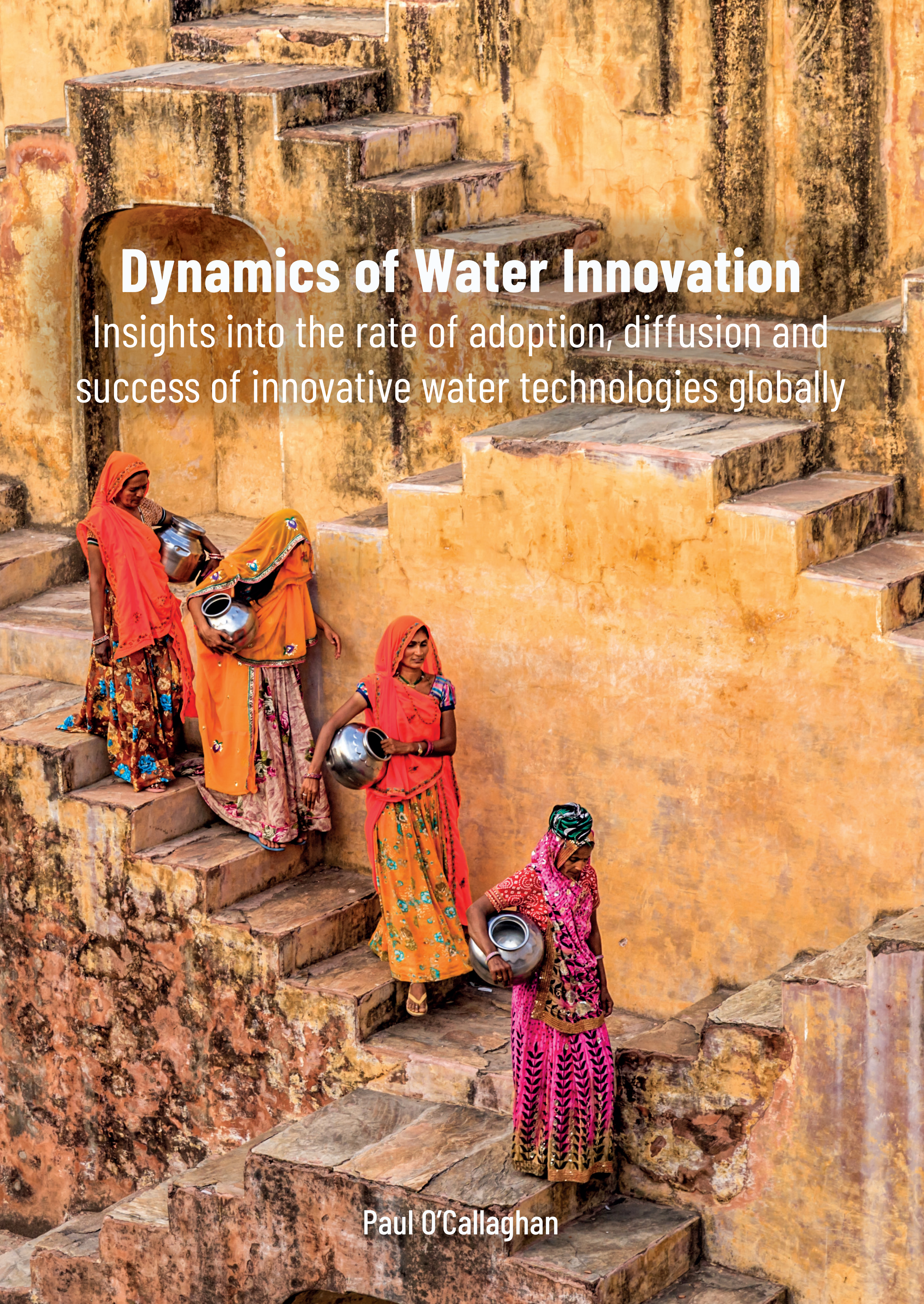
Dynamics of Water Innovation

Insights into the rate of adoption, diffusion and success of innovative water technologies globally



Paul O'Callaghan

Propositions

This thesis:

1. The occurrence of localized and isolated cases of higher-level impact in terms of adoption and diffusion can be attributed to the fragmented nature of the water sector.

2. A crisis or acute need is required to drive diffusion of technologies with radical functionality.

Others:

3. The greatest challenges facing scientists motivated to develop solutions is to combat specialization.

4. The next frontier in sustainable development is low-end disruptive innovation to improve affordability in the provision of water services in the developing world to meet Sustainable Development Goals.

5. The number of people that have been lifted out of poverty in the past several decades is evidence that the human society is getting better.

6. Storytelling helps us to understand universal truths, build empathy and raise consciousness, the latter being the most important step in human evolution.

Propositions belonging to the thesis, entitled
The Dynamics of Water Innovation

Paul O'Callaghan
Wageningen, 9th December 2020

Dynamics of Water Innovation

Insights into the rate of adoption, diffusion and success of emerging water technologies globally

Paul O'Callaghan

Thesis committee

Promotor
Prof. Dr C.J.N. Buisman
Professor of Biological Recovery and Re-use Technology
Wageningen University & Research

Co-promotor
Dr A. ter Heijne
Associate professor, Environmental Technology
Wageningen University & Research

Other members
Prof. Dr C. Kroeze, Wageningen University & Research
Dr A. Soares, Cranfield University, Bedford, UK
Dr G. Pearce, Membrane Consultancy Associates Ltd, Reading, UK
Dr R. Hübner, SKion Water GmbH, Bad Homburg, Germany

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Dynamics of Water Innovation

Insights into the rate of adoption, diffusion and success of emerging water technologies globally

Paul O'Callaghan

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Paul O'Callaghan
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Chapter 1

General Introduction

1. The water challenge

Human society needs access to safe water and sanitation in order to flourish. Access to water and sanitation is a basic human right and water is essential for healthy ecosystems, agriculture and industry. The importance of access to water and sanitation is embodied in the United Nations Sustainable Development Goal No. 6: "Ensure availability and sustainable management of water and sanitation for all" (United Nations, 2020).

Increasingly the world faces growing water challenges (Addams et al., 2009; Kwok et al., 2009; Alves et al., 2014; Elsevier, 2011). These challenges relate to both water supply and water quality, and are due to mounting pressures including population growth, urbanisation, increased industrial demand, climate change and water scarcity. Our current water system is inefficient, wasteful and capital intensive. Due to the mounting pressures listed above, we can no longer afford an inefficient and wasteful system (Naik and Stenstrom, 2014; Daigger, 2009; Kwok et al., 2010; Daigger et al., 2019).

The field of water technology innovation can help to address some of these water challenges. There is however a limited amount of human and financial capital available to develop technological solutions to address water challenges. By 2050, more than half of the global population (57%) will live in areas that suffer water scarcity at least one month each year (United Nations, 2018).

Water scarcity is driving change and innovation in the water sector. This will require new thinking and new approaches. There are many opportunities for both system-level changes, as well as incremental improvements within the existing paradigm. A better understanding of the water innovation process will contribute towards more effective and efficient use of capital in research and development (R&D) and a higher rate of successful innovation diffusion. The rate of innovation and technology uptake in the water sector is often reported as being relatively slow due to the conservative nature of the industry. Each year millions of dollars are invested globally in water technology research and development and much of this research does not go on to be developed into products and technologies that are actually deployed. In a BlueTech Research survey conducted with 60 research institutes in 10 countries investigating all licensing opportunities from 2013-2019, only 9% of the 300 technologies identified were successfully licensed, while the majority of technologies were either found to be still available or discontinued (BlueTech Research, 2019). There are hundreds of water technology start-ups at any given point in time working to develop new technologies, however, only a handful of these companies will succeed. Larger water technology companies have internal research departments and, here too, much of this research does not make its way into the market.

At the same time, there are mounting pressures on water resources and on our current water system. There are also opportunities to leverage new technologies, and new approaches, to solve water issues and provide more efficient use of limited freshwater resources. Policy makers are increasingly realising the importance of innovations in the water sector and thus numerous research agendas and international forums, such as the Horizon2020 programme, the Strategic Research and Innovation Agenda of the Strategic Forum for International Science and Technology Cooperation of the European Commission and Member States, the European Innovation Platform on Water (EIP Water), the Joint Programming Initiative of EU Member states on Water (JPI Water), Water Europe (Previously the Water Supply and Sanitation Technology Platform (WssTP), are including this topic as an issue to be tackled urgently giving utmost priority (Schmidt et al., 2018; Nagel et al., 2018; Bikfalvi et al., 2018; Ajami et al., 2014).

2. The field of water technology

For the purposes of this thesis, the field of study covers the use of technologies that enable use of water in municipal and industrial settings. This includes the collection, treatment and use of drinking water and the collection, treatment and discharge of used water. This also relates to the use of water in industrial manufacturing and production, and in commercial buildings for cooling and heating.

The case studies studied in this thesis relate specifically to treatment technologies that alter the quality of the water or by-products produced from treating water or wastewater. This involves altering the purity of the water and removing or destroying, organic and inorganic chemical contaminants as well as biological agents, such as bacteria, viruses and protozoa. It also involves treatment of sludges produced during the treatment process including biogas.

For the purposes of analysis, the author has developed the Water Technology Taxonomy of various water technologies. Some of the key elements of this taxonomy are shown below in Figure 1 and Table 1, which will help to illustrate the diverse nature of the scientific disciplines that relate to managing water in urban and industrial settings.

In addition to requiring the use of a very wide range of treatment technologies, there are also a wide range of individual applications for drinking water, process water, and wastewater treatment, as illustrated in Figure 2 as the Water Technology Application Taxonomy developed by and reproduced here with the permission of BlueTech Research.

A water technology that has been successfully commercialized is the ultraviolet (UV) light water disinfection. An example of this technology at a water treatment plant in Ireland is illustrated in Figure 3. However QUAY technologies, that patented for microwave-powered UV systems for water disinfection, promised to offer significantly improved reliability and bulb life resulting in lower overall operating costs when compared with traditional technologies, however it never made its way through commercialization as the technology solution was deemed to be technically non-viable. An example of a stalled technology at risk of "death by pilot", which remained in the same stage (innovators) of technology development for the last 10 years and more, is the super critical water oxidation (SCWO). The photograph in Figure 4 was taken at a SCWO plant in the South of France. This technology was being commercialized by a French start-up company but was never successfully introduced to the market.

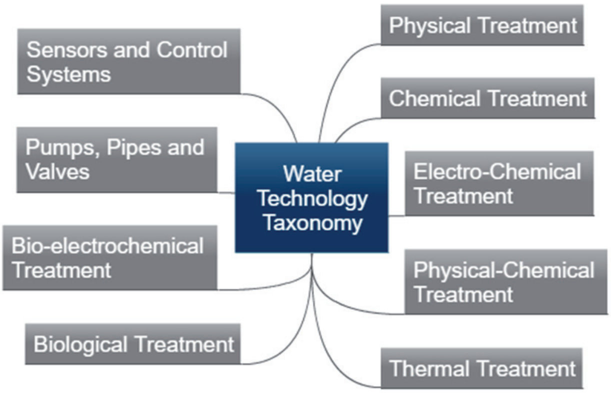

Figure 1: Water technology taxonomy (copyright and provided courtesy of BlueTech Research).

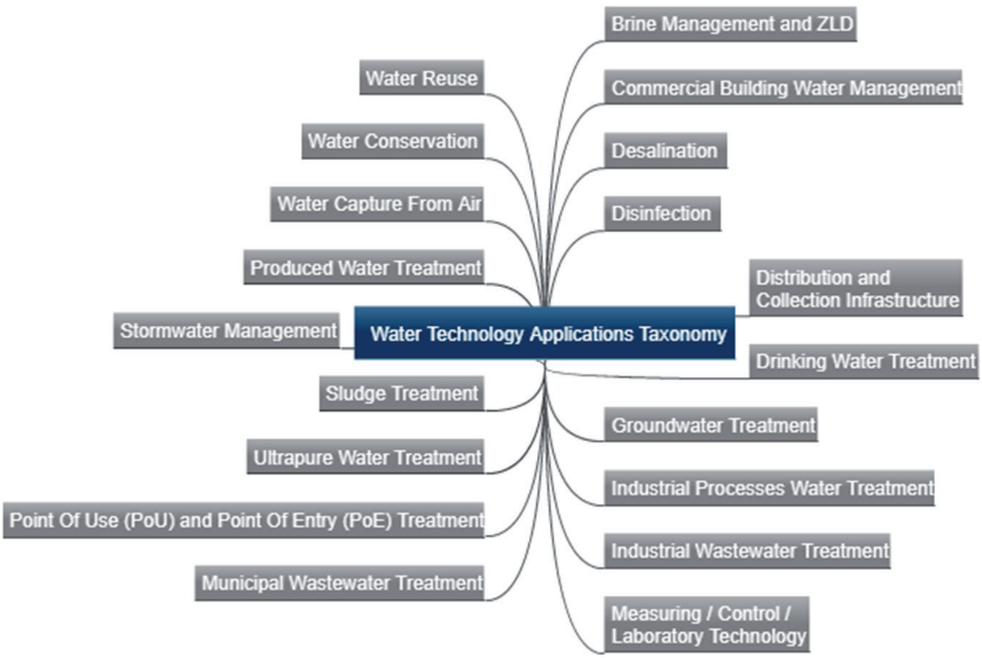

Figure 2: Water technology application taxonomy (copyright and provided courtesy of BlueTech Research).

Table 1: Technology class and sub-class of water technology taxonomy (copyright and provided courtesy of BlueTech Research)

Technology class	Technology sub-class
Biological treatment	Aerobic Anaerobic Biological Nutrient Removal Bio-catalysts
Physical treatment	Membrane filtration (MF, UF, NF, RO, FO) Non-membrane filtration Cavitation Vortex separation Mechanical Vapor Compression
Chemical treatment	Photochemical treatment Advanced oxidation Coagulation Dewatering Disinfection & biocides Adsorbent Absorbent Ion exchange Anti-scalants
Electro-chemical treatment	Electro-deionization Capacitive deionization Electro-dialysis Electrocoagulation Electrochemical oxidation
Physical-chemical treatment	Dissolved air flotation Micro and nanobubbles Supercritical water oxidation Wet air oxidation
Thermal treatment	Gasification Pyrolysis Hydro-thermal carbonization Multiple effect distillation and multi-stage flash Thermal hydrolysis
Sensors and control systems	Artificial intelligence and decision support tools Smart metering On-line sensors Data management systems

Ultrafiltration membranes, as shown in Figure 5, are used as part of a Membrane Bioreactor (MBR) treatment plant. For example, an industrial wastewater treatment plant in the Guangzhou Province in China is known to be using UF hollow-fiber membranes. This is an example of a technology that has been successfully commercialized and is widely adopted in China to meet strict effluent limit guidelines that are imposed on industrial wastewater discharges, which are some of the most stringent in the world.

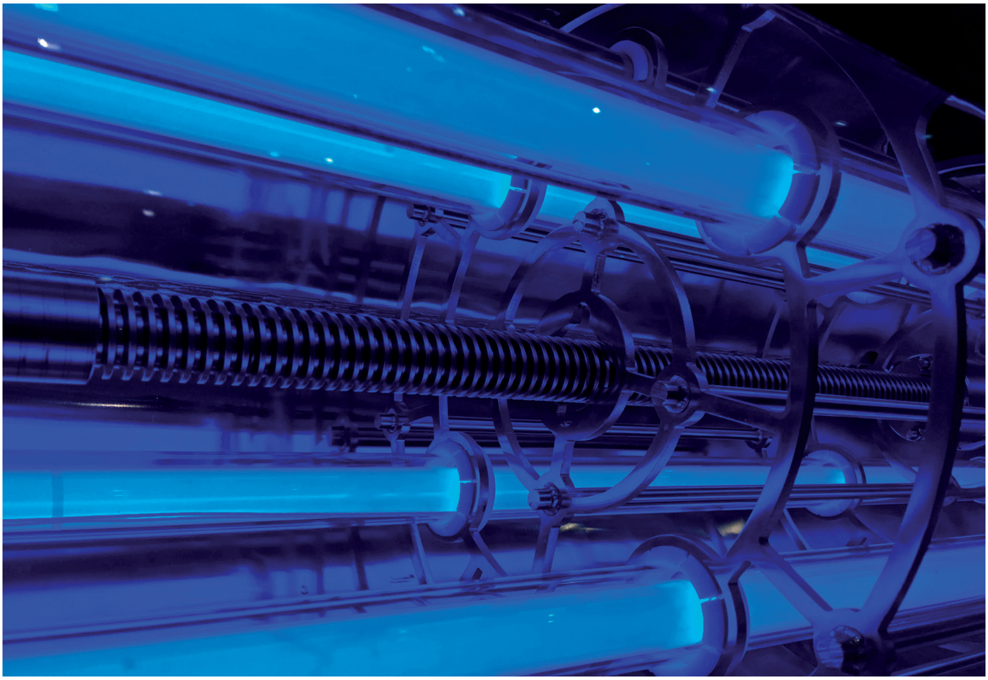

Figure 3: Ultraviolet light water disinfection system at a water treatment plant in Ireland.

Figure 4: Supercritical water oxidation plant in France.

Figure 5: Filament UF membrane in water filter isolated on white background.

Another example of successful water technology innovation is the Reverse Osmosis membrane. Figure 6 shows racks of Reverse Osmosis membrane modules at the Orange County water reclamation plant. This plant currently holds the Guinness Book of World Records for the “most wastewater recycled in 24 hours” (www.guinnessworldrecords.com). This plant successfully deploys a range of treatment technologies, including Membrane Ultrafiltration, Reverse Osmosis, Advanced Oxidation and Ultraviolet light disinfection, to enable in-direct potable water re-use. An example of a resource recovery technology is THIOPAQ (Figure 7) used for the removal of sulphur from biogas through biological oxidation of hydrogen sulphide gas to elemental sulphur. This technology enables the extraction of biosulfur from natural gas, landfill gas or biogas. The bio-sulphur is suited for use as fertilizer or fungicide as it is more bioavailable to crops than chemically produced sulphur. The company Paques offers the technology to treat biogas from anaerobic digestion, while a licensee, the company Paquell, offers the technology in oil and gas applications.

Figure 6: Reverse Osmosis membrane modules at Orange County, California (courtesy of Brave Blue World foundation).

Figure 7: THIOPAQ installation in the Netherlands (courtesy of Paques).

3. Problem statement of this thesis

The problem that is to be addressed in this thesis is that the process of water technology development and technology diffusion is not well understood. There are no models that can be used to analyse success and failure nodes. The factors affecting success or failure of any water technology, and the timelines for the technology to move through different stages of technology diffusion are not well analysed and studied. There is currently relatively little data and theory available (Krozer et al., 2010; Montalvo, 2008; Montalvo and Kemp, 2008). It is widely recognised that given the large amount of applied research in water, there is a relatively low percentage success rate in terms of successful deployment.

There are many elements required to solve global challenge including finance, technology, regulation and policy. Bringing these different aspects together requires that people from different disciplines work together with a shared understanding of the problems, the motivation to want to solve them and a clear pathway to implementing solutions. The galvanizing force is the ability of a community to work together. Without this galvanizing force, nothing happens.

The purpose of this thesis is to give the scientific community and the community of global water professionals and policy makers, a framework for shared discussion. Similar to the way in which evolution of language allows us to share ideas, our ability to see the world through models that we can describe, provides a common ground that allows us to work together to solve problems. The hope is that the ideas contained in this thesis will provide the starting point for a body of work that will continue to be studied academically. Many of the issues addressed in this thesis have therefore only been discussed anecdotally. There are certain shared assumptions, beliefs, and often these can become self-reinforcing and limiting if they are incorrect or are not challenged.

The bottlenecks and failure rates act as a disincentive to those wishing to develop new technologies. Investors are wary to invest and end-users are slow to adopt and researchers may find it difficult to build sustainable research programs around water technology research and development if there is a low rate of success of technology transfer and successful technology diffusion.

Understanding how long it takes for new water technologies to diffuse into the market, the different drivers that can affect the rates of adoption, the diverse types of innovation that exist and how to measure and quantify market impact, are areas that are covered in the subsequent chapters of this thesis.

Understanding the inter-relation of all of these issues will help the community of stakeholders involved in water innovation to understand how capital may be put to work more efficiently to ensure that applied research leads to an advancement and successful deployment.

Investor – challenges
Capital is not used efficiently when it is invested into water technology companies that do not provide a return on this investment for the investor. This can occur when the true capital requirements are not understood, or the likely level of impact and the time required to achieve this impact are not clear. A water technology can run out of time or money, or both. This leads to a write-down on the investment and discourages other investors to invest in water.

Investor – benefit of the thesis
Use of the ideas and concepts outlined in this thesis may help to inform investment strategy of venture capital and strategic investors to classify different types of innovation they are being presented with, set realistic expectations of timelines for a return on investment and gain insights into which types of innovation are likely to have the greatest level of market impact.

End-user – challenges
From the perspective of an end-user, municipal and industrial, having a bad experience with adopting a new technology that does not work, does not solve a need, or deliver value, can discourage these end-users from trying out new solutions in the future. End-users need to understand if they think they are innovators, early adopters, or part of the early and late majority. They then need to understand what stage the technologies are at. A water utility that identifies itself as being part of the early majority is not suited to engaging in pilot testing and being the first adopter of an unproven technology.

End-user – benefits of the thesis
It may help end-users such as water utilities and industrials to appreciate the innovation life cycle and understand their role as early adopters of new technologies and to identify what exactly their innovation drivers are, and how new technologies map to their needs. The role of a water utility or industrial end-user is not to adopt new water technologies. It is to understand their innovation needs and then adopt appropriate solutions that map to those needs. The role of the inventor, entrepreneur and investor, is to develop a deep understanding and appreciation of those needs and research, develop and introduce solutions that are then successfully adopted.

Applied research – challenges
Applied research and development resources are not used efficiently when they are focused on solving a problem that does not need to be solved or does not have enough value as a pain point for the end-user.

Applied research – benefits of the thesis

A better understanding of the process and dynamics of water technology innovation will contribute to more efficient R&D that will lead to a higher degree of success in the diffusion of innovation in the water technology sector. Having clearer insights into how to successfully valorise research and development to achieve tangible results to solve water issues will create value for society.

There are also cases where all of the stakeholders need to be able to see the bigger picture and often hyper-focused on using the solutions they have at hand, in accordance with what is commonly referred to as the Law of the Instrument or the Law of the Hammer, which describes a cognitive bias that involves an over-reliance on a familiar tool. It was described by Maslow that in a situation where "if you only have a hammer, everything starts to look like a nail" (https://medium.com/thethursdaythought/when-all-you-have-is-a-hammer-everything-looks-like-a-nail-the-einstellung-effect-on-67ee8449f740).

