO2) at the sediment-water interface. While acknowledging that benthic processes play an important role in nutrient in-stream retention and elimination, they argue that most representations remain simplistic, resulting in a high degree of uncertainty. Aiming to minimize this, they connected a benthic sub-model of diagenetic nutrient transformation to a main model of water column processes in order to produce a more true-to-life representation. The benthic sub-model was validated independently with empirical data from three well-documented case sites. To address the problem of equifinality – where many different parameter sets produce representations that are equally good and limited data makes it impossible to determine a definitive configuration of parameters – a range of 'acceptable' or likely simulations were identified. Using this approach, the number of parameters that required calibration was reduced to three. Empirical data were used to calibrate these parameters, while also validating the parameters that were not calibrated. This was further verified using the Generalised Likelihood Uncertainty Estimation (GLUE) method to evaluate uncertainty associated with the model outputs resulting from calibrated *parameter uncertainty*.

In another example, Polus, Flipo, *et al.* (2011) used geostatistics to reduce uncertainties in distributed physically based models in their study of nitrate concentrations in the Seine River. They combined geostatistics with process-based modelling in order to reduce spatial and temporal discrepancies between simulations and observations that are hidden by using statistical criteria (e.g. root mean squared error (RMSE) or Nash-Sutcliffe efficiency) alone. Temporal variograms uncovered discrepancies between observed and simulated results, which were attributed to an incorrect quantification of river inputs or an inaccurate description of physical processes occurring within the river. The method of using cross-variograms was used to perform a sensitivity analysis, which helped to describe and minimize *model outcome uncertainties*.

Beaudoin, Gallois, *et al.* (2016) take a systematic approach to addressing uncertainties in their evaluation of the agronomic model STICS (*Simulateur mulTIdisciplinaire pour les Cultures Standard*) for predicting yield and nitrogen leaching at the basin scale, dedicating two pages to outlining their uncertainty assessment and detailing what uncertainty was taken into account, the extent to which it was taken into account, the reasoning behind these choices and its potential implications. Specifically, '*sources of uncertainties in this study include model structure (formalisms and parameters), input data, and spatial and temporal upscaling*' (Beaudoin, Gallois, et al., 2016: p. 21). The Quality Assurance Protocol (QAP) proposed by Refsgaard, Henriksen, *et al.*, (2005) was used to evaluate the reliability of model predictions '*by combining sensitivity analysis and agronomic expertise of STICS inputs and outputs. The strategy consisted in using the outstanding variability of soil, climate, and agricultural systems for assessing the model sensitivity to its inputs*' (Beaudoin, Gallois, *et al.*, 2016: p. 2). The QAP was based on three principles (Refsgaard *et al.*, 2005). The first (validation test against independent database) was '*realized through numerous tests carried out at the agricultural plot level and annual scale concerning soil water and mineral N content, biomass production, and N uptake by crops*' (Beaudoin, Gallois, *et al.*, 2016: p. 23). The second (uncertainty assessment associated to model predictions) was addressed through an independent study for 15 crops, which '*showed a limited dependency of model errors on crops or environments, indicating a satisfactory robustness with a small systematic error (RMSEs = 10 %)*' and by comparing several model runs of varying model input quality (Beaudoin, Gallois, *et al*., 2016: p. 23). The third principle (continuous interaction between water manager and modeller) was addressed through collaboration with the Seine-Normandie Water Agency, who '*[provided] water and nitrate databases, objectives specifications, and [questioned] about model outputs*' (Beaudoin, Gallois, *et al*., 2016: p. 23).

While the main objective of the previous studies was to answer scientific questions, the choice of uncertainty assessment may also be partially influenced by regulations and public policy. For example, in their study of river flux uncertainty, Moatar, Meybeck, *et al*. (2013) place *input uncertainty* at the centre of focus in response to a regulatory requirement to 'accurately estimate' annual and inter-annual contaminant and nutrient fluxes, which are prone to significant statistical errors. Infrequent (weekly to monthly) discrete sampling representing only a fraction of the daily river fluxes was identified as a primary source of *input uncertainty*, which was addressed using methods to compensate for limited data. This allowed for the quantification and differentiation of nitrate concentration and flux trends when applied to the Seine River. In another example, Ledoux, Gomez, *et al*., (2007) highlight the benefit of using uncertainty probability modelling, which '*enables to produce threshold probability maps displaying the probability that a certain regulatory index level be exceeded*' (p. 42). At the same time, they caution that '*the representativeness of databases established at such a large spatial scale is questionable. As a consequence, a large uncertainty is attached to the simulation results; it is the reason why* *we have made an attempt to quantify it by calibrating the model on a statistical way and by expressing the results in terms of probability of transgression of concentration thresholds*' (Ledoux, Gomez, *et al*., 2007: p. 46)

3.1.2 Implicit Approaches

Implicit approaches refer to studies that address uncertainty indirectly, without necessarily mentioning uncertainty itself, detailing which uncertainties were addressed (and which were not) or outlining the specific methods used. For example, in their study of inorganic nitrogen dynamics in the downstream section of the Seine, Chesterikoff, Garban, *et al*., (1992) uncertainty is only referred to once: *'In spite of the uncertainty remaining on the quantitative determination of several of the processes involved, Fig. 8 offers a clear and coherent picture of the nitrogen cycling in the river Seine.'* (p. 14). Similarly, in their study of the origin and fate of phosphorus in the Seine watershed, Némery and Garnier (2007) mention uncertainty in general, ambiguous terms: *'The results are, however, subject to uncertainties inherent in this type of data.'* (p. 6) *'To evaluate the relevance of our runoff calculation, which is subject to many uncertainties, the relationship between discharge and TPP content in suspended sediment is presented at three nested sites (Figure 6)'* (p. 8). In other example, Ruelland (2004) presents the catchment quality model Seneque as an interactive decision-support tool that practitioners can use to '*explore errors and uncertainties inherent to modelling*' without explicitly stating which uncertainties can be addressed or how they might be addressed. The question of uncertainty is instead addressed in more general terms, cautioning users with less modelling expertise to remain critical of such a 'black-box' model. At the same time, this type of message is not always explicitly expressed to an operational audience. This type of simple caution may, in fact, have more of an impact than complicated assessment methods that non-experts may not understand.

In other instances, there is no mention of uncertainty or how it is taken into account, though account for uncertainty may be inferred indirectly. For example, in their study of phytoplankton development at the scale of an entire drainage network, Billen, Garnier, *et al.*, (1994) state that the catchment quality model (Riverstrahler) is validated through its application to the Oise and Marne rivers. In some instances, uncertainty can be represented as error ranges, estimates or confidence intervals without going into detail about how these results were obtained. For example, studying the influence of temperature and substrate concentration on bacterial growth yield in the Seine, Barillier and Garnier (1993) refer to a confidence interval of ± 95% for carbon content as part of table legend.

3.2. The Field-Oriented Approach of Water Managers

Researchers tend toward an academic-oriented approach, focusing on uncertainties related to the model itself (e.g. associated with the inputs, the model, or its parameters) with less attention to the implications on subsequent decisions. The uncertainties that are considered, the extent to which they are addressed, and the methods that are used, often depend on the objective and scope of the study, and therefore only provide a partial idea of the uncertainties involved in a context that is much wider for decision makers. They are then tasked with assembling the pieces of the puzzle, which includes identifying and prioritising relevant uncertainties, the appropriate strategies to manage them (if possible), and assessing their impact, in a way that allows them to make sound decisions.

In practice, practitioners often adopt a more field-oriented approach that combines formal scientific knowledge with experiential or tacit knowledge. The most common approach to uncertainty adopted by PIREN operational partners draws on their local expertise in the field and access to input data. Although there is no centralised system of measurements and monitoring within the region, an inventory has been built over the years with observational data from regular or occasional monitoring that extends to two-thirds of the water bodies (AESN Representative, 8 June 2016). Serving as a reference, this inventory is then used to assess the reliability of modelling results by determining what they deem to be an acceptable level of uncertainty according to how closely the modelling results relate to observational data and based on the tacit knowledge of technicians. However, in cases where operational partners have less explicit knowledge and guidance on how to use and interpret modelling results, this approach can be susceptible to an underutilization or misuse of formal scientific knowledge: *"It's all very empirical. I think that if the PIREN saw what we do with the results they would be a little disappointed because they would say that it's very degraded"* (DRIEE Representative, 12 May 2017).

Whilst some may consider that practitioners may not be as vigilant as they should be regarding uncertainty (PIREN Researcher, 23 June 2016), in practice, they are faced with issues of time, resources, objectives and competences which play a big role in how they deal with uncertainty. In some cases, higher precision is not considered to be a high priority: *"We make comparisons. In terms of absolute value, the results are bad. For relative value, it's still interesting to be able to have an idea of the impact"* (SIAAP Representative, 20 July, 2016). This sentiment was echoed in the majority of interview participants who, when asked if they prefer having a model with a high level of uncertainty over no model at all, responded that even a model that gives bad results provides some information that they can work with (SIAAP Representative, 29 November, 2016). In many cases, the question of uncertainty may be avoided altogether so as not to further complicate an issue that is already complex or to uncover new problems or consequences that they may not be prepared to deal with (DRIEE Representative, 12 May 2017).

Explicit uncertainty assessments, when performed by operational partners themselves, were typically relegated to internal modelling departments. In this case, operational partners using similar methods as in the academic-oriented approach is not unusual, since modellers come from a similar academic background and would likely have similar perspectives. Methods such as sensitivity analysis, scenario analysis, and comparing model outputs to observed data were common, though comparatively less academically rigorous than the methods used by researchers, mostly due to constraints in time, money, and objectives. In fact, internal modelling expertise was few and far between among PIREN operational partners, mostly due to the heavy time and financial investment involved (AESN Representative, 8 June, 2016). Partners with internal modelling expertise (with dedicated departments) justify this investment by the value and frequent use of modelling deemed necessary for their work, whereas those without prefer to outsource modelling work through formal contracts with consultancies and/or formal and informal associations with PIREN researchers.

4. Discussion

The academic-oriented approach commonly adopted by researchers reflects the perspective that the impossibility of accounting for all uncertainties necessitates focus on those that are identifiable, quantifiable, and mostly associated with the model (e.g. inputs, parameters, and outputs). Studies addressing uncertainty therefore typically focus on *statistical* and *epistemic uncertainty* associated with *input uncertainty*, *model uncertainty*, and *parameter uncertainty*. This approach often remains highly academic, yet pragmatic, since a lack of empirical data prevents us from mathematically closing the system of equations that describes the system behaviour. Sensitivity and uncertainty analyses as well as comparison with empirical data appeared among the most commonly found approaches, though they may be implemented differently or used in combination with other methods depending on available data and/or specific study objectives.

While each method has its advantages, its limitations become more apparent in the context of decision-making. For instance, while certain processes may be considered sufficiently represented, others remain a mystery if there is no adequate means to acquire the necessary data or validate the results (PIREN Researcher, 16 June 2016). Stochastic approaches can be used to determine the sensitivity of the model parameters, however it still does not give a direct response to uncertainty (PIREN Researcher, 29 June 2016). While helpful in identifying and minimising uncertainty related to processed output data, sensitivity and uncertainty analyses focus entirely on *input* or *parameter uncertainty* in the computer model while not accounting for model structure uncertainty (Uusitalo *et al*., 2015). Comparing model outputs with empirical data may allow for a straightforward assessment and validation of the model, while at the same time addressing model structure uncertainty, however, it is limited to the availability and reliability of the data itself, as well as the measurement and sampling protocols (PIREN Researcher, 28 April 2016), and can be considered subjective.

These academic-oriented methods are reflective of the researcher's academic background and training, which focuses on statistical uncertainty in the conceptual or computer model, input data, model implementation and the processed output data, rather than ambiguity or framing uncertainty, which may be seen as outside of their role or expertise. However, focusing mainly on statistical uncertainty *"implicitly assumes that the functional relationships in the given model are reasonably good descriptions of the phenomena being simulated, and the data used to calibrate the model are representative of circumstances to which the model will be applied"* (Walker, Harremoës, *et al.*, 2003: p.12). Though it may be implicitly taken into account, uncertainties related to framing and ambiguity are largely left out of the discussion as well as the scientific literature, suggesting that it is a lower priority for both researchers and decision-makers. The general assumption is that problems are framed objectively, without explicitly accounting for the multiple opinions, experiences, expectations, values, and forms of knowledge that exist among the actors involved.

In the context of model-based decision support, uncertainty is both abundant and omnipresent, since a model is only a representation of reality at a given time and space. Limited by what is considered *known* and *unknown*, as well as what is *knowable* and *unknowable*, we are left to 'make do' with what we have: "*we think that what we put in the model must be good enough, but there is no direct evidence. It's all clusters of evidence around the issue but we do not know how to address it directly*" (PIREN Researcher, 16 June 2016). While the academic-oriented approach may be suitable in a research context, the methods and approaches commonly used by PIREN researchers to address uncertainties often do not translate (easily) into practice for practitioners who have different objectives (e.g. reach environmental targets, justify project proposals or decisions), must take into account other factors (e.g. social, political, economic) each with their own associated uncertainties, and whose actions are subject to real-world consequences, which need to be considered at different spatial and temporal scales. More importantly, while these methods are helpful in identifying, quantifying and minimizing uncertainties that influence model outcomes, less attention is paid to explicitly communicating the limits of our knowledge and how these uncertainties may affect management and planning decisions. As a consequence, practitioners are often left with the difficult task of knowing which uncertainties require attention (amid numerous definition and classification ambiguities), the best methods to address them, and how to address the remaining knowledge gaps (e.g. communication or further research).

Modelling tools produced and used in the context of the PIREN-Seine help support management, policy, and planning decisions within the Seine River basin. However, they are not decision support tools in the traditional sense. That is to say, they are models that are used by experts to conduct scientific research that may also (directly and indirectly) support decisions (*see* Chong, Bach, et al., 2017). With the exception of the SIAAP, most PIREN operational partners do not use the model themselves, but only the results of the model. When this information reaches the decision maker, uncertainty (if accounted for) is typically summarised or averaged into confidence intervals or estimates which do not detail which uncertainty is addressed (and which are not) and what implications this may have on subsequent decisions.

5. Conclusions

A qualitative analysis of the ways in which different actors reconcile uncertainties in the empirical example of the PIREN-Seine in France illustrates how uncertainty in the hydroinformatic process remains a critical challenge, with the potential for serious implications for evidence-based policy. Efforts to address remaining gaps could benefit from comprehensive approaches that take into account the heterogeneity of methods, perceptions, and types of knowledge that are at play in such science-practice spaces. Formalised guidelines (e.g. Brugnach *et al.*, 2009) and frameworks (e.g. Kwakkel *et al.*, 2010; Van Der Sluijs *et al.*, 2005; Van Der Sluijs *et al.*, 2005; Walker *et al.*, 2003) have been developed to address these gaps within the water sector and should be implemented on a greater scale in practice. As a basis for discussion and debate, these tools could not only enhance communication and transparency between actors from different backgrounds, but also serve as a more comprehensive template for identifying areas that require more attention and provide an essential element to better translation of science to practice.

Supplementary Material

Interview Question Guide

BACKGROUND/HISTORY
What is your involvement in the PIREN-Seine? - How did you get involved? - How long have you been involved?
How did the program get started? (Ex. Demand from researchers, industry or government?)
What is your background/training/experience?
How would you describe the relationship between researchers and partners in the program?
Do you think science should play a role in influencing policy?
How is the program funded? - **Who finances it?** - **How much funding does the program have in total?** - **How much does each partner contribute?** - **What are the financial obligations from both sides?**
In general, do you think there's a large gap between research and policy? - How does the program help to overcome this? - What could be improved? •
MODELS: DEVELOPMENT, EVOLUTION, USE
Were you involved in the development of any modelling tools? - Which ones? - How were you involved? (Ex. did you develop the code, a module, provide feedback, etc.)
Who was involved in the development? (Ex. research teams, universities, institutions, partners, etc.) - How were the different actors involved? (Ex. funding, feedback, research, etc.)
What was the reason/need for developing this model?

Were there other models that existed at the time that could have done the same thing? If so, why develop a new model instead of using the existing one?
What were the main challenges in developing this model?
How has the model evolved? (Ex. different modules, more functionality, etc.)
What are the advantages/limits of the model?
Who uses the model? - Which actors? (Ex. Specific researchers, partners)
How do you use the model? - What does the model allow you to do, that you could not do (or not as easily do) without? - Do you run the model yourself or do you use the results?
What are some of the challenges in using this model? - Would you say it is easy to use for someone without training/expertise in modelling?
Would you prefer to be able to use the model yourself or just use the results?
Is the model used outside of the context of this program?
Do the outputs of the model meet the needs/demands of the user? If not, what could be improved?
Would you say it's more of a research model or an operational model? - What do you consider to be a 'research' or 'operational' model?
What type of user is the model designed for?
What type of use is the model designed for?
Can you think of any models that were developed within the context of the program but were not used or forgotten over time?
Would you say there's a big industry demand for modelling tools? - What types of tools are they looking for? (Ex. deterministic models, planning and visualisation tools, etc.)
TRUST/UNCERTAINTY

What methods/techniques are used to address uncertainty?
What uncertainties are addressed?
How is uncertainty taken into account in the modelling process/decision-making process?
Do partners/decision makers ask for specific information on uncertainty? (Ex. specific studies, figures)
What is considered to be an 'acceptable' level of uncertainty and how is this determined?
Can you think of a time where modelling results or the model itself were put into question?
What do you need in order to 'trust' a model?
Does the lack of available/reliable data pose a problem for you in trusting the model?
Would you say there is generally a lot of trust in modelling? (Ex. among decision-makers, general public)
Would you prefer to have a model with a high level of associated uncertainty or to not have a model at all?
SCENARIOS
What simulations/scenarios were made with this model?
Who is involved in the construction of a scenario?
How do you determine which scenarios to test? - Out of an infinite number of possible future scenarios, how do you decide on the plausible scenarios to test? •
ROLE OF MODELLING IN DECISION-MAKING
When are models used/their results taken into account in the decision-making process?
Besides modelling, what other factors influence the final decision?
Do you use this model more for daily management, or long-term planning?

Is it required by the regulating authority to use this model?
Can you give me specific examples of when the model (or its results) was used to make a decision?
Do you think that the knowledge/tools produced by this program have a big influence on policy in the country?

References

Ascough, J. C., Maier, H. R., Ravalico, J. K., and Strudley, M. W. (2008). Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. Ecological Modelling, 219(3–4), 383–399.

Barillier, A. and Garnier, J. (1993) Influence of temperature and substrate concentration on bacterial growth yield in Seine River water batch cultures. Applied and environmental microbiology, 59(5), 1678–1682.

Beaudoin, N., Gallois, N., Viennot, P., Le Bas, C., Puech, T., Schott, C., Buis, S., and Mary, B. (2016) Evaluation of a spatialized agronomic model in predicting yield and N leaching at the scale of the Seine-Normandie Basin. Environmental Science and Pollution Research, 25(24), 1–30.

Billen, G., Garnier, J., and Hanset, P. (1994) Modelling phytoplankton development in whole drainage networks: the RIVERSTRAHLER Model applied to the Seine river system. Hydrobiologia, 289(1–3), 119–137.

Brugnach, M. F., Henriksen, H. J., van der Keur, P., and Mysiak, J. (2009) Uncertainty in adaptive water management: concept and guidelines.

Chesterikoff, A., Garban, B., Billen, G., and Poulin, M. (1992) Inorganic nitrogen dynamics in the River Seine downstream from Paris (France). Biogeochemistry, 17, 147-164.

Chong, N., Bach, P., Moilleron, R., Bonhomme, C., and Deroubaix, J.-F. (2017) Use and Utility: Exploring the Diversity and Design of Water Models at the Science-Policy Interface. Water, 9(12), 983.

Cladière, M., Bonhomme, C., Vilmin, L., Gasperi, J., Flipo, N., and Tassin, B. (2014) Modelling the fate of nonylphenolic compounds in the Seine River – part 1: Determination of in-situ attenuation rate constants. Science of The Total Environment, (468–469), 1050–1058.

Glaser, B. G., Strauss, A. L., and Strutzel, E. (1968) The Discovery of Grounded Theory; Strategies for Qualitative Research. Nursing Research, 17(4), 364.

Hall, J. W. (2003) Handling uncertainty in the hydroinformatic process. Journal of Hydroinformatics, 5(4), 215–232.

Isendahl, N., Dewulf, A., Brugnach, M., François, G., Möllenkamp, S., and Pahl-Wostl, C. (2009) Assessing Framing of Uncertainties in Water Management Practice. Water Resources Management, 23(15), 3191–3205.

Kwakkel, J. H., Walker, W. E., and Marchau, V. A. (2010) Classifying and communicating uncertainties in model-based policy analysis. International journal of technology, policy and management, 10(4), 299–315.

Ledoux, E., Gomez, E., Monget, J. M., Viavattene, C., Viennot, P., Ducharne, A., Benoit, M., Mignolet, C., Schott, C., and Mary, B. (2007) Agriculture and groundwater nitrate contamination in the Seine basin. The STICS–MODCOU modelling chain. Science of The Total Environment, 375(1–3), 33–47.

McIntyre, N. R., Wagener, T., Wheater, H. S., and Yu, Z. S. (2003) Uncertainty and risk in water quality modelling and management. Journal of Hydroinformatics, 5(4), 259–274.

Mishra, S. (2009) Uncertainty and sensitivity analysis techniques for hydrologic modeling. Journal of Hydroinformatics, 11(3–4), 282.

Moatar, F., Meybeck, M., Raymond, S., Birgand, F., and Curie, F. (2013) River flux uncertainties predicted by hydrological variability and riverine material behaviour: Predicting Uncertainties When Monitoring Riverine Material Fluxes. Hydrological Processes, 27(25), 3535–3546.

Némery, J. and Garnier, J. (2007) Origin and fate of phosphorus in the Seine watershed (France): Agricultural and hydrographic P budgets: Phosphorus Cycle in the Watershed. Journal of Geophysical Research: Biogeosciences, 112(G3).

Polus, E., Flipo, N., de Fouquet, C., and Poulin, M. (2011) Geostatistics for assessing the efficiency of a distributed physically-based water quality model: application to nitrate in the Seine River. Hydrological Processes, 25(2), 217–233.

Radwan, M., Willems, P., and Berlamont, J. (2004) Sensitivity and uncertainty analysis for river quality modelling. Journal of Hydroinformatics, 6(2), 83–99.

Refsgaard, J. C., Henriksen, H. J., Harrar, W. G., Scholten, H., and Kassahun, A. (2005) Quality assurance in model bas ed water management – review of existing practice and outline of new approaches. Environmental Modelling & Software, 20(10), 1201–1215.

Ruelland, D. (2004) SENEQUE, logiciel SIG de modélisation prospective de la qualité de l'eau. Revue internationale de géomatique, 14.

Strauss, A. and Corbin, J. M. (1997) Grounded Theory in Practice, SAGE.

Thouvenot, M., Billen, G., and Garnier, J. (2007) Modelling nutrient exchange at the sediment–water interface of river systems. Journal of Hydrology, 341(1–2), 55–78.

Uusitalo, L., Lehikoinen, A., Helle, I., and Myrberg, K. (2015) An overview of methods to evaluate uncertainty of deterministic models in decision support. Environmental Modelling & Software, 63, 24–31.

Van Der Sluijs, J., Craye, M., Funtowicz, S., Kloprogge, P., Ravetz, J., Risbey, J., 2005. Experiences with the NUSAP system for multidimensional uncertainty assessment. Water Sci. Technol. 52, 133–144.

Van Der Sluijs, J.P., Craye, M., Funtowicz, S., Kloprogge, P., Ravetz, J., Risbey, J., 2005. Combining Quantitative and Qualitative Measures of Uncertainty in Model-Based Environmental Assessment: The NUSAP System. Risk Anal. 25.

Vezzaro, L., Mikkelsen, P. S., Deletic, A., and McCarthy, D. (2013) Urban drainage models – simplifying uncertainty analysis for practitioners. Water Science & Technology, 68(10), 2136.

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

PART 2

DEALING WITH UNCOMFORTABLE KNOWLEDGE IN 'EVIDENCE-BASED POLICY'

In the paradigm of evidence-based policy, science is increasingly called upon to provide a sound basis for decisions. But scientific knowledge is often uncertain, incomplete and sometimes contradictory. *How then, do practitioners reconcile the demands of evidence-based policy with the limitations of scientific knowledge and its tools?* This section aims to elucidate this question using the example of PIREN to explore how and why uncertainty is reconciled in practice. Tracing the path of research production and utilisation – from quantification, simplification, negotiation and elimination – highlights how ignorance can be socially constructed as a way of dealing with 'uncomfortable knowledge'.

The Production and Utilisation of Knowledge

In the preceding section, the example of PIREN illustrated how, on its own, an academic-oriented approach to dealing with uncertainty in the modelling process leaves gaps that must be 'smoothed over' in practice when applied to a real-world context. Hommes *et al*., (2008: 1642) arrived at a similar conclusion, finding a purely analytical approach which focuses primarily on reducing uncertainties to be insufficient for dealing with the type of complex unstructured problems characteristic of water resources management issues because it "*creates knowledge* *that is not relevant to the policy debate as it does not match the interests of the actors involved*".

Participative approaches and increased emphasis on translation can render scientific knowledge more accessible and applicable for practitioners, while explicit and transparent discussion of uncertainties can contribute to greater understanding of the limits of scientific knowledge and its tools, such as models. A number of frameworks and guidelines have been proposed to address uncertainty in the modelling process (e.g. Brugnach *et al.*, 2009; Kwakkel *et al.*, 2010; van der Keur *et al.*, 2010; Van Der Sluijs *et al.*, 2005; Van Der Sluijs *et al.*, 2005; Walker *et al.*, 2003) to analyse how problems are framed, which uncertainties are accounted for, to what extent, how they impact subsequent decisions, and how different actors perceive them (e.g. as a risk/priority).

However, the underlying issue of uncertainty in the modelling process is not a lack of awareness, understanding or communication but rather a fear that explicitly acknowledging uncertainty will open the door to what Rayner (2012) refers to as 'uncomfortable knowledge'; understood as knowledge that is in tension or outright contradiction with the socially constructed narratives used to justify decisive action in a world that is complex, dynamic and highly uncertain.

In the classical view of knowledge production and utilisation, scientists impart scientific truths and establish certainties which are then transferred to practitioners to 'draw the obvious conclusions' in order to transform them into informed decisions (Callon *et al.*, 2009). In practice, this process is much more complex. First, in a decision context, many types of knowledge exist (Brugnach, 2017) and may be equally legitimate: a single truth may have many sides according to how a question is framed, how it is interpreted (and by whom), as well as the socio-political context from which it emerged. Rather than a one-way linear transfer from scientists to practitioners, knowledge is often co-produced by integrating different types of knowledge and perspectives. Water managers also have unique access to data through monitoring stations and installations, which help make scientific knowledge more robust.

Second, the academic nature of scientific knowledge means that it is not readily adapted for use in a decision context, often requiring translation before it can be accessible and applicable for practitioners (Brugnach *et al.*, 2007b; Isendahl *et al.*, 2009; Vezzaro *et al.*, 2013). As a result, scientific knowledge is not always used, even when it is available (Dilling *et al.*, 2011; Feldman and Ingram, 2009; Kirchhoff, 2013; Lemos *et al.,* 2012).

Third, the nature of knowledge is such that it is neither linear nor static, but evolves as knew truths add to or displace old ones. This can either affirm what was previously known or uncover knowledge that challenges or contradicts it ('uncomfortable knowledge'). Conflicting but equally probably truths may also co-exist until one is disproven and the other is accepted as canon by what is considered a legitimate, authoritative body. In some cases, knowledge can be ignored because it is in contradiction with other interests (e.g. Dedieu and Jouzel, 2015; Kleinman and Suryanarayanan, 2013).

Objective Facts in Subjective Spaces

When science is called upon to support decisions – as required by evidence-based policy – it can no longer claim to operate in isolation from societal values, judgements, biases and political interests. From a post-normal perspective, modern environmental issues are quintessentially 'wicked' problems that are "*so deeply entangled in webs of barely separable facts, interests and values that the parties* *concerned cannot find agreement on the nature of the problem, not to speak of the solution*" (Saltelli and Giampietro, 2016: 32).

In a decision context, science can no longer be considered objective facts of nature, but rather as socially constructed objects or 'hybrid facts' (Latour, 1993) that have been shaped by the values, interests and biases of the actors and institutions involved. Therefore, *"the use of science in guiding human affairs is always a political act*" (Sarewitz, 2016). When it comes to the final decision, the proportionality of actions, social acceptability and economic cost often take priority over scientific truths (Callon *et al.*, 2009).

The political nature of decisions can incite actors with a vested interest in the veracity of the knowledge produced within these spaces to assert the credibility of these claims (Grundmann, 2009). For example, a study by Nilsson *et al.*, (2008) showed that "*[policy] tools are likely to be selected primarily on the basis of organizational routines and standard practices and on the expectation that they will produce evidence that speaks directly to, and supports, the core beliefs of governing coalitions"* (352). This is also known as 'politically based evidence making' or what Weiss (1979) refers to as 'endarkenment', which Saltelli and Giampietro (2016) believe to be synonymous with evidence-based policy:

> "*Evidence-based policy cannot be separated from policy-based evidence, with its high reliance upon quantification. The accumulation of data, indicators and mathematical models in support of a given framing of an issue obscures and detracts from the more important task, namely to understand and take into account the implications of the choice of a given frame, bearing in mind that other actors may also act as storytellers and present different perceptions of the issue to be tackled*" (57).

At the same time, while the turn from evidence-based policy to policy-based evidence is commonly attributed to political motivation, it can also be driven by something as innocuous as the constraints of short policy cycles (Guimaraes Pereira and Saltelli, 2016).

Governing by Numbers: Scientific Truths and the 'Illusion of Precision'

To understand the apprehension surrounding the question of uncertainty, we return to the paradox of evidence-based policy. On one hand, we expect science to uphold the Cartesian ideals of precision and control, in some instances with an astonishing degree of certainty. Take, for example, the IPCC global temperature target of 1.5°. On the other hand, it is now widely acknowledged that this level of certainty can be dangerously misleading, particularly in the case of climate change. For example, a recent study by Urban (2015) reported that climate change would drive 7.9% of species to extinction. While such a precise number may give an air of confidence, it is virtually meaningless considering that we cannot know how many species actually exist (Sarewitz, 2016; Van Der Sluijs, 2016). Why then, do we continue to produce such exact figures?

According to Saltelli *et al.*, (2016), the tendency to view science as a 'truth-telling machine' is embedded in scientific training and tradition. Many Science and Technology Studies (STS) scholars (e.g. Feynman, 1975; Latour, 1993; Lyotard, 1979; Toulmin, 1990, 2001) trace this tradition back to 17th century Western philosophy, which gave birth to the Cartesian dream of power and control over nature:

> "*There is an 'implicit scientific catechism' that students learn by example but that working scientists must leave behind: chiefly, that every scientific problem has one and only one correct solution, precise to several significant digits; that quantitative data and mathematical techniques produce certainty; and that error in science is the result of stupidity or malevolence. […] For centuries, philosophers and historians preached the inexorable progress of Truth. […] Instances in which great scientists had been partly or wholly wrong were glossed over. It became nearly inconceivable that research based on numerical data and mathematical methods could be wrong or futile*" (Saltelli and Giampietro, 2016: 19).

In the paradigm of evidence-based policy, this belief has been transferred to practitioners with the added benefit that numbers give the illusion of objectivity in what are essentially subjective decisions:

> "*The appeal of numbers is especially compelling to bureaucratic officials who lack the mandate of a popular election, or divine right. Arbitrariness and bias are the most usual grounds upon which such officials are criticized. A decision made by the numbers (or by explicit rules of some other sort) has at least the appearance of being fair and impersonal. Scientific objectivity thus provides an answer to a moral demand for impartiality and fairness. Quantification is a way of making decisions without seeming to decide. Objectivity lends authority to officials who have very little of their own*" (Porter, 1995: 8)

Quantification is an essential part of simplifying complex systems, which allows them to be understood and managed in a systematic way. This is why scientists and practitioners find themselves increasingly compelled to transfer agency to computer algorithms and technological systems (e.g. models) (Sarewitz, 2016). Modelling tools are ideally suited to this context since they produce abstract representations of a system, allowing it to be reproduced, simplified, analysed and understood (Juston *et al.*, 2013). Models are also capable of producing precise numbers (or a range of numbers), which makes it easier to unite different actors over a single, common reference. Take, for example, the 195 members of the United Nations Framework Convention on Climate Change (UNFCC) that signed onto the Paris Agreement, agreeing to limit the increase in global average temperature to 1.5° C.

As science cannot produce such crisp figures with any sense of certainty, arriving at these numbers typically involves the compression of vast amounts of scientific knowledge and the negotiation between the actors involved. For example, Carré *et al.*, (2017) highlighted how large amounts of data are routinely compressed in order to produce a single measure per River Basin District required by the WFD in France. In another study of water quality standards in France, Carré *et al.*, (2018) found that scientific evidence had little bearing on how nitrate standards were applied locally, which was instead the product of national or regional negotiations.

According to Giampeitro *et al.*, (2013), compression occurs at normative and representative levels: the former through the adoption of a common world-view, while the latter occurs through the selection of characteristics that are considered relevant to the system in question. Practices of quantification and reduction are rooted in the evidence-based policy model, which fosters what Lakoff (2010) termed 'hypocognition': a process characterised by radical simplifications, linearisations and the compression of data, issues, explanations and solutions.

The desire for more numerical tools, capable of integrating different types of data and multiple processes, in parallel to growing concerns over uncertainty can sometimes be the source of discomfort between knowledge producers and users. Decision-makers may rely on precision and accuracy to simplify the decision process or wish to have scientific evidence (even if it is highly uncertain) to evaluate or monitor general trends. Cognisant of the potential implications of uncertainty, scientists and technicians are often reluctant to provide precise figures (at least not without ample caution) to decision-makers who tend not to look beyond these numbers. When scientists are unable or unwilling to comply with these demands, decision-makers can become frustrated with science and seek out other ways of obtaining the information they desire (e.g. from consultants). As a result, scientists may feel that their work is becoming less relevant to real-life application.

Dealing with 'Uncomfortable Knowledge'

Much like religion, science offers a way of reducing the feeling of vulnerability in the belief that "*all social problems would ultimately be solved by knowledge*" (Saltelli and Giampietro, 2016: 37). This follows what van der Sluijs (2016) describes as the 'deficit view' of uncertainty at the science-policy interface, where uncertainty is seen as a temporary problem which can be remedied with better data and improved models, either reducing uncertainty until a precise answer is finally reached or quantifying the remaining uncertainty in confidence intervals or error bars:

> "*This corresponds to the 'speaking truth to power' model of interfacing science and decision making. It assumes that we need to produce a quantitative answer, because that is what we believe science is able and supposed to do. And where there is uncertainty, we just speak truth-with-error-bars to policy*" (159).

The 'evidence evaluation view' is seen as another, more pragmatic approach to uncertainty, calling on experts from different disciplines to form a consensus ('speaking consensus to power and to policy') (Van Der Sluijs, 2016). To a certain extent, these are reflected in the perspectives and approaches to uncertainty in

PIREN, which was explored in the preceding section. For example, the 'deficit view' of uncertainty was used to put certain issues aside until further knowledge can provide enough certainty (e.g. nitrites) to act, while the 'evidence evaluation view', in which scientific consensus acts as a proxy for truth (or 'speaking consensus to power and to policy') (Van Der Sluijs, 2016) was employed to give certainty to uncertain knowledge (e.g. whether the Seine River will be ready for the Olympic Games in 2024).

Both perspectives view science as a 'truth-telling machine' producing objective truths and establishing certainties which are transferred to decision-makers to draw 'the obvious conclusions' (Callon *et al.*, 2009). This is the foundation of evidence-based policy on which modern institutions and practices have been built (Sarewitz, 2016). However, this view is in direct contradiction with reality, whose complexities cannot be fully captured using a single reductionist framing of the world:

> "*So far the conventional scientific approach to dealing with sustainability issues has been to try to isolate the best course of action by means of deterministic models. This strategy assumes that it is possible to predict the behaviour of complex self-organizing systems (including reflexive systems, such as human societies) and that the quality of the scientific input to the policy process is ensured by the rigour of the methods applied. This assumption overlooks the abundance of uncertainties which – when properly appraised – imply the total inability of these tools to generate useful inferences*" (Saltelli and Giampietro, 2016: 46).

The act of compression leaves out the 'unknown knowns' – knowledge that exists but is actively excluded by societies or institutions because they undermine key organisational arrangements or prevent institutions from pursuing their objectives – as well as the 'known unknowns' – recognised knowledge gaps that are considered irrelevant to the selected framing (Rayner, 2012). Reducing the problem to a finite set of attributes and goals can make it easier for practitioners to act. The resulting hypocognition is what Ravetz (1987) and Rayner (2012) liken to 'socially constructed ignorance', which is the product of the sense-making processes of individuals and institutions:

> "*To make sense of the complexity of the world so that they can act, individuals and institutions need to develop simplified, self-consistent versions of the world. The process of doing so means that much of what is known about the world needs to be excluded from those versions, and in particular that knowledge which is in tension or outright contradiction with those versions must be expunged*" (Rayner, 2012).

On one hand, the processes of quantification, simplification and reduction are needed to make sense of the world in order to act. On the other, they help foster ignorance by negotiating what is kept in and what is left out of the narrative. This begins with how the problem is framed and subsequently represented in the model: *"Quantitative analysis predicated on the selection of a structure – a 'frame' – for approaching a problem. This framing choice already entails a major compression of the information space that can later be used for governance purposes"* (Saltelli and Giampietro, 2016: 40).

Uncomfortable knowledge or 'awkward data' (Heimer, 2012) that does not fit neatly within these established narratives becomes inconvenient truths that must be tamed in order to resolve the feeling of uncertainty. Socially constructed ignorance can become established in these narratives, especially when scientific tools are used to reinforce them: "*The choice may produce situations in which an elephant in the room goes unnoticed, especially if the chosen mode of story-telling has been dressed with a convenient suite of indicators and mathematical models*" (Saltelli and Giampietro, 2016: 43).

Rayner (2012) outlines four common strategies employed by actors and institutions to deal with uncomfortable knowledge: *denial, dismissal, diversion* and *displacement*. The strategy of *denial* is akin to 'turning a blind eye', choosing to ignore or engage with undesirable information. *Dismissal* acknowledges this knowledge but rejects it as erroneous or irrelevant. *Diversion* is a strategy used to draw attention away from an uncomfortable issue. *Displacement* transfers the management of a real problem to a representation of that problem; a strategy commonly employed when tools such as models are used.

In the following article entitled: *Eyes wide shut: Exploring practices of negotiated ignorance in water resources modelling and management*, the example of PIREN is used as a basis for exploring the dynamics behind the social construction of ignorance and shedding light on how various actors contribute to this process. We illustrate how ignorance is 'negotiated' between these actors, whether it is recognised ignorance (*we know what we do not know*) or total ignorance (*we do not know what we do not know*), in order to take decisive action. Finally, we reflect on the implications this may have for water resources management and planning in practice and how ignorance can be turned into a learning opportunity.

ARTICLE

EYES WIDE SHUT: EXPLORING PRACTICES OF NEGOTIATED IGNORANCE IN WATER RESOURCES MODELLING AND MANAGEMENT

Natalie CHONG, José-Frédéric DEROUBAIX, Céline BONHOMME

Published in Journal of Environmental Management, August 2018

Journal of Environmental Management 227 (2018) 286-293

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Eyes wide shut: Exploring practices of negotiated ignorance in water resources modelling and management

Natalie Chong*, José-Frédéric Deroubaix[a], Céline Bonhomme

Laboratoire Eau Environnement et Systèmes Urbains (LEESU), École Nationale des Ponts et Chaussées, University of Paris-East, 6-8 Avenue Blaise Pascal, 77455, Champs-sur-Marne, France

Abstract

Formalised methods to address uncertainty are becoming the norm in hydrological modelling, yet they remain fragmented and highly academic, thus limiting their utility for practitioners. Using a qualitative, empirical study of the PIREN-Seine program in France, this paper explores the processes behind this trend in an effort to elucidate its prevalence despite inherent limitations when applied to a decision-making context. We identify: 1/ displacement of 'uncomfortable knowledge', 2/ fragmented responsibility, 3/ confidence, and 4/ relational framing as interconnected factors which concurrently support the production of scientific knowledge and the social construction of ignorance, whether it be wilful or unintentional. We posit that ignorance is implicitly negotiated among researchers and practitioners in order to reconcile cognitive dissonance and maintain confidence, thereby allowing water managers to take action in the face of uncertainty. Finally, we put forth the notion that having our 'eyes wide shut' can be interpreted in two ways: one facilitates the normalisation of ignorance, leaving us vulnerable to unexpected surprises; the other promotes transparent and explicit communication in support of more adaptive and robust decisions.

Keywords: Model-based decision support; Negotiated ignorance; Social production of ignorance; Science-practice interface; Uncertainty

1. Introduction

Environmental problems are rife with uncertainties, differing not only in type and source, but also their impact on subsequent decisions. In the context of model-based decision support, formalised methods exist to identify, quantify and minimise uncertainties. Yet, they remain fragmented and highly academic, leaving practitioners to discern how this information can be incorporated into sound decision-making.

Researchers produce valuable knowledge that supports management and policy decisions, but tend to only focus on uncertainties associated with the model (e.g. its inputs, parameters or outputs). In the context of decision-making, however, uncertainty is also influenced by the values, interpretations and framing of individual actors (Brugnach et al., 2008; Dewulf et al., 2005) as well as the institutions they serve.

Modelling tools have the double advantage of helping scientists gain a deeper understanding of environmental processes, while at the same time, supporting management, policy and planning decisions (Argent et al., 2009; Brugnach et al., 2007a; Brugnach and Pahl-Wostl, 2008; Chong et al., 2017; Liu et al., 2008); the idea being that enhanced knowledge leads to more informed decisions. In reality, the production of knowledge is not always straightforward and linear.

First, scientific knowledge is not the only type of knowledge that is used in decision-making (Brugnach, 2017), and second, it often requires translation in order to be integrated into policy (Brugnach et al., 2007a; Isendahl et al., 2009; Vezzaro et al., 2013). Third, new knowledge can sometimes uncover new unknowns (Walker et al., 2003) which may cast doubt on what was previously known or lead to 'uncomfortable knowledge' (Rayner, 2012). 'Uncomfortable knowledge' is what has been excluded from and/or is in tension or outright contradiction with the simplified narratives developed by individuals and institutions in order to act in a complex, dynamic world (Rayner, 2012).

Fourth, while knowledge and ignorance are often seen as polar opposites, where increasing one effectively minimises the other, many authors (e.g. McGoey, 2012; Ravetz, 1987; Rayner, 2012; Smithson, 1989) contend that ignorance is socially constructed.

Acknowledging and/or disregarding certain information – whether explicitly or implicitly – to advance strategic objectives can be a way of constructing ignorance. For example, in their study of insecticides causing Colony Collapse Disorder for bees in the United States, Kleinman and Suryanarayanan (2013) illustrated how the Environmental Protection Agency used ignorance to justify not implementing regulatory measures; a decision which worked in favour of large agrochemical corporations.

In another example, Dedieu and Jouzel (2015) demonstrated how actors can rationalize 'uncomfortable knowledge' learned through an investigation into the direct and indirect sources of pesticide poisoning of French farmers by finding 'good reasons' to ignore it. While the flaws and limitations of their policy tools were acknowledged, the fault was ultimately attributed to victims failing to follow proper procedure, rather than questioning the adequacy of the assessment tools themselves.

Similar studies (e.g. Heimer, 2012; Lohmann, 2008; Marris et al., 2014; McGoey, 2012, 2007; Stankiewicz, 2009) have highlighted factors that contribute to the social production of ignorance, but few focus attention to the unintentional production of ignorance, which may prove to be more hazardous if knowledge (and ignorance) is taken for granted. In recent years, the relationship between science and practice has become increasingly collaborative, but significant gaps still remain. Characterised by ambiguity and complexity, these gaps create the necessary conditions for the social construction of ignorance, whether it be wilful or unintentional.

This paper explores the driving forces behind the social construction of ignorance, using the empirical example of the PIREN-Seine program (*Programme Interdisciplinaire de Recherche sur l'eau et l'environnement du bassin de la Seine*) in France. Drawing primarily from documentary analysis and interview material, we look at the ways in which researchers and practitioners reconcile uncertainty in the context of model-based decision support.

In doing so, we identify four interconnected factors, which support the social construction of ignorance. Then, we illustrate how knowledge and ignorance are produced and 'negotiated' between various actors. Negotiation occurs when shared facts and narratives are explicitly and/or more often implicitly agreed upon by mutually establishing what is *known* from what is *unknown*, as well as what is considered to be *knowable* and *unknowable*.

The outcome of this negotiation is ultimately reflected by the uncertainties that are addressed (and which are not), as well as the methods used to address them, which provides insight into the prevalence of an academic-oriented approach to addressing uncertainty, despite its limitations in a decision-making context.

2. Methods and Materials

A qualitative, empirical study was conducted based on Grounded Theory (GT) (Glaser et al., 1968; Strauss and Corbin, 1997). GT is a novel, iterative research methodology, characterized by the systematic collection and analysis of data led by raising generative questions to identify core theoretical concepts and develop tentative linkages. As one of the longest research programs of its kind, the PIREN-Seine (PIREN) serves as an exemplary case to explore the diversity of interactions and exchanges between researchers and practitioners, while internal interest for critical reflection of the program and it's nearly 30 years of work allowed for accessibility and transparency. Documentary analysis, exploratory interviews and observations served as the basis for this study.

2.1. Documentary Analysis

To provide a foundational background, we analysed relevant documents produced by the PIREN-Seine dating back to its formation in 1989. This body of literature includes hundreds of peer-reviewed journal articles and a handful of books, in addition to a wealth of grey literature (including 700+ reports, booklets, and synthesis documents), reflecting a variety of studies from different disciplines.

As the borders of PIREN are permeable, we also extended our analysis to scientific literature produced by these actors that involved modelling and included some reference to uncertainty in the context of the Seine River basin, without specifically mentioning the PIREN-Seine.

2.2. Exploratory Interviews and Observation

To provide further insight into how uncertainty is reconciled in practice, exploratory interviews and observation were necessary. A total of 40 semi-structured interviews lasting from 1 to 4 hours were conducted from 2015 to 2017. Interview participants included PIREN researchers from different academic disciplines and operational partners (modellers, public institutions, and regulating authorities) with varying modelling expertise. A general guide (*see Appendix A*) was used to structure interviews around specific themes and questions were adapted according to the role of the participant and their relation to modelling activities.

Interviews were recorded, transcribed and coded according to emergent themes, perspectives and ideas. Data gleaned from interviews were supported by observation from 2015 to 2017. This included official PIREN-Seine meetings, seminars, workshops and conferences, as well as unofficial interactions and exchanges. Notable events include three general assembly and annual planning meetings organised for researchers and operational partners to collectively reflect upon the previous year's work in order to co-define future research objectives.

2.3. Modelling Tools

Modelling tools underpin a large part of the work conducted by PIREN. As water quality is its primary focus, hydrological models are the most common, though other types of models can also be found (e.g. agronomic, economic). The majority of models used and developed within this context are primarily considered to be research tools that provide indirect decision support. Therefore, only a small number were appropriated and used directly by operational partners (*see* Chong et al., 2017 for a detailed description of the different types of use and utility). Two commonly used and cited models are found in the table below (Table 1).

Table 1 – Commonly used models within the PIREN-Seine

Model	Type	Key References
ProSe	River quality	(Even et al., 1998a; Garnier and Mouchel, 1999)
Riverstrahler/Seneque	Catchment quality	(Billen et al., 1998; Garnier and Mouchel, 1999)

3. Results

Empirical data obtained from the PIREN-Seine highlights a number of key underlying processes that are involved in reconciling uncertainty in order to act or take a decision (*see* Fig. 1). The primary process is knowledge production, where facts are constructed using scientific and empirical data and shared among researchers and practitioners. This knowledge is subject to uncertainties of different types and sources, with varying impacts on subsequent decisions.

When decisions or actions are based on uncertain knowledge, a secondary process of ignorance construction may occur in order to reconcile uncertainty. Embedded in this secondary process is the explicit and/or implicit negotiation of facts to build shared narratives, which simplify complex problems into ones that can be adequately 'managed'.

The treatment of uncertainty among PIREN actors may vary depending on the individual or the institution they serve. The most commonly used methods focus primarily on statistical uncertainty in the model inputs, parameters and outputs, while other uncertainties are rationalised as inevitable.

These methods tend to be fragmented and highly academic, making it difficult to translate into information that is considered useful for practitioners. That is to say, they are typically part of scientific studies and may not be easily applicable to practice, may be too detailed or focused on uncertainties that are not directly relevant to management or planning decisions, and are not treated in a comprehensive manner that incorporates other uncertainties that practitioners must take into account. Despite the inherent limitations of an academic-oriented approach, its application to the decision-making context is justified through the construction of ignorance.

Using the example of the PIREN-Seine, this paper focuses on four interconnected factors that may support the construction of ignorance at the science-practice interface: 1/ displacement of 'uncomfortable knowledge', 2/ fragmented responsibility, 3/ confidence, and 4/ relational framing.

3.1. Displacement of 'uncomfortable knowledge'

According to Rayner (2012), the social construction of ignorance is a way of dealing with 'uncomfortable knowledge', and can manifest in four different management strategies: *denial*, *dismissal*, *diversion*, and *displacement*.

Denial is a refusal to acknowledge or engage with information, whereas *dismissal* acknowledges the existence of information, but rejects it as erroneous or irrelevant. *Diversion* is a way of drawing attention away from an uncomfortable issue, while *displacement* is used to deflect from the management of the real-life problem by pulling focus towards managing a representation of that problem (e.g. in a model). Though all of these strategies may be present to some extent within the PIREN-Seine, *displacement* appeared to be the most prevalent in the context of model-based decision support.

Depending on the role of modelling in the decision-making process and the level of impact on subsequent decisions, uncertainty is not always a subject that is discussed explicitly. When it is, the discussion is often limited to uncertainties that are considered relevant or can be adequately addressed. Meanwhile, knowledge that is deemed too uncertain or irrelevant may be tabled until it becomes more certain or a potential liability, which facilitates the displacement of 'uncomfortable knowledge'.

One example is the SIAAP[2] with the model ProSe. The SIAAP uses ProSe to support medium- to long-term management and planning decisions. Though it is considered reliable,

---

[2] SIAAP (*Syndicat Interdépartmental pour l'Assainissement de l'Agglomération Parisienne*) is the public sanitation company of greater Paris

they believe that the model is '*not good enough on nitrites to make reliable simulations that can support discussion*' (SIAAP Representative, 11 November 2016). At the same time, they acknowledge that nitrites are likely to become a priority issue in the near future. Including highly uncertain 'uncomfortable knowledge' in the present narrative could potentially undermine their expertise as well as the model itself. Instead, the question of nitrites is displaced until they feel confident that it can be adequately addressed or until it becomes a liability.

Another example is the focus on model-related uncertainty. According to one researcher, the biggest source of errors and uncertainty is the model inputs, rather than the fault of the modeller or the model itself (PIREN Researcher, 29 June 2016). The majority of PIREN actors agree that a model is only as good as its inputs ('*garbage in, garbage out*'). Focusing on model-related uncertainty displaces other uncertainties from the narrative, making the problem technical and subsequently manageable.

Comparing model outputs with empirical data is a straightforward measure of validity, however it is limited to the availability and reliability of data: *'the most basic and important thing is to confront [the results] with data. That works, but it is not always so simple because when you want to simulate a natural environment, the discharges, the morphology, the contribution of aquifers…generally, we do not have [this data].'* (PIREN Researcher, 16 June 2016). Displacing this knowledge allows for confidence to be maintained in the model and by extension, its results.

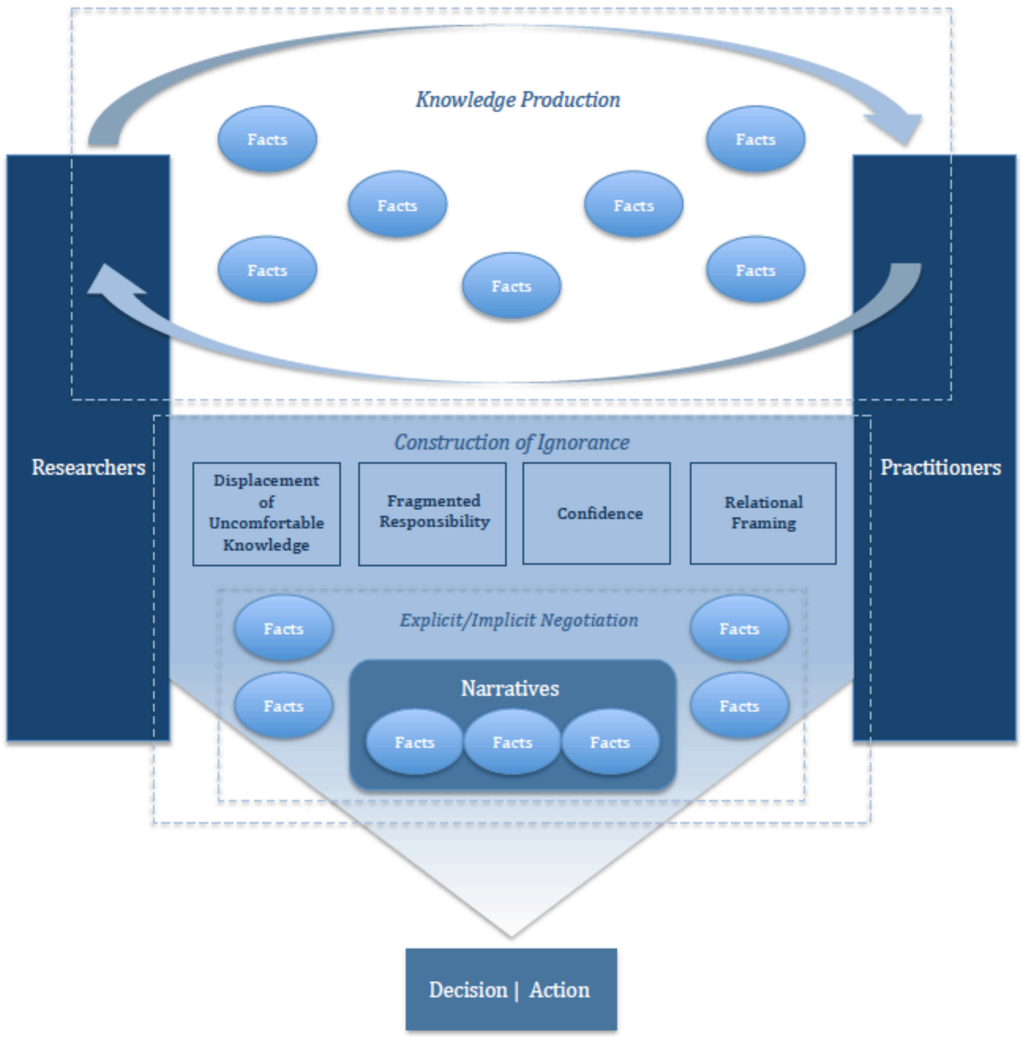

Figure 1 – Processes of reconciling uncertainty in model-based decision support

3.2. Fragmented responsibility

In addition to the displacement of ‘uncomfortable knowledge’, Dedieu and Jozel (2015) identified the fragmentation of responsibility as another mechanism involved in what they refer to as the ‘domestication of uncomfortable knowledge’.

Fragmenting responsibility is a way of distributing ignorance along organisational boundaries, making it more difficult to see 'awkward patterns' (Heimer, 2012). Within the PIREN-Seine, two types of fragmentation mechanisms can be observed. The first distinguishes between science and practice, while the second between individual and institutional boundaries.

3.2.1. Fragmentation along boundaries of science and practice

PIREN functions as a scientific research program, producing scientific knowledge that can support management, policy and planning decisions. Characterised by science-practice collaboration, it maintains a distinction between the two in order to preserve the scientific objectivity and legitimacy of the program and its participants.

In practice, this boundary is malleable, as several PIREN actors play parallel roles outside of the program. One example is ARMINES, the consultancy arm of *École des Mines Paris Tech*. While ARMINES is considered separate from the PIREN-Seine, it involves a number of PIREN researchers, allowing them to play a dual role as both researchers and consultants. In some cases, this work is an extension of PIREN research involving contracts with PIREN operational partners.

The majority of operational partners prefer to demand specific studies on an *ad hoc* basis, an approach that allows them to economise on time and resources. This is most common among partners without in-house modelling expertise. Modelling work is left to the experts, which can minimise misuse of the model.

However, it can also lead to feelings of increased ignorance from practitioners: 'we're not going to go as far as questioning the model because we don't have the competence. We don't have the time nor the skills to see how it was modelled, so we take it as a whole, we say OK and we try to adopt it according to local feedback' (DRIEE[3] Representative, 12 May

[3] DRIEE (*Direction Régionale et Interdépartementale de l'Environnement et de l'Énergie*) is the regulating authority charged with the development and implementation of state policies concerning environment, energy and sustainable development.

2017). On one hand, the lack of internal expertise necessitates trust in researchers. On the other, confidence can be maintained by leveraging tacit knowledge and field expertise to address their own ignorance.

In cases where operational partners have internal modelling expertise, scientific objectivity can be seen as an advantage. For example, the SIAAP uses results from ProSe to justify its management and planning proposals to the regulating authority (DRIEE). While this is not necessarily a requirement, ProSe is perceived as lending legitimacy to their findings, since it '*gives scientific results, not subjective results*' (SIAAP Representative, 11 November 2016). ProSe serves as both a 'research' model and an 'operational' model, as it is used directly by the SIAAP. They are unable to make changes to the code, however, modelling results may be considered subjective depending on what is modelled and how it is interpreted.

Within the boundaries of the PIREN, researchers must uphold scientific principles while also being accountable to its financial partners. Although researchers *'take care in ensuring that calibration and validation measures are rigorous'* (PIREN Researcher, 29 June 2016), this process is typically less formal that what is required for validating a commercial model.

This approach is justified, as the objective is to conduct research, not to produce a commercial, ready-to-use model (PIREN Researcher, 29 June 2016). The latter requires formal quality assessment procedures, including calibration and validation steps and beta testing. With the former, models like ProSe undergo a more informal process, developing over time by interested parties through ongoing feedback, testing, and validation by empirical data. In a research context, formal quality assessments may not be necessary, but it can become problematic if the model and its underlying assumptions are presumed to be correct.

Whereas developing a commercial model must follow a formal quality assessment procedure, which involves calibration and validation steps undertaken by developers, followed by beta testing using other databases before it is ready to be used, models like ProSe undergo a more informal process, where the model is developed over time through feedback from researchers and practitioners and validation through empirical data. Although a formal quality assessment may not be necessary in a research context, the assumption of scientific objectivity can become problematic if the model and its underlying assumptions are presumed to be correct.

3.2.2. Fragmentation along individual and institutional boundaries

More often than not, uncertainty was left implicit between modellers and practitioners. Explicit discussions were typically observed among individuals with modelling expertise, while the question of uncertainty all but disappears towards the later stages of the decision process: '*We don't know how to integrate errors in the decision-making chains. There's a moment where we must make the uncertainty disappear. We don't integrate it quantitively*' (PIREN Researcher, 21 February 2018).

This not only implies confidence in those with modelling expertise, but also transfers to them the responsibility of addressing uncertainty. Further discussion among decision makers is no longer deemed necessary, since they do not have the competences and presume that it has been addressed.

The fragmentation of responsibility may be perceived as being more efficient, but it can become problematic if uncertainty is not properly addressed or left ambiguous. Therefore, explicit communication of uncertainty becomes all the more important. In practice, it was observed that modelling results are not always used 'properly' in the decision-making process (*EPTB*[4] *Seine Grand Lacs* Representative, 3 March 2017), highlighting the need for effective communication and translation of this information for decision-makers.

The example of the SIAAP and ProSe on the question of nitrites highlights another type of fragmentation: one that exists along individual and institutional boundaries. For the SIAAP, ProSe is a good model, despite its representation of nitrites. Developers of ProSe contend that nitrites can be adequately represented provided that the simulation is properly defined. Despite ongoing collaboration, a difference in interpretation and perception seems

[4] EPTB Seine Grand Lacs (*Établissement Public Territorial de Bassin Seine Grands Lacs*) is the public institution responsible for the management of lakes and reservoirs within the Seine River basin.

to have emerged from the fragmentation of roles and responsibilities between researchers and practitioners resulting in parallel narratives.

3.3. Confidence

Klauer and Brown (2004) define uncertainty in terms of a lack of confidence due a belief that knowledge is often ambiguous, inadequate, inaccurate, or unreliable. Sigel *et al.* (2010) posit that uncertainty is not only subjective, but also multi-layered. Confidence is relational to the knowledge itself (e.g. '*I am confident this fact is true*') as well as the ability to evaluate the reliability of one's own knowledge (e.g. '*I do not feel competent to judge whether this is true*').

In the context of the PIREN-Seine, confidence is built through collaborative relationships and the perception of scientific objectivity. Long-term collaborative relationships among PIREN actors foster mutual understanding and communication. Formal and informal interactions and exchanges along with the feeling of scientific objectivity contribute to confidence in PIREN researchers as well as the program itself. This confidence also extends to the knowledge and tools that are produced, such as the modelling tools that are developed and used.