4. State of the art

Studies on innovation theory have been carried out in the Information Technology (IT) industry sector and much of the current thinking and innovation theory, arises from work done by others, such as Clayton Christensen and Geoffrey Moore in this area (Moore, 1991; Christensen, 1997). The models developed in the IT industry look at the technology deployment process in terms of market segmentation, and define the following categories: Innovators, Early Adopters, Early Majority, Late Majority and Laggards (Wenger et al., 2009).

There is the well-recognised 'Valley of Death', as defined in technology development theory in the IT sector, where many technologies fail as they try to move from Applied Research to Innovators, and subsequently from Early Adopters to Early Majority, sections of the market (Moore, 1991; Christensen, 1997). The 'Valley of Death' is also referred to as 'The Chasm' and the challenges in overcoming this are well documented in the seminal work 'Crossing the Chasm' by Moore (Moore 1991). The chasm in Rogers Adoption curve is illustrated in Figure 8. The adoption curve is also overlain with the Gartner Hype Cycle, which also describes the process of technology development and diffusion, including the peak of inflated expectations, trough of disillusionment and the slope of enlightenment. The Chasm, (or Valley of Death), coincides with the Trough of Disillusionment (Gartner, 2018). The Trough of Disillusionment is defined as the period when "Interest wanes as experiments and implementations fail to deliver. Producers of the technology shake out or fail. Investment continues only if the surviving providers improve their products to the satisfaction of early adopters" (www.gartner.com/en/research/methodologies/gartner-hype-cycle). The chasm in the adoption curve is a point where new technologies often fail.

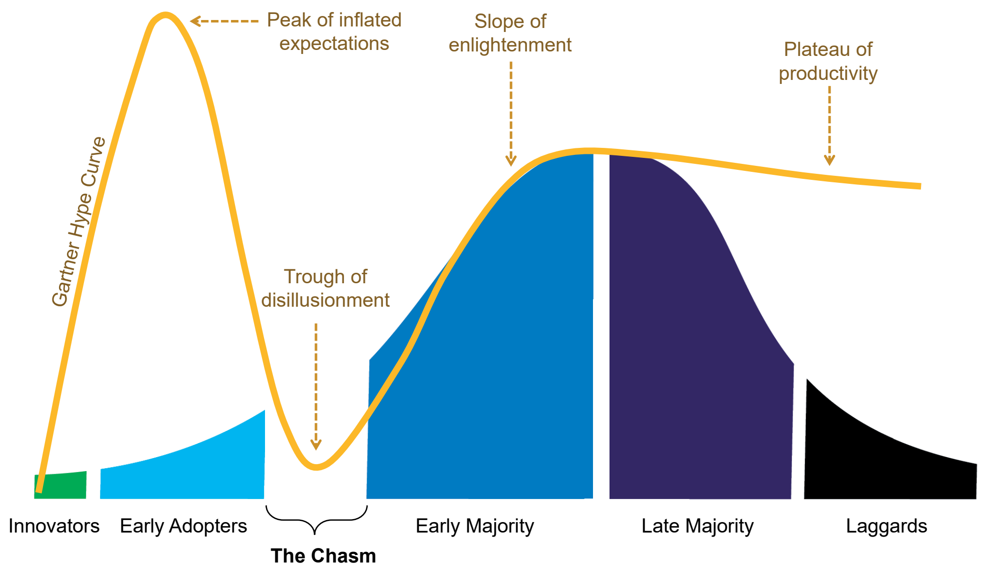

Figure 8: The chasm (Moore, 1991; Khateeb, 2017).

A technology S-curve can be overlain on this market segmentation to track technology development, deployment and maturity. These theories also describe distinct types of innovation: sustaining innovation and disruptive innovation. Those within the industry develop sustaining innovation typically while new entrants typically bring about high level market impact innovation i.e. disruptive innovation. Other studies of innovation and the diffusion of innovations have focused on many industrial and manufacturing sectors to examine the multitude of factors that affect innovation (Montalvo, 2006; Etzkowitz, 2003), however few relate to water related research (Hegger et al., 2011; Krozer et al., 2010; Lobina, 2012; Mvurliwenande et al., 2013; Peuckert, 2012; Partzsch, 2009; Wehn and Montalvo, 2014).

5. Objectives for the thesis

The objective of this research is to examine the area of water technology innovation, using empirical data, and to adapt and build models specifically for the water industry.

The water industry has different drivers compared to the IT sector, however, the same theories relating to sustaining innovation and disruptive innovation and market segmentation can be used to develop models which can then be tested with empirical data. The benefit of using such a model is that it allows data from disparate technologies to be used to gain an overall understanding at a macro level, of water technology development and deployment. Where there are differences in the rate at which technologies have moved through the various sections of the technology development process, key differentiating factors can be identified. If these factors can be identified, through objective analysis, then this may inform future water technology development to help ensure greater innovation efficiency, higher success rates, shorter times to market and more efficient use of capital. The next generation of water technologies may represent systems level changes and will include both sustaining innovation and disruptive innovation. The models will help future researchers inform their work in this area.

The water sector is different to the IT sector, due to slow rates of adoptions, splintered scientific disciplines, and high capital intensity. There is relatively little academic work that relates specifically to the analysis of innovation in water technologies. A key foundational reference paper addressing this gap is *Introduction of New Process Technology into the Wastewater Treatment Sector* by Denny Parker (Parker, 2011).

The absence of available research literature on water technology innovation has been recognised by other academics in the field, including Uta Wehn and Carlos Montalvo. This led to a call for papers, for a special issue of the Journal of Cleaner Production (JCP) (Wehn & Montalvo, 2018). This subsequently led to the publication of the JCP Special Issue which included a range of paper on this topic. The papers were varied and highlighted a number of initiatives that were designed to foster water innovation including the European Innovation Partnership (EIP), VIA Water in the Netherlands, the European Water and Sanitation Technology Platform (WSSTP and Water Innovation Network (WIN) in Sweden.

The European Innovation Partnership (EIP) on water was first established in 2012 with the purpose of finding innovative solutions to water challenges which would prove to be beneficial for the jobs and economic growth in Europe. The major task of EIP is to 'identify, test, scale up, disseminate and stimulate the uptake of innovative solutions by the market and society for 8 major water related challenges', as specified in the 2020 headline target. Water issues in developing countries in Africa have been supported by the VIA Water – a Dutch research programme. It was aimed at facilitating innovative solutions for water problems in seven African countries: Benin, Ghana, Kenya, Mali, Mozambique, Rwanda and South Sudan. Innovative projects are supported by VIA Water funds. As per VIA Water, in Africa, there are twelve 'pressing needs' for water (Figure 9). Dutch Ministry of Foreign Affairs helped his programme financially with $ 14 million dollars for the period of 2014-2018. With the utilisation of a virtual network-centered incubator model that was designed and executed in Sweden, called the Water Innovation Accelerator, it was possible to advance water-related innovation. This can assist several researchers as well as policy makers in the field of water innovation (Gabrielsson et al., 2018).

The aims of this research were:

1. To create a technology diffusion model applicable for the water sector, including defined stages in the technology research, development, and deployment process with clear definitions that can be applied to the water sector as well as defining key factors which can affect the model by accelerating, or decelerating successful technology development and deployment and to test the robustness of the model created by gathering empirical data on wide range of water technology types and applications.
2. To create a framework to measure disruptivity or in other words, market impact of innovation technologies in the water sector. There are different approaches to developing and implementing water technology innovation. Case studies to be applied to the framework to measure the level of market impact for each technology.
3. To identify the factors that play a key role in creating market for new technologies such as legislation.
4. To define terminology and characteristics to be used to classify different innovation types in the water sector.

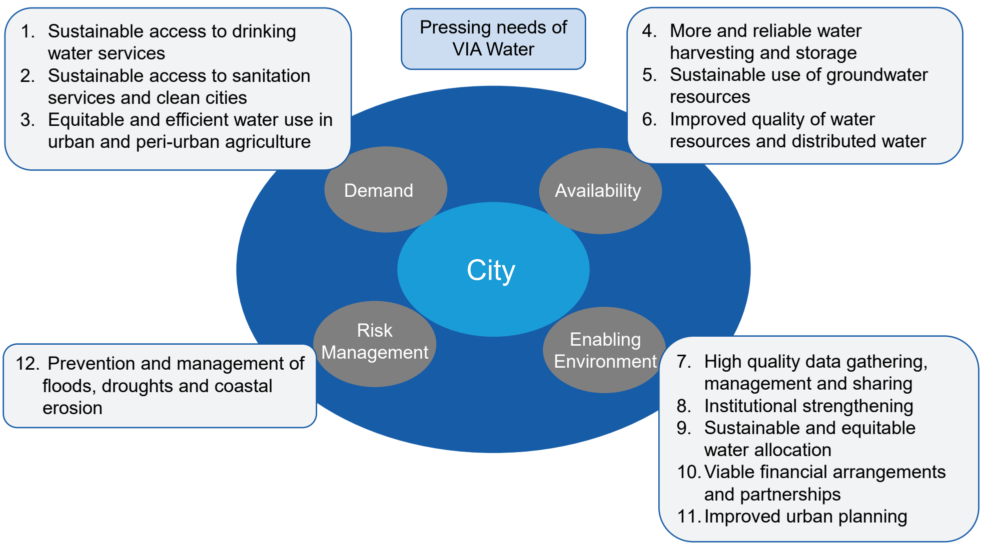

Figure 9: The twelve 'pressing needs' of water in African cities as listed by VIA Water (Nagel et al., 2018).

6. Thesis outline summary

Chapter 2 focuses on development of a set of criteria that can be used to study industry adoption and dissemination of water technologies through various stages of a market adoption model. It tests the applicability of these criteria on a diverse array of over 488 water technologies. Based on case studies, it seeks to define the typical and reasonable time frames in which a water technology moves through these defined stages of industry adoption and dissemination. The development of these criteria, and the definition of reasonable industry average timelines to move through these stages, is an important contribution to the understanding of the process of water technology development. The criteria and defined timelines described in this chapter are foundational, and are used as the basis for subsequent research and analysis to examine the success rates for different water technologies, and common factors linked to why some technologies succeed and others fail.

Chapter 3 analyses six case studies of new water technology innovations in the last 30 years and investigates the differences in timelines for moving through the various stages of water technology commercialisation. The concept of two different types of innovation were explored: Crisis / Needs Driven and Value Driven. It was found that the case studies that mapped to the crisis / needs driven innovation moved relatively quickly compared to value-driven innovations and in most cases involved new entrants. New entrants refer to new companies or start-ups that have recently entered the water technology market. The case studies, which could be mapped to value driven innovation had a slower rate of technology diffusion and they involved a combination of existing companies as well as new entrants.

Chapter 4 critically reviews two theories of innovation: Disruptive Innovation Theory, and Innovation Diffusion Theory (IDT). While important, Disruptive Innovation Theory is found to have limited applicability to water – for example, there are limited opportunities for lower-end innovation which competes on price in a regulated market like water, and there is also limited opportunity to be market-creating. Although the question arises: is there a market-creating equivalent of the Ford production line that would unlock solutions to water problems in developing countries? Innovation Diffusion Theory is found to be more applicable to water, with some important caveats. In conclusion, this chapter proposes a practical framework, with industry examples, for studying water technology innovation. Such a framework could provide a common shared basis to support further research into this topic, including the question: can the disruptive potential of an innovation be predicted?

Chapter 5 proposes a novel framework to measure market impact and technology diffusion, based on three criteria: number of reference plants, number of countries in which the technology is adopted in, and the annual market value represented by the technology. A total of 11 technologies have been investigated and divided into three levels of market impact: Level 1 being the highest level of market impact (i.e. Unicorn Technologies), Level 2 being the medium level, (i.e. Lion Technologies) and Level 3 being the lowest (i.e. Horse Technologies). Timelines have been investigated to understand the speed of these technologies moving through the different levels of market impact, to provide investors and water technology experts a tool to quantify market impact in the water sector.

Finally, **Chapter 6** summarizes some of the main contributions and conclusions of this thesis. It also includes a reflection on the limitations of this work, recommendations for how others can use this thesis and suggestions for further research work.

2

Chapter 2

Development and Application of a Model to Study Water Technology Adoption

1. Introduction

A substantial amount of research addresses numerous water-related challenges, including water scarcity (Addams et al., 2009; Kwok et al., 2009), emerging contaminants (Holtz, 2006), climate change (McCarthy, 2008), ageing infrastructure, urbanization, population growth, and resource recovery (Kalogo and Monteith, 2008). These pressures will become more acute and urgent in the decades ahead (Alves et al., 2014; Elsevier, 2011), driving real change in water management strategies, which creates opportunities for technology development and innovation. Key areas, which are seeing increased activity in terms of water technology innovation, include water reuse, energy and resource recovery, and low-energy desalination (Daigger, 2009; Naik and Stenstrom, 2014; O'Callaghan, 2008).

'Diffusion of Innovations' is a multidisciplinary theory of how, and at what rate, new technology spreads, and why this happens in a specific manner (Rogers, 2003). As the word 'diffusion' is ambiguous within the water sector, the phrase 'dissemination and adoption' will be used. Dissemination and adoption of new technology across industries frequently takes many years before the technology is widely used. Several researchers have attempted to explain the reasons for this in a mix of reviews, case studies, modelling, and policy papers (Krozer et al., 2010; Montalvo, 2008; Montalvo and Kemp, 2008). Kemp and Volpi (2008) concluded that the adoption of any type of innovation is influenced by both technology and market factors. Factors that play a role include government policy, specific characteristics of any new technology, receptiveness of potential adopters, and economic factors such as the age structure of capital (for the latter, see for example Hritonenko and Yatsenko, 2008). The adoption of technologies can also fail in the so-called 'valley of death' in which they stall while moving through the different defined segments of the market (Moore, 1991).

The author wishes to analyze the key factors that are linked to successful water technology development. This chapter focused on studying water technology innovation by defining key stages in water technology adoption and dissemination, the typical timelines associated with each stage, and defining the factors that can be used to assign a water technology to a particular stage. The stages in the model itself will not be new; they will build on previous models. What will be unique is the analysis of the typical time it takes for a water technology to move through the stages of this model, and to develop criteria that can be used to objectively assign a water technology to each stage of the model. The development of this framework is foundational for future work, which will analyze success factors to help ensure efficient use of capital to develop water technologies.

1.1. Applied research and development: an important source for water technology innovation

Many of the water technologies in use today have their origins in applied research at research institutes. Some examples of this are illustrated in Table 1. However, many of the technologies developed in research institutes, are not successfully commercialized and adopted. In a BlueTech Research survey conducted with 60 research institutes in 10 countries investigating all licensing opportunities from 2013-2019, only 9% of the 300 technologies identified were successfully licensed, while the majority of technologies were either found to be still available or discontinued (BlueTech Research, 2019).

Table 1: Examples of commercialized technologies developed at research institutes

Technology area	Source for applied research	Resultant commercial process
Forward osmosis	McCutcheon et al. (2005), Yale University	Oasys (Membrane Brine Concentrator)
Struvite crystallization	Adnan et al. (2003), University of British Columbia	Ostara (Pearl Process)
Reverse osmosis membranes	Jeong et al. (2007), University of California, Los Angeles	NanoH2O Membranes
Chemical oxidation	Monzyk et al. (2013), Battelle Memorial Institute	Ferrate
Nutrient removal	De Kreuk et al. (2005) and Van der Star et al. (2007), Delft University of Technology; Blonigen et al. (2005)	Annamox, Sharon, Nereda

1.2. Existing water technology adoption models

We have reviewed a range of theories and models, including the Technology Adoption Life Cycle (TALC) and the Technology Life Cycle (TLC) models. The TALC model is based on an earlier model known as the Diffusion Process, which was originally devised to study the rate of hybrid corn adoption by farmers in two Iowa farming units (Beal and Bohlen, 1957). This model describes how a new product or innovation moves through different segments of the defined adopter groups: Innovators, Early Adopters, Early Majority (about 34% of the population), Late Majority (last major group to adopt, also about 34% of the population), and Laggards. This classification into adopter groups is well suited for consumer products used by the general population. Wenger and coworkers (2009) have shown how the Diffusion Process model can be adapted to specific technology domains, such as education and digital technology. Moore (1991) revised the TALC model to look at gaps present between the adopter groups in high-tech markets.

The Technology Life Cycle (TLC) typically follows an S-curve shape as technology moves from research and development through the 'ascent phase' to maturity and finally declines (Christensen, 1992). The TLC is a measure of technology maturity, and is distinct from the Technology Adoption Life Cycle (TALC). The TLC's S-curve can be overlaid with the TALC model to analyze the adoption of innovations and maturity of adopted technologies. This can be seen in Figure 1, which shows the conceptualization of technology adoption by Rogers (2003). These two curves focus not on the state (maturity) of the technology but, rather, on the characteristics of the people adopting the technology (Parker, 2011). Rogers found that the adopter groups identified in TALC statistically fitted a bell-shaped curve representing a normal distribution.

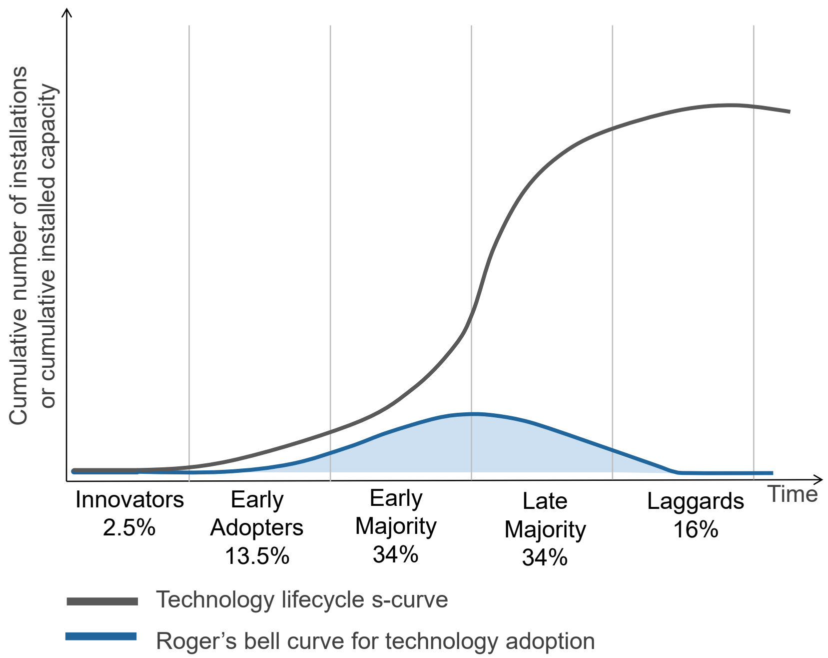

Figure 1: Figure overlaying the Roger's bell curve for technology adoption with classical technology lifecycle s-curve indicating technology maturity across classes of adopters (Parker, 2011; Rogers, 2003).

Technology Readiness Levels (TRLs) are a measure of technology development in research and development institutes (Mankins, 1995), of which business sectors and governmental organizations use different variations. So far, the commercial aspects of TRLs have not been defined, because initially TRLs were mainly applied to technologies in specific systems developed for the research institutes' own use only (e.g., NASA's space missions). For example, there are no clear definitions of technologies in their initial stages of development in the TRLs applied by the E.U. in its Horizon 2020 Framework Programme for Research and Innovation (European Commission, 2013; Schild, 2013):

- TRL 1 - basic principles observed
- TRL 2 - technology concept formulated
- TRL 3 - experimental proof of concept
- TRL 4 - technological validity in a laboratory
- TRL 5 - technology validated in a real environment
- TRL 6 - technology demonstrated in relevant environment
- TRL 7 - system prototype demonstration in an operational environment
- TRL 8 - system completed and qualified
- TRL 9 - actual system proven in operational environment

The TRLs define technology development stages in a granular manner, and a correlation with either Rogers' bell curve (TALC) or the S-curve (TLC) is difficult. Vyakarnam (2013) attempted such a correlation and suggested that the translational journey from laboratory to market should make use of TRLs in early technology stages, and use Rogers' TALC model in later stages of technology development (i.e., once the technology is ready for market introduction). In the literature, only Parker (2011) has applied the S-curve to five case histories to examine the pace of dissemination and adoption, as well as the stages of technology development, and by which events they were shaped and influenced.

This chapter defines a Water Technology Adoption (WaTA) model, which covers the entire technology life cycle from development through to maturity, and can serve as a practical framework for water industry professionals and water technology researchers. This model is based on interviews with water industry leaders, a review of existing technology and dissemination and adoption models, innovation theory, an analysis of empirical water technology data, and insights gained by the author and his coworkers through their collective experience in the global water industry.

The first objective of the research was to define key stages in a water technology's dissemination and adoption. The second aim was to provide a well-defined set of criteria that could be used to classify water technologies according to relevant stages. This could then, for example, be used in subsequent research to determine if there are particular technology areas that move faster than others, to identify accelerators and decelerators, and identify any common factors that might affect success and failure rates in technology dissemination and adoption.

This chapter is structured as follows. After this introduction, the Methodology describes the process in defining six different stages of water technology adoption and dissemination. The Results and Discussion section explains how the author tested the model and validated the six stages by applying them to a data set of 488 water treatment technologies. Finally concluding remarks and suggestions for further work are outlined in the last section.

2. Methodology

In this section the development of criteria for assigning water technologies to particular stages of the WaTA model is explored.

2.1. Development of definitions and criteria

The author adapted existing models to create one that was suitable for the analysis of water technologies from Applied Research through to Maturity. Activities such as Pilot and Demonstration were mapped to the Innovators Stage, and the stages of Early Majority and Late Majority were grouped together into one stage (Figure 2), for reasons outlined later in this section. To develop the definitions for each stage, the author began studying a discrete number of case studies for water technologies which were previously introduced to market, including membrane bioreactors, ultraviolet disinfection, moving bed bioreactor (MBBR), and ultrafiltration membranes; and developing criteria that the author believed could have been used to define when these technologies were at a particular stage in the WaTA Model.