Building and maintaining confidence is a key factor in the construction of ignorance, since it insulates facts from outside challenges. Yet, while all interviewees expressed an overall trust in the models, it was not unconditional. In most cases, trust was not necessarily associated with the performance of the model, but rather in knowing its limits. This suggests that more knowledge increases confidence. However, the fact that many interviewees had limited modelling expertise pointed to the contrary. We posit that both are true: confidence is contingent on proximity to modelling activities, but for different reasons.

3.3.1. More knowledge increases confidence

There are two notable examples where PIREN operational partners were directly involved with the development and use of models: the SIAAP with ProSe and the AESN[5] with Seneque. In both cases, a closer proximity to modelling activities led to increased confidence, though it was not always consistent.

Early versions of ProSe were met with scepticism from practitioners: '*it was difficult to use with results that were not very good*' (SIAAP Representative, 20 July 2016). Interest was renewed when later versions demonstrated their potential utility for management and planning, inciting the SIAAP to invest human and financial resources towards its development.

Originally conceived as a 'research model', ProSe was not specifically designed for use by the SIAAP. However, they are one of PIREN's main financial partners and are also involved in a ProSe working group. As such, they contributed local expertise on installations, input data for the model, and feedback on the uses and limits of the model in practice (SIAAP Representative, 16 June 2016). Today, ProSe is considered to be '*the only model for predicting the quality of the river on which the Master Plan of Sanitation is based*' (SIAAP Representative, 27 June 2016).

The SIAAP's confidence in ProSe is the result of their direct involvement in different stages of the modelling process as well as their institutional positioning. First, their involvement and financial investment in the PIREN-Seine program and the ProSe working group has allowed them access to the model and, to a certain extent, influence on the model's development. Having internal expertise and access to necessary data results in a better understanding of how the model functions and in turn, better utilisation of the model; whereas a closer position on the ground gives the advantage of better calibrating and validating the model (SIAAP Representative, 11 November 2016). Familiarity with the model combined

[5] AESN (*Agence de l'Eau Seine-Normandie*) is the public institution responsible for water management in the Seine-Normandy Watershed.

with field expertise allows them to maintain confidence by understanding the model as well as its limits.

Second, direct appropriation of the model enables them to run their own simulations: ‘now, the water authorities are asking us for simulations using ProSe. They specifically refer to ProSe. The water authority, the state! Even if we do not want to use [ProSe] anymore, we will be asked to.” (SIAAP Representative, 27 June 2016).

While being one of the only institutions in the basin with in-house expertise on ProSe increases their bargaining position, it could also end up being a double-edged sword. On one hand, direct appropriation of the model lends more legitimacy to the SIAAP in the eyes of the regulating authority. On the other, investment in ProSe and preference by the regulating authority may discourage the use of other models that may become more suitable in the future.

Presently, the investment in time and resources is justified by constructing the narrative of confidence in the model: ‘we have confidence [in ProSe]. We have people who are trained on it and we have no reason today to use a different model because if we were to change, we would have to find another model, we would have to calibrate it and re-train people. Right now, we have no interest in doing that.’ (SIAAP Representative, 20 July 2016).

Since confidence is relational to knowledge (and knowing the limits of this knowledge), it can be maintained even if the model performs poorly, as long as it is deemed ‘good enough’ to suit the needs of the user. In the example of the SIAAP and ProSe, uncertainty over nitrites does not diminish overall confidence in the model. Instead, confidence can be maintained by knowing which parameters they can trust and which they cannot. Knowledge that is considered too unreliable is left out of the narrative until it can be deemed ‘manageable’ or becomes a liability.

In a similar example, the close proximity of the AESN in the use and development of the model Seneque greatly contributed to confidence in the model. Like ProSe, Seneque was originally developed for research purposes and later used by the AESN to evaluate the status of water bodies within the Seine-Normandy basin. As another main financial partner of the PIREN-Seine, the AESN contributed to the development of Seneque by providing input data and feedback (AESN Representative, 8 June 2016). This collaborative relationship allowed for a better understanding and use of the model for management and planning purposes, while investments in time and resources contributed to building confidence.

Presently, Seneque is no longer used in-house at the AESN, who have opted instead to outsource this work to PIREN researchers on an *ad hoc* basis. Reasons for this include the loss of internal expertise, the absence of a working group, and a lack of maintenance (e.g. updates, data).

3.3.2. Less knowledge increases confidence

While previous familiarity with the model contributed to a greater feeling of confidence in Seneque at the AESN, a lower level of confidence was expressed in their ability to assess uncertainties in the input data: *'In terms of chemistry, the model works. The problem is that afterwards, it is necessary to re-examine the input data. That requires a true understanding of the data.'* (AESN Representative, 8 June 2016). In the absence of a continual knowledge exchange between PIREN researchers and the AESN on Seneque, it was less clear for those were not involved in the development of the model, how to adequately address uncertainty (AESN Representative, 8 June 2016).

In more uncertain cases, it was more economical to transfer confidence to the expertise and the model itself, while leaving room for error. In practice, this margin of error is often represented as a precautionary measure: '*in order to try and eliminate as much as we can the uncertainties associated with the model, what we try to do in standard simulations is to input sensitive environmental conditions that take the worst case scenario*' (SIAAP Representative, 11 November 2016).

Whereas the lack of knowledge would presumably increase uncertainty and subsequently reduce confidence, our analysis suggests the contrary. The example of the AESN and Seneque demonstrates how confidence can be maintained even after the proximity to modelling activities has become more distant.

At the other end of the spectrum is the DRIEE, who was not involved in the development of any PIREN models. In this case, confidence in the expertise of the PIREN was sufficient to extend to the models and modelling results, despite a lack of internal modelling expertise. Uncertainty can be further reconciled through the use of tacit knowledge and field-expertise to compensate for knowledge gaps and maintain confidence.

3.4. Relational Framing

Most PIREN researchers adopt an academic-oriented approach to uncertainty, which may not be easily applied to a decision-making context. Consequently, many operational partners have adopted a more field-oriented approach, integrating other frames of reference such as tacit knowledge and local expertise. In practice, how uncertainty is reconciled depends on the role of models in the decision-making process and the potential impact on subsequent decisions.

Greater uncertainty tends to be accepted when models are used for monitoring future trends and guiding long-term planning: 'we make comparisons. In terms of absolute value, the results are bad. For relative value, it's still interesting to be able to have an idea of the impact' (SIAAP Representative, 20 July 2016). As the objective is to assess a general trend, precise results are not considered a requirement (AESN Representative, 8 June 2016).

While practitioners may be justified in their approach, ambiguity can open the door to unforeseen consequences if uncertainty is not explicitly communicated and/or translated in a decision-making context. For example, one practitioner states: *'It is sufficient for us managers. I don't need to know that the dissolving constant of such and such is 0.2 rather than 0.217, as long as the outputs of my model correspond to the reality in the field'* (SIAAP Representative, 27 June 2016). From a practitioner's perspective, this may be considered negligible. However, a researcher may contend that a difference of this magnitude could put into question the functioning of the entire modelled system.

In the context of future scenarios, greater uncertainty is accepted as a given, since we cannot obtain measurable data (AESN Representative, 8 June 2016), rendering it impossible to predict future events with a comfortable degree of accuracy (*EPTB Seine Grands Lacs* Representative, 3 March 2017). The co-construction of scenarios fosters implicit understanding and agreement through collaboration, while the hypothetical nature of scenario planning allows for more robust decision-making.

4. Discussion

The social construction of ignorance is not always straightforward or necessarily intentional. Our study of the interactions between individuals and institutions in the PIREN-Seine suggests that negotiation processes are embedded mechanisms that build common narratives based on shared facts. What is considered to be *known*, *unknown*, *knowable*, and *unknowable* is implicitly agreed upon and subsequently normalised through regularity (i.e. the frequency of occurrence), which gives the appearance of legitimacy (i.e. the credibility of a certain party gives it validity). These narratives are further reinforced through regulatory measures or common practice. We further posit that 'negotiating' ignorance serves to maintain confidence and reconcile cognitive dissonance in order for practitioners to take action.

4.1. Reconciling cognitive dissonance

In psychology, cognitive dissonance is the common psychological discomfort that can be felt by someone who holds contradictory beliefs, ideas or values, or when information contradicts the beliefs, ideas or values that a person holds (Festinger, 1962). Due to its uncomfortable nature, we naturally seek to resolve it in different ways.

This is illustrated by the example of the SIAAP and ProSe. On one hand, the SIAAP wants a process-based model. On the other, accurate representation of these processes is not required if the variables that are taken into account are in line with their objectives and correspond (more or less) to what is observed. Regarding nitrites, they recognise that they could be penalised in the future (SIAAP Representative, 11 November 2016), but it is presently excluded from the narrative. Cognitive dissonance is reconciled by setting the issue of nitrites to the side, as it has been implicitly 'negotiated' as an *unknown*.

One way to deal with cognitive dissonance is to lump all *unknowns* into the same category, making it easier to displace. As it is impossible to account for all uncertainty, any attempts to do so are not only considered unrealistic but also futile. This partially explains why uncertainty is rarely discussed explicitly in practice.

The fragmentation of responsibility further alleviates cognitive dissonance through the distribution of ignorance, by distinguishing the technical and the scientific (modelling results) from the political (the final decision): '*…after, the decisions are political. There are times when a decision-maker will say "yes" or "no" and that's above us. We do technical studies, we give elements of response, but after, the decisions that are taken are above us*' (*EPTB Seine Grands Lacs* Representative, 3 March 2017). In reality, these categories are not mutually exclusive since researchers and technicians play a big part in defining what is modelled and how it is modelled, which limits the scope of possible scenarios.

When confidence may be undermined by discrepancies in modelling results, cognitive dissonance is resolved by making exceptions: *'sometimes we find weird things in the model that don't correspond to what we see in reality, but generally I have confidence. Occasionally when find things that are weird, we don't directly put the model into question but we make exceptions let's say; we adapt our decision, our recommendation to what is said locally.'* (DRIEE Representative, 12 May 2017).

The field-oriented approach of practitioners may help offset these discrepancies, but it could become problematic if the underlying causes are not properly understood. The SIAAP continues to use ProSe while acknowledging that it has been calibrated and validated with data that may not be reliable in a highly dynamic and evolving system such as the Seine (SIAAP Representative, 10 March 2017). Underlying assumptions that are not carefully taken into account could have serious impacts on subsequent decisions, since an inaccurate representation of processes can produce misleading results.

4.2. Taking action in the face of uncertainty

After maintaining confidence and reconciling cognitive dissonance, negotiated ignorance serves the fundamental objective of enabling practitioners to take action in the face of uncertainty. From a practical standpoint, it could be a question of economising time as well as human and financial investment. In research, the pursuit of knowledge is a long and continual process, necessitating iterative cycles of data acquisition, testing and validation. Practitioners are often faced with specific time-sensitive objectives, requiring sound information with which to base their decisions. To reconcile the two worlds, 'uncomfortable knowledge' must be 'negotiated' in order to create narratives that support decisive action.

Ravetz (1987) distinguishes between *'usable ignorance'* and *'usable knowledge'* to describe how incomplete science can be integrated into policy in situations of varying uncertainty. He posits that scientific facts are debatable and used as evidence to support arguments in the political process. '*Usable knowledge*' can be used as political tool, providing input when necessary and correcting commonly accepted views, since science is seen as a symbol of modern industrialised society. On the other hand, '*usable ignorance*' can be an opportunity, focusing on the limits of knowledge rather than its absence.

In the context of model-based decision support, '*usable ignorance*' can provide guidance as to which problems can be addressed, which to ignore and to what extent. It can also help identify and prioritise areas where further research is needed and mobilise necessary resources.

Negotiation should be a continual and iterative process as we uncover new *knowns* and *unknowns*. Negotiated ignorance should therefore be seen as a dual process where learning incorporates new and different forms of knowledge, while at the same time, unlearning what was previously established if it is no longer considered reliable.

5. Conclusions

Uncertainty remains a complex and ambiguous issue for researchers and practitioners alike. Our analysis of the PIREN-Seine in France gives insight into how ignorance can be socially constructed at the science-practice interface in order to reconcile uncertainty. We highlighted four interconnected factors that can support the construction of ignorance in the context of model-based decision support. We argued that explicit and/or implicit negotiation is an embedded process that works towards constructing simplified narratives that serve to maintain confidence, reconcile cognitive dissonance and enable action. While efficient, we caution that the process of reductionism – where 'uncomfortable knowledge' is essentially excluded from the final decision – may create narratives that are not sufficiently robust or adaptive to address 'wicked problems'. Finally, we posit that having our 'eyes wide shut' can be interpreted in two ways: one facilitates the normalisation of ignorance, leaving us vulnerable to unexpected surprises; the other promotes transparent and explicit communication to support more adaptive and robust decisions.

Acknowledgements

This study was made possible by the funding and support of the PIREN-Seine program and the École Nationale des Ponts et Chaussées. The authors would like to extend their gratitude to the researchers and practitioners who generously contributed their time, insight and knowledge to this study.

Appendix A. Interview Question Guide

BACKGROUND/HISTORY
What is your involvement in the PIREN-Seine? - How did you get involved? - How long have you been involved?
How did the program get started? (Ex. Demand from researchers, industry or government?)
What is your background/training/experience?
How would you describe the relationship between researchers and partners in the program?
Do you think science should play a role in influencing policy?
How is the program funded? - **Who finances it?** - **How much funding does the program have in total?** - **How much does each partner contribute?** - **What are the financial obligations from both sides?**
In general, do you think there's a large gap between research and policy? - How does the program help to overcome this? - What could be improved? •
MODELS: DEVELOPMENT, EVOLUTION, USE
Were you involved in the development of any modelling tools? - Which ones? - How were you involved? (Ex. did you develop the code, a module, provide feedback, etc.)
Who was involved in the development? (Ex. research teams, universities, institutions, partners, etc.) - How were the different actors involved? (Ex. funding, feedback, research, etc.)
What was the reason/need for developing this model?
Were there other models that existed at the time that could have done the same thing? If so, why develop a new model instead of using the existing one?

What were the main challenges in developing this model?
How has the model evolved? (Ex. different modules, more functionality, etc.)
What are the advantages/limits of the model?
Who uses the model? - Which actors? (Ex. Specific researchers, partners)
How do you use the model? - What does the model allow you to do, that you could not do (or not as easily do) without? - Do you run the model yourself or do you use the results?
What are some of the challenges in using this model? - Would you say it is easy to use for someone without training/expertise in modelling?
Would you prefer to be able to use the model yourself or just use the results?
Is the model used outside of the context of this program?
Do the outputs of the model meet the needs/demands of the user? If not, what could be improved?
Would you say it's more of a research model or an operational model? - What do you consider to be a 'research' or 'operational' model?
What type of user is the model designed for?
What type of use is the model designed for?
Can you think of any models that were developed within the context of the program but were not used or forgotten over time?
Would you say there's a big industry demand for modelling tools? - What types of tools are they looking for? (Ex. deterministic models, planning and visualisation tools, etc.)
TRUST/UNCERTAINTY
What methods/techniques are used to address uncertainty?
What uncertainties are addressed?

How is uncertainty taken into account in the modelling process/decision-making process?
Do partners/decision makers ask for specific information on uncertainty? (Ex. specific studies, figures)
What is considered to be an 'acceptable' level of uncertainty and how is this determined?
Can you think of a time where modelling results or the model itself were put into question?
What do you need in order to 'trust' a model?
Does the lack of available/reliable data pose a problem for you in trusting the model?
Would you say there is generally a lot of trust in modelling? (Ex. among decision-makers, general public)
Would you prefer to have a model with a high level of associated uncertainty or to not have a model at all?
SCENARIOS
What simulations/scenarios were made with this model?
Who is involved in the construction of a scenario?
How do you determine which scenarios to test? - Out of an infinite number of possible future scenarios, how do you decide on the plausible scenarios to test? •
ROLE OF MODELLING IN DECISION-MAKING
When are models used/their results taken into account in the decision-making process?
Besides modelling, what other factors influence the final decision?
Do you use this model more for daily management, or long-term planning?
Is it required by the regulating authority to use this model?

Can you give me specific examples of when the model (or its results) was used to make a decision?
Do you think that the knowledge/tools produced by this program have a big influence on policy in the country?

References

Argent, R.M., Perraud, J.-M., Rahman, J.M., Grayson, R.B., Podger, G.M., 2009. A new approach to water quality modelling and environmental decision support systems. Environ. Model. Softw. 24, 809–818.

Billen, G., Garnier, J., Mariotti, A., 1998. Bilan des transferts d'azote dans le bassin de la Seine: l'approche du modèle SENEQUE.

Brugnach, M., 2017. The Space in Between: Where Multiple Ways of Knowing in Water Management Meet. J. Southwest 59, 34–59.

Brugnach, M., Dewulf, A., Pahl-Wostl, C., Taillieu, T., 2008. Toward a Relational Concept of Uncertainty: about Knowing Too Little, Knowing Too Differently, and Accepting Not to Know. Ecol. Soc. 13.

Brugnach, M., Pahl-Wostl, C., 2008. A broadened view on the role for models in natural resource management: Implications for model development, in: Adaptive and Integrated Water Management. Springer, Berlin, Heidelberg, pp. 187–203.

Brugnach, M., Tagg, A., Keil, F., de Lange, W.J., 2007. Uncertainty Matters: Computer Models at the Science–Policy Interface. Water Resour. Manag. 21, 1075–1090.

Chong, N., Bach, P., Moilleron, R., Bonhomme, C., Deroubaix, J.-F., 2017. Use and Utility: Exploring the Diversity and Design of Water Models at the Science-Policy Interface. Water 9, 983.

Dedieu, F., Jouzel, J.-N., 2015. Comment ignorer ce que l'on sait ?, How to ignore what one already knows: Domesticating uncomfortable knowledges about pesticide poisoning among farmers. Rev. Fr. Sociol. 56, 105–133.

Dewulf, A., Craps, M., Bouwen, R., Taillieu, T., Pahl-Wostl, C., 2005. Integrated management of natural resources: dealing with ambiguous issues, multiple actors and diverging frames. Water Sci. Technol. 52, 115–124.

Even, S., Poulin, M., Billen, G., Garnier, J., 1998. Modèles PROSE et SENEQUE : établissement de versions de référence applicables aux études de gestion.

Festinger, L., 1962. A Theory of Cognitive Dissonance. Stanford University Press.

Garnier, J., Mouchel, J.-M., 1999. Man and River Systems: The Functioning of River Systems at the Basin Scale. Springer Science & Business Media.

Glaser, B.G., Strauss, A.L., Strutzel, E., 1968. The Discovery of Grounded Theory; Strategies for Qualitative Research. Nurs. Res. 17, 364.

Heimer, C.A., 2012. Inert facts and the illusion of knowledge: strategic uses of ignorance in HIV clinics. Econ. Soc. 41, 17–41. https://doi.org/10.1080/03085147.2011.637332

Isendahl, N., Dewulf, A., Brugnach, M., François, G., Möllenkamp, S., Pahl-Wostl, C., 2009. Assessing Framing of Uncertainties in Water Management Practice. Water Resour. Manag. 23, 3191–3205.

Klauer, B., Brown, J.D., 2004. Conceptualising imperfect knowledge in public decision-making: ignorance, uncertainty, error and risk situations. Environ. Res. Eng. Manag. 1.

Kleinman, D.L., Suryanarayanan, S., 2013. Dying Bees and the Social Production of Ignorance. Sci. Technol. Hum. Values 38, 492–517.

Liu, Y., Gupta, H., Springer, E., Wagener, T., 2008. Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management. Environ. Model. Softw. 23, 846–858.

Lohmann, L., 2008. Carbon Trading, Climate Justice and the Production of Ignorance: Ten examples. Development 51, 359–365.

Marris, C., Jefferson, C., Lentzos, F., 2014. Negotiating the dynamics of uncomfortable knowledge: The case of dual use and synthetic biology. BioSocieties 9, 393–420.

McGoey, L., 2012. Strategic unknowns: Towards a sociology of ignorance. Econ. Soc. 41, 1–16.

McGoey, L., 2007. On the will to ignorance in bureaucracy. Econ. Soc. 36, 212–235.

Ravetz, J.R., 1987. Usable knowledge, usable ignorance incomplete science with policy implications. Sci. Commun. 9, 87–116.

Rayner, S., 2012. Uncomfortable knowledge: the social construction of ignorance in science and environmental policy discourses. Econ. Soc. 41, 107–125.

Sigel, K., Klauer, B., Pahl-Wostl, C., 2010. Conceptualising uncertainty in environmental decision-making: the example of the EU Water Framework Directive. Ecol. Econ. 69, 502–510.

Smithson, M., 1989. The Social Construction of Ignorance, in: Ignorance and Uncertainty. Springer New York, New York, NY, pp. 216–263.

Stankiewicz, P., 2009. The role of risks and uncertainties in technological conflicts: three strategies of constructing ignorance. Innov. Eur. J. Soc. Sci. Res. 22, 105–124.

Strauss, A., Corbin, J.M., 1997. Grounded Theory in Practice. SAGE.

Vezzaro, L., Mikkelsen, P.S., Deletic, A., McCarthy, D., 2013. Urban drainage models – simplifying uncertainty analysis for practitioners. Water Sci. Technol. 68, 2136.

Walker, W.E., Harremoës, P., Rotmans, J., van der Sluijs, J.P., van Asselt, M.B., Janssen, P., Krayer von Krauss, M.P., 2003. Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. Integr. Assess. 4, 5–17.

Chapter 3

The Role of Boundary Organisations

The process of ‘negotiating’ ignorance outlined in the previous chapter demonstrated the role of models as ‘boundary objects’, mediating interactions and exchanges between actors from different worlds. Underlying these dynamics is the question of confidence. In the present chapter, we explore the concept of ‘boundary organisations’ to elucidate how relationships between science, policy and practice are governed and how confidence is constructed in the process. Specifically, we aim to elucidate the central question: *what functions do boundary organisations need to perform in order to enhance the role of boundary objects such as models?*

The Social Construction of Boundaries

The notion of boundaries is far from new; it is a primal concept that can manifest in many ways. Whether it is used to carve out geographical territories, to define or assign identities, roles or status, or more generally, to differentiate one thing (physical or abstract) from another, all boundaries are the product of social construction (Cash *et al*., 2003; Jasanoff, 1995, 1987). As such, the act of defining boundaries is context-dependent and inherently political. Often, it is a way of staking a claim, whether it is to physical resources or abstract concepts such as credibility or legitimacy. Gieryn (1983) outlined several cases in the Victorian era, where attempts to create boundaries between ‘science’ and ‘non-science’ were a way for scientists to pursue their own professional objectives by maintaining scientific autonomy and gaining intellectual authority and career opportunities over 'non-scientists'.

More recently, organisers of a public debate in France argued that neuroscience is a pseudoscience in an effort to exclude neuroscientists from taking part in the scientific council of the Ministry of Education (APLP public debate, 2018). Whereas Gieryn (1983) demonstrated how the borders of 'science' can be moulded to appear empirical, theoretical, pure or applied when compared to 'non-science' in order to support scientists' claims to authority or resources, the example of the public debate in France showed how members of one academic discipline used boundary definition to assert authority and legitimacy over another in order to limit their influence on the national education system. Ironically, among those strongly opposed to the idea were psychoanalysts, who, at one time or another, were also put under the same scrutiny (Gieryn, 1995a; Grünbaum, 1979). Today, similar boundary defining efforts continue to divide societies over contentious topics such as climate change, genetically modified organisms (GMOs), and vaccinations.

According to Jasanoff (1987), political undercurrents of boundary definition stem from the act of deconstructing and reconstructing knowledge claims, which engender discord among various actors who have a shared interest in *how* and *by whom* this knowledge is interpreted. Demarcating science from policy distinguishes interpretive authority, thereby allowing these actors to define boundaries according to their own interests. This runs counter to the common conception of science as *the only way* of representing objective truths about the natural world.

Jasanoff (1987) argues that this perception is the result of a long and successful campaign upholding the Mertonian norms of *universalism*, *communalism*, *disinterestedness*, and *organised scepticism* that has been supported by attempts to articulate the boundaries of 'science' from 'non-science' (Popper, 1959). Considering the political nature of boundary definition, boundaries are rarely static. Instead, they are functionally malleable: constantly evolving to suit the context and objective of those involved in boundary construction.

The Evolving Nature of Science: New Modes of Knowledge Production

In recent decades, new modes of knowledge production have emerged within the backdrop of mutable boundaries, marking a fundamental shift in how we do science. Often referred to as 'post-normal science' (Funtowicz and Ravetz, 1993), 'Mode 2' (Gibbons *et al*., 1994), or 'postacademic science' (Ziman, 1995), this new paradigm is characterised as a transformation of science from the era of scientific discovery ('normal', 'Mode 1', or 'academic' science) whose sole motivation is the pursuit of scientific knowledge to fulfil ones' intellectual curiosity (science for the sake of science).

Whereas the old paradigm is defined by the domination of disciplinary science, strong internal hierarchy among disciplines, and a strong sense of scientific autonomy (Gibbons *et al*., 1994), new forms of knowledge production differ in their *objective* (application, user- or client-oriented), *source* (multiple types of knowledge produced by different sources connected through networks that are sometimes transitory), *organisation* (research defined by transdisciplinarity, with its own theoretical structures and methods), *accountability* (science accountable to social, political, and economic criteria), and *reflexivity* (questions of legitimacy and 'good science' as research becomes increasingly framed according to social values, political objectives, and the media) (Weingart, 1997).

While they are often used interchangeably, they are not entirely synonymous. For example, 'postacademic science' delves deeper into how institutional changes and new scientific practices characterised by the new paradigm impact the scientific ethos that upholds 'real science' (Ziman, 2000). Moriarty (2008) shares concerns that the trend towards the commercialisation of research is in direct contradiction to the core academic principles that maintain the 'purity' of science. According to this perspective, the increasing focus away from 'pure' science could, in fact, end up compromising innovation and the essence of scientific discovery in the name of efficiency and public action. In doing so, it also risks losing the objectivity that is at the heart of the scientific ethos.

Major proponents of 'post-normal science' argue that it can be more effective than traditional methodologies in certain situations (Funtowicz and Ravetz, 1995). According to Ravetz (2006), 'post-normal science' describes "*the stage we are at today, where all the old comfortable assumptions about science, its production and its use, are in question*" (47). Rejecting the notion that 'normal' science is the answer to our most pressing environmental issues, 'post-normal science' acknowledges knowledge gaps and the uncertainty that rules political and environmental issues and recognises that resolving these issues requires the integration of different types of knowledge and perspectives (Funtowicz and Ravetz, 1995; Funtowicz and Ravetz, 1993; Ravetz, 1999, 2011).

Though it may be described in different ways, the noticeable shift in the way we do science has been well documented. Described by some as a change in the science-society contract (Gibbons *et al.*, 1994; Nowotny *et al.*, 2001; Waterton, 2005), extensive changes in institutions and financial structures meant that science could no longer be held accountable only to itself. Considered to be one of the first official markers of this shift, the Rothschild Report of 1972 (HMSO, 1972, 1971) renegotiated the contract between science and society from one where science was granted autonomy from the state, to a 'customer-contractor' relationship. Not only did this introduce the idea of accountability for scientists, but it also brought about a new funding structure that was commercially- and/or contract-dependant with which to support it.

What followed was a Government strategy towards privatization, where a distinction was made between 'basic' and 'applied' sciences under the guise of bringing "*efficiency, competitiveness and accountability to the fore of the publicly funded research agenda"* (Waterton, 2005: 4). The resulting cuts to publicly funded research necessitated scientists to seek external contracts that required them to demonstrate applicability in order to win bids. The argument follows that the strong *quid pro quo* mentality characterised by this new paradigm would inevitably shape what types of knowledge are produced and how they are represented, by defining project boundaries and guiding parameters that dictate what constitutes legitimate scientific work.

Macro-level socio-economic changes have been assessed at the level of the European Union (EU), specifically concerning the fundamental changes that have taken place in key institutions and funding structures. For example, Luukkonen (2014) notes how the introduction of the European Research Council (ERC), and its ability to quickly gain status and legitimacy changed the landscape of European research funding. In direct response to Ziman's concern over the sanctity of science, Nowotny[6] (2006) argues that the ERC and its objective to fund 'frontier research' based on scientific excellence is, in fact, a way to preserve 'real science'

[6] Nowotny is currently serving as President of the ERC

While Ziman is more restrictive in his definition of ‘real science’, Nowotny (2006) emphasises the bottom-up approach of the ERC whose purpose is to fund ‘individual, curiosity-driven research’ that is not constrained by pre-defined themes or practical utility instead encouraging ‘excellent science’ that is both socially and scientifically robust through competition among curiosity-driven individuals. However, this type of competition is still vulnerable to biases that influence what research is promoted (and what is not) which may subsequently add value, credibility or legitimacy to one research subject, researcher, or institution, over another. There is also the geographical dimension to consider, as western, rich, industrialized and democratic countries still dominate prominent research domains. Nevertheless, the move from a focus on ‘pure’ science towards ‘applicable science’ is reflected in the budget of the Horizon 2020 program: a total of 816 million euros was dedicated to the objective of ‘spreading excellence & widening participation’, while 462 million euros was earmarked for ‘science with and for society’ (European Commission).

For clarity and consistency, ‘normal’, ‘Mode 1’, or ‘academic’ science will henceforth be referred to as the old paradigm, while ‘postnormal’, ‘Mode 2’, or ‘postacademic’ science will be referred to as the new paradigm.

The Emergence of Boundary Organisations

Dominated by the new paradigm, science and policy are becoming entangled in a relationship that can be mutually beneficial at times, and contentious at others. While the interests of the two regularly intersect, scientists and decision-makers are not always confronted with the same challenges and often seek to answer different questions. Decision-makers are not only required to meet regulatory objectives and negotiate between different stakeholders with competing interests and specific responsibilities, but they must also do so while working under limited time and resource constraints, dealing with uncertainty and being held accountable for their actions (or lack thereof). Scientists are interested in scientific questions, which may not always translate (or easily translate) into action, and are under pressure to publish (or perish), maintain scientific integrity, and seek funding for their work. Though contractual agreements for specific deliverables under certain timelines are not uncommon, research is generally considered to be part of a boundless quest for knowledge, with new information expanding or elucidating what was previously known or unknown.

The intensification of complex environmental problems, underlined by new paradigm thinking has resulted in closer collaborative relationships between science and politics, inevitably giving rise to the concept of 'boundary organisations' (BOs) in the 1990's as a way of curbing concerns over the 'politicisation' of science and the 'scienticisation' of politics (Gieryn, 1995a; Kirchhoff *et al.*, 2013). By providing a neutral environment where both are able to maintain their own identities and pursue their own goals, while at the same time, keeping each other in check (Guston, 2001, 2000), boundary organisations offered a way of stabilising emerging science-policy interactions in an attempt to coordinate productive interaction.