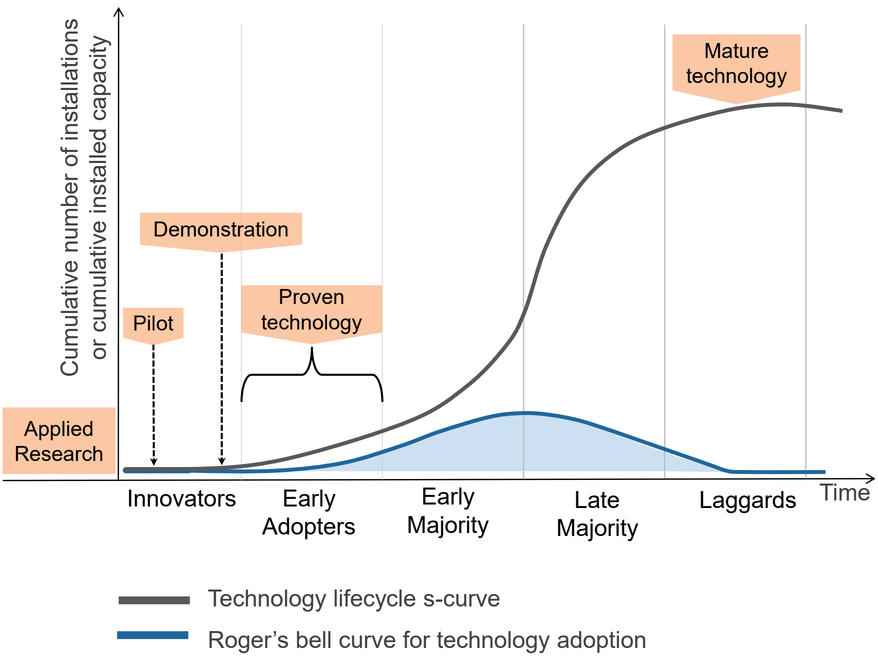

Figure 2: Illustration of stages of the water technology diffusion (WaTa) model and how these relate to different stages of the water technology development process, such as Pilot stage and Demonstration stage. Applied Research is shown as preceding the technology adoption stages.

In particular, the author sought to define the following for each stage of the model:

- Criteria for assigning a technology to this stage
- Activities undertaken in this stage
- Objectives/outcomes sought at this stage
- Duration of this stage
- Corresponding stage in other models

2.2. Research interviews to test the validity of the criteria and definitions

The objective of the research interviews was to assess whether the criteria used to assign a water treatment technology to a particular stage of the model were robust, and would be understood and usable in a consistent and objective way by water industry stakeholders. There were 13 interviewees selected to provide representative coverage across key stakeholder groups, including consulting engineers, water treatment technology providers, academics, water utility end users, and water technology investors; and on the basis of their extensive expertise in developing new water treatment technologies and implementing innovation. The lead author conducted these research interviews between September and December 2015.

The interviewees were contacted by e-mail, in advance, and given standard background information on the purpose of the research interview. During the interview, the interviewees were guided through the different stages of the WaTA model. The definitions for each stage were outlined, criteria for classification were shared, and feedback was solicited on each stage. For each of the criteria, the author asked the interviewees if the criteria were clear, if they agreed or disagreed with these definitions, if they believed the criteria needed to be modified, and if additional criteria should be used.

The collective responses were analyzed, tabulated, and cross-compared for each stage of the WaTA model. This led to refinements to the definitions, based on the feedback of the interviewees, and to additional criteria. The research interviews provided confidence that the criteria outlined in this chapter can be applied by anyone in the water industry, based on accepted terminology and definitions. In addition, this also enables a consistent approach to mapping technologies to different stages of an adapted S-curve (TLC) and Rogers' TALC model, if desired.

2.3. Testing of the criteria to assign technologies to different stages of the water technology adoption model

The author then attempted to apply the criteria that were developed, and further refined through research interviews, to a data set of over 488 different water technologies. The objective was to determine if the criteria would be robust and useful when applied to a diverse set of water technologies. The data set used in this study pertains to

488 proprietary technologies contained in the BlueTech Research database of water technologies. The author was granted access to the database to support this research. The technologies represent a broad section of technologies that are used in municipal, and industrial, water and wastewater resource recovery. This was supplemented with a data set of 28 mature water treatment technologies.

Figure 3 depicts the distribution of the sample data set across the five different water technology classes and illustrates the spread and representation across these different technology classes. For the purposes of this study, the author excluded sensors, control systems, and data analytics because their characteristics are significantly different to water and wastewater treatment technologies. The following are five different classes of water technologies that are represented in the data set.

1. Biological Treatment
2. Chemical Treatment
3. Physical Treatment
4. Physical-Chemical Treatment
5. Electro-Chemical Treatment

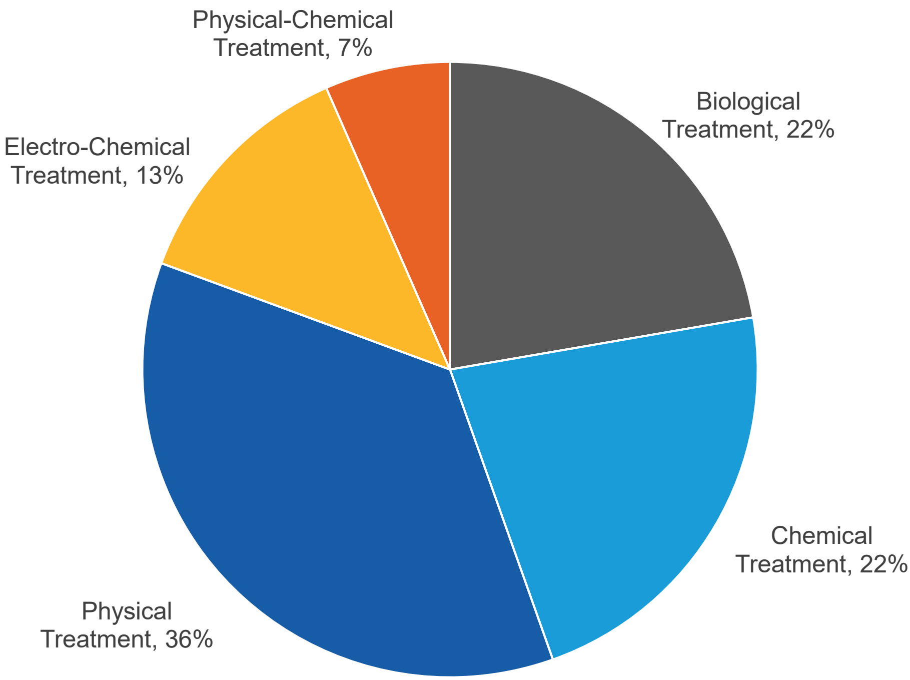

Figure 3: Illustration of the distribution of the test data set across different water technology classes.

2.4. Analysis of average time spent at each stage of the model

The author also wished to determine the average time spent by a technology at different stages of the WaTA model. To determine this, the author prepared and analyzed a number of case studies, including ultraviolet disinfection, membrane bioreactors, phosphorus removal as struvite, and sludge thermal hydrolysis. Figures 4 and 5 give the timelines for ultraviolet disinfection and membrane bioreactors, respectively. Based on the case studies analyzed, a set of average or typical timelines were developed, which are presented in the next section. Figure 4 illustrates the stages in the Ultraviolet (UV) disinfection case study, timelines, and key stages in the adoption and dissemination of this technology. Figure 5 illustrates the timelines that were required to commercialize and achieve technology adoption and dissemination of the Membrane Bioreactor (MBR) technology.

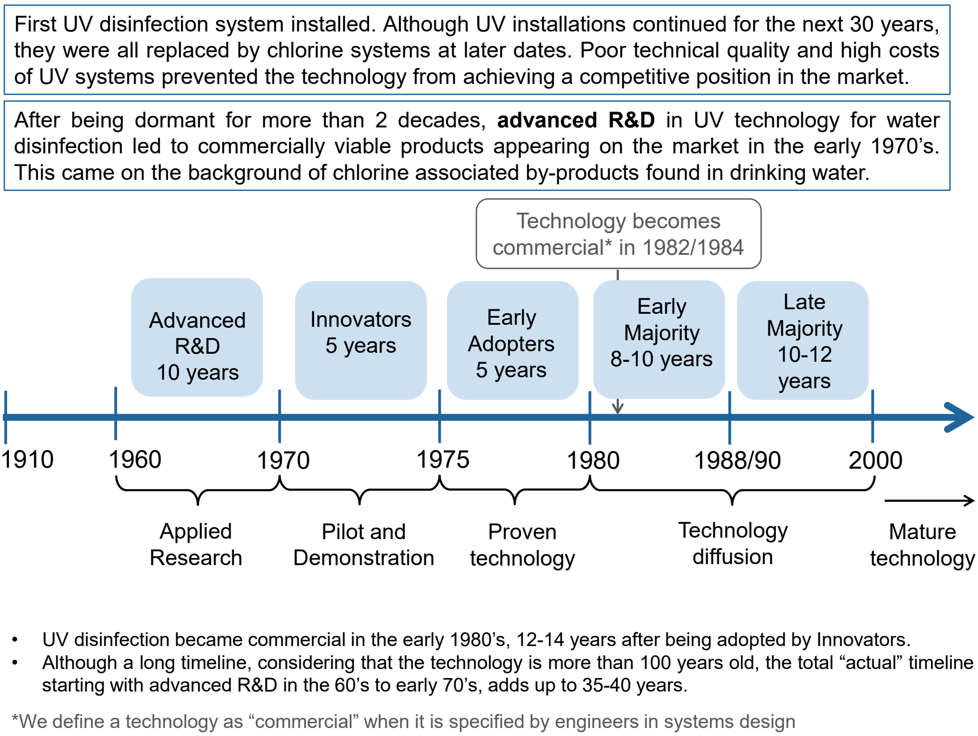

Figure 4: Analysis of the Ultraviolet (UV) water disinfection technology timeline.

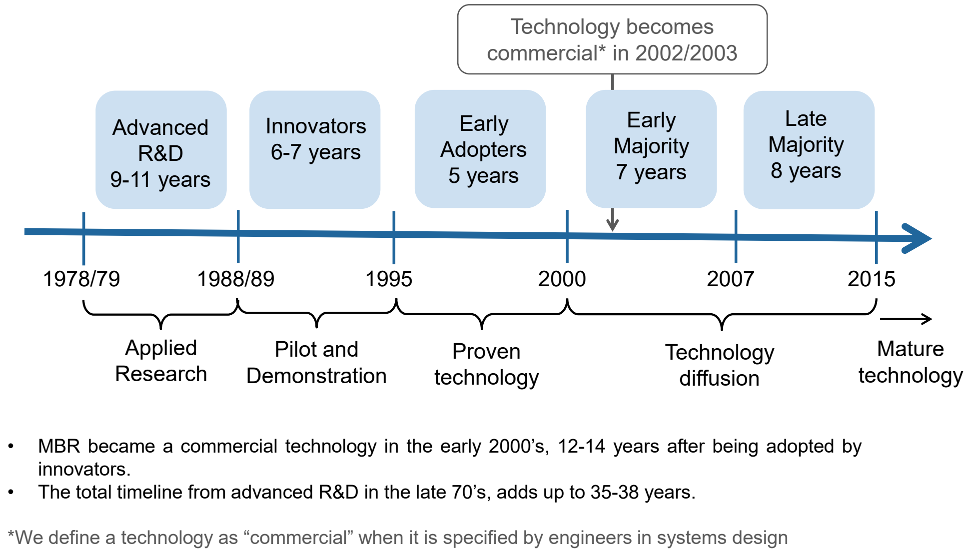

Figure 5: Analysis of the Membrane Bioreactor (MBR) wastewater treatment technology timeline.

3. Results and discussion

A key output from the research was the development of the following detailed definitions of each stage of WaTA. Figure 6 displays the criteria for assigning a technology to each stage, activities undertaken in this stage, the objectives/outcomes sought, the typical duration of this particular stage and the corresponding stage in other models. The following describes, in more detail, the definitions developed to define each stage.

Stage 1: Applied Research Stage

The Applied Research stage matches E.U. Horizon 2020 TRLs 1 to 5, but has no counterpart in Rogers' TALC model. The following simple criterion can be used to assess whether a technology is at the Applied Research stage: research and development is taking place in a laboratory setting, with the aim of developing a water treatment technology with a real-world application. New water treatments are occasionally derived from existing technologies used in adjacent industry sectors (e.g., sludge dewatering derived from fruit juice filtration technology), whereas most successful new water treatment technologies originate from applied research. Examples include, forward osmosis technology, struvite crystallization, reverse osmosis membranes, short-cut ammonia removal, granular activated sludge, and membrane aerated bioreactors (see Table 1). Applied water technology research mainly occurs in research institutes, national laboratories, or research and development divisions of small- and medium-sized enterprises (SMEs) and large water technology companies.

THE STAGES OF THE WaTA MODEL

- Criteria for assigning a technology to this stage
- Activities undertaken in this stage
- Objectives/ outcomes sought at this stage
- Duration of this stage
- Corresponding stage in other models

1. Applied Research stage

- **Critera:** R&D in laboratory setting with aim of developing a water treatment technology with real-world applications
- **Activities:** Bench-scale tests with synthetic streams to analyze fundamental mechanisms and gather data on fundamental performance criteria
- **Objective:** Confirming the scientific basis (Proof of Concept)
- **Timeline: Typically, 6 to 8 years, but can be longer or shorter**
- **Corresponding stage in other models:** E.U. Horizon 2020 TRLs: 1 to 5

2. Pilot stage (Innovators)

- **Criteria:** Technology tested in real-life applications; deployment of pilot-scale process at, for example, drinking water or wastewater treatment facility; no full-scale facility operational yet
- **Activities**: Gathering operational data, which can be used as design criteria for scale-up
- **Objective:** Addressing fundamental engineering issues
- **Timeline: Typically, 2 to 3 years**
- **Corresponding stage in other models:** E.U. Horizon 2020 TRLs: 6 to 9, TALC (bell curve): First part of Innovators

3. Demonstration stage (Innovators)

- **Criteria:** Technology scaled up and part of formal product offering; 1 to 3 units operational at similar scale in similar applications
- **Activities:** Construction and deployment of technology in full-scale systems in target applications; results presented in papers and at conferences
- **Objective:** Testing commercial viability, proving value proposition
- **Timeline: Typically, 3 to 5 years**
- **Corresponding stage in other models:** TALC (bell curve): Second part of Innovators

4. Early Adopters

- **Criteria:** Now a proven technology, but not widely accepted by end users yet; commercial sales of 1st-generation units taking place; at least 3 units operating at similar scale, in similar applications, at separate locations; still limited awareness and technical understanding among end users and water professionals
- **Activities:** Larger water utilities starting to adopt; debuggging and improvements
- **Objective:** Creation of client base and reference projects so that technology can become specified in tender documents and requests for proposals
- **Timelines: Typically, 6 to 8 years**
- **Corresponding stage in other models:** TALC (bell curve): Early Adopters

5. Early & Late Majority

- **Criteria:** Consulting engineers now specify the technology; technology appears in tender documents and RFPs; at least 3 companies actively offer versions of the technology; more than 30 full-scale units in operation
- **Activities:** Time to double total number of installations shortest in this stage; technology continues to be improved; price tends to reduce
- **Objective:** Efficiencies gained in engineering design and process optimization
- **Timelines: Typically, 12 to 16 years**
- **Corresponding stage in other models:** TALC (bell curve): Early and Late Majority

6. Maturity Stage

- **Criteria:** Technology included in engineering manuals and textbooks, university courses and curriculums; know-how and expertise in the hands of most companies offering proprietary technologies; technology becoming a commodity technology with multiple suppliers offering competing products; engineering professionals designing generic nonproprietary versions
- **Activities**Technology continues to be value-engineered, with small improvements in efficiency
- **Outcome:** Technology becoming at risk of being displaced by newer technologies
- **Timelines: 15 to 20 years, or longer**
- **Corresponding stage in other models:** TALC (bell curve): Laggards

Figure 6: Criteria for defining stages of the WaTA Model.

Typically, tests are carried out with synthetic feed water streams designed to mimic real-world conditions. For example, sodium chloride solutions can be used to model salinities likely to be encountered in seawater, and brackish water, desalination applications. For biological removal of organic contaminants, sugars are frequently used to create wastewater streams with a synthetic biological oxygen demand. These bench-scale tests with synthetic streams allow researchers to analyze fundamental mechanisms, confirm the scientific basis for the technology (Proof of Concept), and gather data on fundamental performance criteria, such as the rate of removal of particular contaminants, kinetics, and removal efficiencies. However, limitations include the fact that in real-life conditions, a wider range of compounds and materials are present, and at fluctuating concentrations. This can interfere with the process through various mechanisms, including inhibition of biological processes, membrane fouling, chemical deposits, and corrosion. There can also be unintended effects during scale-up for example, as a result of changes in fluid dynamics, mixing, or heat exchange when the size of reactors is increased.

At the end of the Applied Research stage, a pilot installation may be tested with natural water or wastewater. Once technologies have completed the Applied Research stage at an institute, assuming the results are promising, the technology will typically be examined for the purposes of an Invention Disclosure and Patent Cooperation Treaty (PCT) patent filing. The technology is then handed over to the institution's Technology Transfer Office or its equivalent.

Stage 2: Pilot Stage (Innovators)

The Pilot stage matches E.U. Horizon 2020 TRLs 6 to 9 and corresponds to the first part of the Innovators step in the TALC model. The criteria for this stage are as follows: (1) The technology is tested outside the laboratory in real-life applications; (2) Until at least one full-scale plant is operational, the technology remains in the Pilot stage. This stage concerns, for example, the deployment of a pilot-scale reactor at a municipal or industrial water resource recovery facility, a desalination facility, or drinking water treatment facility.

Pilot stage testing is typically carried out to gather data on operations, such as the technology's robustness in real-world conditions, which can then be used as design criteria for the scale-up to a full-scale plant. The data gathered is dependent on the process, but can include parameters such as reaction rates, membrane flux rates, removal efficiencies, chemical and energy consumption, time between cleaning cycles, and variation in performance following extended periods of operation. A pilot plant is basically a smaller-scale version of the technology, envisaged as a commercial full-scale system in terms of size and capacity.

Issues frequently identified during the Pilot stage include:

- Inhibition of a biological process as a result of substances not present in the synthetic feed used in the laboratory.
- Membrane fouling as a result of inorganic deposits and biofouling.
- Reaction rates, removal and flux rates or other key performance criteria are different from expected data.

At this stage, the technology is typically being developed by a company and has left the research institute or laboratory. It is linked to commercial activity, and pilots can therefore be funded by the potential end user or by the company offering the technology.

The Pilot stage is not to be confused with all pilot testing. A fully commercial technology may still be 'piloted', or undergo pilot testing at particular sites to reduce the risk of failure in a full-scale application, but this may, for example, concern a new application for the technology. This type of pilot testing would be part of a feasibility study, which can take place during the later stages of this model. Many efforts to bring new solutions to market fail at the Pilot stage, or can remain stalled at this stage and have difficulty moving beyond it. In the context of the WaTA model, failure is defined as failure on the part of the technology developer to move the technology forward. If this happens, there is a potential for the technology to be successful as it can still be ultimately picked up by another entity, which then continues to try and move the innovation forward.

Stage 3: Demonstration Stage (Innovators)

This stage no longer matches any TRLs, but is equivalent to the second part of the Innovators step of the TALC model. The criteria for this stage are as follows: (1) The technology must now be of a size and scale that would be practical in the real-world target applications; (2) The technology must form part of a formal commercial product offering; (3) The technology is deemed to remain at this stage until there are three units operating at a similar scale, in similar applications. The Demonstration stage involves the construction and deployment of the technology in full-scale systems in target applications. The criterion of having no more than three units operating at a similar scale, in similar applications, in this stage is based on the concept of 'proven innovation', frequently contained in tendering documents, often requiring three reference plants at a similar scale treating a similar stream (see also next stage). The author noticed that the following technologies were already offered by one to three companies at the Demonstration stage: capacitive deionization, ceramic ultrafiltration membranes, struvite crystallization, granular activated sludge, forward osmosis, short-cut nitrification, membrane bioreactors, anaerobic membrane bioreactors, and supercritical water oxidation.

Stage 4: Early Adopters

This stage corresponds to the Early Adopters step of the TALC model and meets the following criteria:

- The technology is now a 'proven technology', but is not yet widely accepted by end users in the market.
- There are some commercial sales of first-generation units to early adopters.
- At least three units, but typically less than twenty-five units, are now operating at a similar scale in similar applications.
- The technology remains at the Early Adopters stage until it has been fully commercialized and then moves to the Early and Late Majority stage. The Early Majority, typically, will only adopt a 'proven technology' that is accepted by a sufficient number of end users.

The definition of 'proven technology' or 'proven innovation' is embodied in many state regulatory bodies engineering guidelines, such as the following (Ontario Ministry of the Environment, 2008): (1) At least three separate installations must be operating at (near-) design capacity; (2) The technology should have an operating record of a minimum of three years, at three separate locations; (3) The technology should show reliable and consistent compliance with design performance criteria, for a minimum of three years, without major failure of either the process or the equipment.

At the Early Adopters stage, the technology is still a 'new technology', and is unlikely to be specified by a consulting engineer or appear in formal tender documents. There is limited awareness and technical understanding or expertise, in relation to the technology, among end users and water professionals. In the water sector, these Early Adopters tend to be the larger water utilities, serving populations greater than 100,000 people, or operating facilities with capacities greater than 20,000 m^3 per day. The Early Adopter water utilities typically have strong internal teams, with a high degree of expertise and capability. They are visible as leaders in the industry and may participate in technical committees and present papers at water conferences.

Stage 5: Early and Late Majority

For the purposes of the Water Technology Adoption (WaTA) model, the author has proposed that it makes sense to combine Early and Late Majority into one stage. Based on analysis and research interviews, the author does not believe there are clearly defined differences in water between these two segments, and that both can be defined as one cohesive stage. The technology is now commercialized and moving into the Early and Late Majority step of Rogers' TALC market adoption model. As the water sector does not display a difference between the Early Majority and Late Majority sections, this stage constitutes adoption by roughly 68%. The criteria for assessing whether a technology has reached this stage are as follows:

- Consulting engineering companies begin to specify the technology for a project during the design phase.
- The technology now appears in formal tender documents and requests for proposals (RFPs).
- At least three companies are actively offering versions of this technology to end-users.
- There are more than 30 full-scale units in operation.

The technology is now no longer only used by Early Adopters, but is typically still only offered by a handful of companies (usually not more than six) at the start of the Early and Late Majority stage. As the market adopts the technology, new players will enter towards the end of the Early and Late Majority stage (and at the start of the Maturity stage).

The definition for the point at which a technology is deemed to be 'commercialized' and moving out of the Early Adopters stage is based on case studies for ultraviolet disinfection, membrane bioreactors, sludge thermal hydrolysis and struvite precipitation, and research interviews with CEOs and CTOs of technology companies and end users. At the Early Adopters stage, the rate of technology installation increases most rapidly, and the time taken to double the number of cumulative installations is the shortest; the technology is now entering the log-phase in terms of technology dissemination and adoption. This can be observed when cumulative annual installations are plotted, and an inflection point is apparent in the TLC S-curve. When the technology moves from the Early Adopters to the Early and Late Majority stage there are typically 25-30 full-scale plants successfully in operation. The technology now also begins to be specified by design engineers in projects and appears in formal tender documents.