While the potential for optimising the use of research in policy appeared promising, some reiterated the 'boundary problem' (Gieryn, 1995b) of how we distinguish 'science' from 'non-science' within these arrangements, since scientific claims are socially constructed through various social influences and constraints which can place usual strains on science (Jasanoff, 1995, 1987). As Hoppe *et al.* (2013) point out, this issue continues to be an on-going challenge, even among more notable examples, such as the IPCC and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

First introduced in the context of developing a US technology-transfer policy, Guston (2001, 1999) put forth three defining criteria of boundary organisations, which include: 1/ involvement of actors representing both sides of the boundary as well as those in between (information producers, users, and mediators); 2/ strategic positioning at the boundary of two comparatively different social worlds (e.g. science and policy), in order to govern mutual accountability, and; 3/ creation of a neutral and legitimate space for exchange which creates opportunity and incentives for the production and use of 'boundary objects' and 'standardised packages'. Hoppe *et al.* (2013) refers to this as double participation, dual accountability, and use of boundary objects, which may be weaker or stronger depending on the organisation, or may be absent altogether.

Boundary objects refer to a common reference point (e.g., object, artefact, conceptual model, classification system, etc.) that is shared between various stakeholders, facilitating interaction and collaboration towards common objectives despite opposing perceptions (Star and Griesemer, 1989). Standardised packages expand on this concept, encompassing the collective work across divergent social worlds expressed by boundary objects, while also incorporating the stabilisation of facts described by Latour (Fujimura, 1992). Though boundary objects and standardised packages both serve as an interface between multiple social worlds, standardised packages refer to a scientific theory accompanied by a standardised set of technologies which is adopted by actors from multiple social worlds in order to stabilize facts between them (Fujimura, 1992).

The concept of boundary organisations has since gained popularity in academic fields studying science-policy relations and the production and transfer of knowledge, owing largely to its general attributes (which are open to interpretation) and ability to capture the dynamic nature of these interactions (Gustafsson and Lidskog, 2018) as opposed to linear models of knowledge use which described science as objective facts being transferred to a passive audience (Nutley *et al.*, 2007).

At the same time, the concept of boundary organisations is not exempt from criticism, summarised by Gustafsson and Lidskog (2018) as having static theoretical assumptions (e.g., Miller, 2001; von Heland *et al.*, 2014); describing relationships and organisations as fixed rather than part of an on-going process (e.g., Mørk *et al.*, 2012; Pesch *et al.*, 2012); oversimplifying the divide between science and policy and thus neglecting the heterogeneity within each as well as the blurred borders which divide them (Miller, 2001; Wehrens *et al.*, 2013); failing to recognise asymmetrical and evolving power relations concerning accountability (e.g., Parker and Crona, 2012; Wehrens *et al.*, 2013), and; an insufficient consideration of multiple boundaries, stakeholders, and scales (e.g., Cash *et al.*, 2003; Cash and Moser, 2000; Hisschemöller and Sioziou, 2013; Klerkx and Leeuwis, 2008).

More recently, the notion of boundary organisations has evolved to incorporate other well-established theories and concepts which address former weaknesses in the original conception or new theories and concepts which expand its definition and use to a larger context (Gustafsson and Lidskog, 2018). New insights have been gleaned from a growing number of empirical studies, though the literature remains largely theoretical. Therefore, it remains difficult to draw any long-term conclusions about whether boundary organisations are able to change the efficacy of the system.

Exploring the Role and Functioning of Boundary Organisations

Despite being able to trace common foundations in Guston's three criteria, Gustafsson and Lidskog (2018) found that the concept of boundary organisations comprised a multitude of organisations who are fundamentally different in their objectives, institutional arrangements, governance, membership criteria, production of boundary objects or standardised packages, duration, and scale. Therefore, no boundary organisations are alike: each has a distinct form and function and vary in their ability to conduct effective boundary work. Drawing from relevant empirical studies, they outline four main uses of the concept in the context of scientific research (Gustafsson and Lidskog, 2018: 6):

1. **Contextualisation**: use of the concept is limited to setting the scene, rather than as a tool for analysis
2. **Recommendations**: use of the concept as a 'normative good' and recommended solution, without providing guidance regarding the institutional creation of such an organisation
3. **Description**: use of the concept as an empirical category to describe and label the object of study
4. **Analysis**: implicit or explicit use of Guston's original criteria (governance, membership, boundary objects) to create a basis for analysis, though different definitions may be used

It is generally agreed that boundary organisations are an interface between science and policy, allowing various stakeholders from multiple social worlds to interact and exchange resources (e.g., knowledge, data, skills, tools, techniques, instruments) through financial and/or institutional arrangements. In doing so, they act as intermediaries (Gulbrandsen, 2011) that can stabilize the contested boundaries of science and policy (Pesch *et al.*, 2012), mediate the fields of science and application (Hellström and Jacob, 2003), and link science and decision-making across multiple levels (Cash *et al.,* 2003).

A growing body of work on the subject has suggested that boundary organisations serve several functions including linking different interests across different scales, levels, and organisations (Cash, 2001); facilitating knowledge (co-) production (Dilling and Lemos, 2011; Edelenbos *et al.,* 2011; Meadow *et al.,* 2015; van Kerkhoff and Lebel, 2015); enhancing knowledge usability (Kirchhoff *et al.*, 2013; Lemos *et al.,* 2012; McNie, 2007); building trust, credibility and legitimacy (Cash *et al.*, 2003; Commenges *et al.*, 2014; Sarkki *et al.*, 2014; White *et al.*, 2010); and social learning (e.g., Berkes, 2009; Mostert *et al.*, 2007; Pahl-Wostl, 2002; Pahl-Wostl *et al.*, 2007; Tippett *et al.*, 2005).

Social learning originates from Bandura's social learning theory (1977), a psychology concept that referred to the way people learned through observation and imitation. In the context of complex environmental problems such as water resources management, this concept has evolved from a focus on individual learning to include group dynamics, where collective action is based on shared meanings and values (Pahl-Wostl *et al.*, 2007) and organisations can learn as well as individuals they comprise (Berkes, 2009).

Social learning focuses on the process of developing management options in a collaborative multiparty environment within the context of the natural environment as well as its governance structure (legal and organisational framework, cultural and socioeconomic environment) (Mostert *et al.,* 2007; Pahl-Wostl *et al.*, 2007; Tippett *et al.,* 2005). Due to the interdependent nature of environmental problems, social relations must be explicitly taken into account when dealing with management issues, since social processes have an influence on problem definition, problem framing, implementation, the representation and management of boundaries, ground rules, and negotiation strategies (Pahl-Wostl *et al.,* 2007). This is facilitated by relational practices such as joint field visits, training sessions, or task-oriented actions that foster reciprocity and reflexivity (Bouwen and Taillieu, 2004) through shared ownership, mutual understanding and openness for feedback and criticism.

These processes result in two types of outcomes (Pahl-Wostl *et al.,* 2007): the implementation of measures to address an environmental problem or an increased capacity to address an environmental problem, which then feeds back through single-loop learning (instrumental change given the constraints of norms and beliefs) or double-loop learning (radical changes in underlying values and beliefs). Social learning can occur at different scales: at the level of processes between collaborating stakeholders (short-medium scale), at the level of change in actor networks (medium-long scale), and at the level of change in governance structures (i.e., formal and informal institutions, cultural values, norms, and paradigms) (long scale).

At its core, boundary work is a matter of managing negotiations, requiring boundary organisations to play the roles of *convening*, *collaboration*, *mediation*, and *translation* (Franks, 2010; Tribbia and Moser., 2008). *Convening* and *collaboration* are interrelated: the former refers to the act of assembling different actors in order to exchange information and perspectives and foster trust, while the latter focuses more on the management of these exchanges towards collective aims, such as the co-production of boundary objects. Mediation helps negotiate competing objectives to foster effective collaboration, while translation involves making information accessible and comprehensible to multiple parties.

Neither the PIREN-Seine nor the CRC for Water Sensitive Cities make the explicit claim of being boundary organisations, though they both engage in boundary work and their role and functions resemble the characteristics described by boundary organisations theory. For example, they involve stakeholders from different sides of the boundary, they position themselves at the science-policy interface, and they create an environment for interaction and exchange, which produces 'boundary objects' (e.g., modelling tools) and 'standardised packages' (e.g. concept of water sensitive urban design). The main functions of boundary organisations are also present in both examples. It is therefore worth examining these examples under the lens of boundary organisations in order to identify the roles and functions that can help or hinder the processes of: 1/ enhancing the use and usability of its knowledge and tools and 2/ reconciling uncertainty in model-based decision support in practice.

Enhancing the Use and Utility of Knowledge and Tools

The PIREN-Seine and the CRC for Water Sensitive Cities work to mobilise resources and stakeholders (e.g. researchers, managers, practitioners, and decision-makers), thereby orienting research and tools towards shared goals of water management in France and Australia respectively. One of the main roles of boundary organisations in this context is to effectively link research and practice by enhancing the use and usability of the knowledge and tools produced by narrowing the gap between research production and its use in management and policy.

One strategy is co-production, which typically involves collaboration from both sides of the boundary. Using a broad definition, *anything* that is produced within the boundaries of these organisations can be considered a co-production. While the actual production (e.g., building the model) may be carried out by researchers, operational partners are often involved in various stages of the development process, whether it is contributing the formulation of the problem, providing input data, or applying the model in management or planning situations.

In the PIREN-Seine, co-development can occur on two levels: organisational and individual. At the organisational level, partners are involved in the development of each phase of the program, providing feedback and contributing suggestions as to what issues should be prioritised in the upcoming phase. Here, the main role of PIREN is to mediate between differing objectives, needs, and expectations between and among researchers and operational partners. Regular meetings are organised in the form of seminars, workshops and conferences throughout the year, which provide spaces of exchange and dialogue between different actors and allow them to share their perspectives and build trust through official and unofficial exchanges. For example, a number of workshops held in phase 7 allowed different actors to come together and collectively envision future urban and agricultural scenarios. This is a prime example of how the knowledge and tools of PIREN support enlightenment through the exploration of possibilities integrating different perspectives. Co-directive meetings and general assemblies are specifically held to reflect on the work of the previous phase and collectively set the objectives of the next phase. In this case, more formal procedures are in place for mediation:

> "*Propositions [from partners] are put forth to be discussed with researchers during the General Assembly and to also see if there are any particular oppositions, etc. and if there are things that interest them. Then, the valuation decisions are taken with the Co-directive and the transfer cell. Together, we decide which theme or what action will be addressed. Afterwards, everything is presented and validated with program partners. That's how it works*" (Transfer Cell Representative, 24 May 2018)

At the individual level, co-production can occur between specific research teams and operational partners towards a specific objective, for example, the development of ProSe and Seneque. These examples are typically ephemeral, occurring when the objectives of two or more parties are aligned on a specific issue, and time and resources are dedicated to achieving a common objective through temporary arrangements. In this way, the PIREN-Seine plays a role in convening and collaboration, benefitting from a dynamic agglomeration of different actors and institutions:

> "*PIREN is vast enough with different teams that they can evolve and innovate more than a single team can, so partners can benefit from a consortium of researchers that is constantly evolving*" (PIREN President of the Partner Committee, 18 August 2018)

By providing spaces for formal and informal exchange, PIREN helps to connect people through a 'trusted' network of actors and provides opportunities for collaboration among actors that might otherwise be operating within their own 'silos':

> "*The developers of [other models] want to respond to projects outside of the PIREN without having to talk to us. It's normal. So the development around their tools is done without us, but we take advantage of having the PIREN to gather around the table together, exchange, and also do things together. That's what's good about it.*" (Researcher-Lecturer, Hydrology, 1 February 2018).

The trust in the scientific knowledge and tools produced by each program has contributed to the adoption of models in practice. In PIREN, this trust has resulted in the AESN choosing to use Seneque over Pegase, a similar model adopted by other the Water Agencies in France. The same can be said for MUSIC in the case of CRCWSC, whose success is based on its legacy of expertise.

Though co-production is generally thought to be an advantage of PIREN's approach, what constitutes a *true* co-production may be a point of contention among a number of actors. This is reflected in the interviews concerning the propriety of code of the ProSe model. Whereas the SIAAP considers itself to play an integral part in the development of the model (SIAAP Representatives, 27 June 2016; 3 March 2017), PIREN researchers consider ProSe to be the production of researchers, since the SIAAP cannot change the code (Researcher, Hydrogeology, 28 April 2016; Researcher-Lecturer, Hydrogeology, 29 June 2016) and their involvement was limited to providing certain data and feedback (Researcher-Lecturer, 21 February 2018). Some go further to differentiate two visions of co-development: one that is characterised by the distribution of tasks between the conceptual model and the program (or application of the model); the other believes that without the SIAAP providing data and applying ProSe to the Seine, the conceptual model is useless (Researcher-Lecturer, 21 February 2018).

The CRC for Water Sensitive Cities also incorporates elements of co-production into their approach on two levels. At the organisational level, researchers worked with government organisations and private industry partners to understand and identify the key knowledge gaps in the development of Tranche 1 of the program. Since the CRCWSC's main mission is to operationalize research outputs, research objectives were largely influenced by the needs of industry partners. In this way, CRCWSC plays the role of convening, mediating and translation.

CRCWSC brings together relevant actors in organised spaces of exchange such as seminars, workshops and conferences, acting as a mediator between the different actors to define research objectives. It is also engaged in translation not only to ensure that research outputs were relevant and applicable to practice but also to facilitate their implementation. At the individual level, industry partners served as beta-testers for modelling tools and contributed to scenario-building activities, facilitated by CRCWSC, who played the role of collaboration and translation. CRCWSC's inclusion of support mechanisms, such as training and capacity building workshops, also helped in translation.

These interactions and exchanges may occur outside of the boundary organisation, for example, through external contracts with consultancies. While the knowledge and tools that are produced by these boundary organisations are perceived as scientifically objective, thereby enhancing trust, credibility and legitimacy, they are not necessarily tailored to individual interests and objectives. At the same time, boundary organisations such as PIREN and CRCWSC offer the advantage of access to scientific knowledge and expertise with a relatively low investment:

> *"Today partners bring 700,000 euros per year. If we consider the whole budget of what's spent - the phd students, etc. – which are paid by research not partners, it's between 5-10 million per year if you take into account the salaries of researchers, post-docs, phds, etc. Each partner can't do it alone. There's a mass financial effect, a leverage effect. If I put one euro, the PIREN puts ten"* (PIREN President of Partner Committee, 14 August 2018).

In theory, the level of collaboration and investment implied in the co-production of knowledge and/or tools should enhance their use and utility. However, as we have discussed in Chapter 2, the level of involvement is just one of the factors that determine use and utility. Another strategy is to focus on the usability of knowledge by first asking *how* it will be used (e.g., for enlightenment, to justify decisions or to enhance negotiating power) and *by whom* (e.g., researchers or practitioners, modellers or non-modellers), while also considering how boundary organisations can be leveraged for support.

In CRCWSC, the main intended users of the knowledge and tools produced are industry partners – including governments, land developers, city planners, and water authorities – primarily for decision and negotiation support. As the CRCWSC's overall objective is to operationalize research outputs, its role as a boundary organisation is primarily in collaboration and translation. Whereas

Tranche 1 was focused on identifying key research gaps, Tranche 2 is dedicated to Tools and Products (TAP), which builds on Tranche 1 research to "*enable industry adoption and utilisation of key intellectual property outputs from CRCWSC research, to support mainstreaming of water sensitive technologies and practices.*" (from the CRCWSC website). This is done through the WSC Toolbox, which assimilates the previous portfolio of tools and research outputs into three main transition platforms, each supporting different stages of management and planning.

The WSC Transition Platform (TAP 1) is based on the Water Sensitive Cities Index and focuses on the visioning and concept planning stage by providing guidance on developing common WSC objectives and transition strategies as well as evaluating targeted interventions. The WSC Scenario Platform (TAP 2) is intended to be a tool for developing water sensitive business cases by allowing the user to create concept designs and policy solutions towards water sensitive solutions.

Using the WSC Modelling Toolkit as its base, it comprises a library of separate but connected models that quantify the benefits of green infrastructure initiatives. A sub-program will be added to include TARGET, an updated extreme heat mapping model, WMEF4Water, an urban metabolism framework that quantifies the water balance of an urban area, and a cost-benefit analysis tool for economic evaluation of water sensitive scenarios. The WSC Design Platform (TAP 3) is built off of DAnCE4Water and models the evolution and interaction of urban infrastructure, water networks and population demographics. It provides users (mainly planners, designers and engineers) with advanced tools for developing different water management scenarios.

As a boundary organisation, CRCWSC provides the knowledge and tools (boundary objects) that allow actors from different worlds to communicate, thereby fostering collaboration. The involvement of end users throughout the development process is intended to build trust through close working relationships and asking for feedback, while at the same time familiarising the user to the tool early on (Researcher, Civil Engineering, 7 June 2017). Another main role of CRCWSC is translation, which is supported through Training and Outreach sub-program that includes user guidelines, reference material, and capacity-building workshops.

A key process underlying collaboration and translation is social learning. This is facilitated by the strong and clear objective of CRCWSC to promote water sensitive urban design, which comes in a standardised package of tools and concepts ready for implementation. The type of social learning processes occurring within CRCWSC represents single-loop and double-loop learning on all three scales (short-medium, medium-long, and long). This is achieved through the involvement of actors at different scales (researchers, practitioners, decision-makers) and being involved at all stages of the management and planning process from research to implementation to policy:

> "*We have a lot of government partners, and so a lot of our work turns into policy very quickly. Like the Victorian Government's most recent policies pretty much reflect all our work because the Victorian Government is an essential partner. By having that connection, the research is continually feeding into what we call the end-users and they change their operation or they adapt their operation to capture the new research and new thinking that comes through.*" (Researcher-Professor, Civil Engineering, 20 June 2017)

In the PIREN-Seine, the knowledge and tools aim to serve the needs of researchers and practitioners – including water managers and technicians – primarily for enlightenment and decision support. As the underlying objective of the program is to develop a common vision and gain a more comprehensive understanding of the functioning of the Seine River basin, the primary role of PIREN as a boundary organisation has been convening and collaboration.

Knowledge is transferred by creating formal and informal places of exchange, enlightening practitioners on new research developments, while also offering them opportunities for participation and feedback. An overview of the program's research outputs is showcased through publications such as activity reports, fascicules, journal articles, and booklets. Instances where a sub-group of actors collaborate on a specific task or project enhances knowledge transfer through the direct link of producers and users. However, translation efforts continue to be hindered by an already limited amount of time and resources of researchers.

Recently, increasing demand from operational partners to make research outputs more accessible has resulted in the creation of a dedicated transfer cell (*cellule de transfert*) in 2016, whose functions include convening, collaboration, mediation and translation. Besides organising the places for exchange and collaboration, the transfer cell also acts as a communicative link to mediate between the different objectives of researchers and partners. Another important function is to valorise and popularise research outputs, which is done according to the target audience:

> "*There are different degrees in the popularisation. The booklet is a valuable document but it's not popularised. They're scientific productions of researchers aimed at professionals, people who already have knowledge in this subject and who want to look at these subjects one day and have it available as a quick reference and be sure that it's reliable*" (Transfer Cell Representative, 24 May 2018)

Next, there are the 4-page leaflets, which are a synthesised document designed for a wide audience "*so that anyone, who is in a municipality, an administrative agent or something like that, who comes across this leaflet can read it. He's going to understand the latest results, what happened, etc.*" (Transfer Cell Representative, 24 May 2018). The last stage of popularisation is posters, designed to convey a simple message to the general public, with "*a central idea to communicate. It can be made with a minimum of words, a minimum of ideas. The posters we're trying to do is transfer [of scientific information], it's a poster for a mainstream audience*" (Transfer Cell Representative, 24 May 2018).

Though the transfer function of PIREN is still in its early stages, the positive feedback from operational partners is a sign of progress. Having documents that are produced by a well-established scientific research program that can be understood by a wide audience allows partners to communicate with different actors. Within institutions, simplified documents such as the 4-page leaflet allows partners to justify their investment in PIREN to senior actors who may not have the time or competence to read more complex documents such as the booklets. Partners also benefit from the added credibility and legitimacy that PIREN reference documents lend to their work, which is perceived as trustworthy and reliable, particularly if they have contributed in some way to its production.

In terms of modelling, previous attempts at making the tools themselves more usable and applicable to direct management support (e.g. Seneque and ProSe) has been a constant struggle, due in part, to differing objectives. As a result, the respective teams behind the development of ProSe and Seneque adopted parallel approaches to enhancing the use and utility of their models. The ProSe development team formed a working group with interested members of the SIAAP, which resulted in enhancing their capacity to use the tool themselves. But, recent feedback from researchers and the SIAAP suggest that they are beginning to outgrow the model. The Seneque team worked with interested members of the AESN in order to build a GIS interface to make it more 'user-friendly'. However, they found that the tool was too inflexible for research purposes. On the management side, the user group was extremely limited (one person at the AESN who later changed roles) and the tool suffered from lack of maintenance and updated input data.

The recent turn to expert-based tools in PIREN can be understood as a strategy that allows researchers and operational partners to maximise their resources towards a common goal. For researchers, expert-based tools offer the advantage of enhanced flexibility, capable of evolving and adapting to different questions without having to invest time and resources into making it usable to novice users. For operational partners, this strategy offers a better return on investment, allowing them access to expertise and scientific evidence without investing in in-house training. This is particularly advantageous for partners who only require models on an *ad hoc* basis.

The focus on expert-based tools has enabled Seneque to be reborn into the modelling platform or modelling environment known as Pynuts. The development of these tools is part of a transition from single-focus models to modelling chains and platforms that draw upon a library comprising blocks of code that can be arranged and rearranged according to the desired output. On one hand, this strategy can be seen as a way of enhancing communication between models through a common library of code, thereby improving its use and utility to address a wider range of environmental problems. On the other, it is a response to internal institutional pressure for researchers to sell user licences for their modelling tools. Rather than selling the tools themselves, this strategy enables researchers to serve as 'gatekeepers' to the knowledge and tools that are produced. This can be seen as a way of preventing misuse, although they still do not have control over how the modelling results or scientific knowledge will be used in the decision context.

Social learning within the PIREN-Seine typically occurs as single-loop learning on the short-medium scale at the level of collaboration between stakeholders for a number of reasons. First, the operational boundaries of PIREN are limited to water actors within the Seine River basin and do not include elected officials or policymakers. Influence on policy is therefore limited compared to the CRCWSC and changes usually occur at the institutional level.

Second, the institutional involvement of water actors is limited to one or two key contact people who participate in PIREN activities according to their own interests and agenda, as well as that of the institution they represent. Often, the transfer of knowledge and tools does not permeate beyond this contact person's role and responsibility. Attempts at double-loop learning occur at a longer scale with the development of more recent agricultural scenarios. Although this represents a minority of research activities and actors within PIREN, the debate centred on these scenarios is contributing to long-term policy changes at the national level.

A fundamental issue that has not been addressed in PIREN is that of interdisciplinarity. While the PIREN-Seine is an interdisciplinary research program, its composition is still dominated by hydrologists, engineers, agronomists, hydrogeologists, chemists, biogeochemists, microbiologists, and modellers. Social sciences in the form of sociology, geography, economy, urban planning, and history are also represented, but to a lesser extent. In Phase 7, Axes 1 and 2 of the program are dominated by researchers from natural sciences with a primarily quantitative focus. Only a handful of social science researchers comprise Axe 3, which is dedicated to pooling and enhancing the knowledge produced by the other two axes in order to gain a better understanding of the quantitative and qualitative management of water in the Seine basin.

Apart from participating in formal and informal exchanges both inside and outside of the PIREN-Seine, most research teams tend to work within their own 'silos'. Throughout various meetings, presentations and workshops, a number of researchers had a hard time understanding the details of what was being presented: *"I find it all very interesting, but I have no idea what they're saying with all their graphs and diagrams"* (Researcher, Economy, 1 December 2016); *"I didn't* *understand a word at the beginning. What are they talking about? Really, people were in kind of a scientist corridor*" (Researcher-Professor, Geography, 21 February 2018).

Comprising actors with blended research-practice-policy profiles who act as 'knowledge brokers' (Bergenholtz, 2011; Meyer, 2010; Oldham and McLean, 1997; Urquhart *et al*., 2011; Ward *et al.,* 2009), CRCWSC benefits from having a vast network of prominent water actors who can mediate between supply and demand. In fact, a large majority of interviewees have had extensive experience in research and practice. In many cases, they also came from interdisciplinary backgrounds mixing natural and social sciences. Whereas many industry partners also have a background in research, a number of senior water actors have returned to research. Similarly, some individuals with a background in engineering are now integrating social science methods to study the adoption of CRCWSC tools and techniques.

Individuals with blended profiles can also be found within PIREN but to a comparatively lesser extent. The majority of PIREN actors tend to stay within their domains (academic or professional), with a few notable exceptions. While several operational partners completed their doctoral studies under the supervision of PIREN researchers, most researchers stay within their academic disciplines. This could be a reflection of culture, since in countries such as Australia, having a more diverse profile is seen as a strength. Conversely, in France, interdisciplinarity still tends to be undervalued, although this mentality is slowly changing: "*When I began my Ph.D., they asked me: 'you managed a team of 30 people. Why do you want to do research?' You're either a researcher or a manager. You can't be both*" (Researcher, Civil Engineering, 28 March 2018).

Reconciling Uncertainty in Model-based Decision Support

Another major role of boundary organisations is to reconcile uncertainty. To understand how boundary organisations help actors cope with uncertainty in model-based decision support, we must first distinguish between two primary types of modelling: predictive/deterministic modelling and exploratory modelling. Predictive/deterministic modelling uses hard quantitative techniques to forecast the future, whereas exploratory modelling generates a portfolio of possible futures.

CRCWSC's approach focuses on 'deep uncertainty' through exploratory modelling and scenario building:

> "*It's an emerging trend these days, whereby policies are no longer based on any sort of static determination of what the future looks like because there's just so much uncertainty. A lot of planning is tested against a whole range of different possible future scenarios*" (Researcher-Professor, Civil Engineering, 15 June 2017)

'Deep uncertainty' refers to the 'known unknowns' as well as the 'unknown unknowns'. To cope with this, exploratory scenario planning allows for the construction of any number of plausible future scenarios, where modelling enables us to rapidly assess a chosen set of likely scenarios:

> "*Modelling is a very important tool in supporting scenario planning because it's about being able to rapidly determine what the future scenarios are and capture that from a biophysical, quantitative way to enable planning to then be applied based on those conditions*" (Researcher-Professor, Civil Engineering, 9 June 2017)

While CRCWSC industry partners have expressed interest in exploratory modelling and its potential in strategic planning, use of the concept deep uncertainty in practice remains limited due to the deeply engrained mentality of evidence-based policy:

> "*Industry just needs one answer. Under deep uncertainty, there isn't one answer. Exploratory modelling might not be what they want. Maybe it could be useful when you're framing issues or during the brainstorming phase*" (Researcher, Policy Analyst, Civil Engineering, 14 June 2017)

CRCWSC's focus on exploratory modelling effectively eschews discussion over model-based uncertainties, since the purpose is enlightenment. Generally speaking, uncertainties do not seem to be the priority for researchers:

> "*There's not a lot of interest for quantifying uncertainties. Researchers are a bit naïve. It's more about parameter uncertainty, but the bigger uncertainty is what is being modelled and what is being built*" (Researcher-Professor, Ecohydrology, 17 October 2017)

This is echoed on the operational side, as model-related uncertainty also seems to be a low priority for practitioners:

> "*Modelling uncertainty was small compared to climate change uncertainty or growth uncertainty*" (Government and Water Sector Consultant, 31 July 2017)

At the same time, deterministic models such as MUSIC still underpin exploratory modelling platforms such as the WSC Toolkit. MUSIC is also currently the only CRCWSC tool that is being used in practice despite the many uncertainties involved:

> "*MUSIC is used across Australia and people don't question it but we hardly know if it's accurate. However, this issue is not limited to MUSIC: "Many stormwater pollution models used worldwide have low accuracy and high uncertainty and there is little understood about the sources and magnitude of this uncertainty*" (Consultant, Civil Engineer, 26 July 2017)

Model-related uncertainty may be considered a low priority in the decision context since "*models are used to form judgements, not make them*" (Government and Water Sector Consultant, 31 July 2017). Additionally, they are often one tool among many other forms of decision support. Moreover, avoiding uncertainty may sometimes be a conscious strategy:

> "*Decision-makers ignore uncertainty because it might undermine the decision. The reality is that in many situations, it won't change their situation. It may even be unhelpful because it'll create doubt and people will just stall and do nothing*" (Researcher-Professor, Ecohydrology, 17 October 2017)

PIREN has traditionally focused on predictive scenarios based on deterministic modelling, forecasting the future using hard quantitative techniques. This approach can be useful in research settings since predictive modelling is more appropriate for closed systems with manageable uncertainties (Bankes et al., 2002). Uncertainties become more significant in practice, since real-life systems are open, dynamic and complex. A number of studies addressing different uncertainties can be found in the scientific literature. Yet, as we have seen in Chapter 2, they remain fragmented and not readily accessible or applicable to practitioners. Generally speaking, discussion of uncertainties remains relatively taciturn, partially due to the fact that the majority of PIREN modelling tools are used for enlightenment.

In cases where models are used for direct decision support, uncertainty has become a bigger priority. For ProSe, interactions and exchanges facilitated by

PIREN in addition to a dedicated working group have enhanced communication and understanding on model uncertainties between researchers and the SIAAP. Familiarity with ProSe helps to reconcile uncertainty since they have a better understanding of the sources of uncertainties and the limits of the model. When a higher socioeconomic risk is involved, precautionary measures are used to compensate for uncertainties in the model (SIAAP Representative, 29 November 2016).

As boundary organisations, PIREN and CRCWSC help water actors reconcile uncertainty through convening, collaboration and mediation, which builds an environment of trust, credibility and legitimacy. Underlying these processes is social learning, which is an essential process for building the capacity to cope with uncertainty and change (Folke *et al.*, 2005).

Convening and collaboration enhance the capacity of different actors (modellers and non-modellers) to understand the model functions and limitations, while mutual communication and understanding contributes to building trust. Mediation becomes important in negotiating what is *known*, *unknown*, *knowable*, and *unknowable* in order to establish shared narratives. However, mediation does not guarantee that what is agreed upon will be 'correct'. Actively mediating the borders of science and policy ensures that the knowledge and tools maintain credibility and legitimacy as 'objective' scientific outputs. Yet, as we have seen in the PIREN and CRCWSC, the distinction between 'science' and 'non-science' is not only a matter of *whom* but *in what context.* In reality, the two are not mutually exclusive. For example, scientists can have a dual status as researchers in PIREN and consultants in ARMINES).

The social construction of boundaries between 'science' and 'non-science' preserves the perceived scientific objectivity of PIREN and its work, by maintaining that the research conducted by the PIREN is not driven by the specific needs of any one partner. At the same time, one of the primary motivations behind the participation of operational partners is the interest in using research outputs to support management, policy and planning decisions. For the SIAAP, ProSe lends legitimacy and credibility to their work in the eyes of the DRIEE, since it was a model created by PIREN, and thus perceived as giving objective results (SIAAP Representative, 29 November 2016). In this case, the fact that ProSe is considered a research model developed by researchers was enough to assuage questions of legitimacy or credibility, despite the subjectivity behind its use (e.g. what is modelled and how it is framed) and the interpretation of results, particularly further down the decision chain.

More recently, the SIAAP has capitalised on the completion of Phase 7, leveraging their role as one of PIREN's major funding partners to renegotiate its position to be recognised as its own research group and requesting to be co-signer of the model ProSe. This would likely give the SIAAP access to the model code, further solidifying their legitimacy not only as managers within the basin but also as researchers. If accepted, this could fundamentally challenge PIREN's stance on preserving scientific autonomy and objectivity as it takes one step closer to the realm of regulatory science. At the same time, jeopardising the partnership with the SIAAP would result in a major financial loss for PIREN.

Beyond Boundary Organisations: Towards a Multi-scalar Approach to Boundary Work

The examples of PIREN and CRCWSC fit the definition of boundary organisations, since they can both be characterised by double participation, dual accountability, and use of boundary objects. In terms of functions, knowledge (co) production, knowledge usability, the creation of trust, credibility and legitimacy, and social learning were also present, albeit not always to the same extent. A straightforward comparison highlights the strong performance in terms of knowledge production in both examples. While CRCWSC would appear to have an advantage over PIREN on knowledge usability, this disparity is much smaller once the diversity of uses outlined in Chapter 1 has been taken into account. Both perform comparatively well in creating trust, credibility and legitimacy, through long-term partnerships and exchanges, which is also supported by regulatory instruments. Though neither appears to take an active role in facilitating social learning, it can occur through the creation of spaces for exchange and interaction.

Yet, while the PIREN and CRCWSC appear to fulfil the characteristics of the boundary organisation concept, a subsequent question inevitably remains: *what makes a boundary organisation effective or successful*? Despite numerous attempts to define 'best practices', Hoppe *et al.* (2013) argue that detailed instructions on making 'successful' boundary arrangements are too limiting, pointing instead to their ability to "*[adjust] to their diverse national contexts of policy issue politics and political-cultural spheres*" (296). Using the example of the IPCC, Hoppe *et al.* (2013) also advocate for opening up the debate by reframing environmental issues as unstructured policy problems, where the objective of boundary work would be to provide "*pluralized strategic advice, conceptual clarification, and critical deconstruction of issues of uncertainty and normativity*" (296). In doing so, politicians would be allowed to develop their own policy framings to respond to environmental problems and fit boundary arrangements to this purpose.

Are Boundary Organisations Necessary?

In order to glean insight into the role of boundary organisations, we must also understand *why* and *when* they are needed or indeed *if* they are truly necessary to achieve desired outcomes. In the examples of PIREN and CRCWSC, the concept of boundary organisations is unable to fully capture the complexity of the myriad science-policy interactions that exists. In many instances, the work carried out by the two programs could not be isolated to their respective boundaries, which themselves were constantly evolving.

Discussing the work of these programs often necessitated the consideration of parallel arrangements that existed outside of 'official' boundaries. For example, the development and use of some of the main PIREN models sometimes required further work through external contracts with organisations such as ARMINES or INRA. Similarly, it was impossible to speak of the CRCWSC's work without referencing previous CRCs (e.g. CRC for Catchment Hydrology, CRC for Freshwater Ecology, eWater CRC) or associated research programs such as the EU-funded projects, in which much of CRCWSC's scientific production and tools were founded. Moreover, the myriad boundary interactions taking place within these spaces typically occur at different levels and scales, further adding to this complexity. In light of these observations, a multi-scalar approach which focuses on boundary work as a whole rather than limiting itself to boundary organisations would be more appropriate. Looking at different scales will allow us to 'zoom out', providing a more comprehensive view of various interconnected and dynamic relationships, while at the same time 'zooming in' to assess the importance of boundary work conducted on the individual level.

Whereas boundary organisations have more defined criteria, boundary work is a wider concept which opens up the scope of our study. The science-policy interactions described by Jasanoff (2004) as a process of continuing co-productions between scientists and decision-makers, commonly occurs at the macro-level (Hoppe *et al.,* 2013). This type of boundary work is emblematic of boundary organisations, where boundary demarcation is more distinct. It was found in our characterisation of PIREN and CRCWSC and can also apply to lateral arrangements at the science-policy interface. For example, in scientific committees or councils or the way in which universities, research centres, and public institutions are distinguished by their respective roles and responsibilities within the region. The European Commission is a prominent example where different boundary arrangements provide valuable resources for advice, political articulation of research questions and steering of knowledge production (Hoppe *et al.*, 2013).

Boundary work occurs regardless of boundary organisations, however, they offer the advantage of orienting resources and knowledge towards common interests on a larger scale. Focusing on boundary work demarcates the respective spheres of science, policy and practice not only within organisational boundaries, but also on an individual level, according to the context in which scientific knowledge and tools are produced.

At the meso- and micro-levels, boundaries become increasingly blurred as different types of boundary work require a specific configuration of actors who may sometimes need to play multiple roles on each side of the boundary. For example, PIREN researchers who also serve as consultants working for ARMINES. Whereas research conducted in PIREN is considered scientific, studies conducted through ARMINES may not be held to the same esteem since it is tailored to individual operational needs and is not necessarily subject to the same scientific checks such as peer review, even if the same actors are involved. Boundary spanning common in CRCWSC, where many actors within the water sector have played the role of researcher and practitioner, enabling them to draw from dual expertise in order to increase their credibility and legitimacy.

One paradox of boundary work is that dual accountability often leads to a split between 'sacred' front-office (the official story) and 'profane' back-office (what actually occurs) narratives:

> "*In order to enable boundary work as a productive interaction, it is in the institutional self-interest of both science and politics to co-produce the linear knowledge transfer story as official legitimation of their relationship*" (Hoppe *et al.*, 2013: 285)

Whereas PIREN strategically draws the line between science and policy in order to preserve its credibility and legitimacy, CRCWSC is able to do so while maintaining more permeable borders. PIREN's strategy is to create a strong 'front-office' narrative which separates science and policy, whereas CRCWSC assumes the role of policy advisor by directly involving itself into every level of management and planning.

Another paradox of boundary work is that on one hand, it encourages scientists to innovate through public funding. On the other, increasing pressure for public action is diverting time and resources away from the 'pure' scientific endeavour, which may end up inhibiting innovation. This begs the question: *can 'good' science continue to exist if scientists no longer have full autonomy to pursue scientific discovery?* As they are increasingly compelled to make their work applicable to practice, their work may end up resembling that of consultants more than scientists. At the same time, the pursuit of scientific discovery requires extended time commitments that can no longer be afforded in an age of urgent environmental issues.

Stabilising the Paradigms of Knowledge Production

The characteristics of the new paradigm of knowledge production can be seen as a reflection of an increasingly interconnected, knowledge-based world, displacing but not entirely replacing the old paradigm. The perceptible shift towards participation, accountability, and application is indicative of a new paradigm in science that embraces evidence-based policy. At the same time, the examples of PIREN and CRCWSC show that the constructs of 'pure' or 'real' science are still fresh in the minds of both scientists and practitioners in practice.

In the PIREN-Seine, the old paradigm mentality remains a dominant philosophy, often leveraged as a way of maintaining scientific credibility and legitimacy. Operational partners play an influential role in co-defining the program's research objectives for each phase, and as funders, they hold researchers accountable to fulfilling predefined deliverables (e.g. *x* number of workshops per year, *x* number of scientific productions). At the same time, the scientific underpinning of the program is mutually respected. As researchers are not expected to produce specific or necessarily 'usable' results that are readily applicable to practitioners, they are allowed a certain amount of autonomy. Partners have the opportunity to express their concerns and prioritise their needs which are then discussed with researchers to determine what is considered relevant or feasible within the program. Nevertheless, PIREN's work is considered to be scientifically objective since research is led by scientists from recognised research institutions and is subject to peer review.

In CRCWSC, the new paradigm mentality is embraced and actively promoted, adopting it as its principal *modus operandi* that regards the production of science in terms of a 'public good' (Researcher-Professor, Civil Engineering, 9 June 2017). However, while it is true that the majority of CRCWSC researchers aim for applicability and knowledge transfer, some spoke of capitalising on the opportunity to fund what they considered to be 'pure' scientific research projects (Researcher-Associate Professor, Microbiology, 20 January 2016). At the same time, a closer look at the CRCWSC research program reveals two different philosophies. Underlying Tranche 1 appears to be the old paradigm – 'science for science', whereas Tranche 2 appears to be driven by the new paradigm – 'science for regulation'. Thus, while a distinction between the two may seem straightforward, they are not mutually exclusive.

This co-existence of paradigms recalls what Hoppe *et al.* (2013) refer to as 'sacred' or front-office narratives of idealized worlds working in parallel with the more 'profane' or back-office truth that the spaces of engagement and transgression between science and policy are in fact fluid and vague. Contrary to the linear model of knowledge production, transfer, and use upon which many conceptions of science-policy interfaces are built (Landry *et al.*, 2001; Nutley *et al.*, 2007; Weiss, 1979), the type of boundary work that occurs in practice is typically more ambiguous, manifesting in ephemeral and/or dynamic arrangements between different configurations of actors depending on the context and objective of the issue at hand (Hoppe *et al.*, 2013; Waterton, 2005). Each configuration will give rise to its own set of 'profane' compromises that are made in order to uphold these 'sacred' narratives.

Within PIREN, the narrative of 'science for science' maintains its profile of scientific autonomy and legitimacy, while the narrative of 'co-production' anchors scientific research to salience, applicability, and accountability. The fact that boundary work outside of PIREN is often carried out by the same researchers in a different arrangement through external contracts is a testament to these contrasting narratives. A higher emphasis on the first narrative has resulted in a compromise in direct usability for practitioners. Whereas PIREN produces knowledge and tools that are considered useful for enlightenment, more direct uses such as decision support or negotiation support often require additional commitment on both sides (knowledge producer and user) that may need to take place through parallel arrangements.

The scientific autonomy granted in this arrangement is not without its limits. A large part of PIREN funding is dependent on the support of its operational partners, necessitating some of its research to be relevant to management and policy needs. Within PIREN boundaries, this demand has been more or less satisfied with work on well-developed models such as ProSe, Seneque, MOCOU and STICS, in addition to scenario building activities and the production of scientific publications and documents. However, in many cases, it was necessary to seek out external contracts and or/arrangements operating outside of the program in order to make this scientific knowledge more usable or tailored specifically to management needs.

'Science for the public good' appears to be the primary 'sacred' narrative of CRCWSC, while it is still grounded in 'science for science' for the same reasons as PIREN. Working on a limited time scale for both research and application has the potential for compromising scientific rigour and quality in favour of producing usable knowledge and tools that are delivered at the end of the program. Scientific quality is upheld by the expertise of the researchers and knowledge inherited from other research programs. However, the time devoted to developing usable tools within the program may not be sufficient to ensure their transfer and usability as well as the necessary maintenance and support after the program has concluded.

In the context of the shifting paradigms of science and management, individual scientists are engaging in micro-level boundary work as a way of obtaining multiple funding contracts. On one hand, different funding sources shape the kind of research that is being conducted and subsequently the types of knowledge that are produced, as well as how the results are communicated (Hunt and Shackley, 1999; Waterton, 2005). On the other, more pressure to acquire research funding underlined by an increasing demand for political accountability and usability has resulted in a diversity of concurrent science-policy arrangements, making parallel demands on scientists, which can sometimes create a loss in identity (Waterton, 2005).

On an individual level, the co-existence of the new and old paradigms can cause a sense of disillusionment and disorientation: *"I feel a bit lost. I find myself asking what are we really doing here? What is this for? What is the point of it all?"* (Postdoctoral Researcher, Hydrological Engineer). Other examples of existential turmoil appear to be more prevalent among newer generations of scientists who are finding it more difficult to reconcile the value of 'pure' science with our modern world, where science is increasingly framed according to societal needs. On the other hand, those who remain content with conducting 'science for science', unencumbered by its potential application, may be driven to make more compromises in the future, as funding is becoming inextricably linked to applicability.

The closer relationship between science and policy may cause feelings of discomfort as researchers are increasingly called upon to support decisions, while at the same time, remain limited to a specific role: "*Even if I want my research to have an influence on policy, I'm not a policy-maker. That's not my role"* (Researcher, Economist, 1 December 2016). Within the PIREN, researchers face mounting pressure to respond to the call for policy-relevant science from operational partners as well as their home institutions, which can be a major source of friction. For example, many researchers from *École des Mines* are also under contract with ARMINES, which is an important source of funding (Researcher, Hydrologist, 9 June 2016). As such, they are often faced with the dual pressure of fulfilling the duties asked of a researcher ('publish or perish') as well as those of a consultant (to offer tailored services and/or products in a set amount of time) (Researcher-Lecturer, Hydrogeology, 21 February 2018).

In addition to providing consultancy services through ARMINES researchers are being pressured to obtain funding by licensing its modelling tools. However, this may run counter to the ideals of a scientist who maintains old paradigm thinking. In Australia, internal conflict may also be experienced by researchers embracing new paradigm thinking. While they want their research to be applicable, the heavy investments in time and resources required to making it usable is taken away from the pursuit of 'pure' research, which is already strained by the continual search for new funding (Researcher-Professor, Ecohydrology, 17 October 2017).

Exploring the different scales of boundary work offers insight into how to enhance the role of boundary organisations. Specifically, they can be used to help ground research activity in a 'home base', which focuses resources and coordinates actors around common objectives, while integrating parallel arrangements to become more efficient. At the same time, providing a dedicated space and clearly demarcating activities in 'pure' research and 'applied' research can help offset some of the destabilising effects brought on by the shift in paradigms. This role must also be considered in the wider context of multi-scalar boundary interactions and boundary organisations that exist within the same space. Boundary organisations could therefore benefit from forming boundary chains (Kirchhoff *et al.,* 2015; Lemos *et al.,* 2014) or Triple Helix Clusters (university-industry-government) (Etzkowitz, 2012; Etzkowitz and Leydesdorff, 2000; Etzkowitz and Zhou, 2006; Jacob, 2006; Viale and Etzkowitz, 2005) to leverage different level arrangements into concerted action.

Conclusions and Perspectives

Chapter 1 explored the diversity and design of modelling tools in water resources management. Scientific advancement coupled with increased computing power has led to the development of a wide range of modelling tools that serve different functions. Yet, the examples of the PIREN-Seine in France and the CRC for Water Sensitive Cities in Australia highlighted the fact that not all are created equal in terms of use and utility; which are not only dependant on the user profile, but also the context in which models are developed and used.

The PIREN example illustrated how a model can still be considered *useful* even if it is not *used* in the manner characterised as Direct++ or Direct+ (e.g. entering and running simulations independently). Often, having access to modelling results rather than the tool itself was sufficient for practitioners with neither the time nor expertise to run simulations themselves or whose *ad hoc* usage did not warrant investment in internal expertise (i.e. Direct user types). Therefore, it was not necessary for a model to be 'user-friendly' in order for it to serve a purpose, just as a model's 'usability' did not ensure that it would be used.

The strategy adopted by the PIREN as it transitions into the next phase of the program (Phase 8) has been to develop more expert-based models (e.g. Pynuts) based on a library comprising blocks of code. Rather than investing time and resources to develop, test and maintain a user interface on a model that may not be used, this approach offers the benefit of developing a more flexible, adaptable model, which ends up being more useful for both researchers and practitioners.

While the number of end-users is limited, this strategy can be seen as a way of insulating the model from misuse. In this case, it becomes more important to ensure that the limits and assumptions of the models are made explicit and are mutually understood. Selling ‘services’ rather than the model itself helps maintain the role of scientists and re-establish the boundary between science and practice. However, this may not align with the objectives of some practitioners who benefit from traversing those boundaries. The history of ProSe, for example, is a reflection of the conflicting objectives in terms of what processes and parameters should be included.

In the CRCWSC example, a focus on the end-user has prioritised more ‘user-friendly’ models to support decision-making and develop business proposals for urban planning. While it is still too early to evaluate the impact of these models, the success of MUSIC suggests that supporting structures such as capacity training and user manuals may enhance their use and utility. At the same time, the context in which MUSIC was developed is unique in that it benefits from eWater, an organisation providing technical support, maintenance and upgrades, as well as government endorsement. It is also important to note that the function of MUSIC is different from that of over CRCWSC models: whereas MUSIC supports water managers for short- to medium-term management and planning, modelling tools such as DAnCE4Water are designed for a diverse audience to support longer-term scenario planning.

In both examples, the history of model development has a big impact on use and utility. In some cases, good timing, marketing and mutual investment have an overriding influence over what models are used or considered useful. For example, the MUSIC and ProSe models were developed at a time when no equivalent models were available. Over time, trust is built among actors, which fosters collaboration, which in turn, results in a better alignment of objectives. Beyond the technical role of transforming scientific knowledge and data into information that can guide decisions, models also play an important role in facilitating communication and mediation among a diverse set of actors.

Chapter 2 delved into the fundamental challenge of uncertainty in the modelling process, focusing on the PIREN example to elucidate why the treatment of uncertainty in practice appears to be minimal despite a growing concern. The common perspectives and approaches to addressing uncertainty were outlined in **Part 1**, while **Part 2** explored the ways in which different actors deal with uncomfortable knowledge in order to take an action or decision.

The analysis in **Part 1** revealed a number of gaps in the academic-oriented approach of researchers, which focused on uncertainties that were easily identifiable, quantifiable and mostly technical. The highly academic and fragmented nature of these methods contributed to an environment of ambiguous knowledge, where practitioners were compelled to adopt a more field-oriented approach. On one hand, PIREN provides an environment of trust and collaboration, allowing practitioners to maintain confidence and reconcile the cognitive dissonance felt when left with methods that are not easily comprehensible, accessible or applicable in practice. On the other, it can lead to unfavourable outcomes if the model assumptions and limitations are not explicitly discussed or understood. Actors at the science-practice interface could therefore benefit from existing frameworks and guidelines to enhance communication and mutual understanding of uncertainties.

Furthering this analysis, **Part 2** highlighted the underlying challenge of dealing with uncertainty in the modelling process. First, uncertainty is not only a technical problem to be resolved with more data and knowledge; it is a multifaceted question that can be understood in many ways, according to the type, source, location as well as the way it is framed or how it relates to different actors. The perception of uncertainty can differ according to the individual, their background and training, as well as the institution they represent, which also reflects the ways in which uncertainty is treated (or not).

Second, it is important to consider the question of uncertainty within the larger socio-political context of the modelling process. Whereas evidence-based policy favours simplification, quantification and compression, which is necessary for the 'management' of complex environmental problems, it also opens the door for the social construction of ignorance, which leaves us unprepared to adapt and respond to unforeseen events.

Chapter 3 analysed the concept of boundary organisations in the context of a new paradigm of science and management. Originally, boundary organisations were intended to provide a neutral space for exchange between different social worlds, while maintaining the distinction between them through mutual accountability. Yet, changing societal demands and a growing dependence of research on public funding has prompted actors to take on hybrid roles. These factors inevitably shape the type of knowledge and tools that are produced and how they are represented.

While there is no 'recipe for success', the performance of a boundary organisation is ultimately dependant on whether the mutually agreed upon objectives are perceived to be met according to the actors involved. Boundary organisations such as the PIREN-Seine and CRC for Water Sensitive Cities can facilitate the co-production of knowledge, which helps to build and maintain trust, credibility and legitimacy among actors. This role may serve to reconcile uncertainty while also enhancing the use and utility of scientific knowledge and tools. Whereas boundary organisations can be seen as a way of orienting resources and towards common objectives, modelling tools act as 'boundary objects', providing a common reference for diverse actors to communicate, debate and collaborate on shared issues.

In the new paradigm of science and management, the lines between science, policy and practice are becoming increasingly blurred. It is no longer possible to isolate 'objective' scientific facts from subjective interests, values and biases in the policy arena. New modes of funding have fostered a more direct link between research and action. But the negotiation involved in reconciling the interests of science and practice raises a number of questions in terms of the role of scientists in policy and practice. In this context, the concept of boundary organisations may not sufficiently capture the interactions and exchanges occurring on an individual level. On one hand, boundary spanning or boundary crossing can be a way of brokering knowledge so that the objectives of science, policy and practice are better aligned. On the other, it can lead to the 'politicization of science' or the 'scientization of politics'.

As the title suggests, this thesis sought to elucidate the multi-dimensional functionality of modelling tools in water resources management. This study was largely retrospective, leveraging the long history of the PIREN-Seine and the cumulative work underpinning the CRC for Water Sensitive Cities. On one hand, looking to the past presents a learning opportunity, echoing the aphorism of Spanish philosopher George Santayana, who warned: "*Those who cannot remember the past are condemned to repeat it*" (1905), which was later paraphrased by Winston Churchill in a speech to the House of Commons as "*those who fail to learn from history are doomed to repeat it*" (1948). On the other hand, the past can no longer be considered the key to the future:

> "*We live in a world of contradiction and paradox, a fact of which perhaps the most fundamental illustration is this: that the existence of a problem of knowledge depends on the future being different from the past,*

> *while the possibility of the solution of the problem depends on the future being like the past*" (Knight, 1964: 313)

Nevertheless, having a good understanding of the past remains an essential element to navigating future practices. Exploring the interconnected themes of 1/ use and utility, 2/ uncertainty and 3/ boundary organisations has led to new insights and highlighted prevailing gaps at the interface of science, policy and practice. Yet, a number of fundamental questions are still up for debate in the present and future directions of models in the context of water resources management, which will be discussed in the following sections.

Models: Solution or Delusion?

Continued investment in modelling tools in science and practice suggests that for the foreseeable future, the place of modelling in water resources management is secure. But *is this investment warranted or are there 'better' options?*

Models, by definition, represent a section of reality through a single, reductionist frame. Therefore, they are necessarily false; a fact that is universally accepted and widely acknowledged. Yet, in the paradigm of evidence-based policy, models are often considered a source of objective scientific truth. On one hand, evidence-based policy is oriented towards precise figures, which enables decisive action (or justifies inaction). On the other, it continues to demand from science a level of certainty and precision that it simply cannot provide.

While we are beginning to acknowledge this fallacy, it is still deeply ingrained in our conception of what constitutes 'good science', making it more difficult to question its legitimacy or break free from this mentality:

> "*The traditional view is that science involves empirical observation, theory formulation, theory testing, theory revision, prediction, control, the search for lawful relationships and the assumption of determinism; and scientists are the 'experts' in carrying out this process. Within this traditional view of science came a range of methods to support these processes and these are carried out by researchers who consider them normal, if not essential, to produce good science*" (Bosch *et al.*, 2007: 230)

Models are a fundamental tool for transforming scientific knowledge and data into a range of scenarios with which to explore and test different management, planning and policy options. However, there is still the question of supply and demand. Whereas potentially useful models are not always used because they are not readily accessible for practitioners; the ones that are used are not always the most appropriate:

> "*Usually, scientists attempt to answer the questions of policymakers by using an existing model or toolkit that is on the shelf but which does not really match the decision-making needs*" (Van Der Sluijs, 2016: 172)

According to Turnpenny *et al.*, (2008) the use of policy tools such as models is often shaped by organisational norms and routines, where practitioners rely on tools in which they have invested. In France, political pressure to make the Seine swimmable for the 2024 Olympic Games has prompted actors within the PIREN to respond to this question using methods and models, which may not be readily suited for the task. Whereas the question of swimmability is concerned with microbiological water quality and bacterial concentration, the model ProSe was originally developed to understand the grand cycles of phosphorous and nitrogen; one of the main issues resulting from the SIAAP's wastewater treatment plants. Although ProSe has a biological component (the submodel RIVE), it was not specifically designed to directly respond to questions of swimmability. Usage of these models, therefore, demands the integration of variables that were not among the primary objectives of the model.

While in this case, model uncertainty can be increased exponentially, boundary organisations work to ease this tension through discussion and negotiation between actors to collectively establish the veracity of modelling results in a given context. However, this certainty stems from an understanding of its limits, which often gets lost in translation along the decision chain:

> "*At a given moment, a small simulation, when it becomes indispensable, one can accept the uncertainty or a poor-quality simulation, one just needs to be aware of it when using the interpretation of the results. But the difficulty is that sometimes you're not always in control of the interpretation and the decision of the results […] Afterwards, nothing prevents someone from making a photocopy of the page and saying, 'This is the reality' and completely obscure the 10 lines above that say, 'Yes, but not in these conditions'*" (SIAAP Representative, 10 March 2017)

The majority of interview participants agreed that having any information is preferable to having none, even if it is incomplete, uncertain or entirely false. This type of wilful ignorance could be justified if the results are used to evaluate or monitor a general trend. At the same time, using scientific evidence without a true understanding of its limits or how it was produced can make it easier to pass regulatory science for academic science. Barbier *et al.*, (2010) describe this process as transforming the socio-technical infrastructure into an 'indisputable black box'.

Many types of models now exist to simulate different processes on different spatial and temporal scales, with varying levels of complexity. While each model is a source of new and potentially useful knowledge, the quantity and diversity of these tools can also produce ambiguous or conflicting knowledge, which is not conducive to decision making.

This was the case in Denmark when five of the country's top scientists were tasked with identifying the most vulnerable part of a strategic groundwater resource near Copenhagen. They were given the same question, basic data and measurements from the same area. Yet, using different models and approaches produced contradictory results, leaving practitioners in a difficult position:

> "*However, imagine that science has spoken and that it is now up to policymakers to make a wise decision. What can they do? They can say, 'Let us be precautionary and assume the worst case, since if we guard against the worst case, then we are more or less sure that we can protect the zone'. But the cost of that strategy may be disproportionately high. They may say, 'We need more information before we can decide'. That is the infamous paralysis by analysis pitfall: more information produces contradictions, so the decisions are postponed in an infinite loop of evidence-gathering and indeterminate analysis*" (Van Der Sluijs, 2016: 157)

In a post-normal world, where decisions are urgent, stakes are high and values in dispute (Funtowicz and Ravetz, 1993), time is considered a luxury that we can no longer afford. Decisions must be taken even when the best available knowledge is imperfect, incomplete and uncertain. In this context, models can be considered a functional delusion, transforming complex environmental problems into ones that are more 'manageable'. Models can indeed be useful, with the caveat that the limits and assumptions of models are properly communicated and understood. *But do we really need more models or do we need 'better' ones? More importantly, which models are needed when and how do we select the 'right' one for the job?*

Models as a 'Boundary Object'

In recent years, the perceived role of modelling has begun to shift from that of a crystal ball, enabling prediction and control, to that of a compass, used to navigate complex systems. Many authors (e.g. Bruijn *et al.,* 2010; Edelenbos *et al.,* 2003; Hommes *et al.*, 2009; Koppenjan and Klijn, 2004; Orr *et al.*, 2006; Pahl-Wostl, 2006) now advocate for the adoption of a process-based approach to water resources management, which takes into account participation, communication, collaboration, social learning, and the diversity of perceptions. In this context, models can serve as a communication tool, facilitating interactions and exchanges between different actors across different boundaries.

The examples of PIREN and CRCWSC illustrate two approaches to using models as 'boundary objects'. CRCWSC has a 'fixed-frame' approach, where the tools, strategies and discussions are framed within the concept of water sensitive cities. In contrast, PIREN has adopted a 'scoping' approach, using models as a tool for framing the discussion around 'objective' scientific evidence that can be discussed and debated among different actors to co-define the problem as well as potential solutions.

Models as Boundary Objects in a 'Scoping' Approach

Models have been used as a mediation tool on a number of marginal, yet notable cases within the PIREN. The model ProSe was used to facilitate debate among a diverse group of actors (scientists, elected officials, representatives of kayakers and fishermen) in the Deux Morin catchment of France (De Connick, 2015). Modelling was used to structure the discussion incorporating different perceptions, knowledge and representations of the river to reach an agreement on management options.

In another case involving the Deux Morin, modelling was used to resolve disputes over the removal of obstacles and sluice gates; a contentious issue due to their emblematic status among local stakeholders (Carré *et al.*, 2014). An agent-based conceptual model ARDI was used to build a common representation of the river, based on a diagram of Actors, Resources, Dynamics and Interaction. ProSe, which was used to simulate flow rates and water levels, was coupled with the model ANAQUALAND, a model used to simulate fish movement behaviour, and used as an interactive platform to facilitate role-playing activities where different actors could test out different scenarios according to different perspectives. Debate and discussion around these activities eventually led to a better understanding of the situation from different perspectives, fostered compromise and the discovery of new solutions.

A similar approach was applied in the Seine-et-Marne region of France using Co-click'eau (Chantre *et al.,* 2016; Gisclard *et al.,* 2015) to facilitate territorial dialogue concerning the impact of diffuse agricultural pollution on water quality (Tournebize *et al.,* 2018, 2017). Co-click'eau is a participatory approach that facilitates the co-construction of scenarios, helps design these scenarios through an online simulation tool in order to formulate concrete actions. This was used in conjunction with METE'EAU, a perception tool that integrated the question of biodiversity, to facilitate role-playing activities.

These examples highlight the role of modelling tools beyond prediction and control to facilitate dialogue and collective action. Participatory approaches help to build and maintain trust among a diverse group of actors with conflicting interests. Role-playing activities enable social learning, as actors are obliged to assume a position that is different from their own. Modelling provides a neutral space for discussion and debate while also providing a framework for more robust solutions. Trust may be improved if actors are able to contribute to the construction and selection of modelling tools, which also helps to 'democratise' the scientific process.

Yet, these activities remain marginal due to a number of limitations. The examples above reported positive outcomes in increased mutual understanding of the issue, but it was not always reciprocal. In the Seine-et-Marne case, agriculture is a historically contentious issue. Farmer representatives were originally reluctant to participate but were eventually able to express their concerns. In the end, they felt heard by other participants, who could better understand their perspective. However, the strong position of farmers prevented them from being receptive to outside perspectives (PIREN Researcher, Hydrologist, 5 October 2018). This goes back to the issue of trust, which requires more time and effort to build, particularly for deeply contentious issues such as agriculture in France.

Participative approaches are also a way to deal with uncertainty, creating more transparent dialogue and exchange between those who traditionally produce knowledge and those who use it. In the Deux Morins, a more prudent action plan was created through the testing of different scenarios, which allowed them to better understand the consequences of removing dams (Carré *et al.*, 2014). Conversely, De Connick (2015) found that while this approach allowed actors to define and discuss uncertainties, it did not go as far as reducing uncertainties or making them acceptable enough to form policies. While the integration of different perspectives and transparent discussion address relational, ambiguous and framing aspects of uncertainty, model-related uncertainties were still rarely discussed. In this context, they could be considered less of a priority since models were used to facilitate discussion and exploration of possible options. However, it becomes important if modelling results are used as a basis for concrete actions.