Stage 6: Maturity Stage

This stage corresponds to the Laggards section in Rogers' TALC model. The criteria are the following:

- The technology is now included in standard engineering manuals and textbooks, as well as in university courses and curriculums as design projects for students.
- The know-how and expertise required to design and implement the technology is no longer in the hands of a small number of companies offering proprietary technologies.
- It is now becoming a commodity technology with multiple suppliers (greater than ten), offering competing products.
- The knowledge of process design enables engineering professionals to be able to design generic nonproprietary versions of this technology.
- The rate of increase in annual cumulative installations levels off, as market saturation occurs.
- Original patents are nearing the end of their life or may have expired.

During the Maturity stage, the systems continue to be value-engineered, and sustaining innovation keeps delivering small improvements in efficiency. A mature technology is, itself, now at risk of being displaced in the market by newer technologies.

3.1. Results of testing criteria on a sample data set of water technologies at different stages of the Water Technology Adoption (WaTA) model

The results of testing the criteria on the sample data set are illustrated in Figure 7. Figure 7 illustrates how the technologies in the test data set were assigned across the different stages of the Water Technology Adoption (WaTA) model using the criteria set out in Figure 6. The testing on 488 different proprietary technologies showed that the model is quite robust, as it was possible to use the criteria to classify all the technologies into relevant stages. The criteria and defined stages of the WaTA model can be applied across a wide range of different water and wastewater treatment technologies. The first three stages of the model (Applied Research, Pilot, and Demonstration) proved to be relatively straightforward to classify. It is also relatively clear when a technology has moved from the Demonstration to the Early Adopters stage because this is based on the number of full-scale plants in operation. The most challenging classification is between the Early Adopters and Early and Late Majority stages because their definitions are more qualitative in nature, and the transition is a function of both the market

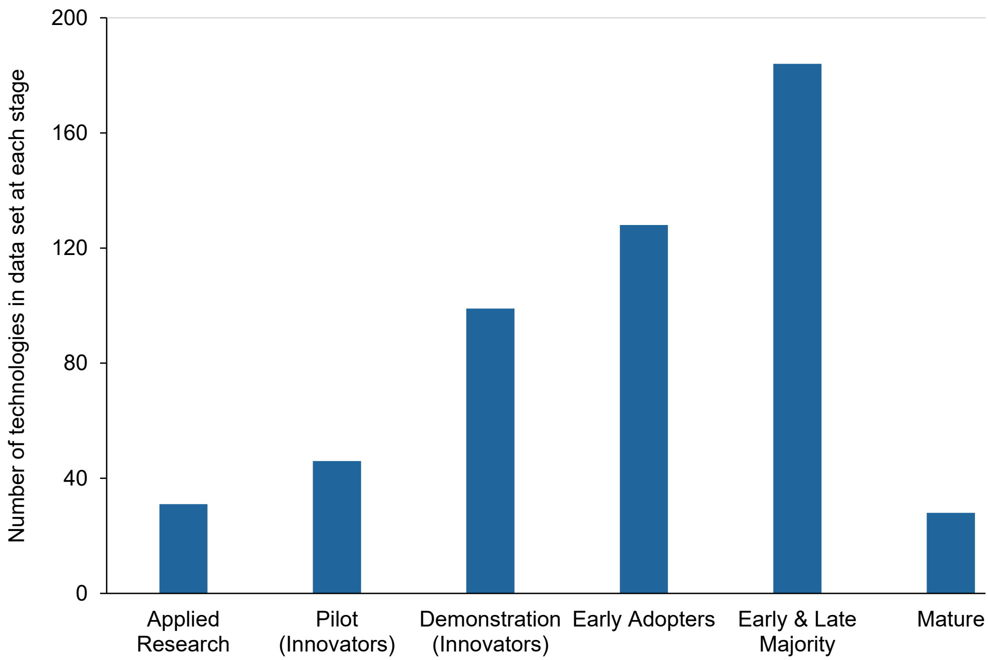

Figure 7: Distribution of the test data set across the stages of the Water Technology Adoption Model (WaTA).

and the technology. The technology itself may undergo improvements, with second-generation systems being developed and deployed in the first major market segment (the so-called Early Majority), using the experience gained in the Early Adopters stage. A key transition point between Early Adopters and Early and Late Majority is when the technology is deemed 'commercialised'. It was found that this transition also correlated with the existence of over 30 full-scale plants in operation. Once this number of plants is in operation, the knowledge and experience gained from earlier generations allow improvements in subsequent generations, and the Early Majority customers now regard this as a proven and accepted technology.

3.2. Average water technology adoption timelines

Based on the analysis of case studies outlined in Section 2, a set of average timelines for each stage were developed and proposed. These are illustrated in Figure 8. It was found that the Applied Research stage typically takes seven to ten years, but can vary between four and twelve years.

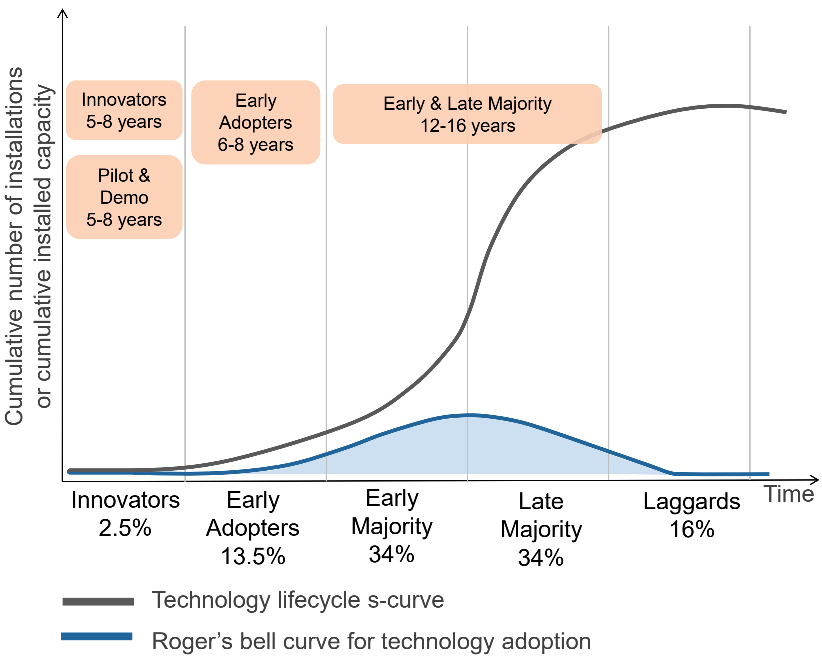

Figure 8: Water Technology Adoption (WaTA) model timelines.

Figure 8 outlines the average timelines that are proposed based on this research that can be assigned to each stage of the Water Technology Adoption model (WaTA). The Pilot stage typically takes two to three years, but can take as many as five. This is because it can take time to find sites and clients that are willing to host pilot tests, each pilot test typically operating over four to twelve weeks. A minimum of four weeks is frequently required to establish stable operating conditions, and monitor any variability in performance. A water technology can be at the Demonstration stage for three to five years. The combined time for Pilot and Demonstration, which relates to the Innovators stage, is typically the region of five to eight years.

Once a technology has been shown to operate reliably in three demonstration-scale plants, it moves on to the Early Adopters stage of the WaTA Model. The Early Adopters stage can last a further 6 to 8 years, and the Early and Late Majority stage can typically last 12 to 16 years as the technology continues to be adopted, until a technology is regarded as mature. A mature technology can remain in use indefinitely, until it is replaced by an alternative. To give an example, activated sludge wastewater treatment was first developed in 1914, and is still in use over 100 years later.

4. Conclusion

The author has a number of key conclusions from this work. Firstly, the proposed model, along with the accompanying definitions and criteria, are suitable for the study of water technology adoption. This will be foundational for future analysis of different types of water technologies. One of the key findings of this present study is that it is possible to develop generalized timelines for successful technology commercialization. The average timelines that the author has identified for each stage of the model support an industry belief that the process of water technology development and adoption can take more than a decade. Analysis indicates that from the year that pilot testing commences to when the technology is moving into the Early Majority section of the market and is commercialized, can take in the region of 11 to 16 years. This needs to be considered by any companies that are actively seeking to introduce a new technology to the water market. Having established timelines that are reasonable and typical, the author believes that this sets an important benchmark against which velocity, or rate, of progress can be measured. Technologies that are taking much longer than the average timelines outlined in this model run the risk of stalling out and failing to be adopted. The author believes that certain factors may accelerate adoption, and that there may be differences in timelines between different types of technologies – this will be explored in future research.

Another important conclusion arising out of this work is that velocity, or the rate, at which technologies move through the process of dissemination and adoption is an important metric to track and analyze, and that the extent of any deviation from these industry averages can be an indication of potential failures in this process. Because of the nature of the definitions, there will be a degree of subjectivity in the use of this model, and it is possible for a technology to straddle adjacent categories. It is important when measuring technology stage to consider reference plants by all companies that are offering a particular technology class, rather than looking at the references for one company in isolation. However, from the perspective of an end user who is looking to adopt a new technology, they typically wish to see that one particular vendor has three full-scale plants in operation before they will consider that the technology has moved beyond 'Demonstration'. No credit is given for the fact that a different company with a competing or similar technology may also have operational reference plants.

5. Future work

There are many exciting possibilities for future applications of this model:

- Future papers could examine if there are any reasons why certain technologies move faster than others, perhaps linked to differences in external factors, or technology-related factors i.e. any differences in timelines between water treatment and wastewater treatment technologies.
- Future papers could also seek to examine the rate of improvement in performance and efficiency over time, and the impact and feedback loop that this has on the rate of adoption. The average success rates for water technologies could also be studied to see what percentage of the technologies succeed, versus what percentage fail, or remain stalled out.
- Analysis of the relationship between the duration of the latency period, (Applied Research, Pilot and Demonstration stages) and the total life span of a technology, could also be interesting to investigate. This could allow the determination, for example, of the optimum life span of a patent (monopoly), balancing the need for monopoly and drivers for innovation versus hampering innovation as a result of an extended monopoly. It could also allow the assessment of the best technology development approaches for different life span durations.
- The establishment of typical timelines for each stage also provides an objective means by which to measure velocity, or rate, of progress of a given technology against timelines that might be considered reasonable. There is also a need to investigate whether an algorithm can be developed that would enable velocity to be calculated as a value, and relate it to the industry averages as a possible predictive indicator of success or failure.
- The ability to measure the velocity of technologies as they move through this process over time against industry baseline averages could be a valuable diagnostic tool to determine their likely rate of success, and could also help pinpoint when a technology appears to be taking longer (or moves faster) than usual.

3

Chapter 3

Analysis of Factors Affecting Rates of Technology Adoption

1. Introduction

It has been claimed that the water sector is less innovative than other sectors (Kwok & O'Callaghan, 2009; Wehn & Montalvo, 2018) with less invested in R&D (Ipektsidis et al., 2016). A paper in the recent special issue of the Journal of Cleaner Production, The Dynamics of Water Innovation (2018) (Wehn & Montalvo, 2018), noted that relative to the scope of innovation studies, there is a striking absence of academic studies on the dynamics of water innovation. In particular, it was noted that there was a lack of studies examining how relevant actors (fail to) interact to generate, finance, diffuse and apply water innovations and how these processes can be fostered, guided and steered. At the same time, it is widely accepted that water challenges exist (United Nations, 2016) and that new solutions and innovative approaches are required to meet these needs (Ajami et al., 2014; Krozer et al., 2010; Partzsch, 2009).

The slow nature of the water technology adoption process (Ipektsidis et al., 2016), compared to other sectors like the energy sector, can act as a disincentive towards new investment into research and development and water technology commercialization. Despite these perceptions, the author identified 121 early stage companies that received a combined cumulative investment of $1.75 billion in the period of 2006 – 2016.

Given the amount of capital being invested, the success rate of investment in water technologies is often questioned and the author wished to understand the factors that may affect rates of adoption of water technologies to enable efficient and informed use of capital. When human capital or financial capital is deployed, a return on investment is required in order for this to be sustainable. If a new technology is not adopted, there is no possibility for value creation from the deployment of the technology.

Based on analysis of case studies, a Water Technology Adoption (WaTA) model was developed (O'Callaghan et al. 2018). This model defined six stages: 1. Applied Research, 2. Pilot (Innovators) 3. Demonstration (Innovators), 4. Early Adopters, 5. Early and Late Majority and 6. Mature. It was noted that it can take 11-16 years for a technology to move from Innovators to Early Majority and Late Majority section of the market.

Within these water industry averages, the author had observed that some technologies appeared to move faster than others through various stages of the Water Technology Adoption (WaTA) model. The analysis of factors that can drive and accelerate water technology innovation and diffusion, such as policy, regulation, innovation accelerators and water clusters has been the subject of a number of recent papers (Gabrielsson et al., 2018; Schmidt et al., 2018; Tanner et al., 2018).

The author was curious to investigate if there were any patterns that were discernible, external factors or technology related factors that could be linked to faster or slower rates of technology adoption. In this chapter, the rate of adoption has been measured as the number of full-scale plants built per year. To support this analysis, the author decided to select six case studies of new water technology innovation in the last 30 years and analyse the respective timelines for moving through various stages of water technology commercialisation.

2. Methodology

To allow for analysis of the timelines, it was necessary to select water technologies that had already moved through the first stages of the Water Technology Adoption (WaTA) model and reached at least stage 4, the Early and Late Majority. In the context of this chapter, the term 'water technologies' refers to drinking water treatment, and wastewater treatment technologies. The availability of data to support the analysis was one factor that was used to determine which technologies were short-listed for analysis. In the absence of available historic data, it would not be possible to analyze the rate of technology diffusion. The technologies were also selected for being diverse geographically and across different types of treatment from drinking water to wastewater.

The six short-listed technologies, including the type of water technology each represents and the period of years studied in this chapter, are presented in the Table 1.

Table 1: The technologies studied in this chapter

Name of technology	Type of water technology	Time period studied	Country
Sequencing Batch Reactor (SBR)	Wastewater Treatment	1981-1989 1985-1992	Japan USA
Biological Phosphorous Removal (BPR)	Wastewater Treatment	1972-1982	South Africa
Ultrafiltration Membranes	Drinking Water Treatment	1985-1995 1995-2004	UK North America (USA & Canada)
THIOPAQ Biogas Desulphurization Process	Wastewater Treatment	1990-2009	Europe
Sludge Thermal Hydrolysis	Wastewater Treatment	1996-2016	Global
Ultraviolet Disinfection	Drinking Water Treatment	1982-1992	USA

To gather the data on these six case studies, the author contacted informed industry professionals in Australia, Japan, Europe and North America with detailed knowledge of these technologies and databases that tracked the technology deployment. In each case we focused on the time period moving from the Innovators stage (Pilot stage and Demonstration stage) to Early Adopters and then to Early Majority.

The general methodology followed was to obtain data on the number and the size of plants that were installed over the ten-year period following the first full-scale commercial installation. The criteria used to assign technologies to a particular stage in the water technology diffusion model were taken from our Water Technology Adoption (WaTA) model (O'Callaghan et al., 2018), a brief overview of the different stages is explained as follows.

Starting with the first stage, the Applied Research Stage corresponds to when research and development (R&D) is taking place in a laboratory setting with the aim of developing a water treatment technology with a real-world application. After which, the technology will be tested outside the laboratory in real-life applications and will remain in the second stage, known as the Pilot Stage, until at least one full-scale plant is operational. Many efforts to bring new solutions to market fail at this stage or can remain stalled at this stage and have difficulty moving beyond it.

Once the technology is of a size and scale that would be practical in real-world target applications and forms part of a formal commercial product offering, the technology has entered the third stage, known as Demonstration stage. The technology is deemed to remain at this stage until there are three units operating at a similar scale in similar applications. The Early Adopters stage corresponds to a technology that is 'proven' where commercial sales of first-generation units are taking place, but is not yet widely accepted by end-users in the market. Between three and thirty units are now operating at a similar scale in similar applications. The technology remains in the Early Adopters stage until it has been fully commercialised and reaches the final stage: Early and Late Majority stage. The Early Majority typically will only adopt what is deemed to be a 'proven technology'.

The following is a brief description of each of the technologies analysed and the methods used to obtain the data.

Sequencing Batch Reactors (SBR)

A Sequencing Batch Reactor (SBR) is a wastewater treatment technology based on the activated sludge process (USEPA, 1999) that uses suspended bacterial growth in an aerated reactor to achieve biochemical oxygen demand (BOD) removal.

The key innovation of the SBR technology was the use of timed cycles to enable solids separation to be achieved by allowing a quiescent phase in the aeration basin where solids were allowed to separate and were removed from the bottom of the tank using a decanter. The ability to perform multiple unit processes in a single tank using a timed control sequence provided a number of valuable advantages over conventional activated sludge technology such as reduction in capital costs and reduced footprint by eliminating the secondary clarifier.

This chapter is focused on the time period of 1981 to 1992 using the data obtained from Mr. Paul Cardinal, former CEO of Austin BioJet, and also from the book Sequencing Batch Reactor (Wilderer et al., 2001). The first SBR plants were constructed in Australia and Japan and the technology was subsequently introduced into North America (Strous et al., 1998; Wang & Li, 2009) with various biological nutrient removal configurations.

Biological Phosphorus Removal (BPR)

Biological Phosphorus Removal enables phosphorus to be removed from wastewater through a process known as luxury phosphorus uptake where phosphorus is taken up by Poly-phosphate Accumulating Organisms (PAO) and stored within the bacterial cells (Blackall et al., 2002; Zhou et al., 2007). Daspoort Pretoria WWTP (SA) was the first pilot plant where BPR was observed in 1972. Soon after in 1973, Barnard found that phosphorous was removed by fermenting biomass and returning the product to un-aerated zone (Seviour et al., 2003).

There was an acute need in South Africa at the time to remove phosphorus from wastewater as it was leading to eutrophication of surface water bodies (Oleszkiewicz & Barnard, 2006). An alternative method of removing phosphorus through chemical dosing was not viable or possible at the time in South Africa as this used metal salts, such as ferric chloride and aluminum sulphate. This would have led to increased total dissolved solids levels in water bodies, which were already elevated (Schutte et al., 1987).

The author contacted one of the original technology inventors for Biological Phosphorus Removal: Dr. James L. Barnard, Black and Veatch. He has published numerous papers on the subject of biological phosphorus removal (Barnard, J. L., 1975) and was able to assist the author of this chapter in analyzing the evolution of the technology 1972 to 1982.

Ultrafiltration Membranes for Drinking Water Treatment

The use of ultrafiltration membranes for drinking water treatment is now widely accepted and used. When the technology was first deployed in the late 1980's and early 1990's, it was more expensive than the conventional treatment processes such as media filtration and coagulation. A key catalyst to the introduction and use of this technology in drinking water treatment was the need to provide a method to remove cryptosporidium from drinking water. This was linked to outbreaks of cryptosporidium in the UK (Atherton et al., 1995) and USA (Solo-Gabriele & Neumeister, 1996).

The period studied in this chapter was 1985 to 2004. Data on the number of installations was obtained for the UK, the United States and Canada from Dr. Graeme Pearce based on records he maintained and from Zenon, a leading pioneer in the use of ultrafiltration membrane technology for drinking water treatment.

THIOPAQ Sulphide Removal from Biogas

Following successful trials, the first commercial unit for biogas desulphurisation was built in 1993 (Benschop et al., 2002). THIOPAQ is a technology used for the removal of sulphur from biogas through biological oxidation of hydrogen sulphide gas to elemental sulphur. This technology enables the extraction of biosulfur from natural gas, landfill gas or biogas. The bio-sulphur is suited for use as fertilizer or fungicide as it is more bioavailable to crops than chemically produced sulphur. Data on the number of installations was provided by Dr. Cees Buisman, who started working on the first THIOPAQ pilot plant in the Netherlands in 1990.

Sludge Thermal Hydrolysis

Sludge thermal hydrolysis uses pressure and temperature to achieve cell lysis of secondary activated sludge, leading to increased conversion of sludge volatile solids to methane gas during the anaerobic digestion process. Data to support this study was obtained by contacting the technology provider CAMBI, a pioneer in introducing this technology. The key advantages and value of this technology is that it increases the efficiency of the anaerobic digestion process, produces a Class A Biosolid, leads to improved sludge dewaterability and increases anaerobic digester capacity.

The technology was first piloted in 1989 by the company Cambi, and the first full-scale installation of Thermal Hydrolysis Process (THP) was developed and implemented at a plant for the City of Hamar in Norway in 1995 (Kalogo & Monteith, 2008). The world's largest sludge pre-treatment system was built in 1999 at Ringsend WWT in Dublin, using Design Build Operate (DBO) model which provided lower whole-life costs for the 20 Year DBO.

Ultraviolet Disinfection

The germicidal effectiveness of ultraviolet C radiation varies between species and peaks at about 260-265 nm, which corresponds to the peak of UV absorption by bacterial DNA (Kowalski, 2009). UV disinfection uses 254 nm UV light to germicidially irradiate various species/contaminants/microorganisms.

This case study focuses on the evolution of the Trojan UV technology for the treatment of municipal wastewater in the period of 1982-1992. Data was accumulated from a review of related literature (Johnson & Qualls, 1984; Petrasek et al., 1980; Scheible et al., 1981; Severin, 1980) and research interviews with the founder of Trojan UV, Hank Van der Laan.

In the late 1970's and early 1980's, there was an environmental need, in one of the largest US watersheds (Chesapeake Bay), related to the toxicity levels of its harvested shellfish, which was attributed primarily to the effluent discharges from municipal wastewater systems surrounding that particular watershed (Pace et al., 1988). As a result of this, US Congressmen began inquiring whether UV had the ability to disinfect municipal wastewater. In 1982, Trojan UV demonstrated the technology at the first full-scale installation in Tillsonburg WWTP, Ontario (Canada) for disinfection of municipal water.

3. Results & discussion

SBR Wastewater Treatment

The SBR data is presented in Figure 1 and Figure 2 for two geographic locations. When compared with the data of the other technologies, the SBR data showed that the technology moved much faster relative to the other technologies. The key contributory factors are listed below:

- A smaller footprint and capital cost advantage of at least 25%, due to the elimination of the secondary clarifier and associated civil works.
- State-level Innovative and Advanced Technology Grants, that covered up to 60% of the process costs of the plant (i.e. excluding non-related costs such as laboratories, ground works, civil works, offices, etc.) – this made it very attractive to the end-user clients in Tennessee. Such a financial incentive was not present in the other five case studies (UV Disinfection, Biological Phosphorus Removal, UF Membrane Filtration, Thermal Hydrolysis and THIOPAQ).
- A regulatory driver that required biological nutrient removal.