Modelling can provide the framework for discussion and debate, but in doing so it can limit the scope of possibilities to the model's capabilities. As existing PIREN models are not readily adapted for this use and could not cover all of the user expectations, the discussion had to be reframed according to what questions could be answered by the available models (Carré *et al.*, 2014). While the models needed to be adapted, there were still fundamental constraints posed by the model limitations. For example, in the Deux Morins, the model was limited to hydraulic aspects and could not function when the Morin was dry (De Connick, 2015). Instead of reflecting on how to deal with dry situations, this led to actors avoiding the issue altogether. In the second Deux Morins example, ProSe could only perform on the downstream section of the river covering a 44km stretch (Carré *et al.*, 2014).

The ephemeral nature of these experiences in the PIREN is also due in part to constraints in time and competences. Despite a growing number of social scientists within the PIREN, they still represent the minority. In the Seine-et-Marne case, consultancies specialising in facilitation needed to be brought in because facilitation was considered to be a special skill-set separate to that of researchers. On one hand, mediation from an external party contributes to the sense of neutrality in debates and discussions. On the other, having a third party presents difficulties in knowledge transfer and translation. Facilitators are often difficult to find and are hired as interns on temporary contracts, making it difficult to transfer the necessary knowledge to produce the desired outcomes (INRA Researcher, Agronomy, 28 August 2018).

Participatory approaches also demand enormous commitments in time in order to build trust and carry out the activities, which include collective envisioning, discussion and debate, co-constructing, testing and re-testing scenarios, and in some cases, forming action plans. Therefore, it was common that not all actors could participate or only participated on an occasional basis. The voluntary nature of participation also meant that the actors involved are not necessarily the ones who can enact change, as decision-makers are usually too busy.

In the Seine-et-Marne, Tournebize *et al.*, (2018) reported that out of the 68 people mobilised by the project, 49 participated in workshops (coming once or participating in all):

> "*Apart from a hard-core group of 13 people who came to at least 3 out of 5 meetings, the other participants came to the workshops very occasionally, sometimes only to the field visit. The 'hard core' group was composed of 5 farmers, 2 industry actors, 2 community representatives, 1 representative of state services, and 1 representative of the Hunting Federation of Department 77*" (Tournebize *et al.,* 2018: 3)

In addition to time constraints is the related issue of resources and financing required for preparing and conducting these approaches. Carré *et al.*, (2014) reported that the total cost of their experiment in the Deux Morins was "*28 hours of workshop time, 32 people directly involved, 12 meetings to prepare the workshops, 130 days of software development, with the program entirely funded by Water Agency and PIREN-Seine research program.*"

A growing number of empirical examples have illustrated the advantages offered by participatory approaches, despite continued challenges. While these approaches are endorsed on an international and national level through regulations such as the WFD, actual implementation in practice remains marginal. The question remains: *are we willing to make the necessary investment?* If so, *who is responsible for implementation?* More importantly, *how do we ensure adequate representation and participation in order to enact real change?*

Models as Boundary Objects in a 'Fixed-Frame' Approach

As indicated by its name, the CRC for Water Sensitive Cities is structured around the concept of water sensitive cities. This, of course, is reflected in the knowledge and tools that have been produced, aiming to guide practitioners towards the adoption of water sensitive practices and policies.

In Tranche 2 of the program, CRCWSC tools have evolved to form the Water Sensitive Cities (WSC) Toolbox, comprising three main platforms aimed at guiding the user from conception to design and implementation of water sensitive solutions (*see* Figure 1 below). As per the CRCWSC website, the WSC **Transition** Platform builds off of the WSC Index and is designed to support the early stages of conception. In addition to the WSC Index, it includes a management action database and a monitoring tool for target setting and ongoing evaluation. The benefit of this tool is that it can be accessed online and used either individually or as a whole.

Next, the WSC **Scenario** Platform supports the creation and evaluation of concept designs and technology/policy solutions towards water sensitive solutions. This has evolved from the WSC Modelling Toolkit. Additional models include TARGET (an extreme heat mapping model); UMEF4Water (an urban metabolism framework that quantifies the water balance of an urban area), and; a cost-benefit analysis tool. The WSC **Scenario** Platform is organised as a library of individual but connected models capable of quantifying the advantages of green infrastructure initiatives to support the development of robust business cases.

Finally, the WSC **Design** Platform is a tool intended to support the design and implementation of water sensitive cities by modelling the evaluation of urban water structure, water networks, population demographics and their interactions over time. Users can also upload input data such as land use maps or drainage schematics to develop more personalised water management scenarios.

The Training and Outreach sub-program is aimed at enhancing the use and utility of the WSC Toolkit through user guides, reference material and capacity building workshops. Collaboration between researchers and practitioners throughout the program has contributed to the development of tools that are intended to meet the industry needs. The process of beta testing allows practitioners to familiarise themselves with the tool, which builds confidence while providing feedback contributes to a sense of ownership. Case studies provide empirical examples with concrete results.

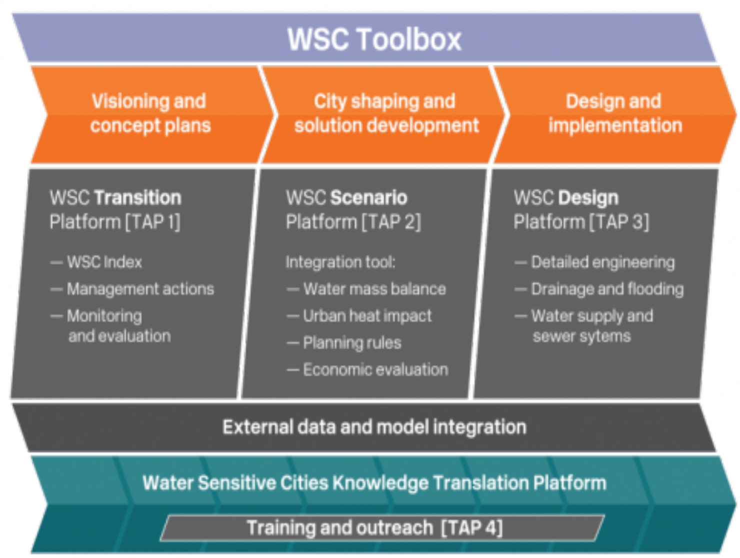

Figure 1. Revised Water Sensitive Cities Toolbox
(CRC for Water Sensitive Cities Website, 2018)

Key Factors Contributing to Models as a 'Boundary Object'

The contrasting examples of PIREN and CRCWSC illustrate how each approach is a reflection of their respective contexts and their functioning as a boundary organisation. A 'fixed-frame' approach works for CRCWSC because it has a clearly defined objective: to achieve water sensitive cities. The way the program is structured also allows for tools to be designed specifically to harness and apply research outputs, making a more direct link from research to practice. At the same time, structuring the tools and discussion around water sensitive solutions could limit the scope of possible solutions by framing the narrative around cities. Having a clearly defined objective is helpful for mobilising action, but the focus on urban areas could overlook conflicts and influences affecting water use from neighbouring peri-urban or rural areas.

A 'scoping' approach is more suited to the context of the PIREN. On one hand, it reflects the mentality of the PIREN as a research program. Whereas CRCWSC assumes the role of a policy advisor, the PIREN prefers to draw the line between research and policy, even if the lines are often blurred, for example, in the case of ARMINES. On the other, water quality issues are complex and diverse, requiring different solutions according to the specific context. A 'scoping' approach allows for a more open exploration of different options according to local actors.

Regardless of the approach that was taken, a number of factors were identified as being essential to the functioning of models as 'boundary objects'. In both cases, intermediaries were necessary. While the aim of CRCWSC tools is to be transferred directly to the practitioner, an intermediary is needed to run the model and/or facilitate discussion. Though it is still too early to say, the experience of MUSIC indicates that an external organisation such as eWater will be necessary to maintain the models after the program is finished. Previous experiences in the

PIREN revealed a need for models that can be adapted for this boundary object function. The new modelling strategy of the PIREN presents new opportunities for participatory approaches, yet the expert nature of these models means that an intermediary will still be required to run the model. These examples also highlighted a need for more social scientists and possibly the integration of organisations specialised in facilitation.

In the context of this thesis, the models studied in the examples of PIREN and CRCWSC can be characterised as deterministic models or modelling tools that are underpinned by deterministic modelling techniques. In other words, regardless of the type of modelling tool, their degree of complexity, or use and utility, the underlying rationale is that these tools are based on an understanding of the variables and the relationships between them, reinforced by empirical evidence and experience, which are presumed to produce results that are more or less, correct and scientifically objective. It is this deterministic quality and that allows for the convergence of different actors to discuss and debate 'tangible' issues such as the meaning of which processes were included, which were not, which variables were considered and which were neglected and their subsequent impact on management, policy and planning decisions.

What Qualifies as Adequate Representation?

The question of representation is multiple. For a deterministic water model, representation may refer to which biological, chemical or physical processes are represented and how (due to equifinality); the temporal (e.g. hourly, daily, annually) and spatial (e.g. urban system, catchment, river segment, groundwater) scales; or the inclusion of other systems or fields (e.g. economics, agronomy, biodiversity, social behaviour). In the context of management and policy, representation is often a reflection of power, according to which actors or institutions are represented, to what extent, and what is transformed in the process of representation. Here, we explore the question of representation on both levels to elucidate what qualifies as adequate representation. Specifically, *in a world that is complex and increasingly interconnected, how and where do we draw the line?*

Technological Representation: Is More Data Necessarily Better?

The question of complexity vs. use and utility was discussed in the introduction of this thesis and later explored in the examples of the PIREN-Seine and the CRC for Water Sensitive Cities. Modelling tools that are more complex (e.g. including more processes) and detailed (e.g. on a finer temporal/spatial scale) may provide a more accurate representation of reality, but in practice, use and utility depend on a variety of factors (e.g., objective and expertise, knowledge and tools, support structures). This would suggest that the adequate level of technological representation in a model is contingent on how the model and/or its results are used. Yet, current trends are moving towards acquiring increasing amounts of data, leading to a potential revolution in terms of models that are used or considered useful.

Though the concept of artificial intelligence (AI) techniques is decades old, increasing abundance of data and computing power has enabled the advancement of other forms of modelling, such as statistical models and machine learning (ML). For Chau (2006), AI is a way of bridging the gap between science and practice of classic numerical modelling systems, which are seen as insufficiently user-friendly and lack knowledge transfers in model interpretation. According to Chen *et al.*, (2008), knowledge-based or AI techniques are being used more and more to due to its potential over classical modelling techniques in terms of capability and efficiency. For example, Big Data (BD) may enhance decision support by allowing causality inferences to be made based on chains of sequence, whilst ML can uncover interesting patterns that would otherwise go unnoticed using datasets (Zhou *et al.,* 2017). Perhaps one of the greatest advantages of ML is its capacity to handle and combine vast numbers of predictors in nonlinear and highly interactive ways (Mullainathan and Spiess, 2017), allowing new kinds of data to be used, "*whose sheer volume or complexity would previously have made analyzing them unimaginable*" (Obermeyer and Emanuel, 2016: 1216).

The logic behind these new trends echoes the argument for more complex models: more data equals better representation. From a practitioner's point of view, this is a pragmatic approach, which also addresses the question of uncertainty. It may also be easier from a logistical standpoint to install monitoring stations than to develop expertise in models that need to be constantly updated and may not be as accurate. Real-time control and artificial intelligence can support management by partially automating the decision process, while machine learning can identify patterns that can help anticipate and respond to highly dynamic systems.

One potential consequence of ML taking over classical deterministic modelling techniques is the loss in fundamental understanding. While the capacity to process and learn from enormous amounts of data has to potential to provide more accurate predictions over classical deterministic modelling techniques, ML relies on statistical methods that no longer include physical processes. In ML, the internal representation and understanding of physical processes that are at the heart of deterministic modelling techniques are replaced with mathematical algorithms that relate input data and observational data to make predictions. But while algorithms are useful in predicting outcomes, correlation should not be confused with causation (Kleinberg *et al.*, 2015; Obermeyer and Emanuel, 2016). Statistical methods can lead to better results in terms of representation, but this 'black box' approach no longer rests on processes that we can explain. The trust in AI to produce accurate results combined with a loss in the fundamental understanding of the processes could make it more difficult for non-experts to identify and recognise potential errors in the code.

In the PIREN example, this risk is becoming less hypothetical as the SIAAP has become increasingly interested in AI techniques and real-time control for the optimisation of their wastewater treatment system at the daily time step. The lack of such tools in PIREN has led them to invest in another research program, MOCOPEE (Modelling, control and optimisation of the wastewater treatment process), in which the SIAAP is considered a research team as well as its (sole) financial partner. While this arrangement may respond more closely to operational needs, a turn to statistical tools may inevitably result in the loss of the boundary function of models such as ProSe.

Currently, the role of models as a boundary object keeps the relationship between science and practice intact. The uncertainty surrounding models necessitates a stronger relationship between researchers and practitioners in order to collectively agree on what is acceptable and what is not based on science. But if the limitations of the model were already getting lost in translation farther down in the decision chain, it is likely that they would disappear entirely once this process is automated. Additionally, the paradigm shift towards statistical methods could inhibit the boundary object function of models since the physical processes that allow actors to discuss and debate no longer exist. This could, in turn, create a larger gap between science and practice, resulting in a trade-off between the illusion of precision and the production of ignorance.

In practice, AI is a relatively new field with as many challenges as opportunities. First, there is the issue of the data itself. Whilst data pre-processing can address issues such as data redundancy, inconsistency, noise, heterogeneity, transformation, labelling, imbalance and feature representation/selection, it also very costly and sometimes even unusable as some data assumptions do not hold for big data (Zhou *et al.*, 2017). The quantity and quality of data is a major issue. ML algorithms require millions of observations before reaching acceptable levels of performance (Halevy *et al.,* 2009; Obermeyer and Emanuel, 2016), whereas biases in data collection can greatly affect performance and generalizability (Obermeyer and Emanuel, 2016). Obtaining enough data to be representative can be a highly costly endeavour, but insufficiently large or representative training datasets can significantly disable the discovery of all patterns (Zhou *et al.,* 2017) and therefore inhibit the potential of ML. On one hand, these new trends offer the advantage of creating a more direct link from research to practice. On the other, these ties could potentially be broken once practitioners have adopted the technology and the process becomes automated.

In practice, data issues continue to present a major challenge. The management of water resources is often divided among several institutions that do not always communicate with each other. Data is collected in different ways, at different points and temporal scales, and according to each institution's objectives. Even the same institution can manage data in different ways. For example, a number of PIREN researchers have commented on the difficulty of treating heterogeneous data from different Water Agencies in France due to their lack of a unified approach even within the same institution. The question of quality control is not only sorting *good* or *useful* data from *bad* or *useful* data but also how *good* data is defined and by whom?

Another challenge is data ethics issues such as data privacy, security, ownership, and liability (Zhou *et al.*, 2017). In many cases, institutions still control what they share and with whom they share it, as too much transparency can leave them open to criticism. Transforming large amounts of data into something that is useful also implies a system of centralised management, which begs the question of *who would be responsible?* This could be the role of a boundary organisation provided they have built the necessary trust, credibility and legitimacy among actors and institutions involved. As data science is a discipline unto itself, this could mean the integration of data scientists into existing science-practice boundary organisations or the integration of a supporting organisation specialised in data management.

Recently, considerable effort has been made to integrate data and make it accessible to a wider audience. In Europe, data dissemination and sharing are being enforced by regulatory framework such as the PSI Directive on the reuse of public data and the Aarhus Convention on access to environmental information. Not only does this open up data to a wider audience, it also helps practitioners to meet the requirements of the WFD. In France, large databases, such as the RNDE (National Network of Data on Water), the National Water Information System, and the Sandre (*Service d'administration nationale des données et référentiels sur l'eau*) water data repository have been put in place following the approval of the National Water Scheme (*Arrêté du 26 juillet 2010 approuvant le schéma national des données sur l'eau*, 2010).

At the watershed scale, the Water Agency is responsible for monitoring the quality of surface and groundwater, while for quantitative monitoring, the DRIEE and the BRGM (*Bureau de Recherches Géologiques et Minières*), the French government geological survey, is in charge of surface water and groundwater respectively (Gilli *et al.*, 2012). The PIREN has also been working towards the interoperability of data, developing DoNuts (Database of Observed NUTrientS), which was originally designed to validate the model pyNuts (Thieu *et al.*, 2016). It has been combined with a web-based mapping tool (CocoNuts) designed for non-expert users to select, explore, analyse and download relevant datasets.

Social Representation: Who's In, Who's Out?

Representation in boundary organisations is plagued with the question of *who should be included and to what extent?* But whereas technical representation was primarily a question of accuracy, the representation of actors and institutions in a boundary organisation is also a question of power. On one hand, more voices mean better representation and could lead to more participation and enhanced collaboration. On the other, the inclusion of more perspectives and actors with conflicting objectives could potentially limit effective action. Here, the question of representation is considered in terms of the institutions and actors involved, as well as their background, training and role (e.g. academic discipline, elected official, technician, researcher)

PIREN focuses on water quality issues within the Seine watershed and includes actors and institutions at the regional and national scale. As the program progressed, the interconnectivity of environmental systems has necessitated them to explore parallel issues of agricultural production, water quantity (e.g. navigation and flooding), climate change, and more recently, the agro-food system, even if it is still framed through issues of water quality. While the perspective of different user groups such as fisherman, farmers and kayakers have been included in a small number of studies; they are not officially represented in the core partners of PIREN.

Continued work on agro-food systems would also necessitate the possible integration of citizen groups or non-governmental organisations (NGOs) since it involves changing consumer habits and citizen participation. However, participation in practice appears to be a double-edged sword. The instrumental, substantial and normative functions of participation can lead to a more efficient and democratic process and enhanced decisions through the integration of different forms of knowledge, however; it can also lead to participation fatigue, disillusionment, or act as a new ruse of power (Barbier and Larrue, 2011).

Recently, PIREN has been open to new proposals in the organisation of Phase 8 of the program. The possibility of opening its doors to new partners has been brought up in several organisational meetings as a way of responding to new political and scientific interests as well as obtaining additional funding. Included in the themes discussed were the hydro-ecology of alluvial plains, which would necessitate partners capable of analysing, modelling and characterising the fauna and riparian flora; the ability of the Seine to contribute to the cooling of buildings, which would necessitate partnerships with private institutions, and; ecosystem services, which came from a strong demand from existing partners. Yet, agriculture, one of the largest polluters of water, is still lacking direct representation within the PIREN. At the same time, many interview participants expressed concern over funding within the PIREN, noting that as the number of research teams and subjects grow, the funding has more or less remained the same. The decision to include new partners may therefore not only be a question of incorporating new competencies but may also be based on their ability to provide funding.

Underlying the discussion of new themes was the types of actors needed to address these subjects. The demand for more social scientists was raised in several meetings, but it was often countered with the issue of *whom?* There are two possible explanations for this. First, the role of social science within the PIREN is not defined clearly enough to be able to identify the profiles that are needed. Second, the type of interdisciplinary social scientist that the PIREN requires is not yet developed in France, as opposed to Australia, where many actors were characterised by interdisciplinary profiles.

CRCWSC focuses on water quantity issues, framed in the context of water sensitive cities. As the objective is the adoption of practices and policies at the local can national scale, its actors and institutions include water managers, local and national governments and urban planners. CRCWSC focuses on water quantity within the city, but it is also affected by a diversity of uses that extend beyond city limits.

Agriculture, for example, is one of the largest consumers of water, yet the list of core partners does not directly include agricultural representatives. Water sensitive practices are focused on urban areas, but the large strain on water resources from agriculture would present major challenges to the efficacy of these practices. Water sensitive practices also tend to overlook issues of inequality, and may not be appropriate for areas that have less access to water resources, receive less rain, or do not have the capacity for implementation.

Towards Digital Catchments: A Happy Compromise?

Recently, the idea of Environmental Virtual Observatories (EVOs) has been gaining attention as an efficient, cost-effective way to address a wide range of environmental issues (e.g. Ceola *et al.,* 2015; Chilingarian and Zolotukhin, 2010; Cieslik *et al.,* 2018; Mackay *et al.*, 2015). While prominent examples such as the UK's Virtual Observatory program and the U.S. National Science Foundation's Earth Cube are still in pilot stages, they have produced promising results.

EVOs offer the advantage of integrating existing modelling approaches with new trends in technology, science and management practices by linking real-time data, models and expert knowledge in a cloud-based computing environment (Buytaert *et al.*, 2012). This can include classic deterministic models that simulate physical, biological and chemical processes, AI techniques, real-time data, as well as the integration of tools that take into account socio-economic aspects. Technical representation is addressed using an interactive platform that integrates different types of data and models to assess and evaluate different systems, parts of the system, or their interactions.

Social representation is also addressed through collaboration between researchers and practitioners in the development of tools, the accessibility of the platform to different types of users (researchers, practitioners, citizens, etc.), and the ability of these users to contribute data (e.g. citizen science). This is also a way of 'democratizing' science so that it is not only in the hands of experts. In a cloud environment, time and space are no longer limiting factors, making it easier to facilitate collaboration and participation between different actors.

By integrating deterministic modelling techniques with new AI techniques, EVOs can serve as boundary objects, preserving the relationship between science, policy and practice, while at the same time maintaining the boundaries between them. In terms of uncertainty, real-time observations and data-mining techniques can reduce input uncertainty, while the construction of scenarios can help to address issues of deep uncertainty, ambiguity and framing.

EVOs would leverage rather than replace scientific expertise to provide enhanced decision support. This is important as ML algorithms may discover many spurious relationships that would require human expertise to discern (Zhou *et al.,* 2017). However, it is unclear whether the modelling or scientific assumptions behind these tools are made transparent. Despite the enormous potential of EVOs, perhaps one of the biggest challenges is the large financial investment required of a project of this magnitude at a time when funding is increasingly scarce. Nevertheless, EVOs could be the way to a happy compromise, satisfying the concurrent demands of science and management without conceding too much of either one.

Bibliography

About the CRCWSC. CRC Water Sensitive Cities. Available online: https://watersensitivecities.org.au/about-the-crcwsc/ (accessed on 2 August 2017).

Ahiablame, L.M., Engel, B.A., Chaubey, I., 2012. Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research. Water. Air. Soil Pollut. 223, 4253–4273.

Alliance ATHENA, 2013. Sciences Humaines et Sociales & Energie. Alliance ATHENA, Paris, France.

Angelakis, A., Mays, L.W., Koutsoyiannis, D., Mamassis, N., 2012. Evolution of Water Supply Through the Millennia. IWA Publishing.

Argent, R.M., Perraud, J.-M., Rahman, J.M., Grayson, R.B., Podger, G.M., 2009. A new approach to water quality modelling and environmental decision support systems. Environ. Model. Softw. 24, 809–818.

Argent, R.M., 2004. An overview of model integration for environmental applications—components, frameworks and semantics. Environ. Model. Softw., Concepts, Methods and Applications in Environmental Model Integration 19, 219–234.

Arrêté du 26 juillet 2010 approuvant le schéma national des données sur l'eau, 2010.

Ascher, W., 1981. The forecasting potential of complex models. Policy Sci. 13, 247–267.

Ascough, J.C., Maier, H.R., Ravalico, J.K., Strudley, M.W., 2008. Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. Ecol. Model. 219, 383–399.

Bach, P.M., Rauch, W., Mikkelsen, P.S., McCarthy, D.T., Deletic, A., 2014. A critical review of integrated urban water modelling – Urban drainage and beyond. Environ. Model. Softw. 54, 88–107.

Baker, M., 2016. 1,500 scientists lift the lid on reproducibility. Nature 533, 452–454.

Baker, R.; McKenzie, N. Troubled waters: What is the Office of Living Victoria up to? *The Age*, 28 February 2014.

Bandura, A., 1977. Social learning theory. Prentice-Hall, Englewood Cliffs, NJ.

Bankes, S., Lempert, R., Popper, S., 2002. Making Computational Social Science Effective: Epistemology, Methodology, and Technology. Soc. Sci. Comput. Rev. 20, 377–388.

Barbier, R., Larrue, C., 2011. Démocratie environnementale et territoires : un bilan d'étape. Participations 1, 67.

Barbier, R., Riaux, J., Barreteau, O., 2010. Science réglementaire et démocratie technique, Regulatory science and technical democracy. A reflection based on water shortage management in France. Nat. Sci. Sociétés Vol. 18, 14–23.

Barillier, A. and Garnier, J., 1993. Influence of temperature and substrate concentration on bacterial growth yield in Seine River water batch cultures. App. and env. micr., 59(5), 1678–1682.

Bates, B., Kundzewicz, Z., Wu, S., 2008. Climate Change and Water. Intergovernmental Panel on Climate Change Secretariat.

Beaudoin, N., Gallois, N., Viennot, P., Le Bas, C., Puech, T., Schott, C., Buis, S., and Mary, B., 2016. Evaluation of a spatialized agronomic model in predicting yield and N leaching at the scale of the Seine-Normandie Basin. Env. Sci. and Poll. Res., 25(24), 1–30.

Begley, C.G., 2013. Six red flags for suspect work: Reproducibility. Nature 497, 433–434.

Benedict, M.A., McMahon, E.T., 2006. Green Infrastructure: Linking Landscapes and Communities, 2nd ed. Island Press, Washington, DC.

Benessia, A., Funtowicz, S., Giampietro, M., Pereira, Â.G., Ravetz, J.R., Saltelli, A., Strand, R., Sluijs, J.P. van der (Eds.), 2016. The Rightful Place of Science: Science on the Verge, First edition. ed. Consortium for Science, Policy & Outcomes, Tempe, AZ.

Bergenholtz, C., 2011. Knowledge brokering: spanning technological and network boundaries. Eur. J. Innov. Manag. 14, 74–92.

Berkes, F., 2009. Evolution of co-management: Role of knowledge generation, bridging organizations and social learning. J. Environ. Manage. 90, 1692–1702.

Beven, K., 2007. Environmental Modelling: An Uncertain Future? CRC Press, London.

Beven, K., 2001. How far can we go in distributed hydrological modelling? Hydrol. Earth Syst. Sci. Discuss. 5, 1–12.

Beven, K., 1993. Prophecy, reality and uncertainty in distributed hydrological modelling. Adv. Water Resour. 16, 41–51.

Billen, G.; Garnier, J.; Mouchel, J.-M.; Silvestre, M., 2007. The Seine system: Introduction to a multidisciplinary approach of the functioning of a regional river system. Sci. Total Environ. 375, 1–12.

Billen, G., 2001. Le PIREN-Seine : un programme de recherche né du dialogue entre scientifiques et gestionnaires; CNRS Éditions; La Revue pour l'histoire du CNRS: Paris, France.

Billen, G.; Garnier, J.; Mariotti, A., 1998. Bilan des transferts d'azote dans le bassin de la Seine: l'approche du modèle SENEQUE; PIREN-Seine: Paris, France.

Billen, G., Garnier, J., and Hanset, P., 1994. Modelling phytoplankton development in whole drainage networks: the RIVERSTRAHLER Model applied to the Seine river system. Hydrobiologia, 289(1–3), 119–137.

Boezeman, D.; Vink, M.; Leroy, P., 2013. The Dutch Delta Committee as a Boundary Organization. Environ. Sci. Policy. *27*, 162–171.

Bonhomme, C., Commenges, H., Deroubaix, J.-F., 2017. Dictionnaire passionnel de la modélisation urbaine. Éditions de l'Oeil d'Or.

Bosch, O.J.H., King, C.A., Herbohn, J.L., Russell, I.W., Smith, C.S., 2007. Getting the big picture in natural resources management: systems thinking as a "method" for scientists, policy makers and other stakeholders. Syst. Res. Behav. Sci. 24, 217–232.

Bouleau, G., 2014. The co-production of science and waterscapes: The case of the Seine and the Rhône Rivers, France. Geoforum 57, 248–257.

Bouleau, G., 2007. La gestion française des rivières et ses indicateurs à l'épreuve de la directive cadre (PhD Thesis). AgroParisTech.

Bouwen, R., Taillieu, T., 2004. Multi-party collaboration as social learning for interdependence: developing relational knowing for sustainable natural resource management. J. Community Appl. Soc. Psychol. 14, 137–153.

Box, G.E.P., 1976. Science and Statistics. J. Am. Stat. Assoc. 71, 791–799.

Brack, W., Dulio, V., Ågerstrand, M., Allan, I., Altenburger, R., Brinkmann, M., Bunke, D., Burgess, R.M., Cousins, I., Escher, B.I., Hernández, F.J., Hewitt, L.M., Hilscherová, K., Hollender, J., Hollert, H., Kase, R., Klauer, B., Lindim, C., Herráez, D.L., Miège, C., Munthe, J., O'Toole, S., Posthuma, L., Rüdel, H., Schäfer, R.B., Sengl, M., Smedes, F., van de Meent, D., van den Brink, P.J., van Gils, J., van Wezel, A.P., Vethaak, A.D., Vermeirssen, E., von der Ohe, P.C., Vrana, B., 2017. Towards the review of the European Union Water Framework Directive: Recommendations for more efficient assessment and management of chemical contamination in European surface water resources. Sci. Total Environ. 576, 720–737.

Brisson, N.; Mary, B.; Ripoche, D.; Jeuffroy, M. H.; Ruget, F.; Nicoullaud, B.; Gate, P.; Devienne-Barret, F.; Antonioletti, R.; Durr, C.; Richard, G.; Beaudoin, N.; Recous, S.; Tayot, X.; Plenet, D.; Cellier, P.; Machet, J.-M.; Meynard, J. M.; Delécolle, R., 1998. STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. Agron. Sustain. Dev. 18, 36.

Brisson, N.; Gary, C.; Justes, E.; Roche, R.; Mary, B.; Ripoche, D.; Zimmer, D.; Sierra, J.; Bertuzzi, P.; Burger, P.; Bussière, F.; Cabidoche, Y. .; Cellier, P.; Debaeke, P.; Gaudillère, J. .; Hénault, C.; Maraux, F.; Seguin, B.; Sinoquet, H., 2003. An overview of the crop model stics. Eur. J. Agron. 18, 309–332.

Brookes, K.; Wong, T. H. F. The adequacy of stream erosion index as an alternate indicator of geomorphic stability in urban waterways. In Proceedings of the 6th Water Sensitive Urban Design Conferene and Hydropolis, Perth, Australia, 5-8 May 2009.

Brown, R. R.; Keath, N.; Wong, T. H. F., 2009. Urban water management in cities: Historical, current and future regimes. Water Sci. Technol. J. 59, 847–855.

Brown Gaddis, E. J.; Vladich, H.; Voinov, A., 2007. Participatory modeling and the dilemma of diffuse nitrogen management in a residential watershed. Environ. Model. Softw. 22, 619–629

Brugnach, M., 2017. The Space in Between: Where Multiple Ways of Knowing in Water Management Meet. J. Southwest 59, 34–59.

Brugnach, M.F., Henriksen, H.J., van der Keur, P., Mysiak, J., 2009. Uncertainty in adaptive water management: concept and guidelines. Water Manag.

Brugnach, M., Dewulf, A., Pahl-Wostl, C., Taillieu, T., 2008. Toward a Relational Concept of Uncertainty: about Knowing Too Little, Knowing Too Differently, and Accepting Not to Know. Ecol. Soc. 13.

Brugnach, M., Pahl-Wostl, C., 2008. A broadened view on the role for models in natural resource management: Implications for model development, in: Adaptive and Integrated Water Management. Springer, Berlin, Heidelberg, pp. 187–203.

Brugnach, M., Tagg, A., Keil, F., de Lange, W.J., 2007. Uncertainty Matters: Computer Models at the Science–Policy Interface. Water Resour. Manag. 21, 1075–1090.

Bruijn, H. de, Heuvelhof, E. ten, Veld, R. in 't, 2010. Process Management: Why Project Management Fails in Complex Decision Making Processes. Springer Science & Business Media.

Brundtland, G., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., Fadika, L., Hauff, V., Lang, I., Shijun, M., Morino de Botero, M., Singh, M., Okita, S., Others, A., 1987. Our Common Future ('Brundtland report'). Oxford University Press, USA.

Buizer, J.; Jacobs, K.; Cash, D., 2016. Making short-term climate forecasts useful: Linking science and action. Proc. Natl. Acad. Sci. 113, 4597–4602.

Buytaert, W., Baez, S., Bustamante, M., Dewulf, A., 2012. Web-Based Environmental Simulation: Bridging the Gap between Scientific Modeling and Decision-Making. Environ. Sci. Technol. 46, 1971–1976.

Callahan, B.; Miles, E.; Fluharty, D., 1999, Policy implications of climate forecasts for water resources management in the Pacific Northwest. Policy Sci. 32.

Callon, M., Lascoumes, P., Barthe, Y., 2009. Acting in an Uncertain World. MIT Press.

Carré, C., Boccarossa, A., Hellier, E., Dupont, N., 2018. Quality standards and monitoring as water management tools: the case of nitrogen in rivers in France and Brittany. Water Policy 20, 1059–1074.

Carré, C., Meybeck, M., Esculier, F., 2017. The Water Framework Directive's "percentage of surface water bodies at good status": unveiling the hidden side of a "hyperindicator." Ecol. Indic. 78, 371–380.

Carré, C., Haghe, J.P., De Coninck, A., Becu, N., Deroubaix, J., Pivano, C., Flipo, N., Le Pichon, C., Tallec, G., 2014. How to integrate scientific models in order to switch from, flood control river management to multifunctional river management? Int. J. River Basin Manag. 12, 231–249.

Cash, D., Clark, W.C., Alcock, F., Dickson, N., Eckley, N., J�ger, J., 2003. Salience, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making. SSRN Electron. J.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. 100, 8086–8091.

Cash, D.W., 2001. "In order to aid in diffusing useful and practical information": Agricultural extension and boundary organizations. Sci. Technol. Hum. Values 26, 431–453.

Cash, D.; Clark, W. C., 2001. From science to policy: Assessing the assessment process. *John F. Kennedy School of Government Faculty Research Working Papers Series RWP01-045*.

Cash, D.W., Moser, S.C., 2000. Linking global and local scales: designing dynamic assessment and management processes. Glob. Environ. Change 2, 109–120.

Castelletti, A.; Soncini-Sessa, R., 2006. A procedural approach to strengthening integration and participation in water resource planning. Environ. Model. Softw. 21, 1455–1470.

Ceola, S., Arheimer, B., Baratti, E., Blöschl, G., Capell, R., Castellarin, A., Freer, J., Han, D., Hrachowitz, M., Hundecha, Y., Hutton, C., Lindström, G., Montanari, A., Nijzink, R., Parajka, J., Toth, E., Viglione, A., Wagener, T., 2015. Virtual laboratories: new opportunities for collaborative water science. Hydrol. Earth Syst. Sci. 19, 2101–2117.

Chantre, E., Guichard, L., Ballot, R., Jacquet, F., Jeuffroy, M.-H., Prigent, C., Barzman, M., 2016. Co-click'eau, a participatory method for land-use scenarios in water catchments. Land Use Policy 59, 260–271.

Chau, K., 2006. A review on integration of artificial intelligence into water quality modelling. Mar. Pollut. Bull. 52, 726–733.

Chen, S.H., Jakeman, A.J., Norton, J.P., 2008. Artificial Intelligence techniques: An introduction to their use for modelling environmental systems. Math. Comput. Simul. 78, 379–400.

Chesterfield, C.; Urich, C.; Beck, L.; Berge, K.; Charette-Castonguay, A.; Brown, R.; Dunn, G.; De Haan, F.; Lloyd, S.; Rogers, B. A Water Sensitive Cities Index - Benchmarking cities in developed and developing countries. In Proceedings of the International Low Impact Development Conference, Beijing, China, 26-29 June 2016

Chesterikoff, A., Garban, B., Billen, G., and Poulin, M. (1992) Inorganic nitrogen dynamics in the River Seine downstream from Paris (France).

Chilingarian, I., Zolotukhin, I., 2010. Transparent scientific usage as the key to success of the Virtual Observatory. ArXiv10013589 Astro-Ph.

Chong, N., Bach, P., Moilleron, R., Bonhomme, C., Deroubaix, J.-F., 2017. Use and Utility: Exploring the Diversity and Design of Water Models at the Science-Policy Interface. Water 9, 983.

Chong, N.; Bonhomme, C.; Deroubaix, J.-F.; Moilleron, R., 2016 Production et usages des modèles dans le cadre du PIREN-Seine; PIREN-Seine: Paris, France, 2016.

Cieslik, K.J., Leeuwis, C., Dewulf, A.R.P.J., Lie, R., Werners, S.E., van Wessel, M., Feindt, P., Struik, P.C., 2018. Addressing socio-ecological development challenges in the digital age: Exploring the potential of Environmental Virtual Observatories for Connective Action (EVOCA). NJAS - Wagening. J. Life Sci. 86–87, 2–11.

Cladière, M., Bonhomme, C., Vilmin, L., Gasperi, J., Flipo, N., and Tassin, B., 2014. Modelling the fate of nonylphenolic compounds in the Seine River – part 1: Determination of in-situ attenuation rate constants. Sci. Tot. Env., (468–469), 1050–1058.

Cladière, M., 2012. Sources, transfert et devenir des alkylphénols et du bisphénol A dans le bassin amont de la Seine, cas de l'Île-de-France. Thèse de doctorat, Paris-Est, Ecole doctorale Sciences, Ingénierie et Environnement.

Clark, W. C.; Tomich, T. P.; van Noordwijk, M.; Guston, D.; Catacutan, D.; Dickson, N. M.; McNie, E., 2011. Boundary work for sustainable development: Natural resource management at the Consultative Group on International Agricultural Research (CGIAR). Proc. Natl. Acad. Sci. 113, 4615–4622.

Commenges, H., Tomasoni, L., Seigneur, C., Bonin, O., Leurent, F., Bonhomme, C., Deroubaix, J.-F., 2017. Who is the Expert? Integrated Urban Modeling and the Reconfiguration of Expertise. J. Urban Technol. 24, 89–108.

Connick, S., Innes, J.E., 2003. Outcomes of Collaborative Water Policy Making: Applying Complexity Thinking to Evaluation. J. Environ. Plan. Manag. 46, 177–197.

Conseil scientifique du Comité de Bassin Seine-Normandie *Evaluation du Programme de recherche PIREN-Seine*; Agence de l'Eau Seine-Normandie: Nanterre, France, 2008.

Corbin, J.; Strauss, A., 2008. *Basics of qualitative research: Techniques and procedures for developing grounded theory,* 3rd ed.; SAGE Publications, Inc.: Thousand Oaks, CA, USA.

Coutts, A.; Harris, R., 2013. A multi-scale assessment of urban heating in Melbourne during an extreme heat event: policy approaches for adaptation; Monash University: Clayton, Australia.

Coucheney, E.; Buis, S.; Launay, M.; Constantin, J.; Mary, B.; García de Cortázar-Atauri, I.; Ripoche, D.; Beaudoin, N.; Ruget, F.; Andrianarisoa, K. S.; Le Bas, C.; Justes, E.; Léonard, J., 2015. Accuracy, robustness and behavior of the STICS soil–crop model for plant, water and nitrogen outputs: Evaluation over a wide range of agro-environmental conditions in France. Environ. Model. Softw., 64, 177–190.

Crona, B., Fidelman, P., 2014. Mediating science and action across multiple boundaries in the Coral Triangle. Glob. Environ. Change 29, 53–64.

De Coninck, A., 2015. Faire de l'action publique une action collective: expertise et concertation pour la mise en oeuvre des continuités écologiques sur les rivières périurbaines (PhD Thesis). Université Paris-Est.

Dedieu, F., Jouzel, J.-N., 2015. Comment ignorer ce que l'on sait ?, How to ignore what one already knows: Domesticating uncomfortable knowledges about pesticide poisoning among farmers. Rev. Fr. Sociol. 56, 105–133.

de Haan, F. J.; Rogers, B. C.; Brown, R. R.; Deletic, A., 2016. Many roads to Rome: The emergence of pathways from patterns of change through exploratory modelling of sustainability transitions. Environ. Model. Softw. 85, 279–292.

de Haan, F. J.; Ferguson, B. C.; Adamowicz, R. C.; Johnstone, P.; Brown, R. R.; Wong, T. H. F., 2014. The needs of society: A new understanding of transitions, sustainability and liveability. Technol. Forecast. Soc. Chang. 85, 121–132.

Department of Environment, Land, Water, and Planning (DELWP). *Victoria Planning Provisions*; Department of Environment, Land, Water, and Planning: Melbourne, Australia, 2017.

Department of Environmental and Resource Management (DERM) *Urban Stormwater Quality Planning Guidlines 2010*; Queensland Government: Brisbane, Australia, 2010.

Dewulf, A., Craps, M., Bouwen, R., Taillieu, T., Pahl-Wostl, C., 2005. Integrated management of natural resources: dealing with ambiguous issues, multiple actors and diverging frames. Water Sci. Technol. 52, 115–124.

Dictionary by Merriam-Webster: America's most-trusted online dictionary Available online: https://www.merriam-webster.com/ (accessed on Oct 30, 2017).

Dietz, M.E., 2007. Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. Water. Air. Soil Pollut. 186, 351–363.

Dilling, L., Lemos, M.C., 2011. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. Glob. Environ. Change 21, 680–689.

Dilling, L.; Lemos, M. C., 2011. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. Glob. Environ. Chang. 21, 680–689.

Edelenbos, J., van Buuren, A., van Schie, N., 2011. Co-producing knowledge: joint knowledge production between experts, bureaucrats and stakeholders in Dutch water management projects. Environ. Sci. Policy 14, 675–684.

Edelenbos, J., Monnikhof, R., de van Riet, O., 2003. A double helix approach: a proposal to forge a better integration of analysis and process in policy development. Int. J. Technol. Policy Manag. 3, 1–21.

Etzkowitz, H., 2012. Triple Helix Clusters: Boundary Permeability at University—Industry—Government Interfaces as a Regional Innovation Strategy. Environ. Plan. C Gov. Policy 30, 766–779.

Etzkowitz, H., Zhou, C., 2006. Triple Helix twins: innovation and sustainability. Sci. Public Policy 33, 77–83.

Etzkowitz, H., Leydesdorff, L., 2000. The dynamics of innovation: from National Systems and "Mode 2" to a Triple Helix of university-industry-government relations. Res. Policy 109–123.

European Commission (Ed.), 2003. Investing in research: an action plan for Europe: communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, EUR. Office for Official Publications of the European Communities, Luxembourg.

European Commission, n.d. Horizon 2020 Structure and Budget.

European Union. *Water Framework Directive*; European Commission: Brussels, Belgium, 2000.

Even, S. *Description du logiciel ProSe, version 4.1 - Logiciel de simulation de l'hydrodynamique, du transport et du fonctionnement biochimique d'un écosystème fluvial*; PIREN-Seine: Paris, France, 2007

Even, S.; Poulin, M.; Garnier, J.; Billen, G.; Servais, P.; Chesterikoff, A.; Coste, M., 1998. River ecosystem modelling: application of the PROSE model to the Seine river (France). Hydrobiologia. 373, 27–45.

Even, S., Poulin, M., Billen, G., Garnier, J., 1998. Modèles PROSE et SENEQUE : établissement de versions de référence applicables aux études de gestion.

Everaert, G., Pauwels, I.S., Boets, P., Buysschaert, F., Goethals, P.L.M., 2013. Development and assessment of ecological models in the context of the European Water Framework Directive: Key issues for trainers in data-driven modeling approaches. Ecol. Inform.

Evolving water management - eWater. Available online: http://ewater.org.au/ (accessed on 24 November 2017).

eWater Annual Report 2011-12; eWater: Canberra, Australia, 2012.

eWater Water Quality Objectives - MUSIC Version 6 Documentation and Help - eWater Wiki
Available online:
https://wiki.ewater.org.au/display/MD6/Water+Quality+Objectives
(accessed on 16 May 2017).

Feldman, D.L., Ingram, H.M., 2009. Making science useful to decision makers: Climate forecasts, water management, and knowledge networks. Weather Clim. Soc. 1, 9–21.

Festinger, L., 1962. A Theory of Cognitive Dissonance. Stanford University Press.

Ferguson, B. C.; Brown, R. R.; Frantzeskaki, N.; de Haan, F. J.; Deletic, A., 2013. The enabling institutional context for integrated water management: Lessons from Melbourne. Water Res. 47, 7300–7314.

Feynman, R.P., 1975. Against Method. New Left Books, London.

Fletcher, T. D.; Andrieu, H.; Hamel, P., 2013. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. Adv. Water Resour. 51, 261–279.

Fletcher, T. D.; Walsh, C. J.; Bos, D.; Nemes, V.; RossRakesh, S.; Prosser, T.; Hatt, B.; Birch, R., 2011. Restoration of stormwater retention capacity at the allotment-scale through a novel economic instrument. Water Sci. Technol. 64, 494–502.

Fletcher, T. D.; Mitchell, V. G.; Deletic, A.; Ladson, T. R.; Séven, A., 2007. Is stormwater harvesting beneficial to urban waterway environmental flows? Water Sci. Technol. 55, 265–272.

Folke, C., Hahn, T., Olsson, P., Norberg, J., 2005. Adaptive Governance of Social-Ecological Systems. Annu. Rev. Environ. Resour. 30, 441–473.

Franks, J., 2010. Boundary organizations for sustainable land management: The example of Dutch Environmental Co-operatives. Ecol. Econ. 70, 283–295.

Fujimura, J., 1992. Crafting Science: Standardized packages, boundary objects, and “Translation.” Sci. Pract. Cult. 168.

Funtowicz, S.O., Ravetz, J.R., 1995. Science for the Post Normal Age, in: Westra, L., Lemons, J. (Eds.), Perspectives on Ecological Integrity. Springer Netherlands, Dordrecht, pp. 146–161.

Funtowicz, S.O., Ravetz, J.R., 1993. The Emergence of Post-Normal Science, in: Science, Politics and Morality. Scientific Uncertainty and Decision Making. pp. 85–123.

Funtowicz, S.O., Ravetz, J.R., 1990. Uncertainty and Quality in Science for Policy. Springer.

Garnier, J.; Mouchel, J.-M., 1999. *Man and River Systems: The Functioning of River Systems at the Basin Scale*; Springer: Cham, The Netherlands, 1999; ISBN 978-94-017-2163-9.

Gelatt, H.B., 1989. Positive Uncertainty: A New Decision-Making Framework for Counseling. J. Couns. Psychol. 36, 252–56.

Geiger, W. F., 2015. Sponge city and lid technology--vision and tradition. Landsc. Archit. Front. 3, 10–22.

Giampietro, M., Mayumi, K., Şorman, A.H., 2013. Energy Analysis for a Sustainable Future : Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism, 1st Edition. ed. Routledge, London.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., Trow, M., 1994. The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies. SAGE.

Gieryn, T.F., 1995. Boundaries of Science, in: Science and the Quest for Reality, Main Trends of the Modern World. Palgrave Macmillan, London, pp. 293–332.

Gieryn, T.F., 1983. Boundary-Work and the Demarcation of Science from Non-Science: Strains and Interests in Professional Ideologies of Scientists. Am. Sociol. Rev. 48, 781–795.

Gilli, É., Mangan, C., Mudry, J., 2012. Hydrogeology: Objectives, Methods, Applications. CRC Press.

Gill, S.., Handley, J.., Ennos, A.., Pauleit, S., 2007. Adapting Cities for Climate Change: The Role of the Green Infrastructure. Built Environ. 33, 115–133.

Gisclard, M., Chantre, É., Cerf, M., Guichard, L., 2015. Co-click'eau : une démarche d'intermédiation pour la construction d'une action collective locale ? Nat. Sci. Sociétés 23, 3–13.

Giupponi, C., 2007. Decision Support Systems for implementing the European Water Framework Directive: The MULINO approach. Environ. Model. Softw. 22, 248–258.

Glaser, B. G.; Holton, J., 2004. Remodeling Grounded Theory. Forum Qual. Sozialforschung Forum Qual. Soc. Res. 5.

Glaser, B.G., Strauss, A.L., Strutzel, E., 1968. The Discovery of Grounded Theory; Strategies for Qualitative Research. Nurs. Res. 17, 364.

Gomez, E.; Ledoux, E.; Monget, J.-M.; De Marsily, G., 2003. Distributed surface-groundwater coupled model applied to climate or long term water management impacts at basin scale. Eur. Water. 1, 3–8.

Gomez, E.; Ledoux, E.; Mary, B. *La démarche de modélisation régionale des écoulements d'eau, de la production et du transfert d'azote sure le bassin de la Seine, structure du modèle d'écoulement*; PIREN-Seine: Paris, France, 1998.

Grant, S. B.; Fletcher, T. D.; Feldman, D.; Saphores, J.-D.; Cook, P. L. M.; Stewardson, M.; Low, K.; Burry, K.; Hamilton, A. J., 2013. Adapting Urban Water Systems to a Changing Climate: Lessons from the Millennium Drought in Southeast Australia. Environ. Sci. Technol. 47, 10727–10734.

Grünbaum, A., 1979. Is Freudian Psychoanalytic Theory Pseudo-Scientific by Karl Popper's Criterion of Demarcation? Am. Philos. Q. 16, 131–141.

Grundmann, R., 2009. The role of expertise in governance processes. For. Policy Econ. 11, 398–403.

Guimaraes Pereira, Â., Saltelli, A., 2016. Institutions on the Verge: Working at the Science Policy Interface, in: The Rightful Place of Science: Science on the Verge. Consortium for Science, Policy & Outcomes., Tempe, AZ.

Gulbrandsen, M., 2011. Research institutes as hybrid organizations: central challenges to their legitimacy. Policy Sci. 44, 215–230.

Gustafsson, K.M., Lidskog, R., 2018. Boundary organizations and environmental governance: Performance, institutional design, and conceptual development. Clim. Risk Manag. 1–11.

Guston, D., 2001. Boundary Organizations in Environmental Policy and Science: An Introduction. Sci. Technol. Hum. Values, Special Issue: Boundary Organizations in Environmental Policy and Science 26, 399–408.

Guston, D.H., 2000. Between Politics and Science: Assuring the Integrity and Productivity of Reseach. Cambridge University Press.

Guston, D.H., 1999. Stabilizing the Boundary between US Politics and Science: The Rôle of the Office of Technology Transfer as a Boundary Organization. Soc. Stud. Sci. 29, 87–111.

Haas, P. When does power listen to truth? A constructivist approach to the policy process. Jour. Eur. Pub. Pol. 11, 569-592.

Habets, F.; Flipo, N.; Goblet, P.; Ledoux, E.; Monteil, C.; Philippe, E.; Querel, W.; Saleh, F.; Souhar, O.; Stouls, A.; Viennot, P.; David, C.; Bacchi, A.; Blanchoud, H.; Moreau-Guigon, E.; Launay, M.; Ripoche, D.; Mary, B.; Jayet, P.-A.; Martin, E.; Morel, T.; Tournebize, J., 2009. *Le développement du modèle intégré des hydrosystèmes Eau-dyssée*; PIREN-Seine: Paris, France.

Halev, A., Norvig, P., Pereira, F., 2009. The Unreasonable Effectiveness Data. IEEE Intell. Syst. 24, 8–12.

Hall, J. W. (2003) Handling uncertainty in the hydroinformatic process. Journal of Hydroinformatics, 5(4), 215–232.

Hattermann, F.F., Kundzewicz, Z.W., 2009. Water Framework Directive: Model supported Implementation. IWA Publishing.

Heberger, M. Australia's Millennium Drought: Impacts and Responses. In *The World's Water*; Island Press: Washington, DC, USA, 2012; 97–125 ISBN 978-1-61091-048-4.

Heimer, C.A., 2012. Inert facts and the illusion of knowledge: strategic uses of ignorance in HIV clinics. Econ. Soc. 41, 17–41.

Hellström, T., Jacob, M., 2003. Boundary organisations in science: from discourse to construction. Sci. Public Policy 30, 235–238.

Hering, D., Borja, A., Carstensen, J., Carvalho, L., Elliott, M., Feld, C.K., Heiskanen, A.-S., Johnson, R.K., Moe, J., Pont, D., 2010. The European Water Framework Directive at the age of 10: A critical review of the achievements with recommendations for the future. Sci. Total Environ. 408, 4007–4019.

Hipel, K.W., Ben-Haim, Y., 1999. Decision making in an uncertain world: Information-gap modeling in water resources management. Syst. Man Cybern. Part C Appl. Rev. IEEE Trans. On 29, 506–517.

Hisschemöller, M., Sioziou, I., 2013. Boundary organisations for resource mobilisation: enhancing citizens' involvement in the Dutch energy transition. Environ. Polit. 22, 792–810.

HMSO, 1972. Rothschild Report: A Framework for Government Research and Development (No. Cmnd 5046). HMSO, London.

HMSO, 1971. Rothschild Report: The Organization and Management of Government Research and Development (No. Cmnd 4814). HMSO, London.

Hojat, M., Gonnella, J.S., Caelleigh, A.S., 2003. Impartial Judgment by the "Gatekeepers" of Science: Fallibility and Accountability in the Peer Review Process. Adv. Health Sci. Educ. 8, 75–96.

Holmes, J.; Clark, R., 2008. Enhancing the use of science in environmental policy-making and regulation. Environ. Sci. Policy 11, 702–711

Hommes, S., Vinke-de Kruijf, J., Otter, H.S., Bouma, G., 2009. Knowledge and Perceptions in Participatory Policy Processes: Lessons from the Delta-Region in the Netherlands. Water Resour. Manag. 23, 1641–1663.

Hommes, S., Hulscher, S.J., Mulder, J.P., Otter, H.S., Bressers, H.T.A., 2008. Role of perceptions and knowledge in the impact assessment for the extension of Mainport Rotterdam. Mar. Policy 33, 146–155.

Hoppe, R., Wesselink, A., Cairns, R., 2013. Lost in the Problem: The Role of Boundary Organisations in the Governance of Climate Change. Wiley Interdiscip. Rev. Clim. Change 4, 283–300.

Horizon 2020 - European Commission [WWW Document], n.d. Horiz. 2020.

Howe, C.; Mitchell, C. *Water Sensitive Cities*; International Water Association (IWA) Publishing: London, UK, 2011; ISBN 978-1-84339-364-1.

Hunt, J., Shackley, S., 1999. Reconceiving Science and Policy: Academic, Fiducial and Bureaucratic Knowledge. Minerva 37, 141–164.

Intemann, K., 2015. Distinguishing between legitimate and illegitimate values in climate modeling. Eur. J. Philos. Sci. 5, 217–232.

Ioannidis, J.P.A., 2014. How to Make More Published Research True. Revista Cubana de Informacion en Ciencias de la Salud (ACIMED). 26, 187-200.

Ioannidis, J.P.A., 2005. Why Most Published Research Findings Are False. PloS medicine. 2, e124.

IPCC, 2018. Global Warming of 1.5 ^{o}C. UN Intergovernmental Panel on Climate Change.

Isendahl, N., Dewulf, A., Brugnach, M., François, G., Möllenkamp, S., Pahl-Wostl, C., 2009. Assessing Framing of Uncertainties in Water Management Practice. Water Resour. Manag. 23, 3191–3205.

ISO, 1995. Guide to the Expression of Uncertainty in Measurement.

Jacob, M., 2006. Utilization of social science knowledge in science policy: Systems of Innovation, Triple Helix and VINNOVA. Soc. Sci. Inf. 45, 431–462.

Jacobs, K., 2002. *Connecting Science, Policy, and Decision-making: A Handbook for Researchers and Science Agencies*; National Oceanic and Atmospheric Administration, Office of Global Programs: Silver Spring, MD, USA, 2002.

Jasanoff, S., 2004. States of Knowledge: The Co-Production of Science and the Social Order. Routledge.

Jasanoff, S., 1995. Procedural choices in regulatory science. Technol. Soc. 17, 279–293.

Jasanoff, S., 1990. The Fifth Branch: Science Advisors as Policymakers. Harvard University Press, Cambridge, Massachusetts; London, England.

Jasanoff, S.S., 1987. Contested Boundaries in Policy-Relevant Science. Soc. Stud. Sci. 17, 195–230.

Johri, A. Boundary spanning knowledge broker: An emerging role in global engineering firms. In Proceedings of the 38th Annual Frontiers in Education Conference (FIE 2008), Saratoga Springs, NY, USA, 22-25 October 2008; p. S2E–7.

Juston, J.M., Kauffeldt, A., Montano, B.Q., Seibert, J., Beven, K.J., Westerberg, I.K., 2013. Smiling in the rain: Seven reasons to be positive about uncertainty in hydrological modelling. Hydrol. Process. 27, 1117–1122.

Kirchhoff, C., Esselman, R., Brown, D., 2015. Boundary Organizations to Boundary Chains: Prospects for Advancing Climate Science Application. Clim. Risk Manag. 9, 20-29.

Kirchhoff, C.J., Carmen Lemos, M., Dessai, S., 2013. Actionable Knowledge for Environmental Decision Making: Broadening the Usability of Climate Science. Annu. Rev. Environ. Resour. 38, 393–414.

Kirchhoff, C.J., 2013. Understanding and enhancing climate information use in water management. Clim. Change 119, 495–509.

Klauer, B., Brown, J.D., 2004. Conceptualising imperfect knowledge in public decision-making: ignorance, uncertainty, error and risk situations. Environ. Res. Eng. Manag. 1.

Kleinberg, J., Ludwig, J., Mullainathan, S., Obermeyer, Z., 2015. Prediction Policy Problems. Am. Econ. Rev. 105, 491–495.

Kleinman, D.L., Suryanarayanan, S., 2013. Dying Bees and the Social Production of Ignorance. Sci. Technol. Hum. Values 38, 492–517.

Klerkx, L., Leeuwis, C., 2008. Delegation of authority in research funding to networks: experiences with a multiple goal boundary organization. Sci. Public Policy 35, 183–196.

Klosterman, R. E., 1997. Planning Support Systems: A New Perspective on Computer-Aided Planning. J. Plan. Educ. Res. 17, 45–54.

Knight, F.H., 1964. Risk, Uncertainty and Profit. Sentry Pres, New York.

Knutti, R., 2008. Should we believe model predictions of future climate change? Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 366, 4647–4664.

Koppenjan, J., Klijn, E.H., 2004. Managing uncertainties in networks: Public private controversies. Routledge.

Kwakkel, J.H., Walker, W.E., Marchau, V.A., 2010. Classifying and communicating uncertainties in model-based policy analysis. Int. J. Technol. Policy Manag. 10, 299–315.

Lakoff, G., 2010. Why it matters how we frame the environment. Environ. Commun. 4.

Landry, R., Amara, N., Lamari, M., 2001. Climbing the Ladder of Research Utilization: Evidence from Social Science Research. Sci. Commun. 22, 396–422.

Lascoumes, P., Le Gales, P., 2007. Introduction: understanding public policy through its instruments—from the nature of instruments to the sociology of public policy instrumentation. Governance 20, 1–21.

Latour, B., 1993. We Have Never Been Modern. Harvard University Press, Cambridge.

Latour, B., Woolgar, S., 1979. Laboratory life: The social construction of scientific facts. Princeton University Press.

Ledoux, E., Gomez, E., Monget, J. M., Viavattene, C., Viennot, P., Ducharne, A., Benoit, M., Mignolet, C., Schott, C., and Mary, B., 2007. Agriculture and groundwater nitrate contamination in the Seine basin. The STICS–MODCOU modelling chain. Science of The Total Environment, 375(1–3), 33–47.

Ledoux, E.; Girard, G.; Marsily, G. de; Villeneuve, J. P.; Deschenes, J. Spatially Distributed Modeling: Conceptual Approach, Coupling Surface Water And Groundwater. In *Unsaturated Flow in Hydrologic Modeling*; Morel-Seytoux, H. J., Ed.; NATO ASI Series; Springer: Cham, The Netherlands, 1989; 435–454 ISBN 978-94-010-7559-6.

Ledoux, E. Modélisation intégrée des écoulements de surface et des écoulements souterrains sur un bassin hydrologique. Doctoral Dissertation, École des Mines, Paris, France, 1980.

Lemos, M.C., Kirchhoff, C., Ramprasad, V., 2012. Narrowing the Climate Information Usability Gap. Nat. Clim. Change 2, 789–794.

Lemos, M.C., Kirchhoff, C.J., Kalafatis, S.E., Scavia, D., Rood, R.B., Lemos, M.C., Kirchhoff, C.J., Kalafatis, S.E., Scavia, D., Rood, R.B., 2014. Moving Climate Information off the Shelf: Boundary Chains and the Role of RISAs as Adaptive Organizations. Weat. Clim. Soci. 6, 273-285.

Le SDAGE 2010-2015 du Bassin de la Seine et des Cours d'Eau Côtiers Normands; Agence de l'Eau Seine-Normandie: Nanterre, France, 2010.

Li, X.; Li, J.; Fang, X.; Gong, Y.; Wang, W. *Case Studies of the Sponge City Program in China*. In Proceedings of the World Environmental and Water Resources Congress 2016, West Palm Beach, FL, USA, 22-26 May 2016.

Liu, Y., Gupta, H., Springer, E., Wagener, T., 2008. Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management. Environ. Model. Softw. 23, 846–858.

Lohmann, L., 2008. Carbon Trading, Climate Justice and the Production of Ignorance: Ten examples. Development. 51, 359–365.

Loi n° 92-3 du 3 janvier 1992 sur l'eau; Assemblée Nationale: Paris, France.

Low, K. G.; Grant, S. B.; Hamilton, A. J.; Gan, K.; Saphores, J.-D.; Arora, M.; Feldman, D. L., 2015. Fighting drought with innovation: Melbourne's response to the Millennium Drought in Southeast Australia: Fighting drought with innovation. Wiley Interdiscip. Rev. Water. 2, 315–328.

Löwe, R.; Urich, C.; Domingo, N. S.; Mark, O.; Deletic, A.; Arnbjerg-Nielsen, K., 2017. Assessment of urban pluvial flood risk and efficiency of adaptation options through simulations - A new generation of urban planning tools. J. Hydrol. 550, 355–367.