SBR technology was first introduced to the US market by a new entrant to the market, Austgen Biojet (ABJ), as opposed to by an incumbent company. ABJ was the sole builder of SBR systems in the US from 1984 until 1987, at which point several jet aerator companies, such as Fluidyne, incorporated SBR technology into their product lines and the company Aqua Aerobic Systems entered the SBR market (Cardinal, P.J., personal communication, February 2018).

Biological Phosphorus Removal Wastewater Treatment

The transfer of biological phosphorus removal from laboratory scale pilots, directly to full-scale demonstration plants, is an example of an exceptionally rapid movement through the Water Technology Adoption (WaTA) model. The two main factors that contributed to accelerated technology adoption were that:

1. There was a high level of knowledge sharing between the utility managers via monthly meetings of the local water institute (Barnard, J. L., Personal Communication, November 2017).

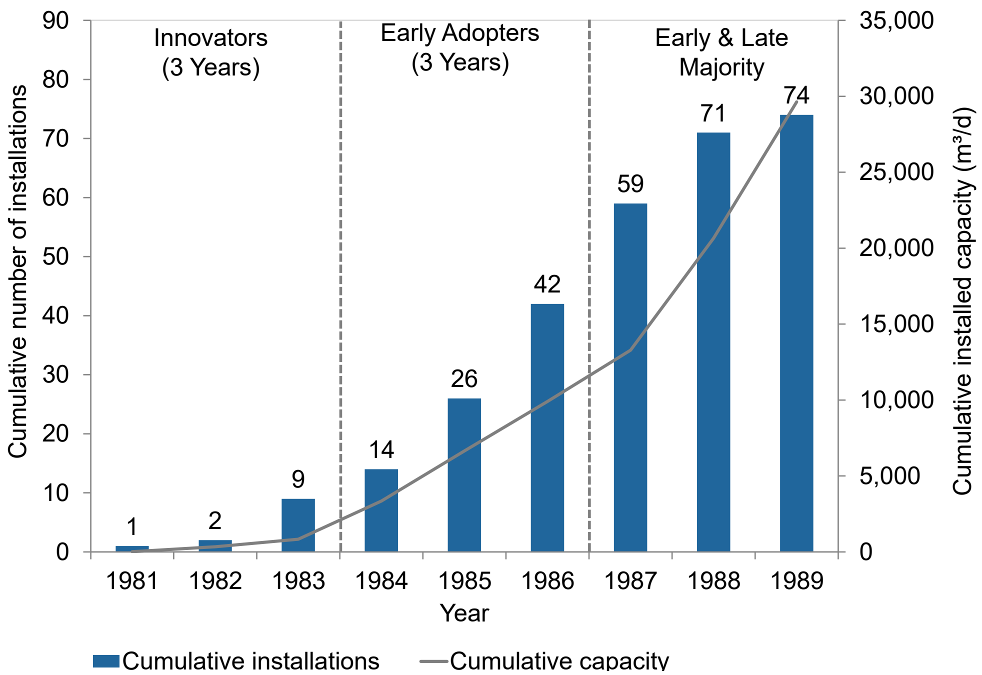

Figure 1: SBR Technology – rate of technology adoption in Japan.

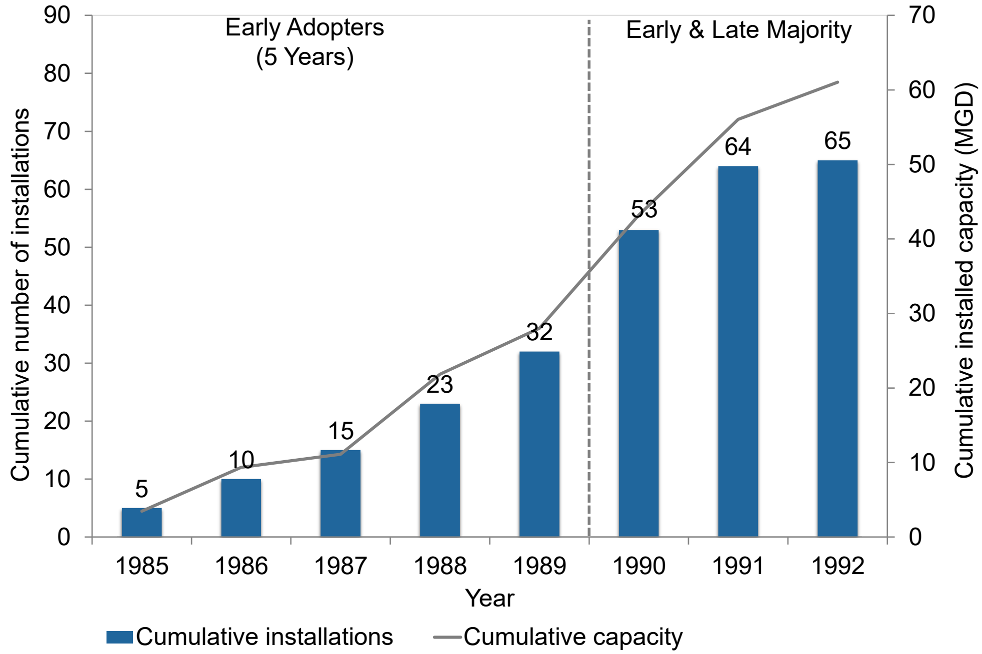

Figure 2: SBR Technology – rate of technology adoption in the USA.

2. There was a high level of competence and wastewater expertise in the wastewater industry at that time (Barnard, J. L., Personal Communication, November 2017).

Another author, Parker, had previously emphasized that sharing information was a key factor for increased rate of adoption in water technology market (Parker, 2011).

The use of BPR technology was not less expensive than the incumbent alternative, which would be to add metal salts such as aluminum sulphate or ferric chloride, to remove phosphorus. However, the inability to use these chemicals, due to salinity issues in the receiving waters, meant that BPR was a compelling alternative.

According to Figure 3, the Biological Phosphorus Removal (BPR) data showed that the first plant was installed in 1972 and by 1974 there were five full-scale plant installations. The crossover point from Innovators to Early Adopters, defined in the Water Technology Adoption (WaTA) model, is three full-scale plants hence the technology moved through the Innovators stage and into the Early Adopters stage within three years. Within the period 1972-1982, this technology seems to have reached market saturation at around 18 installations.

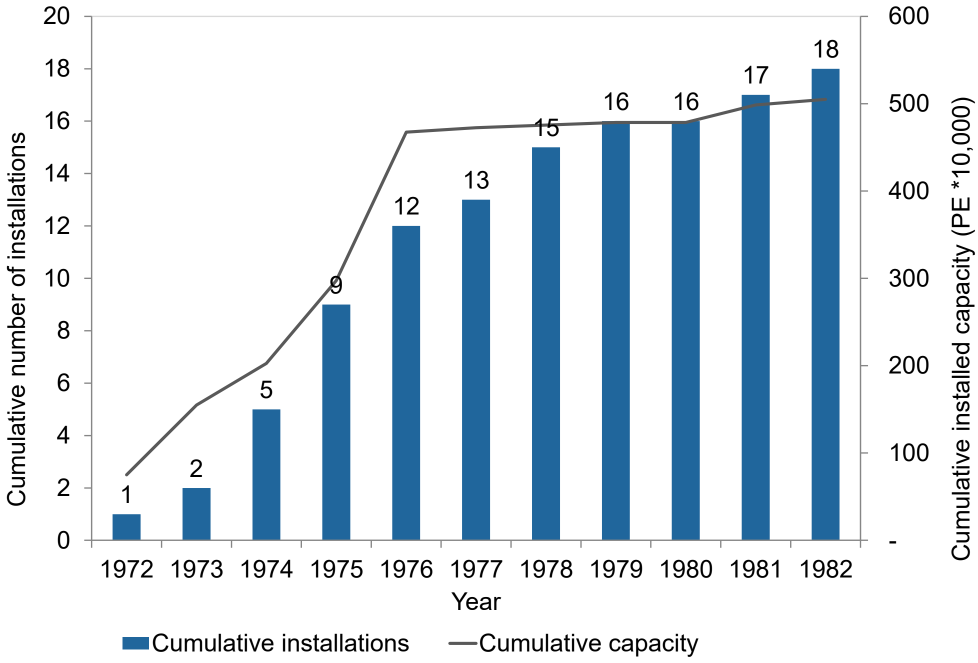

Figure 3: Biological phosphorus removal – rate of technology adoption in South Africa.

In the case of South Africa between 1972-1982, there were less than 30 wastewater treatment plants in the size range studied (>10,000 PE). As such, the standard metric of using the numeric indicator of 30 plants to when a technology moves to Early Majority, does not apply here in this case. In the WaTA model, if one applies the numerical guidelines, this would suggest that it remained at Early Adopters stage. However, if we refer to Rogers (Rogers, 2003), we can see that the Innovators section is 2.5% of the market adopters and Early Adopters is 13.5%, so combined it is 16%. In this instance we estimate that the technology also moved into Early Majority within 3 years by 1974 as 5 reference plants represents more than 16% of the total number of plants. Hence, this technology moved from Innovators to Early Majority stage within 3 years, skipping the Early Adopters stage. As this was a special case, BPR was not included when estimating the average number of years taken for the Crisis and Value Driven types of technologies as they move through the Water Technology Adoption (WaTA) model.

Ultrafiltration Drinking Water Treatment

Figure 4 illustrates the rapid adoption of UF membranes in the UK, which can be explained by the regulations that were introduced in the UK in 1992 (Nichols, G. et al., 2006) in order to reduce risk of Cryptosporidium in water supplies. This required the use of an absolute filtration barrier against Cryptosporidium outbreak that occurred in 1989 in UK. In North America, the uptake in membranes lagged behind the 1993 Milwaukee outbreak by about 4 years with plants being installed in 1997, as can be seen in Figure 5. This outbreak paved the way for the Interim Enhanced Surface Water Treatment Rule, promulgated on December 16, 1998 (USEPA, 2001), which applied to water utilities using surface water, or groundwater under the direct influence of surface. This corresponds to the increased adoption of UF membrane Filtration in North America with the technology moving through the Early Adopters portion of the market between 1997 and 2001 (Figure 5). In the United States, regulations came in the form of the Surface Water Enhanced Long Term treatment regulations (USEPA, 2005).

When first introduced in drinking water treatment references in the early to mid-1990's, UF membranes were a significantly more expensive filtration option when compared to sand filtration. However, after 2000, prices began to come down steadily and project sizes increased, gradually reducing the difference in costs. The first project in the US where membranes represented a competitive bid on a project, which was also open to bid from conventional options, was Olvenhain in California. This took place in 2008 and was won by GE. Prior to that, membranes only won projects in which membranes were specified (Pearce, G., personal communication, February 2018).

There were no grant subsidies to encourage or off-set the use of membrane filtration in the US or the UK markets. UF technology succeeded initially, in the Innovators and

Early Adopters stages, by being specified due to legislative or government drivers and not as a result of financial incentives.

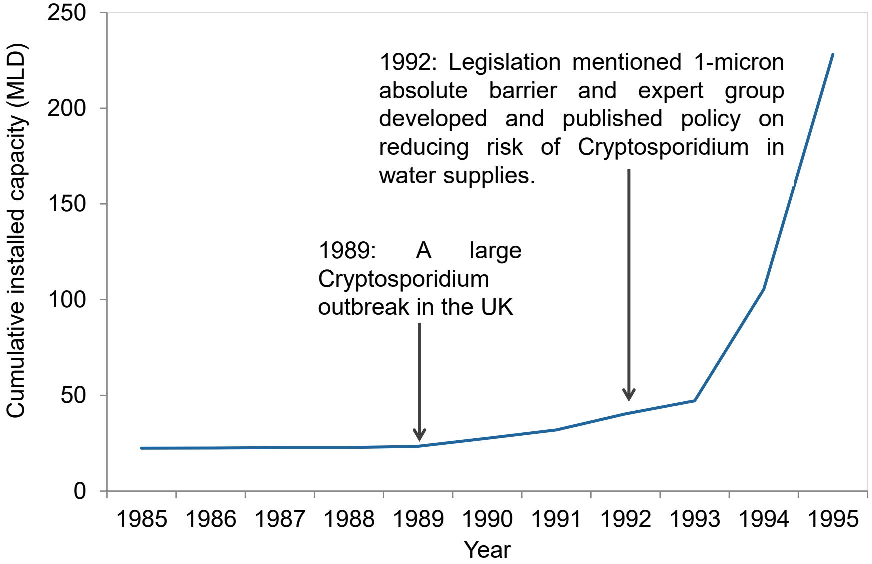

Figure 4: UF Membrane drinking water filtration – rate of technology adoption in the United Kingdom.

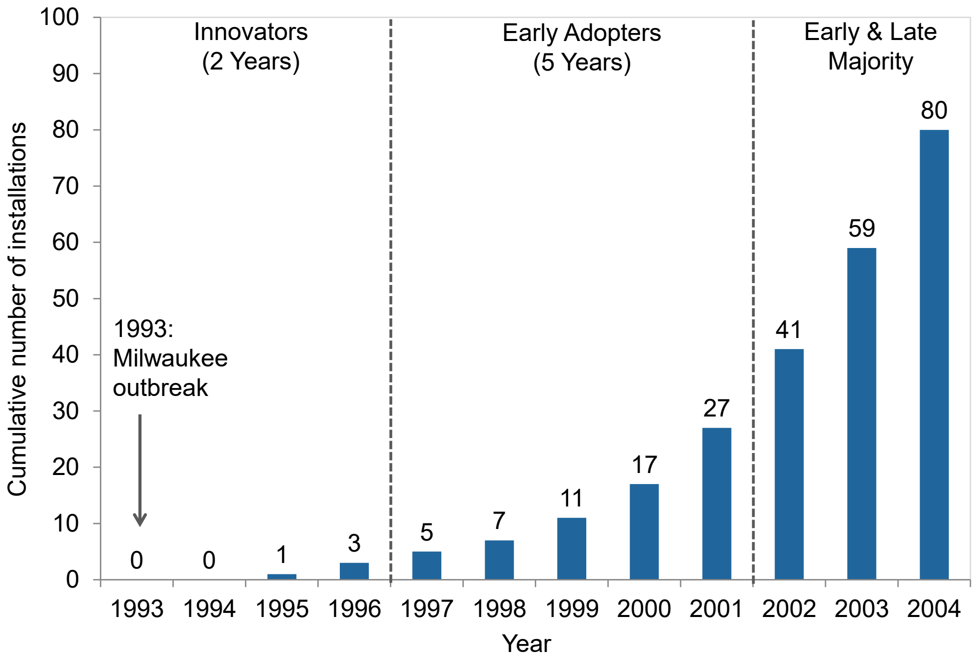

Figure 5: UF membrane drinking water filtration – rate of technology adoption in North America.

UF Membrane filtration could be deemed to be a disruptive innovation in the water sector as it represented a completely new approach to conventional sand filtration and was introduced by new entrants to the market, such as Zenon, Kalsep and Norit X Flow. However, when compared with the theories and definitions of disruptive innovation as outlined in the work of Clayton Christiansen (Christensen, 1997), the technology is neither an example of disruptive innovation nor sustaining innovation, as the technology did not represent in incremental improvement, which would be typical of sustaining innovation, and required a legislative driver to ensure it was specified into contracts when it was first introduced. In this instance an external factor, legislation, was required to stimulate the adoption of a disruptive technology.

THIOPAQ Wastewater Treatment

In 1997, a strong alliance was formed between Paques and Shell, leading to the successful development of THIOPAQ and its deployment to the broader oil and gas industry. Thereafter, the number of plants increased to almost 100 within 20 years, as can be seen in Figure 6.

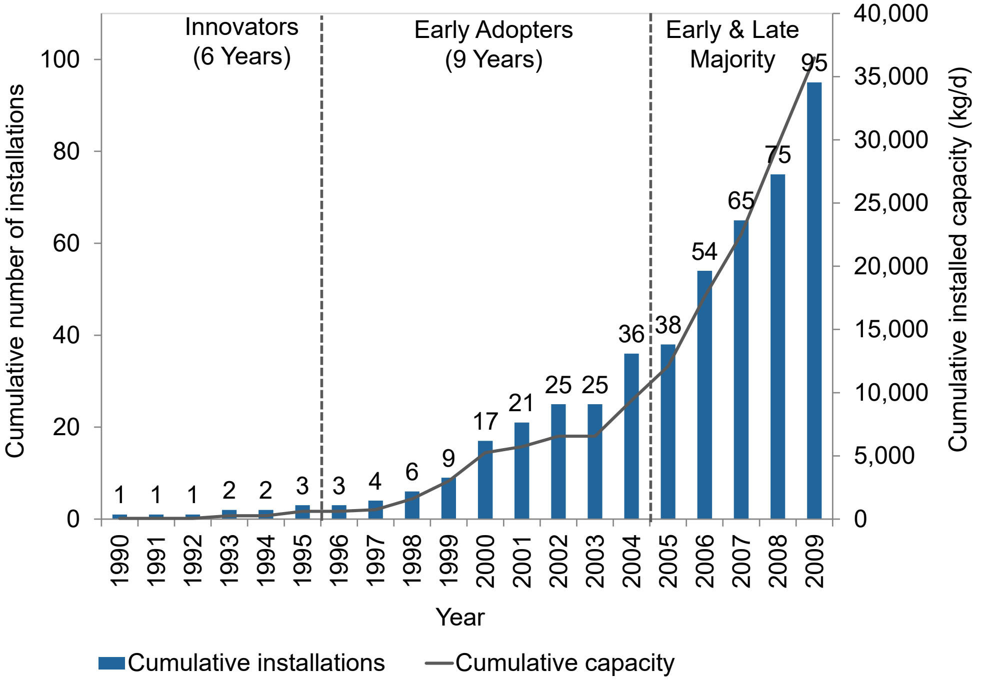

Figure 6: THIOPAQ – rate of technology adoption in Europe.

Hydrogen sulphide gas is present in biogas and in natural gas but has to be removed before it can be used. The main driver then for the removal of hydrogen sulphide, is to enable the biogas and natural gas to be used to generate energy. The prevailing method of removing hydrogen sulphide gas from biogas and natural gas is to use a wet caustic scrubber. This uses aqueous chemicals into which the hydrogen sulphide gas dissolves. The resulting liquid cannot be used as a fertiliser and has to be disposed off once it is saturated and used up. The THIOPAQ technology provides a means of regenerating the liquid produced in a wet scrubber and produces elemental sulphur, which can then be recovered for use as a fertilizer. As such the driver for THIOPAQ specifically, is to help reduce disposal costs and enable recovery and re-use of the sulphur.

THIOPAQ is a value driven technology, as opposed to a crisis/ needs driven technology, when it is viewed as an alternative to chemical scrubbing. One of the challenges with realising the value from the recovery of the sulphur is in matching supply and demand, as the quantities produced at an individual THIOPAQ facility are not significant or impactful when viewed in the context of the elemental sulphur supply chain in the fertiliser industry. As such it is challenging to build a market. Opportunities for local use of the sulphur provide an alternative option.

Sludge Thermal Hydrolysis Wastewater Treatment

Cambi, the company that pioneered the Thermal Hydrolysis technology, was founded in 1992 to develop the steam explosion process for sewage sludge. This was built upon previous R&D work from 1989-1992 when experiments had been carried out to attempt to use the same process in the pulp and paper industry (https://www.cambi.com/who-we-are/history/).

Moving from pilot tests in 1992 to a full-scale plant in 1996 (Figure 7) was relatively fast when compared to average timelines in the water sector (O'Callaghan et al., 2018). The company succeeded in moving through the Innovators section of the Water Technology Adoption (WaTA) model in 5 years. There was a latency period between 2001 and 2006, as can be seen in Figure 7, when the number of plants remained quite static and the technology remained in the Early Adopters stage of the WaTA model for 11 years. The experience of getting quickly to three plants, followed by a latency phase, appears common in the water sector as there are always learnings from the first-generation plants. This means that it takes time to fine-tune operational processes and to design the second generation of products based on operational data from the Innovators stage. In the case of thermal hydrolysis, odor issues were one of the technical challenges that became apparent and needed to be addressed (Kepp et al., 2000).

The tendering and procurement process itself means that projects can only proceed at a certain rate. After 2007, the technology moved steadily forward and can be seen to have entered the Early & Late Majority stage by 2011. The progress of the technology was relatively slow but steady over the period 1996 – 2016, and the market adoption was driven by ability to demonstrate a value to the end user, through increasing the capacity

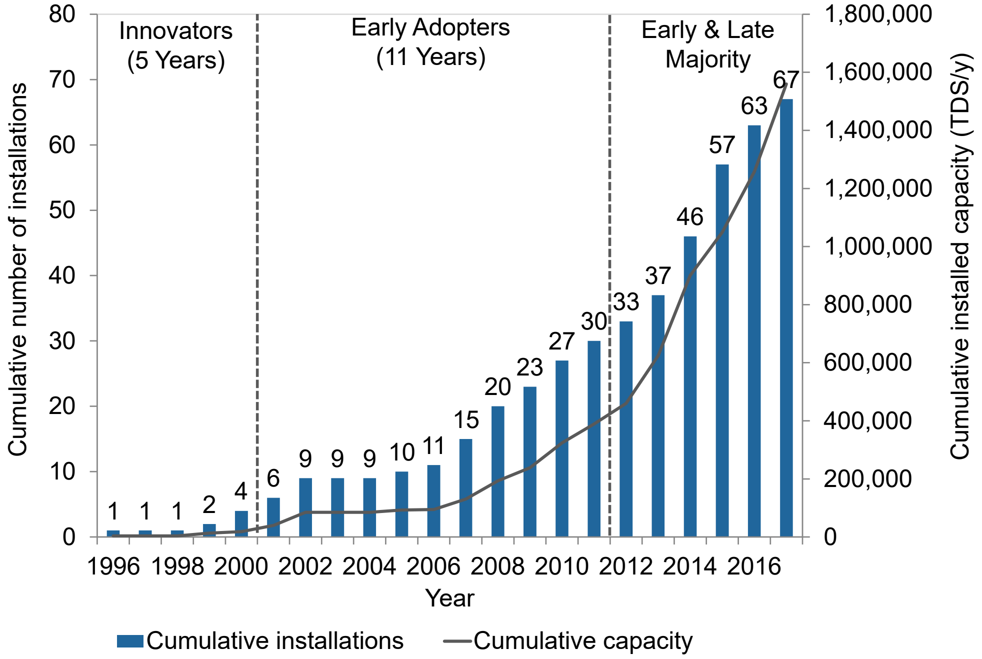

Figure 7: Sludge Thermal Hydrolysis – rate of technology adoption globally.