Luukkonen, T., 2014. The European Research Council and the European research funding landscape. Sci. Public Policy 41, 29–43.

Lyotard, J.-F., 1979. La Condition postmoderne: Rapport sur le savoir. Minuit, Paris.

McIntyre, N. R., Wagener, T., Wheater, H. S., and Yu, Z. S., 2003. Uncertainty and risk in water quality modelling and management. Journal of Hydroinformatics. 5, 259–274.

Macilwain, C., 2016. The elephant in the room we can't ignore. Nature. 531, 277–277.

Mackay, E.B., Wilkinson, M.E., Macleod, C.J.A., Beven, K., Percy, B.J., Macklin, M.G., Quinn, P.F., Stutter, M., Haygarth, P.M., 2015. Digital catchment observatories: A platform for engagement and knowledge exchange between catchment scientists, policy makers, and local communities. Water Resour. Res. 51, 4815–4822.

Makropoulos, C.K., Natsis, K., Liu, S., Mittas, K., Butler, D., 2008. Decision support for sustainable option selection in integrated urban water management. Environ. Model. Softw. 23, 1448–1460.

Malekpour, S.; de Haan, F. J.; Brown, R. R. Marrying Exploratory Modelling to Strategic Planning: Towards Participatory Model Use. In Proceedings of the 20th International Congress on Modelling and Simulation (MODSIM2013), Adelaide, Australia, 1-6 December 2013.

Marlow, D.R., Moglia, M., Cook, S., Beale, D.J., 2013. Towards sustainable urban water management: A critical reassessment. Water Res. 47, 7150–7161.

Marris, C., Jefferson, C., Lentzos, F., 2014. Negotiating the dynamics of uncomfortable knowledge: The case of dual use and synthetic biology. BioSocieties 9, 393–420.

Matthies, M., Giupponi, C., Ostendorf, B., 2007. Environmental decision support systems: Current issues, methods and tools. Environ. Model. Softw. 22, 123–127.

McGoey, L., 2012. Strategic unknowns: Towards a sociology of ignorance. Econ. Soc. 41, 1–16.

McGoey, L., 2007. On the will to ignorance in bureaucracy. Econ. Soc. 36, 212–235.

McGranahan, G., Balk, D., Anderson, B., 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environ. Urban. 19, 17–37.

McNie, E.C., 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. Environ. Sci. Policy 10, 17–38.

Meadow, A.M., Ferguson, D.B., Guido, Z., Horangic, A., Owen, G., Wall, T., 2015. Moving toward the Deliberate Coproduction of Climate Science Knowledge. Weather Clim. Soc. 7, 179–191.

Meyer, M., 2010. The Rise of the Knowledge Broker. Sci. Commun. 32, 118–127.

Miller, C., 2001. Hybrid management: boundary organizations, science policy, and environmental governance in the climate regime. Sci. Technol. Hum. Values 26, 478–500.

Mitchell, B., 2005. Integrated water resource management, institutional arrangements, and land-use planning. Environ. Plan. A 37, 1335–1352.

Mishra, S. (2009) Uncertainty and sensitivity analysis techniques for hydrologic modeling. Journal of Hydroinformatics, 11(3–4), 282.

Moatar, F., Meybeck, M., Raymond, S., Birgand, F., and Curie, F., 2013. River flux uncertainties predicted by hydrological variability and riverine material behaviour: Predicting Uncertainties When Monitoring Riverine Material Fluxes. Hydrological Processes, 27(25), 3535–3546.

Moriarty, P., 2008. Reclaiming academia from post-academia. Nat. Nanotechnol. 3, 60–62.

Mørk, B.E., Hoholm, T., Maaninen-Olsson, E., Aanestad, M., 2012. Changing practice through boundary organizing: A case from medical R&D. Hum. Relat. 65, 263–288.

Mostert, E., Pahl-Wostl, C., Rees, Y., Searle, B., Tàbara, D., Tippett, J., 2007. Social Learning in European River-Basin Management: Barriers and Fostering Mechanisms from 10 River Basins. Ecol. Soc. 12.

Mouchel, J.-M. *Rapport de synthèse 2007-2010 - Introduction Générale*; PIREN-Seine: Paris, France, 2010

Mullainathan, S., Spiess, J., 2017. Machine Learning: An Applied Econometric Approach. J. Econ. Perspect. 31, 87–106.

Muschalla, D., 2008. Optimization of integrated urban wastewater systems using multi-objective evolution strategies. Urban Water J. 5, 59–67.

Némery, J. and Garnier, J., 2007. Origin and fate of phosphorus in the Seine watershed (France): Agricultural and hydrographic P budgets: Phosphorus Cycle in the Watershed. Journal of Geophysical Research: Biogeosciences, 112, G3.

Nilsson, M., Jordan, A., Turnpenny, J., Hertin, J., Nykvist, B., Russel, D., 2008. The use and non-use of policy appraisal tools in public policy making: an analysis of three European countries and the European Union. Policy Sci. 41, 335–355.

Nowotny, H., 2006. Real science is excellent science–how to interpret post-academic science, Mode 2 and the ERC. JCOM. 5, 4.

Nowotny, H., Scott, P.B., Gibbons, M.T., 2001. Re-Thinking Science: Knowledge and the Public in an Age of Uncertainty. Polity, Cambridge.

Nutley, S.M., Walter, I., Davies, H.T.O., 2007. Using Evidence: How Research Can Inform Public Services. Policy Press, Bristol, England.

Obermeyer, Z., Emanuel, E.J., 2016. Predicting the Future — Big Data, Machine Learning, and Clinical Medicine. N. Engl. J. Med. 375, 1216–1219.

Oldham, G., McLean, R., 1997. Approaches to knowledge-brokering. Int. Inst. Sustain. Dev. 23.

O'Mahony, S.; Bechky, B. A. Boundary organizations: Enabling collaboration among unexpected allies. *Adm. Sci. Q.* **2008**, *53*, 422–459.

Orr, P., Colvin, J., King, D., 2006. Involving stakeholders in integrated river basin planning in England and Wales, in: Craswell, E., Bonnell, M., Bossio, D., Demuth, S., Van De Giesen, N. (Eds.), Integrated Assessment of Water Resources and Global Change. Springer Netherlands, Dordrecht, pp. 331–349.

Owens, S., Rayner, T., Bina, O., 2004. New agendas for appraisal: reflections on theory, practice, and research. Environ. Plan. A 36.

Pahl-Wostl, C., Craps, M., Dewulf, A., Mostert, E., Tabara, D., Taillieu, T., 2007. Social Learning and Water Resources Management. Ecol. Soc. 12.

Pahl-Wostl, C., 2006. Transitions towards adaptive management of water facing climate and global change. Water Resour. Manag. 21, 49–62.

Pahl-Wostl, C., 2002. Towards sustainability in the water sector: The importance of human actors and processes of social learning. Aquat. Sci. 64, 394–411.

Pappenberger, F., Beven, K.J., 2006. Ignorance is bliss: Or seven reasons not to use uncertainty analysis. Water Resour. Res. 42.

Parker, J., Crona, B., 2012. On being all things to all people: Boundary organizations and the contemporary research university. Soc. Stud. Sci. 42, 262–289.

Pesch, U., Huitema, D., Hisschemöller, M., 2012. A Boundary Organization and its Changing Environment: The Netherlands Environmental Assessment Agency, the MNP. Environ. Plan. C Gov. Policy 30, 487–503.

Petrucci, G., Bonhomme, C., 2014. The dilemma of spatial representation for urban hydrology semi-distributed modelling: Trade-offs among complexity, calibration and geographical data. J. Hydrol. 517, 997–1007.

Pindyck, R.S., 2013. Climate Change Policy: What Do the Models Tell Us? J. Econ. Lit. 51, 860–872.

Polus, E., Flipo, N., de Fouquet, C., and Poulin, M., 2011. Geostatistics for assessing the efficiency of a distributed physically-based water quality model: application to nitrate in the Seine River. Hydrological Processes, 25(2), 217–233.

Popper, K., 1959. The Logic of Scientific Discovery. Routledge, New York.

Porter, T.M., 1995. Trust in Numbers: The Pursuit of Objectivity in Science and Public Life. Princeton University Press, Princeton, New Jersey.

Qu'est-ce que le PIREN Seine ? | Programme Interdisciplinaire de Recherche sur l'Environnement de la Seine Available online: http://www.metis.upmc.fr/piren/?q=presentation_PIREN-Seine (accessed on Mar 6, 2017).

Radaelli, C.M., 2004. The diffusion of regulatory impact analysis: Best practice or lesson-drawing? Eur. J. Polit. Res. 43, 723–747.

Radwan, M., Willems, P., and Berlamont, J. (2004) Sensitivity and uncertainty analysis for river quality modelling. Journal of Hydroinformatics, 6(2), 83–99.

Raut, B.; de la Fuente, L.; Seed, A.; Jakob, C.; Reeder, M. Application of a space-time stochastic model for downscaling future rainfall projections. In *Hydrology and Water Resources Symposium*; Engineers Australia: Barton, Australia, 2012; pp. 579–586.

Rauch, W.; Urich, C.; Bach, P. M.; Rogers, B. C.; de Haan, F. J.; Brown, R. R.; Mair, M.; McCarthy, D. T.; Kleidorfer, M.; Sitzenfrei, R.; Deletic, A., 2017. Modelling transitions in urban water systems. Water Res. 126, 501–514.

Rauch, W.; Bach, P. M.; Brown, R.; Rogers, B.; de Haan, F. J.; McCarthy, D. T.; Kleidorfer, M.; Mair, M.; Sitzenfrei, R.; Urich, C.; Deletic, A. Enabling change: Institutional adaptation. In *Climate Change, Water Supply and Sanitation*; IWA Publishing: London, U.K., 2015.

Ravetz, J.R., 2011. Postnormal Science and the maturing of the structural contradictions of modern European science. Futures 43, 142–148.

Ravetz, J., 2006. The No-Nonsense Guide to Science. New Internationalist.

Ravetz, I.R., 1999. What is post-normal science. Futur.- J. Forecast. Plan. Policy 31, 647–654.

Ravetz, J.R., 1987. Usable knowledge, usable ignorance incomplete science with policy implications. Sci. Commun. 9, 87–116.

Rayner, S., 2012. Uncomfortable knowledge: the social construction of ignorance in science and environmental policy discourses. Econ. Soc. 41, 107–125.

Refsgaard, J.C., van der Sluijs, J.P., Højberg, A.L., Vanrolleghem, P.A., 2007. Uncertainty in the environmental modelling process – A framework and guidance. Environ. Model. Softw. 22, 1543–1556.

Rekolainen, S., Kämäri, J., Hiltunen, M., Saloranta, T.M., 2003. A conceptual framework for identifying the need and role of models in the implementation of the Water Framework Directive. Int. J. River Basin Manag. 1, 347–352.

Riousset, P., 2012. Pathways towards policy relevance, operationality and usability of models for ex ante impacts assessments. Berlin conference on the human dimensions of global environmental change "Evidence for sustainable development", Berlin.

Rittel, H.W.J., Webber, M.M., 1973. Dilemmas in a General Theory of Planning. Policy Sci. 4, 155–169.

Rossman, L. A. *EPANET 2 User Manual*; US Environmental Protection Agency: Cincinnati, OH, USA, 2000.

Rossman, L. A. *Storm Water Management Model - User's Manual Version 5.1*; US Environmental Protection Agency: Cincinnati, OH, USA, 2004.

Ruelland, D.; Billen, G.; Brunstein, D.; Garnier, J., 2007. SENEQUE: A multi-scaling GIS interface to the Riverstrahler model of the biogeochemical functioning of river systems. Sci. Total Environ. 375, 257–273.

Ruelland, D.; Silvestre, M.; Thieu, V.; Billen, G. *Applicatif SENEQUE 3.4: notice d'utilisation*; PIREN-Seine: Paris, France, 2007.

Ruelland, D.; Billen, G. Riverstrahler, SENEQUE and SENECAM: modelling tools for water resources management from regional to local scales. In Proceedings of the 6th International Conference of EWRA, France, Menton, 7-10 September 2005

Ruelland, D., 2004. SENEQUE, logiciel SIG de modélisation prospective de la qualité de l'eau. Revue internationale de géomatique, 14.

Saleh, F.; Ducharne, A.; Oudin, L.; Flipo, N.; Ledoux, E. *Hydraulic modeling of flow, water levels and inundations: Serein River case study*; PIREN-Seine: Paris, France, 2009.

Salles, D., 2013. Concertation et environnement, in: Euzen, A., Eymard, L., Gaill, F. (Eds.), Le développement durable à découvert. CNRS Éditions, pp. 194–195.

Salles, D., Leroy, P., 2013. Gouvernance environnementale, in: Dictionnaire Critique et Interdisciplinaire de La Participation. GIS Démocratie et Participation, Paris, France.

Saltelli, A., Funtowicz, S., 2014. When All Models Are Wrong. Issues Sci. Technol. 30, 79–85.

Saltelli, A., Giampietro, M., 2017. What is wrong with evidence based policy, and how can it be improved? Futures 91, 62–71.

Saltelli, A., Giampietro, M., 2016. The fallacy of evidence based policy, in: The Rightful Place of Science: Science on the Verge. Consortium for Science, Policy & Outcomes., Tempe, AZ, pp. 31–70.

Saltelli, A., Ravetz, J., Funtowicz, S., 2016. Who Will Solve the Crisis in Science?, in: The Rightful Place of Science: Science on the Verge. Consortium for Science, Policy & Outcomes, Tempe, AZ, pp. 1–30.

Sanders, C.B., Miller, F.A., 2010. Reframing norms: boundary maintenance and partial accommodations in the work of academic technology transfer. Sci. Public Policy 37, 689–701.

Sarewitz, D., 2016. Forward, in: The Rightful Place of Science: Science on the Verge. Consortium for Science, Policy & Outcomes, Tempe, AZ, pp. iii–vii.

Sarewitz, D., Pielke, R.A., 2007. The neglected heart of science policy: reconciling supply of and demand for science. Environ. Sci. Policy 10, 5–16.

Sarkki, S., Niemela, J., Tinch, R., van den Hove, S., Watt, A., Young, J., 2014. Balancing credibility, relevance and legitimacy: A critical assessment of trade-offs in science-policy interfaces. Sci. Public Policy 41, 194–206.

Schroter, S., Black, N., Evans, S., Godlee, F., Osorio, L., Smith, R., 2008. What errors do peer reviewers detect, and does training improve their ability to detect them? J. R. Soc. Med. 101, 507–514.

Shim, J.P., Warkentin, M., Courtney, J.F., Power, D.J., Sharda, R., Carlsson, C., 2002. Past, present, and future of decision support technology. Decis. Support Syst. 33, 111–126.

Siebert, S., Machesky, L.M., Insall, R.H., 2015. Overflow in science and its implications for trust. eLife 4.

Silvert, W., 2001. Modelling as a discipline. Int. J. Gen. Syst. 30, 261–282.

Sigel, K., Klauer, B., Pahl-Wostl, C., 2010. Conceptualising uncertainty in environmental decision-making: the example of the EU Water Framework Directive. Ecol. Econ. 69, 502–510.

Smithson, M., 2008. The many faces and masks of uncertainty. Uncertain. Risk Multidiscip. Perspect. 13–25.

Smithson, M., 1989. The Social Construction of Ignorance, In: Ignorance and Uncertainty. Springer New York, New York, NY, pp. 216–263.

Stankiewicz, P., 2009. The role of risks and uncertainties in technological c onflicts: three strategies of constructing ignorance. Innov. Eur. J. Soc. Sci. Res. 22, 105–124.

Star, S.L., Griesemer, J.R., 1989. Institutional Ecology, "Translations" and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. Soc. Stud. Sci. 19, 387–420.

Star, S.L., 2010. This is Not a Boundary Object: Reflections on the Origin of a Concept. Sci. Technol.Hum. Values. 35, 601–617.

Stern, N., 2016. Economics: Current climate models are grossly misleading. Nature 530, 407–409.

Stiglitz, J.E., 2010. Freefall: America, Free Markets, and the Sinking of the World Economy. W. W. Norton & Company.

Strauss, A., Corbin, J.M., 1997. Grounded Theory in Practice. SAGE.

Systems Engineering Fundamentals, 2000. . Defense Acquisition University Press.

Sverrisson, Á., 2016. Translation Networks, Knowledge Brokers and Novelty Construction: Pragmatic Environmentalism in Sweden. Acta Sociol. 44, 313-327.

Tassin, B., Delbec, M., Gaume, E., Gromaire-Mertz, M-.C., Kanso, A., Mouchel, J-.M., Vinçon-Leite, B., Thouvin, V. 2003. Les modèles pour la gestion des eaux urbaines: Exemples au long du cycle de l'eau. Annalse des ponts et chaussées. 2003, 27-43.

Teske, S., Pregger, T., Simon, S., Naegler, T., Graus, W., Lins, C., 2011. Energy [R]evolution 2010—a sustainable world energy outlook. Energy Effic. 4, 409–433.

Tewdwr-Jones, M.; Allmendinger, P., 1998. DeconstructingCommunicative Rationality: A Critique of Habermasian Collaborative Planning. Environ. Plan. A. 30, 1975–1989.

The Economist, 2013. How science goes wrong. The Economist 11.

Thieu, V., Silvestre, M., Corentin, S., 2016. Mise en place d'un outil web-cartographique d'analyse et de diffusion d'observations environnementales. PIREN-Seine, Paris, France.

Thieu, V.; Billen, G.; Silvestre, M.; Garnier, J., 2006. *SENEQUE and Co: Développements logiciels et améliorations des outils;* Rapport PIREN-Seine; PIREN-Seine: Paris, France.

Thouvenot, M., Billen, G., and Garnier, J., 2007. Modelling nutrient exchange at the sediment–water interface of river systems. Journal of Hydrology, 341(1–2), 55–78.

Thouvenot, M.; Billen, G.; Garnier, J. *Denitrification in the Riverstrahler Model*. In Proceedings of the Denitrification Modeling Workshop Agenda, New York, NY, USA, 28-30 November 2006.

Tippett, J., Searle, B., Pahl-Wostl, C., Rees, Y., 2005. Social learning in public participation in river basin management—early findings from HarmoniCOP European case studies. Environ. Sci. Policy 8, 287–299.

Todd, P., Benbasat, I., 1992. The Use of Information in Decision Making: An Experimental Investigation of the Impact of Computer-based Decision Aids. MIS Q 16, 373–393.

Tomasoni, L., 2014. A quoi sert la modélisation urbaine?: Analyse des usages des modèles dans l'élaboration des normes et pour l'aménagement urbain. Rapport LABEX. Paris, France.

Tortajada, C., 2010. Water Governance: Some Critical Issues. Int. J. Water Resour. Dev. 26, 297-307.

Toulmin, S., 2001. Return to Reason. Harvard University Press.

Toulmin, S., 1990. Cosmopolis: The Hidden Agenda of Modernity. University of Chicago Press, Chicago.

Tournebize, J., Seguin, L., Bouarfa, S., Chaumont, C., Lebrun, J., Bontoux, C., Berthomé, B., Letournel, G., Barataud, F., Arrighi, A., Guichard, L., Bonifazi, M., Birmant, F., Roger, L., Royer, L., Hureau, D., Farinetti, A., Pages, C., Rougier, J.E., 2018. Projet Brie'EAU : Vers une nouvelle construction de paysage agricole et écologique sur le territoire de la Brie : associer qualité de l'eau et biodiversité, Phase VII. PIREN-Seine, Paris, France.

Tournebize, J., Seguin, L., Bouarfa, S., Chaumont, C., Lebrun, J., Melion-Delage, R., Letournel, G., Barataud, F., Arrighi, A., Guichard, L., Bonifazi, M., Birmant, F., Roger, L., Royer, L., Hureau, D., Farinetti, A., Pages, C., Rougier, J.E., 2017. Projet Brie'EAU : des outils de dialogue territorial pour mutualiser les services écosystémiques (qualité de l'eau et biodiversité), Phase VII. PIREN-Seine, Paris, France.

Tribbia, J., Moser., S., 2008. More than information: what coastal managers need to plan for climate change. Environ. Sci. Amp Policy 315–328.

Turnhout, E.; Stuiver, M.; Klostermann, J.; Harms, B.; Leeuwis, C., 2013. New roles of science in society: Different repertoires of knowledge brokering. Sci. Public Policy. 40, 354–365,

Turnpenny, J., Nilsson, M., Russel, D., Jordan, A., Hertin, J., Nykvist, B., 2008. Why is integrating policy assessment so hard? A comparative analysis of the institutional capacities and constraints. J. Environ. Plan. Manag. 51, 759–775.

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kazmierczak, A., Niemela, J., James, P., 2007. Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. Landsc. Urban Plan. 81, 167–178.

United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. United Nations, New York.

Uthes, S., Fricke, K., König, H., Zander, P., van Ittersum, M., Sieber, S., Helming, K., Piorr, A., Müller, K., 2010. Policy relevance of three integrated assessment tools - a comparison with specific reference to agricultural policies. Ecol. Model. 2136–2152.

Urban, M.C., 2015. Accelerating extinction risk from climate change. Science 348, 571–573.

Urich, C.; Rauch, W., 2014. Exploring critical pathways for urban water management to identify robust strategies under deep uncertainties. Water Res. 66, 374–389.

Urich, C.; Bach, P.; Sitzenfrei, R.; Kleidorfer, M.; Mccarthy, D.; Deletic, A.; Rauch, W., 2013. Modelling cities and water infrastructure dynamics. Proc. Inst. Civ. Eng. Eng. Sustain. 166, 301-308.

Urquhart, R., Porter, G.A., Grunfeld, E., 2011. Reflections on Knowledge Brokering Within a Multidisciplinary Research Team: J. Contin. Educ. Health Prof. 31, 283–290.

Uusitalo, L., Lehikoinen, A., Helle, I., and Myrberg, K., 2015. An overview of methods to evaluate uncertainty of deterministic models in decision support. Environmental Modelling & Software, 63, 24–31.

van den Hove, S., 2007. A rationale for science–policy interfaces. Futures. 39(7), 807-826.

van der Keur, P., Brugnach, M., Dewulf, A., Refsgaard, J.C., Zorilla, P., Poolman, M., Isendahl, N., Raadgever, G.T., Henriksen, H.J., Warmink, J.J., Lamers, M., Mysiak, J., 2010. Identifying Uncertainty Guidelines for Supporting Policy Making in Water Management Illustrated for Upper Guadiana and Rhine Basins. Water Resour. Manag. 24, 3901–3938.

Van Der Sluijs, J., 2016. Numbers Running Wild, in: The Rightful Place of Science: Science on the Verge. Consortium for Science, Policy & Outcomes, Tempe, AZ, pp. 151–187.

Van Der Sluijs, J., 2005. Uncertainty as a monster in the science–policy interface: four coping strategies. Water Sci. Technol. 52, 87–92.

Van Der, J., Craye, M., Funtowicz, S., Kloprogge, P., Ravetz, J., Risbey, J., 2005. Experiences with the NUSAP system for multidimensional uncertainty assessment. Water Sci. Technol. 52, 133–144.

Van Der Sluijs, J.P., Craye, M., Funtowicz, S., Kloprogge, P., Ravetz, J., Risbey, J., 2005. Combining Quantitative and Qualitative Measures of Uncertainty in Model-Based Environmental Assessment: The NUSAP System. Risk Anal. 25.

Van Egmond, S., Zeiss, R., 2010. Modeling for Policy Science-based models as performative boundary objects for Dutch policy making. Sci. Technol. Stud.

van Kerkhoff, L., Lebel, L., 2015. Coproductive capacities: rethinking science-governance relations in a diverse world. Ecol. Soc. 20.

Vezzaro, L., Mikkelsen, P.S., Deletic, A., McCarthy, D., 2013. Urban drainage models – simplifying uncertainty analysis for practitioners. Water Sci. Technol. 68, 2136.

Viale, R., Etzkowitz, H., 2005. Third academic revolution: polyvalent knowledge; the DNA of the triple helix. Fifth Triple Helix Conf. 18–21.

Viennot, P.; Ledoux, E., 2007. *Influence de l'augmentation des prélèvements anthropiques en formations aquifères sur le fonctionnement hydrodynamique du bassin de la Seine*; PIREN-Seine: Paris, France.

Viennot, P.; Monget, J.-M.; Ledoux, E.; Schott, C., 2006 *Modélisation de la pollution nitrique des aquifères du bassin de la Seine : intégration des bases de données actualisées des practiques agricoles, validation des simulations sur la période 1971-2004, simulations prospectives de measures agro-environnementales*; PIREN-Seine: Paris, France.

Vogel, C.; Moser, S. C.; Kasperson, R. E.; Dabelko, G. D., 2007. Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. Glob. Environ. Change. 17, 349–364.

Voinov, A., Seppelt, R., Reis, S., Nabel, J.E.M.S., Shokravi, S., 2014. Values in socio-environmental modelling: Persuasion for action or excuse for inaction. Environ. Model. Softw. 53, 207–212.

von Heland, F., Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global Water Resources: Vulnerability from Climate Change and Population Growth. Science 289, 284–288.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global Water Resources: Vulnerability from Climate Change and Population Growth. Science 289, 284–288.

Walker, W.E., Harremoës, P., Rotmans, J., van der Sluijs, J.P., van Asselt, M.B., Janssen, P., Krayer von Krauss, M.P., 2003. Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. Integr. Assess. 4, 5–17.

Walsh, C. J.; Fletcher, T. D.; Bos, D.; Nemes, V.; Edwards, D.; A., O. K. *Little Stringybark Creek: Environmental benefit calculator technical notes*; Melbourne Water, Department of Water and Environment (Victoria), University of Melbourne: Melbourne, Australia, 2012.

Walsh, C. J.; Fletcher, T. D.; Ladson, A. R., 2005. Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. J. North Am. Benthol. Soc. 24, 690–705.

Ward, V.L., House, A.O., Hamer, S., 2009. Knowledge brokering: Exploring the process of transferring knowledge into action. BMC Health Serv. Res. 9, 12.

Water Sensitive Cities Modelling Toolkit Factsheet; CRC for Water Sensitive Cities. Available online: https://watersensitivecities.org.au/wp-content/uploads/2017/06/Fact-Sheet_Water-Sensitive-Cities-modellingtoolkit_Project-D1.5_V3.pdf (accessed on 2 August 2017).

Waterton, C., 2005. Scientists' conceptions of the boundaries between their own research and policy. Sci. Public Policy 32, 435–444.

Wehrens, R., Bekker, M., Bal, R., 2013. Hybrid Management Configurations in Joint Research. Sci. Technol. Hum. Values 39, 6–41.

Weichselgartner, J.; Kasperson, R., 2010. Barriers in the science-policy-practice interface: Toward a knowledge-action-system in global environmental change research. Glob. Environ. Change. 20, 266–277.

Weingart, P., 1997. From "Finalization" to "Mode 2": old wine in new bottles? Soc. Sci. Inf. 36, 591–613.

Weiss, C.H., 1979. The Many Meanings of Research Utilization. Public Adm. Rev. 39, 426.

Werners, S.E., Pfenninger, S., van Slobbe, E., Haasnoot, M., Kwakkel, J.H., Swart, R.J., 2013. Thresholds, tipping and turning points for sustainability under climate change. Curr. Opin. Environ. Sustain. 5, 334–340.

Willuweit, L., O'Sullivan, J.J., 2013. A decision support tool for sustainable planning of urban water systems: Presenting the Dynamic Urban Water Simulation Model. Water Res., Urban Water Management to Increase Sustainability of Cities 47, 7206–7220.

White, D.D., Wutich, A., Larson, K.L., Gober, P., Lant, T., Senneville, C., 2010. Credibility, salience, and legitimacy of boundary objects: water managers' assessment of a simulation model in an immersive decision theater. Sci. Public Policy 37, 219–232.

Wong, T.; Allen, R.; Beringer, J.; R. Brown, R.; Deletic, A.; Fletcher, T.; Gangadharan, L.; Gernjak, W.; Jakob, C.; O'Loan, T.; Reeder, M.; Tapper, N.; Walsh, C. *Blueprint 2013 - Stormwater Management in a Water Sensitive City*; Cooperative Research Centre for Water Sensitive Cities: Melbourne, Australia, 2013; ISBN 978-1-921912-01-6

Wong, T.H.F., Brown, R.R., 2009. The water sensitive city: principles for practice. Water Sci. Technol. 60, 673.

Wong, T.; Fletcher, T.; P. Duncan, H.; Jenkins, G., 2006. Modelling Urban Stormwater Treatment – A Unified Approach. Ecol. Eng. 27, 58–70.

Wong, T. H.; Fletcher, T. D.; Duncan, H. P.; Coleman, J. R.; Jenkins, G. A. A Model for Urban Stormwater Improvement: Conceptualization. In *Global Solutions for Urban Drainage*; American Society of Civil Engineers: Reston, VA, USA, 2002; 1–14.

Xia, J.; Zhang, Y.; Xiong, L.; He, S.; Wang, L.; Yu, Z., 2017. Opportunities and challenges of the Sponge City construction related to urban water issues in China. *Sci. China Earth Sci. 60*, 652–658.

Xu, Y.-P.; Booij, M. J.; Mynett, A. E., 2007. An appropriateness framework for the Dutch Meuse decision support system. *Environ. Model. Softw. 22*, 1667–1678.

Yankelovich, D., 1999. The Magic of Dialogue: Transforming Conflict Into Cooperation. Simon and Schuster.

Young, J. C.; Waylen, K. A.; Sarkki, S.; Albon, S.; Bainbridge, I.; Balian, E.; Davidson, J.; Edwards, D.; Fairley, R.; Margerison, C.; McCracken, D.; Owen, R.; Quine, C. P.; Stewart-Roper, C.; Thompson, D.; Tinch, R.; Van den Hove, S.; Watt, A., 2014. Improving the science-policy dialogue to meet the challenges of biodiversity conservation: having conversations rather than talking at one-another. *Biodivers. Conserv. 23*, 387–404.

Zehnder, A.J.B., Yang, H., Schertenleib, R., 2003. Water issues: the need for action at different levels. Aquat. Sci. - Res. Boundaries 65, 1–20.

Zhang, K.; Manuelpillai, D.; Raut, B.; Jakob, C.; Reeder, M.; Deletic, A.; Bach, P. M. Impact of future rainfall projections from ensemble GCMs on stormwater management. In Proceedings of the 14th International Conference on Urban Drainage (14ICUD), Prague, Czech Republic, 10-15 September 2017.

Zhou, L., Pan, S., Wang, J., Vasilakos, A.V., 2017. Machine learning on big data: Opportunities and challenges. Neurocomputing 237, 350–361.

Ziman, J., 2000. Real Science: What it is, and what it means. Cambridge University Press, United Kingdom.

Ziman, J., 1995. Postacademic Science: Constructing Knowledge with Networks and Norms, in: Beyond the Science Wars: The Missing Discourse about Science and Society.