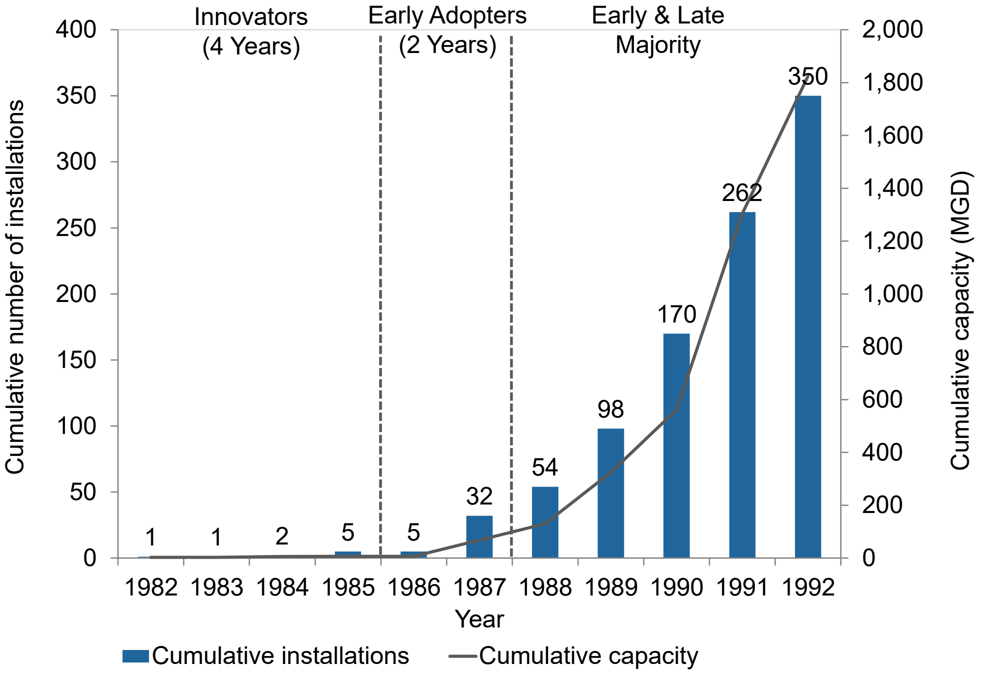

Figure 8: UV disinfection – rate of technology adoption in the USA.

of digesters, increasing biogas yield, and reducing sludge volumes, rather than directly from a regulatory driver, such as to produce Class A Biosolids (Barber, 2016; Oosterhuis et al., 2014).

Ultraviolet Disinfection Drinking Water Treatment

The UV data showed that it took four years to get five full-scale facilities up and running. In the next two years (1986 and 1987), it moved relatively quickly to over 30 operating full-scale plants. The rapid construction of new facilities from 1985 onwards (Figure 8) can be explained by the two main factors:

1. The scientific credibility of the demonstration installations backed up by Johnson & Qualls, 1984 and papers presented at the 56th Annual Conference of WPCF in Atlanta, Georgia Oct 3-7,1983 by Trojan.
2. The strong need in the Chesapeake Bay area (related to the toxicity levels of its harvested shellfish) (Pace et al., 1988).

It was also found that the pilot study at Tillsonburg, Ontario, as described in the above journal paper, was funded in part through a grant from the Canadian Federal Government through its Industrial Research Assistance Program (IRAP), which covered approximately 50% of the costs of the pilot project. UV technology was also a technology that could be added at the end of the existing treatment train, as an add-on technology, and it did not require any changes to the existing wastewater treatment infrastructure. This may have been an enabling factor that facilitated rapid adoption, coupled with the acute need.

Overview

Figure 9 presents the comparison of years at the Early Adopters stage and years at the Innovators stage for each of the technologies studied. The data indicated that the rate of movement across the Water Technology Adoption (WaTA) model varied significantly across the technologies studied.

During the course of the analysis, one thesis that was proposed to help differentiate between the different technologies was that in some cases there was an external driver that accelerated technology adoption, such as a new regulation, or an environmental or health issue. We have referred to these as Crisis / Need Driven Water Technology Market Adoption. In other cases, there was no such external driver or catalyst for adoption, but the technologies themselves had an inherent advantage over the existing technologies used, based on factors such as capital cost savings, operational cost savings, smaller footprint, and life-span of the technology. These will be referred to in this discussion as Value Driven Water Technology Market Adoption. Certain case studies contained a hybrid of these factors, such as SBR, where the technology had an advantage over incumbent technology, and there was a regulatory driver for nutrient removal that favored the use of SBR technology as a method of achieving nitrification and denitrification.

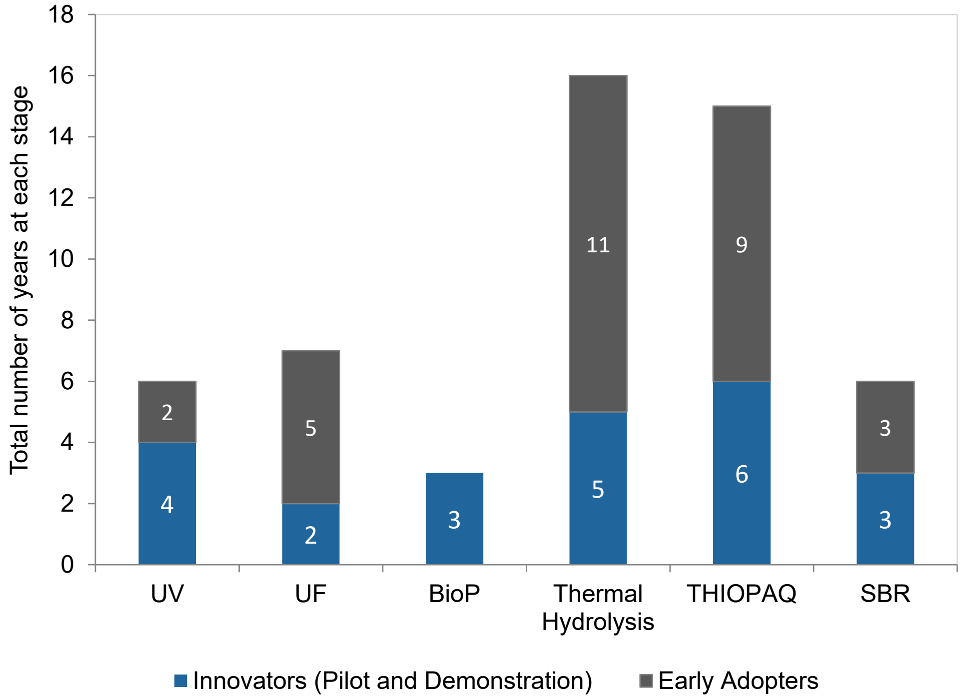

Figure 9: Comparison of Early Adopters stage and Innovators stage for all six technologies studied in this chapter.

Table 2 compares the six case studies and explains the basis of categorization for each of the six technologies: three were grouped into the Crisis / Need Driven Adoption category and two into the Value Driven Adoption category. An exception was the SBR technology, which could be viewed as a combination of both Value Driven and Need Driven Adoption. In the case of SBR, there were also state level grants that supported its deployment.

Table 3 compares time-lines side by side for the two types of technologies as they move through the Water Technology Adoption (WaTA) model. We can see that in the case of Crisis Driven Water Technology Market Adoption, the average number of years required to take the technology through the Innovators stages (Pilot and Demonstration) and the Early Adopters stage of the Water Technology Dissemination is 6.5 years. By comparison, of the three case studies analysed, the timeline required to take the Value Driven Innovation through the same stages of the WaTA model is 12.4 years.

Table 2: Summary of six case studies

Innovation	Crisis / Needs Driven	Value Driven
Ultraviolet Wastewater Disinfection	**Yes.** Concerns regarding the toxicity of harvested shell-fish in the Chesapeake Bay linked to wastewater discharges led to a need to find an effective wastewater disinfection technology.	**No.** It was more expensive than chlorine disinfection when introduced.
Membrane Ultrafiltration for Drinking Water Treatment	**Yes.** A crisis relating to Cryptosporidium outbreaks in USA and UK led to legislation which created the need in the market.	**No.** It was more expensive than sand filtration when introduced.
Enhanced Biological Phosphorous Removal	**Yes.** Issues with deterioration in water quality as a result of eutrophication linked to phosphorus and the inability to use chemical dosing created the need and opportunity for Biological Phosphorus Removal.	**No.** It was higher CAPEX compared to chemical dosing, although it had a lower OPEX.
Sludge Thermal Hydrolysis	**Partially.** There was a requirement to produce Class A Biosolid in certain areas, and Thermal Hydrolysis does achieve this. However, this was not the primary driver for its deployment.	**Yes.** Sludge Thermal hydrolysis leads to increased biogas yields, increases in anaerobic digester capacity and improved sludge de-watering and produces a Class A sludge. These advantages created the basis for value driven technology adoption
THIOPAQ	**No**	**Yes.** THIOPAQ is a biological desulphurization process that removes sulphur compounds from biogas without the need to add chemicals and produces a value-add by-product leading to reduced operational costs.
Sequencing Batch Reactor (SBR)	**Partially.** There were regulatory drivers that required the removal of ammonia and total nitrogen in wastewaters and SBR was one method that this could be achieved.	**Yes.** An SBR eliminates the need for a secondary clarifier, leading to lower capital costs and a smaller footprint. SBR also can be used to achieve biological nutrient removal and regulations requiring nitrogen removal created a needs driver.

Table 3: Timelines comparison of the types of technologies as they move through the Water Technology Adoption (WaTA) model

	Innovators (Pilot and Demonstration)	Early Adopters	Innovators + Early Adopters
Water Technology Adoption Model Average Timelines	5 to 8	6 to 8	11 to 16
Crisis / Needs Driven Adoption	3	3.5	6.5
Value Driven Adoption	4.7	7.7	12.4

The timelines for movement from Innovators and Early Adopters for Value Driven Innovation, of 12.4 years are more in keeping with water industry normal timelines as outlined in the Water Technology Adoption (WaTA) model.

There is a risk for technologies that are Crisis / Needs Driven of being developed before the crisis or need driving adoption takes hold of the market. The author has observed companies developing a technology that was dependent on an external factor, such as implementation of a new piece of legislation, fail when this regulation was not adopted in the anticipated time-frame. One such scenario is the Swedish company, Ocean Saver, a company focused on the Ballast Water Treatment market. The delay in ratification of the International Maritime Organisation regulations meant that this market did not materialise, and the company ceased trading in 2017.

Many companies in the biosolids management space were anticipating that there would be a regulatory ban on the application of sewage sludge to land. MaxWest Environmental was developing a sludge gasification technology in 2008 to 2014 (Peric et al., 2012). It was competing with land application of biosolids as a lower cost alternative, and this was one factor that meant the market conditions were not ready to drive adoption of sludge gasification. The sludge pyrolysis and gasification, in particular, is somewhat of a grave-yard for failed companies, with examples including Enertech SlurryCarb process, MaxWest Gasification System, New Earth Inc. Torrefaction, ThermoEnergy Sludge to Oil Reactor System (STORS), and EnerSludge (O'Callaghan, 2009); all of them have now ceased operating.

It is interesting to consider what might have been the fate of these companies had such a regulatory ban come into effect while they were still developing these technologies. In many cases where the company fails, the intellectual property is handed on to another company and may exist in a latent state until the market conditions are favourable, or further work improves its efficiency and confers a value–driven competitive advantage. The author would posit that if a ban on the land application of sewage sludge were to come into effect that this would lead to success stories of technology adoption of sludge gasification and pyrolysis similar to the creation of UF Membrane Filtration and UF Disinfection technologies.

The three Crisis / Needs Driven innovations – UV Wastewater Disinfection, Biological Phosphorus Removal and UF Drinking Water Filtration – had a crisis or market need to accelerate adoption. The author is of the view that in the absence of a Cryptosporidium outbreak and subsequent legislative and government drivers, the adoption of UF membranes that was observed between 1995 and 2005 would not have occurred, and those companies that were active then, such as Norit X-flow, Zenon and Memcor, would not have succeeded. The technology may never have moved beyond the Innovators stage of the market had the catalyst not arisen that led the creation of a market demand, which in turn led to cost reductions and competition, and had the positive feedback loop of enabling more wide-spread adoption. UF technology succeeded initially in the Innovators and Early Adopters stages, by being specified due to legislative or government drivers and not as a result of financial incentives. A legislative driver was required to enable the diffusion of this disruptive technology.

Similarly, in the absence of the need to disinfect wastewater to reduce shellfish toxicity (Pace et al., 1988), the adoption of UV in wastewater disinfection that was seen in the period 1982 to 1992 would not have occurred with the same velocity. The company Trojan UV would likely not have been able to sustain itself for the next decade until the outbreak of Cryptosporidium accelerated its adoption in drinking water.

In the case of Biological Phosphorus Removal, unlike UF Membrane Drinking Water Filtration and UV Wastewater Disinfection, this was not a disruptive technology. BPR technology was an improvement to the biological treatment process and was not introduced by new entrants and start-up companies but by consulting engineering firms. It was not patented at the outset in South Africa and therefore, it could be designed by engineers who understood the design principles. Thus, the author believes that the main factor for the rapid rate of adoption of BPR was the acute need in South Africa at that time to remove phosphorous from wastewater to prevent eutrophication of surface water bodies.

In the case of the three value-driven case studies, the SBR was introduced by new entrants such as Austin BioJet and Sanitaire, through technology licensing, and as it was an improvement to the activated sludge process. Thermal Hydrolysis was introduced by a new entrant, CAMBI, a start-up company and THIOPAQ was introduced by an existing company, PAQUES. These technologies succeeded in the absence of a crisis, suggesting that if there is a clear value proposition, a crisis is not necessary to allow for the adoption of new innovative technologies.

4. Conclusion

In the water sector, the adoption of a water technology that is driven based on its value proposition takes in the region of 12.4 years to move through the Innovators and Early Adopters stages of the market and to reach Early and Late Majority.

In the case of a technology whose adoption is driven by a crisis or market need, such as a new piece of legislation, or an urgent health or environmental issue, the timeline can be half this, in the region of 6.5 years.

In the case of UF Membrane Drinking Water Filtration and UV Wastewater Disinfection, an external driver was required to enable the adoption of these disruptive technologies and both were introduced by new entrants to the market. It could be argued that it was the legislation / Crisis Driven need that was the disruptive driving force that led to these disruptive innovations being adopted, as opposed to the technologies themselves.

The case studies that can be mapped to being value driven innovations were introduced by existing companies as well as new entrants and did not require an external driver such as legislation to enable their adoption.

Financial incentive mechanisms assisted the first pilot UF system and the first full-scale SBR system in Tennessee. Apart from these two examples, the use of financial inventive mechanisms was not identified as being involved in the other case studies. The author posits that in the case of a Crisis / Need Driven innovation, that an external financial support mechanism is therefore not required to enable technology adoption and in the case of the value driven innovations it is likewise not required, as the technologies have inherent advantages, but in both cases financial support can help to accelerate the adoption rate.

It has been observed that success in Crisis /Need Driven innovation is often about being in the right place at the right time (Schlichte et al., 2019). In general, it can be concluded that we can conclude that Crisis /Need Driven innovation involves disruptive innovation offered by new entrants whereas with value driven innovation, it can be both existing companies as well as new entrants. Non-patented technologies and innovations can be introduced directly by consulting engineering firms without involving proprietary technology companies.

It is also observed that, in most cases, a technology that is adopted in order to meet a crisis or need in the market is more expensive at the outset than the alternatives at the outset. While the value driven adoption has a slower cycle for adoption, it presents lower risk as it is less dependent on external factors and timing of implementation of regulations or the occurrence of some public health related or environmental crisis.

Future work will analyse which technologies constitute a disruptive innovation and if there are ‘faux disruptive innovations’ which are adopted initially but fail to replace the incumbent technologies. Future research work will also analyse the rate of success in investment in water technology companies and how this compares to standard investment models.

4

Chapter 4

The Applicability of Innovation Theories to the Water Sector

1. Introduction

1.1. Why do we need innovation?

Water supply crises have been identified as one of the top five global risks to society in each of the last seven years according to the World Economic Forum (WEF, 2019). Wehn & Montalvo's review paper recognizes that innovation is required to address the mounting challenges with our current water systems (Wehn & Montalvo, 2018a). The authors classify these challenges into social, technological, economic, environmental, and political categories. It is the combination of these factors that prevents continuous innovation of water management practices, especially in developing countries.

The High Level Panel on Water, established by the UN Secretary General and President of the World Bank Group, called for "a fundamental shift in the way the world looks at water" (High Level Panel on Water (HLPW), 2016). In Europe, the urgent need for water innovation is being addressed by initiatives such as the Horizon 2020 program for research, development and innovation activities, LIFE 2014-2020 which focuses on funding for environment and climate action, and grants from the European Research Council for individual researchers to undertake basic research (Wehn & Montalvo, 2018a). Yet the water sector has been reported to be less innovative than other sectors, such as the energy sector, when measured by indicators such as the amount of investment funding attracted by research and development for example (Ipektsidis et al., 2016). The author of this chapter would like to argue that the real issue is not so much the extent of research and development efforts, but the rate of diffusion of technologies and adoption of innovation.

It is well accepted and documented in the literature that mounting pressures globally are affecting both availability of water supply and water quality (Wehn & Montalvo, 2018b). These pressures, which include rapidly increasing global population, urbanisation, climate change, deteriorating water quality and ageing infrastructure, are putting increased demand on water resources. In parallel with increases in population, nations are lifting themselves out of extreme poverty and entering Levels 2, 3 and 4 of the economic pyramid (Rosling et al., 2018). However, as a country becomes wealthier and its Gross Domestic Product (GDP) increases, the personal use of water and the virtual use of water also increase through increased consumption of goods, which all require water as a fundamental input to the manufacturing process. It is estimated that 20% of all human consumptive water use is related to industrial consumption (Kwok et al., 2010).

Moreover, urbanisation is also leading to more people living in cities, and requires water and sanitation services to support this shift. Despite investment in the provision of sanitation, it is difficult for nations to keep pace with the rate of migration of populations to cities. According to WHO/ UNICEF: Joint Monitoring Program reporting, which is the leading source for Water Sanitation and Health (WASH) data to track progress against SDG6 goals, the percent of the population with sewer coverage in sub-Saharan Africa urban areas has declined from 13% in 2000 to 11% in 2015 (WHO & UNICEF, 2017).

Today, more than 2.1 billion people do not have access to clean drinking water, and of the 4.4 billion that lack safely managed sanitation, 2.3 billion do not have basic sanitation facilities (WHO, 2017). The costs associated with a lack of access to water and sanitation place a burden on those who can least afford it (Damon & White, 2018). The challenges are not confined to the developing world or poorer economies. In the United States, deteriorating water quality in shrinking cities such as Flint, Michigan (Zahran et al., 2018; Roy & Edwards, 2019) where water supplies had elevated levels of lead are leading to a crisis in confidence in public water supplies. Similar water quality issues have been reported in cities such as Kentucky (Food and Water Watch (FWW), 2018) and Newark (NRDC, 2019). Environmental watchdog groups such as Environmental Working Group (EWG) are continually reporting on the inadequate level of regulation and compliance monitoring of drinking water quality in the United States (Environmental Working Group (EWG), 2019). By some estimates, in Southern California, 80% of the public does not drink the tap water (Pontius et al., 2003). In addition, the cost of repairing ageing water infrastructure in the United States of America (USA) is estimated by the American Water Works Association to be $1 trillion over the next 25 years. The American Society of Civil Engineers report card gives Drinking Water a Grade D, reporting that 6 billion metres cubed of treated water are lost every day, while wastewater infrastructure receives a D+ Grade (Buckley et al., 2016; Infrastructure Report Card (IRC), 2017a&b). These issues represent a crisis, but also an economic opportunity. In 2018, the global water sector is estimated to be worth USD 770 billion (Water Desalination Report (WDR), 2018). By 2025, it is predicted that this sector will be worth 1 trillion USD per year (RobeccoSAM, 2015).

Availability of affordable, circular and efficient technology to ensure economic and sustainable viability of wastewater for domestic and industrial purposes is still limited (Yenkie, 2019; Castillo et al., 2017; Piao et al., 2016; Plappally et al., 2012; OECD, 2017). The transportation, collection and treatment of water and wastewater uses approximately three percent of all the electrical energy produced in the United States. Due to rising climate change pressures and tightening environmental legislation on wastewater effluents, there has been an increased urgency to develop efficient and sustainable water treatment technologies to treat organic and inorganic pollutants from wastewater prior to discharging into the environment (Lee et al., 2009; Bradford-Hartke et al., 2015; Adapa et al., 2016). Activated sludge treatment plants, for example, provide hygenic water but do not remove and recover nitrogen, phosphorous, micronutrients or trace metals. Zinc is one such trace metal and an essential element whose significance to health is increasingly appreciated and whose deficiency is affecting nearly two billion people in the developing countries (Prasad, 2003; Hambidge and Krebs, 2007). Innovation in the water sector is required to balance constantly changing human and environmental needs as well as evolving water treatment systems that must adapt to existing institutions and practices (Daigger et al., 2019). Therefore, existing technologies are not sufficient to meet the needs of the current and future generation with regards to water challenges.

1.2. The rate of innovation adoption in water is slow

The rate of innovation and technology uptake in the water sector is often reported as being relatively slow compared with other sectors due to the conservative nature of the industry (Thomas and Ford, 2005; Wehn & Montalvo, 2018a). The term 'water innovation' appeared for the first time in the published academic literature in 2004. This term was seen in the title of publication, which referred to water innovation in water resources management in Australia (Barripp et al., 2004; Bowmer, 2004).

Each year millions of euros are invested globally in water technology research and development. However, much of this research does not go on to be commercialized and developed into products and technologies. A study in the Netherlands showed that out of 1,000 water technology companies in the country, only 35% reported investing in research & development (NWP, 2018). Large water companies also invest in internal research and development. Suez reports that it invests over €74M ($87M) in more than 65 research programs each year. This includes not only water related research but all research in areas such as waste management. Against revenues of $19.8B in 2018, the reported figure of €74M ($87M) invested in R&D represents 0.39% of top line revenue. This is a relatively small percentage and it should be put into context by noting that Suez generates a considerable portion of group revenue, not from technologies but from operational contracts. Suez also established Suez Ventures in 2010 with the goal of investing €50M into early stage technology companies (Suez, 2020). Another water technology company, Xylem, reports that it incurred $189M, $181M and $110M in R&D expenditure in 2018, 2017 and 2016, respectively. This is against total revenues of $5.2B in 2018 and $4.7B in 2017, indicating that investment in R&D was 3.63% and 3.85% respectively (Xylem, 2019). Evoqua reported incurred $15.8M and $19.9M of Research and Development expenditure against total revenues of $1.34B and $1.25M in 2018 and 2017 respectively, representing 1.17% and 1.6% of total turnover invested into R&D (Evoqua, 2018). A Japanese water solutions company, Kurita, reported in 2018 that it invested Yen 5.3B in R&D Expenses ($48M), against total net sales of Yen 236.8B ($2.16B), representing 2.25% of total sales. Much of the research work within larger companies does not make its way into the market. There are hundreds of water technology start-ups at any given point in time working to introduce new technologies to the market. However, only a small percentage of these companies will succeed.

Despite a clear need for innovation to address water challenges, it is also widely acknowledged that adoption and dissemination of new water technologies and policies are slow. A previous paper by O'Callaghan and co-authors which presented a Water Technology Adoption (WaTA) Model, noted that the adoption of a water technology was found to take in the region 12 to 14 years to move through Innovators and Early Adopters stages of the market and reach the Early and Late Majority (O'Callaghan et al., 2018).

Ten years after the introduction of Ultraviolet disinfection technology for wastewater treatment in the United States, the total number of full-scale reference plants was 350 installations (O'Callaghan et al., 2018). To put this into context, there are a total of 16,000 wastewater treatment plants in the United States (EPA, 2017). Similarly, 10 years after the introduction of ultrafiltration for drinking water treatment in the United States, the total number of installations was 80 full-scale drinking water treatment plants.

The distribution of the wastewater treatment plants (WWTPs), in terms of the number that fall into different capacity ranges versus population served, is illustrated in Figure 1. It shows that a large percentage of the population is served by a small number of very large wastewater treatment plants, while a large number of small WWTPs serve a relatively small percentage of the total population. This illustrates that it is difficult to have market impact in terms of the total numbers of plants, without having a technology adopted in a large number of relatively small WWTPs. Conversely, it is difficult to have impact in terms of population served, without having the technology installed at a relatively small number of very large WWTPs.

The number of mid-sized to large-scale WWTPs, serving populations of greater 10,000 PE up to 100,000 PE is 2,737 WWTPs. Based on Figure 1, the market penetration, 10 years following introduction of UV Wastewater Disinfection, by which stage the technology had entered the early majority section of the market, was 13% (350 total number of full-scale UV installation plants as quoted above). It must be noted that only a sub-set of all wastewater treatment plants employ UV disinfection technology even today, as it is dependent on whether the discharge consent requires disinfection.

The general point that can be taken from these two examples is that ten years following technology introduction, by which time the technologies were entering the early majority section of the Water Technology Adoption curve, the impact on the market is limited as measured by the average number of people served per WWTP.

The author suggests that this is a function of several factors including:

- The variable treatment capacities and size distribution of the asset base as illustrated in Figure 1.

- The life span and replacement cycle of the installed asset base which can be 10-15 years for the mechanical and electrical equipment, and over 25 years for civil and structural elements such as tanks.
- The length of the engineering design, public tendering and procurement cycle, which can take several years from initiation to project completion.
- The varying local regulatory environment that requires different levels of treatment.

On the other hand, smart phones took less than 10 years to accomplish 40% penetration rate (McGrath, 2013). The water sector offers many opportunities to innovate and deploy new technologies, but in practice this sector has barely tapped the potential those technologies actually offer (Ajami et al., 2014).

Technology is one area where innovation delivers value, but there is equally a need for innovation in water policy. This includes the development of new regulations that will create the space for water innovation, the creation of new finance models, such as those created by Water.org (Damon & White, 2018), and new financial mechanisms and business models, as well as innovation in terms of how the value of water is communicated to the public. Regulatory gaps and misdirected policies slow down the adoption of innovative technologies. The provision of water services is at an exciting yet challenging point, because traditional approaches are being questioned and a combination of new and old technologies are emerging on to the market.

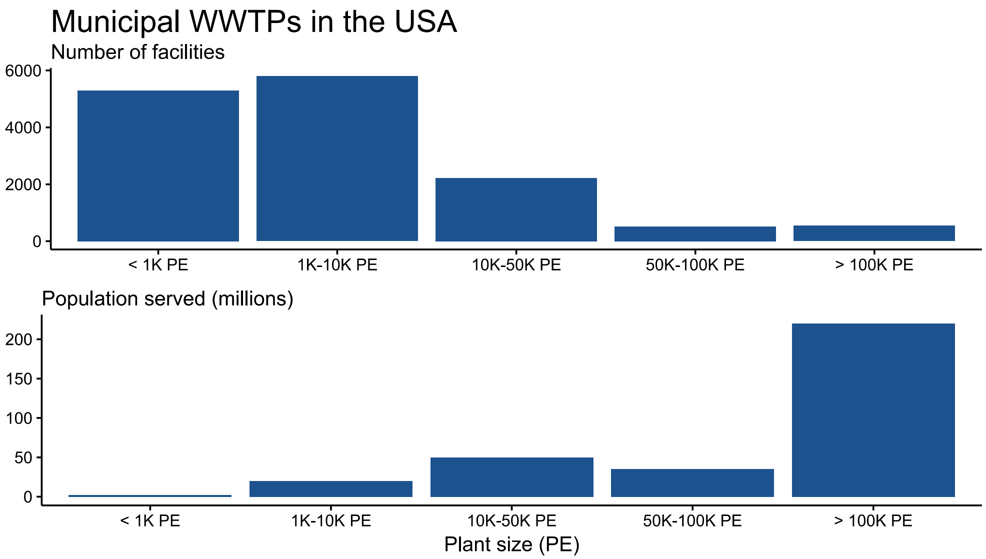

Figure 1: Comparison of number and percentage of population served in different wastewater treatment plants' capacity size range.

1.3. There is a lack of clear terminology, which hampers research into the innovation process

Many authors have developed frameworks to assess the broader category of disruptive innovations and to forecast their market diffusion (Linton, 2002; Hang et al., 2011; Sood and Tellis, 2011). For example, Guo and his co-authors proposed a framework of assessing disruptive innovations based on three multidimensional factors: technological features, marketplace dynamics and external environment (Guo et al., 2019).

The subject of water technology innovation and diffusion is not well understood or studied to date. There are far fewer water innovation studies compared to research into innovation in general, which offers close to four million scholarly titles (Wehn & Montalvo, 2018a). Amongst those few water-related innovation studies, there is even more of a striking absence of academic studies on the dynamics of water innovation or existing insights about models of, and approaches for, studying innovation (Wehn & Montalvo, 2018a). In response to this, the author of this chapter along with his coworkers published a Water Technology Adoption (WaTA) model that presents the average timelines taken for the diffusion of water technology and the innovation drivers that can affect the rate of technology diffusion (O'Callaghan et al., 2018 & 2019).

One of the major problems is that clear innovation terminology in the water sector is urgently required. The term "innovation" in the water sector, and particularly "*disruptive innovation*", is often over-used and misused to the point that it has lost its meaning. The need to define "disruptive innovation" has been noted more generally by others. One paper notes that to facilitate an academic discussion in the business community, a clear definition of disruptive innovation is required; otherwise the term will create confusion and become just a "buzz word" (Nagy et al. 2016; Tellis, 2006). A stipulated definition is needed, giving the term a specific meaning for a specific argument or purpose so that it can be used in the right context. This need has been recognized by many business scholars as being necessary to facilitate meaningful use of this concept (Markides, 2006; Schmidt & Druehl, 2008).

The term disruptive innovation was first launched into the mainstream consciousness of the business world with the publication of a series of seminal papers by Bower and Christensen (Bower and Christensen, 1995; Christensen and Bower, 1996; Christensen, 1997). Since then, this term has gained widespread use, but is also widely misunderstood. The over-use of the term disruptive innovation has reached a point where it has become a synonym for any new 'threatening' substitute to an incumbent technology or substantial on-going change, and there is under-use of the term disruptive innovation as a theoretical concept.

Christensen also states that when core ideas of prior works are obscured by indiscriminate use of its terminology, researchers will face difficulty building on and extending that work. He cites widespread invocation of disruption-related terminology in academic journals, practitioner-oriented publications, and books in multiple disciplines. His papers are an effort to re-invigorate academic interest and spur exciting new research on disruptive innovation in management by providing a review of previous work and suggesting new avenues for research (Christensen et al., 2001 & 2008).

Searching for the prevalence of the terms "disruptive technologies", "disruptive technology" or "disruptive innovation", the review found that between 1993 and 2016, there were 133 academic articles in management journals and 66,773 articles in general-interest outlets (Christensen et al., 2018). This analysis found that, following the publication of three foundational works in the area (Bower and Christensen, 1995; Christensen and Bower, 1996; Christensen, 1997), there was a sustained upward trend of academic articles that cited this foundational research in the area of Disruptive Innovation Theory. The analysis found that while the level of citations had tapered off during the last decade, when it came to popular press articles mentioning disruptive terminology the pattern was different – there was a relatively slow increase, followed by a steep and sustained rise in its use.

This supports our thesis that there has been a divergence from the theoretical framework and concepts captured in the foundational work, and the general use of the terms relative to disruptive innovation.

It has been documented that in the period 2014 to 2016 there has been an increase in general engagement with the theories of innovation, but the overall number of publications on water innovation specifically, was limited to less than 55 papers per year, with these papers addressing topics such as frugal innovation, business models service innovation and analysis of the adoption and diffusion of water innovations (Wehn and Montalvo, 2018a). Wehn and Montalvo have noted that water researchers have been slow to embrace this discourse around water innovation. This was the catalyst for a special edition of the Journal of Cleaner Production (JCP) entitled *The Dynamics of Water Innovation* which provided a very comprehensive review.

Despite the lack of academic papers studying innovation theory as it pertains to water, the term 'water innovation' is becoming increasingly widespread and is increasingly an area of interest for investors, water end-users, water utilities and research institutes.

Venture capital investors constantly seek innovative water companies to invest in. In addition to many specialist venture capital and private equity funds, such as XPV Water Partners, True North Venture Partners, SKIon, and Emerald Technology Ventures, which have an active focus on the water sector, there are large number of corporate investors and family offices looking to invest in the water sector. Universities and research institutes are encouraged to develop innovative technologies. In 2017, the UK Water Utility regulator, OFWAT, called on water utilities to become more innovative in its Pricing Review 19 (PR19) business plans (OFWAT, 2017).

The author analysed data on investments in water for the period 2008 to 2018, based on BlueTech Research Innovation Tracker data, and identified 158 investors which had invested into early stage water technologies, representing investments into 320 unique water technology start-up companies. This is by no means an exhaustive list, as there is no way to analyse and identify all water investments, but nevertheless it does serve to highlight the level of activity.

This chapter aims to address this problem of slow adoption of water innovation technologies by first providing a review of the two common innovation theories: Disruptive Innovation Theory and Innovation Diffusion Theory, and then discussing their applicability to water technologies.

2. Critical review of two different innovation theories

2.1. A review of Disruptive Innovation Theory

The best known and most widely studied and cited theory of innovation is Disruptive Innovation Theory, as developed by Clayton Christensen (Christensen et al., 2015; Christensen et al., 2018; Markides, 2006). In this theory, Christensen described two types of disruptive innovations: a market creating innovation and a low-end disruptive innovation.

Market Creating Innovation

Market creating innovations are those that lead to the creation of new markets (Christensen et al., 2019a&b). By definition then, these are not market taking, meaning that they do not rely solely on capturing market share from existing products in order to create value. These innovations can be categorized as introducing a solution to a problem that has either not been recognized before or has not yet been solved. Market creating innovations develop a new class of customers or a new market.

A good illustrative example of a market creating innovation is the iPhone, which integrated features from a range of existing electronics and packaged them into one device. Technologies were assimilated from mobile phones, computers, cameras, music players and video player and integrated into one hand-held device that could be sold in both the developed and the developing world.

Another example of a market creating innovation that is often cited is the Ford Model T. Ford did not invent the automobile, but with the innovation of the manufacturing line, which made it affordable, the company created a market for a technology that prior to this had been only accessible to the wealthy (Ojomo, 2015; Christensen et al., 2019a). These market-creating innovations are said to often solve unrecognized, or unsolved problems for customers.

Low-end Disruptive Innovation
A low-end disruptive innovation is defined as an innovation that provides a low-cost service or product to customers who are happy with a 'good enough' product (Christensen et al., 2006; Christensen, Bohmer, & Kenagy, 2000; Paap & Katz, 2004; Thomond & Lettice, 2002). A typical low-end disruptive innovation takes advantage of markets in which existing products offer more performance than many customers either want or need. By offering lower functionality at lower cost, they compete for market share in a segment that the incumbents are less interested in pursuing.

By contrast, there is an opposite general trend in Sustaining Innovation, in that incumbents continue to improve and add more functionality to their existing products, sometimes exceeding the needs of particular segments of the market. The conundrum described in the Innovator's Dilemma (Christensen, 1997) is that large incumbent players find it difficult to introduce a lower cost, lower functionality version of what they already provide to capture the lower end of the market which is often deemed to be less profitable, or not large enough to be significant. Over time, Disruptive Innovation Theory describes how low-end innovations can eventually evolve to the point where they compete with incumbents for the higher end of the market, thereby disrupting that market and replacing the incumbent technology (Bower and Christensen, 1995). Recent critiques from business scholars of this theory note that defining disruptive innovations as lower quality products that compete on price would not appear to be an innovation characteristic (Nagy et al., 2016; Besanko et al., 1996).

This definition of low-end disruptive innovation focuses on a business strategy and market entry and overlooks the innovation characteristics. Price is influenced by a variety of factors including the raw material cost base, market competition and the level of cost and profit across the value chain. Low-end disruption is therefore a business strategy to commercialize an innovation as opposed to an innate innovation characteristic. For example, if we take the low-end examples of disruptive innovations, driven by market factors like lower price, the author finds that price is a business strategy, rather than a characteristic of the innovation (Danneels, 2004).

Disruptive Innovation Theory, as defined by the foundational works of Christensen, while seminal and extremely valuable, is a narrow theoretical construct (Markides, 2006) snd is limited in its use to analyse and to study early stage water innovations.

Limitations of Disruptive Innovation Theory
Measuring disruptivity is only possible retrospectively, in that it can only be measured with the benefit of hindsight, based on an effect on the market. It is therefore a function of business strategy, as opposed to an innovation characteristic. The author also proposes that low-end innovation is not widely applicable, thereby not relevant in a regulated market such as water. In the water sector that is mostly driven by regulation, there is

very little opportunity for 'low-end innovation'. In terms of treating drinking water or wastewater, there is a set standard that has to be met and 'good enough' is not relevant: the technology is either compliant or it is not compliant. There is a binary aspect to the performance requirements. This is unfortunate for the billions of people who lack access to water and sanitation, who would welcome any level of improvement, even if it were not at the same level or provided in the same way as those in the developed world. This makes the problem of providing water services in the developing world extremely challenging, if we try to bring people from zero level of access to full access, by relying on local government to provide centralized water and sanitation services compliant with WHO standards. This is an area where a market creating innovation would help to unlock demand, meet an unmet need and solve an unsolved problem.

Moreover, a technology can 'disrupt a market' by taking market share from one player, and not fit the academic definition of a "disruptive innovation." Christensen in a recent review article notes that there is overuse of disruptive innovation/disruption as a synonym for any new threat (or substantial ongoing change) and underuse of disruptive innovation as a theoretical concept. Specifically, he notes that '*Many popular writers invoke disruptive innovation to describe any new technology or startup that aims to shake up an industry and alter its competitive patterns*' (Christensen at al., 2018). To analyse this usage, Christensen carried out an extensive analysis of the appearance of terms related to Disruptive Innovation Theory in academic articles, management articles and popular press that either cited foundational work or used disruption terminology in the period 1993 to 2016. The results suggest an overly broad application of the terms disruption/ disruptive innovation (Christensen et al., 2018).

This is further reaffirmed and discussed in detail by Delmer Nagy and coworkers (Nagy et al., 2016). They note that the problem with the overuse of the term is that if academics in the business community wish to seek ownership of the idea of 'disruptive innovation' they need to offer a clear definition of the term. They note that without clear definition academics and practitioners are left with an extracted definition based on common usage. Therefore, a definition for disruptive innovation that is grounded in the innovation itself is needed. For the purposes of studying and classifying water innovation, particularly at the early technology readiness levels and stages of technology adoption (Innovator to Early Adopter stages), the author proposes that Disruptive Innovation Theory is not a practical framework as it is not grounded in a property of the innovation.

2.2. A review of Innovation Diffusion Theory

In terms of defining innovation, while the most popular and well-known construct is Disruptive Innovation Theory, the author proposes that Innovation Diffusion Theory (IDT) (Rogers, 1995), which focuses on five attributes that affect innovation adoption, is a valuable alternative and practical model to apply when studying early stage water technology innovations. This theory is also described in the literature by Delmer Nagy and coworkers (Nagy et al., 2016) and is summarized here for the purposes of critical review and comparison. Radical functionality and discontinuous types of innovation are described in innovation diffusion literature (Sood & Tellis, 2005), whereas a third type of innovation, sustaining innovation, is described in both disruptive innovation literature and innovation diffusion literature. These innovation types are represented in Figure 2 with examples.

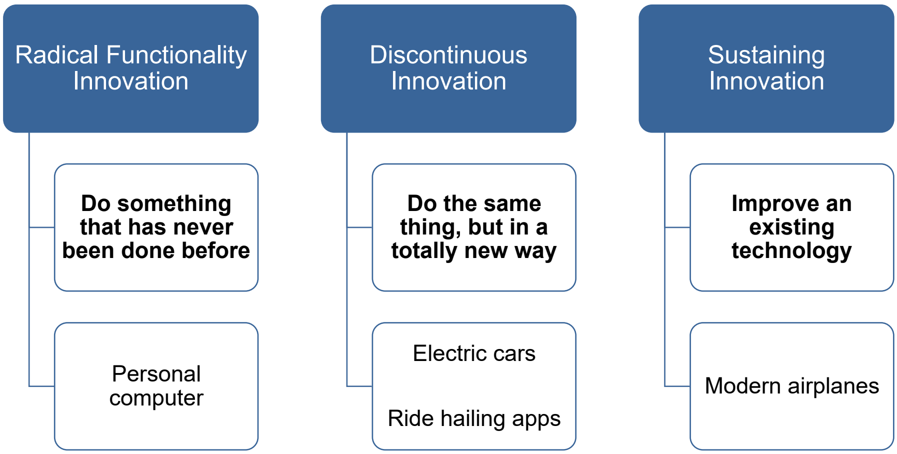

Figure 2: Three types of innovation according to Innovation Diffusion Theory.

Radical Functionality Innovation

Radical functionality is recognized in innovation diffusion literature through articles describing innovations that '*provide a user the ability to undertake a new behavior or accomplish a new task that was impossible before the invention of the innovation*' (Nagy et al., 2016; Abernathy & Utterback, 1978; Anderson & Tushman, 1990; Dahlin & Behrens, 2005; Thomond & Lettice, 2002). This type of innovation can be summed up as doing something that has never been done before.

A general example of radical functionality is the personal computer, as presented in Figure 2. This is also an example of a market creating innovation. Water specific examples would include the membrane bioreactor.

Discontinuous Innovation

As described in innovation diffusion literature, discontinuous innovations are innovations that '*utilize new materials or new processes in the creation of existing technologies*'. As such, they represent a break with the existing technical standards and can affect the entire value chain as a result (Nagy et al., 2016). This type of innovation could be summed up as doing something that is already being done, but in a totally new way. Discontinuous technical standards are recognized as having the potential to change markets in innovation diffusion literature (Dewar & Dutton, 1986).

General examples of discontinuous innovation include electric cars, as presented in Figure 2. The basic functionality is the same as an automobile powered by an internal combustion engine, but the value chain is different as it utilizes a different drive train and batteries to store the energy.

Sustaining Innovation

Sustaining innovation or incremental innovation does not provide radical functionality and '*does not represent a break with an existing technical standard and is not market creating*' (Nagy et al., 2016). Sustaining innovation is continual innovation, which develops existing technologies and products. The majority of product and service innovations represent sustaining innovation because they meet the needs of existing customers by representing an improvement to an existing technology, process or service.

General examples of sustaining innovation would include modern airplanes, as shown in Figure 2. They increased the number of passengers who could be carried on a passenger airplane, providing better performance than was previously available, but did not create new value or new markets.

3. Assessment of the applicability of innovation diffusion theory as a framework to study water technology innovation

From the Innovation Diffusion Theory, the author proposes that the following innovation types are useful in that they represent a property of the innovation and can be defined and applied. To summarise:

1. Radical Functionality Innovation is something that has never been done before, as they '*provide a user the ability to undertake a new behavior or accomplish a new task that was impossible before the invention of the innovation*' (Nagy et al., 2016).
2. Discontinuous Innovation '*utilize[s] new materials or new processes in the creation of existing technologies*' (Nagy et al., 2016), meaning that they do the same thing, but in a totally new way.
3. Sustaining Innovation improves an existing technology and '*does not represent a break with an existing technical standard and is not market creating*' (Nagy et al., 2016).

For researchers, investors, end-users and technologists engaged in the process of bringing innovations to market, it is more useful to have a construct and framework that is grounded in characteristics of the innovation itself (Nagy et al., 2016). This differentiates innovation typology from business strategy. For example, a business strategy can be to compete on price, which is not an innovation characteristic. In this section, we take the three types of innovation described previously and attempt to apply this to the classification of water technology examples, as shown in Figure 3.

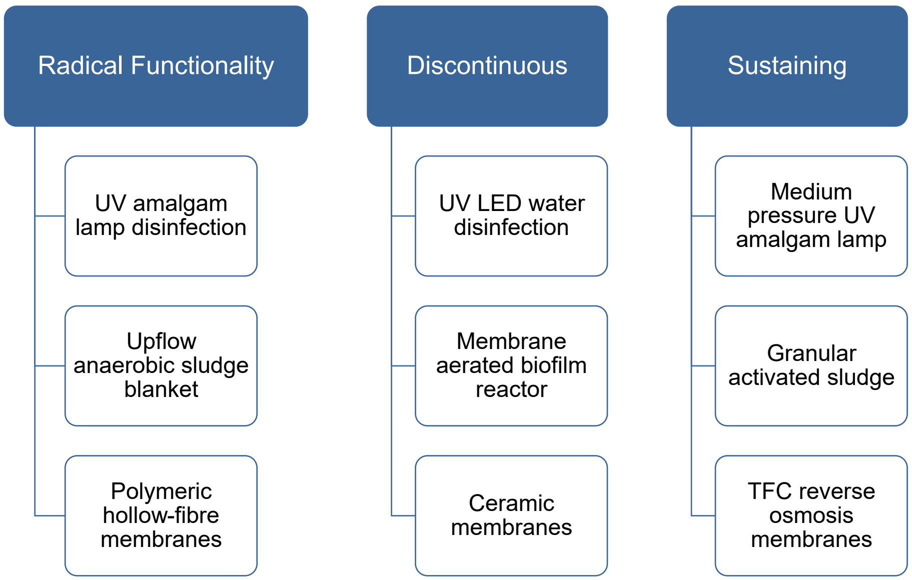

Figure 3: Examples of water technology innovation according to Innovation Diffusion Theory.

Radical Functionality Innovation

Water specific examples of radical functionality include UV amalgam lamp disinfection, upflow anaerobic sludge blanket (UASB) and polymeric hollow-fibre membranes, as described in Table 1.

Discontinuous Innovation

Water specific examples of discontinuous innovation include UV LED water disinfection, membrane aerated biofilm reactor (MABR), ceramic membrane filtration, UASB reactors, and bio-electrochemical treatment. Some of these are described in Table 2.

Sustaining Innovation

Water-specific examples of sustaining innovation include medium pressure UV amalgam lamp, granular activated sludge, TFC reverse osmosis membranes, as described in Table 3.

Table 1: Radical functionality technologies

Name of water technology	Reasons for classifying as radical functionality
UV amalgam lamp disinfection	UV light provided a means of inactivating *Cryptosporidium* oocysts which were resistant to chlorine disinfection. The use of the germicidal effect of UV light also provided a means to disinfect water without the need to add chemical disinfectants, and eliminated the formation of disinfection by-products.
Upflow anaerobic sludge blanket (UASB)	The UASB technology provided a low energy and lower sludge generating technology when compared to aerobic biological and lower footprint and higher rate, when compared to existing anaerobic biological treatment systems. As such this innovation provided radical functionality and was driven by the need to treat high organic strength industrial wastewater.
Polymeric hollow-fibre membranes	The use of hollow fibre polymeric membrane filtration provided a means to provide an absolute filtration cut-off point in the terms of the size of particles that were excluded, which was not possible to achieve with conventional depth media filtration.

Table 2: Discontinuous innovation technologies

Name of water technology	Reasons for classifying as a discontinuous innovation
UV LED water disinfection	A UV LED, when it replaces a UV mercury amalgam lamp for the disinfection of drinking water or wastewater, is discontinuous. It provides the same service as a UV Mercury amalgam lamp, but it does so using entirely different components. It eliminates the use of a ballast, or power system to excite mercury in a conventional UV lamp.
Membrane aerated biofilm reactor (MABR)	A membrane aerated biofilm reactor provides a mechanism to meet the oxygen demand of bacteria without the use of fine bubble diffusers combined with air blowers.
Ceramic membranes	Ceramic membranes provide the same level of filtration as hollow fibre polymeric ultrafiltration membranes, but they do so using a completely different technical standard and manufacturing process. The materials used and the form factor are a break with the existing technical standard.

4. Discussion

In the public utility water sector, there is very little room for low-end innovation, as water is a regulated market. On the contrary, market-creating innovations are often driven by regulation. Examples of market creating innovations include UF drinking water filtration and UV wastewater disinfection (O'Callaghan et al., 2019). While these innovations addressed unsolved problems, it must be noted that regulation and policy played a key role in encouraging the market to adopt these solutions.

Table 3: Sustaining innovation technologies

Name of water technology	Reasons for classifying as sustaining innovation
Medium pressure UV amalgam lamp	Industrial medium pressure UV lamp systems followed the development of low pressure UV lamps and can output approximately 10 times more energy per lamp than low pressure UV lamps. This provides greater disinfection capacity within a single UV vessel, without the addition of numerous lamps to achieve a high level of disinfection, as required with low-pressure systems. The energy efficiency of medium pressure lamps is lower and if a higher energy output is not required, low-pressure lamps are favored.
Granular activated sludge	The granular activated sludge process is a variation and adaptation of the conventional activated sludge process, which selects for compact dense granules held together by extra cellular polysaccharides (EPS), has inherent advantages over the conventional processes, but these all fall into the category of sustaining innovation. The value chain remains unchanged. The functionality provided in terms of final treated wastewater effluent quality, is similar to the conventional wastewater treatment process.
TFC reverse osmosis membranes	In the late 1970s, thin film composite membrane chemistries were developed that subsequently replaced cellulose acetate as the dominant membrane chemistry used in reverse osmosis seawater desalination. The change in chemistry was handled by existing companies using existing manufacturing techniques.

This type of innovation is the exact opposite of Christensen's definition of disruptive innovation because of its complexity, and because it starts at the top of the market and never makes its way down. For example, in the case of UF membrane filtration for drinking water treatment, it was more expensive to begin with than granular depth media filtration and did not start in simple applications at the bottom of the market. Subsequently costs have come down to parity with depth media filtration and today, in China in particular, UF membrane filtration is the dominant technology used at new drinking water treatment plants (Pearce, 2019a).

Membrane bioreactor technology is a radical functionality innovation technology that was at pilot stage in the mid 1990's (O'Callaghan et al., 2018) and today there are over 1,000 plants in operation in over 40 countries representing an annual market value of over $1.6 billion per year (https://www.thembrsite.com/interactive-map-history-of-municipal-mbr-installations). MBR technology was not a low-end innovation. It provided better final treated effluent quality, occupied a smaller footprint and was more expensive than conventional alternatives. It did fill an un-met need in the market, where high effluent quality was required on sites constrained by footprint. On the other hand, variable frequency drive (VFD) is an example of sustaining innovation as it improves energy efficiency in wastewater treatment plants by changing the way in which airflow into aeration basins is controlled (Maktabifard et al., 2018). Thiopaq process instead of caustic gas washers for biogas desulphurization is another example of sustaining innovation.

It is important to divorce the theoretical concept of "Disruptive Innovation" from the phenomenon of "Market Disruption", the latter being of high interest to business academics and stakeholders in the water innovation value chain. The particular type of innovation described as "Disruptive innovation" is not the *sine qua non* for market disruption, with many different types of innovation capable of leading to a disruption in the market (Paap & Katz, 2004; Danneels, 2004; Schmidt & Druehl, 2008; Sood & Tellis, 2011; Ronny & Sebastian, 2015).

An important question is: Can disruptive innovations be predicted before a disruption has occurred, and are these linked to certain types of innovation? In order to make any attempt to answer this, it first needs to be defined (Danneels, 2004). For this, the following questions need be answered: What constitutes a disruption in the water market? How can this be quantified or measured? If a new technology achieves 10% market share, is this disruptive? Are the total numbers of reference sites or the global distribution and adoption important heuristics to measure? Does a new technology need to lead to the replacement of some companies and the establishment of new ones in order to be considered disruptive? This chapter and subsequent work by the author and his coworkers will attempt to address these questions.

If the metric is that a new technology completely replaces an existing technology, then there are very few examples in the water sector of where this has occurred. One possible explanation for this lack of market disruption may be the fragmented nature of the global water market. It is widely recognized and accepted that the municipal water market is highly fragmented. In the United States there are 14,376 wastewater treatment plants active (EPA, 2012) that represent the customer base, the regulations and standards vary from State to State, and from country to country, and there are multiple companies offering multiple solutions, all-capable of doing the same job. Technology adoption in the water sector is also relatively slow because replacement rates can stretch to 30-50 years for existing installations. Compare this to the smart phones market where the technology is replaced every 3-5 years. Growth in the water industry depends solely on growth of population and new regulation; therefore, it is unlikely to unlock non-consumption.

Paap & Katz investigated the relation between technology and disruptivity and concluded that technology creates change in processes, materials, functionality or the utility of a product or service, and does not directly lead to a return. Predicting the future is difficult but anticipating change and preparing for it by focusing on the drivers of the technology is one way to recognize new technologies that may cause disruption (Paap & Katz, 2004).

The search for technology disruption can also be myopic at times, hyper-focused on individual technologies, which represent just one small part of an overall larger picture. If we take the example of fixed line telephony being disrupted by cell phones as an analog, should we really be looking for systems level disruptions in water as opposed to smaller technology changes within the current paradigm? The market creating innovations that can unlock markets may use a combination of both new and existing technologies, combined in new ways.

Sustaining innovation either helps existing companies retain market share, or claw some of it away from others, but this type of innovation does not unlock non-consumption or create new markets. So, it has limited potential to create growth (Christensen, 2019b). Discontinuous innovation and radical functionality all create a market for themselves, but the question remains whether they do it at the expense of someone else or do they unlock non-consumption? Radical functionality innovations fit with the Clayton Christensen definition of market creating innovation, which is one aspect of disruptive innovation. However radical functionality alone is not enough to create a new market. Dewar & Dutton, Maidique & Zirger and many others have given examples of radical innovations that never succeeded in the marketplace (Nagy et al. 2016, Dewar & Dutton 1986, Maidique & Zirger, 1984). In addition to this, Paap & Katz confirm that disruptions are not only caused by the technologies associated with major innovation but rather are often a function of actions and inactions by dominant competitors in the marketplace (Paap & Katz, 2004). Danneels defines disruptive technologies as 'a technology that changes the bases of competition by changing the performance metrics along which firms compete'. He introduces a dimension of performance metrics along which products did not compete previously into this discussion with the example of disk drives where drive capacity exceeded the requirement of a certain market segment and the size of the drive became a basis of competition, creating significant value for that market segment (Danneels, 2004). Similarly, Thomond & Lettice view the change in the perception of the product's value in the mainstream market as an enabler for a "disruptive" innovation to replace existing products and services (Thomond & Lettice, 2002). Tellis adds the internal mindset of a firm and its cultural aspects as an important player in the success and failure of technology adoption, and not only where it has radical functionality or its technology characteristics alone (Tellis, 2006).

5. Conclusion

The fragmented nature of the global water market, long replacement cycles for existing technologies and the market growth dependence on population increases and new regulation all contribute to the slow technology diffusion rates and low disruption in the water sector. This chapter is a response to the fact that innovation is required in water, that innovation as it relates to water is understudied, and that the concepts behind Disruptive Innovation Theory have lost their meaning due to overuse, mainly out of context, and that a practical framework is required to facilitate meaningful academic and industry discussion.

The author proposes to use the framework and theories described in this chapter to evaluate several water technologies to determine if there are any commonalities or patterns that can be discerned. If certain types of innovation have led to market disruption and market creation, other innovation frameworks like the Innovation Diffusion Theory which is more practical and useful than the Disruptive Innovation Theory should be used as analogues when evaluating the potential of new technologies. Three types of innovation are defined: sustaining, radical functionality and discontinuous, where sustaining innovation take market share away from existing technologies and the later two create new markets and unlock non-consumption. This framework is proposed to inform investment strategy in water and provide a clear and objective basis and framework for academic discussion of water technology innovation.

5

Chapter 5

A Novel Framework to Measure Level of Market Impact

1. Introduction

Accelerated population growth, water scarcity and inefficient management of available water resources are some of the challenges faced by the water industry today (Daigger et al., 2019). Available sustainable fresh water resources are decreasing due to water resource scarcity, which is further exacerbated by climate change. Thus, it becomes necessary to implement systems that use available fresh water and other resources more efficiently (Larsen et al., 2016; Daigger, 2009, 2007).

Innovation is vital for driving change, creating industries, sustaining competitive performance and improving the quality of life and environment. However, water utilities are typically slow to adopt new concepts and innovation into their industry (Carter et al., 2017a, Kiparsky et al., 2016; Speight, 2015; Loewe & Dominiquini, 2006). Even though over 90% of utility respondents believe innovation is critical for the future of their organisations, only 40% believe they are effectively leveraging innovation to meet challenges and evolve as utilities (Carter et al., 2017b).

In a previous chapter, the author outlined different types of innovation, including sustaining innovation, radical functionality and discontinuous innovation (O'Callaghan et al., 2020). The author has also studied different innovation drivers: crisis driven and value-driven innovation (O'Callaghan et al., 2019). The rate of adoption and impact of sustaining innovation, is likely to exceed the rate of adoption and the impact of other forms of innovation, such as innovation with radical functionality and discontinuous innovation. In the water sector, the adoption of a water technology that is driven based on its value proposition typically takes in the region of 14 years to move through Innovators and Early Adopters stages of the market and reach the Early and Late Majority. In the case of a technology whose adoption is driven by a crisis or market need, such as a new piece of legislation, or an urgent health or environmental issue, the timeline can be half of this, at just under 7 years (O'Callaghan et al., 2019). While value driven innovation has a slower cycle for adoption, it presents lower risk of failure as it is less dependent on external factors and timing of implementation of regulations or the occurrence of some public health related or environmental crisis (O'Callaghan et al., 2019).

Many technologies are researched and developed, but how many have real world impact? Many research topics such as bio-electrochemical / microbial fuel cell systems and photocatalytic oxidation have a large body of published literature and citations, yet have had relatively little impact in terms of solving real world global water challenges. Loeb, Alvarez, Westerhoff and coauthors in a paper entitled "The Technology Horizon for Photocatalytic Water Treatment: Sunrise or Sunset?" (Loeb et al., 2019), noted that advanced oxidation processes via semiconductor photocatalysis for water treatment have been the subject of extensive research over the past three decades, producing many scientific reports focused on elucidating mechanisms and enhancing kinetics for the treatment of contaminants in water. However, the literature lacks research that focuses on reactor design and the practicalities of implementing and building systems, perpetuating a gap between academic advocation and industrial application. Despite substantial research over the past few decades, the application of photocatalysis in practical water treatment systems has been very limited compared to conventional Advanced Oxidation Processes (AOPs).

As a result of this gap, the author notes that, '*Consequently, scepticism has grown, leading some to question whether photocatalysis will become a mainstream water treatment technology within the next two decades*' (Loeb et al., 2019). The boom in published literature, with 8,000 articles on the topic of photocatalytic water treatment published between 2000 and 2017, can lead to certain amount of hype, and push a technology to the Peak of Inflated Expectations on the Gartner Hype Cycle (Dedehayir & Steinert, 2016; Linden & Fenn, 2003; Bresciani & Eppler, 2008).

Many new technologies are referred to as being disruptive. The term disruptive innovation has been overused to the point that it is has lost much of its meaning (Nagy et al., 2016; Tellis, 2006; Markides, 2006; Schmidt & Druehl, 2008). Disruptivity is not a characteristic of a technology but its effects on the market (O'Callaghan et al., 2020). Several frameworks for assessing and predicting disruptive innovation have been proposed in the literature. Hang and co-workers presented one based on the theory of Christensen and subsequent clarifications in the literature, where the assessor needs to consider key success factors in market positioning, technology and other favourable drivers (Hang et al., 2011). Rafii and Kampas looked at how an incumbent may identify a potential disruptive threat (Rafii and Kampas, 2002), whereas Christensen and his coworkers explored the impact of industry changes on disruptive innovations (Christensen et al., 2004). In addition to this, Hang and coworkers investigated the entrepreneurial process embedded in the theory of disruptive innovation and debated whether the theory of disruptive innovation is useful for ex ante prediction of future innovations (Hang et al., 2015).

Despite this progress made by academics, practitioners still struggle with the innovation challenge to confidently predict whether an early stage disruptive innovation technology would have a good chance to succeed and "disrupt" the market. Disruptive innovation theory is still in its infancy, and many areas of theory remain under-researched due to the lack of understanding and lack of available empirical data (Rasool et al., 2018, Christensen et al., 2018, Nagy et al., 2016; Bower and Christensen, 1995; Christensen and Bower, 1996; Christensen, 1997).

Previous chapters analysed the use of the term disruptive innovation in relation to water technologies, and proposed alternative innovation classification systems (O'Callaghan et al., 2020). It was noted that sustaining innovation either helps existing companies to retain market share, or to claw some of it away from others, but this type of innovation does not counteract non-consumption or create new markets. On the other hand, discontinuous innovation, which can be summed up as doing something that is already being done but in a totally new way, and radical functionality, representing something that has never been done before, can create a market for themselves or take market share from existing technologies (O'Callaghan et al., 2020; Nagy et al., 2016; Sood et al., 2005; Thomond & Lettice, 2002; Dewar & Dutton, 1986).

This chapter looks at what constitutes a disruption, or impact from the perspective of a water treatment technology. The level of impact can only be assessed retrospectively. The author wishes to explore whether certain innovation characteristics of the technology, which can be identified earlier on in the lifecycle of the technology, correlate with different levels of market impact. There may also be differences in the relative rates of impact that correlate to innovation typology. This would be of use to those wishing to invest into the development of new innovations in setting realistic expectations based on how the technologies under development map across this framework. But how can we measure and quantify real world impact? Moving a technology from early stage Technology Readiness Level's (TRL), TRL 1, 2 and 3, through to TRL 6 or more, does not in itself guarantee impact in terms of application, widespread adoption and implementation. Likewise, moving a technology beyond the Early Adopters stage of the Water Technology Adoption (WaTA) model (O'Callaghan et al., 2018) and into the Early and Late Majority section of the market, does not equate to the level of impact.

There are certain cases where technologies have become extremely dominant in particular applications. For example the use of spiral wound thin film composite reverse osmosis membranes in seawater desalination, with over 80% of all newly built seawater desalination plants using this technology in favour of thermal desalination, such as Multiple Effect Distillation (MED), with the exception of some plants in the Middle East where thermal energy is available at low cost (Global Water Intelligence (GWI), 2019).

It is acknowledged in literature that the rate of adoption of innovation in the water sector is relatively slow (Thomas and Ford, 2005; Wehn & Montalvo, 2018). This is referring specifically to the introduction of new technologies, and is much less of an issue with sustaining innovations, which are improvements to existing technologies, which are continually introduced, adopted and are important to technology providers to maintain market share in what are typically mature and regulated markets. Given that the rate of adoption of new technologies in the water sector is slow, it may be the case that the level of impact is also low as measured by how widespread the adoption is. But the question remains: how should we go about quantifying and measuring market impact? What constitutes disruption? Where should we set the bar so that we can objectively define levels of impact? In this chapter, a set of criteria were created that represent a meaningful and robust method to measure the level of impact and adoption. Combining and overlaying this framework with innovation types, as outlined by O'Callaghan et at. 2020, to see if particular innovation types and characteristics are linked to higher levels of impact and adoption, is valuable. The dimension of time was also overlayed to study the rate of impact to look at the typical time-frames associated with achieving certain levels of impact.

2. Framework development

A number of different potential metrics and heuristics that could be used to estimate and quantify the level of impact and adoption were considered.

2.1. Metrics evaluated but not selected for inclusion in the framework

The following were evaluated but not selected for inclusion for use in the analysis in this chapter:

Total number of companies offering the technology

It was found that in almost all cases there were at least three or more companies offering the technology and having a larger number of companies offering the technology does not necessarily equate to greater market impact. It should however be noted that where there are less than three, and in some cases only one company offering the technology, i.e. THIOPAQ, this can be correlated with lower levels of market impact but is not a direct measure of it.

Total percentage of all existing, or newly constructed, treatment facilities that use a particular technology

Another metric that was also considered to assess the level of market penetration, was the percentage of all plants that currently use the technology. In theory, this would be the ultimate measure of how dominant a particular technology has become. The rationale being that, at some point, a disruptive technology would take over from incumbent technologies, or become a standard part of all treatment plants.

Due to the existing global installed base of water and wastewater treatment facilities, many with life spans that can be over 30 years, the time taken to make any measurable impact on the existing stock can take decades if relying on end-of-life replacement. This is analogous to small group of individuals trying to make an impact on the genetic pool of a large population of long-lived individuals.

It was then subsequently considered to apply this criterion to only the percentage of *newly constructed* treatment plants that incorporate a particular technology. This has the effect, however, of excluding all retrofit and upgrade projects, which make up a significant portion of the available annual market opportunity for deployment for certain technologies, such as MBBR.

This heuristic was further complicated by factors such as the notion that certain technologies are suitable at different scales, with anaerobic digestion only making sense at wastewater treatment plants above a certain size, while other technologies require a certain configuration of existing processes, such as the need to have biological phosphorus removal in order to make struvite recovery viable and advantageous. Moreover, there are striking regional differences in the dominance of particular technologies in newly constructed plants. For example, in China, it is estimated that almost half of all new drinking water treatment plants use Ultrafiltration Membrane Technology, whereas in North America and Europe, the percentages are at 10% of less (Pearce, 2019b).

Total volume of water or wastewater (or total mass-loading) treated using the technology
Another metric considered was the total volume of all water or wastewater treated that uses a particular technology. Again, in theory, this represents an ideal metric by which to measure impact. This is affected by the size and scale of the plants, which would penalise technologies that are suitable for use at small to medium treatment plants, and given the mature nature of the water infrastructure, many plants still use legacy technology. The author also wished to be able to include references and impact in industrial wastewater treatment, and data on total flow and total numbers of plants is even harder to attain than it is for the municipal water sector.

2.2. Metrics selected for inclusion in the framework

The following three criteria were ultimately selected as ways to measure or quantify the level of impact and adoption.

1. Total number of reference plants in operation
2. Total number of countries the technology is used in
3. Total annual market value the technology represents

The following is an overview of the three metrics that were brought forward for testing to measure market impact. For each of these three criteria, three different levels of impact were established: these were referred to as Level 1 being the highest level of impact and adoption and Level 3 being the lowest level.

Total number of reference plants in operation
The first metric is the total number of installations to quantify level of impact. Initially using total flow or mass loading was considered, but the relevant unit and metric varies widely by technology type hence it would be difficult to establish a way to cross-compare levels of adoption on this basis. By comparison the total number of facilities is more practical to apply. A limitation of this data point, is that it does not take into the account the size and scale of the facilities. A small number of very large treatment plants could treat much higher volumes than a larger number of very small plants. Similarly the

inverse is also true, a large number of smaller size installations could skew the results. To address this, plants that were treating under 100 population equivalents were excluded, such as in the case of MBR.

It can be expected that in some cases as a technology matures, the size and scale of the installations increases, in much the same way as the capacity of passenger airplanes increased over time as the technology developed. The corollary of this however is that certain technologies are designed for use at smaller scales.

Based on the Water Technology Adoption (WaTA) model (O'Callaghan et al., 2018), one of the metrics used to gauge when a technology has moved into the Early Majority section of the market is when the total number of plants exceeds 30 reference sites. For the purposes of this analysis, a technology remains at a lower level – Level 3 impact – when the total number of plants is less than 100. If the number of plants is greater than 100, this is one of the criteria to hit Level 2. One of the criteria to hit the highest level of impact is when there are more than 1,000 plants in existence.

Total number of countries the technology is used in

A second metric to help assess global level of impact, is the total the number of countries in which the technology has been adopted. For the purposes of this analysis, a technology is at a lowest level – Level 3 impact – when the total number of countries in which the technology is adopted is less than 10. This criteria hits Level 2 when the technology is adopted in 10 to 25 countries, and finally hits Level 1 impact when it is adopted in more than 25 countries.

Total annual market value the technology represents

For this metric, the total annual capital sales value that the water technology market represents was proposed. This was the most difficult of the three proposed metrics to quantify: the information is often deemed to be commercially sensitive and not readily disclosed, and there are different ways to quantify the market value, depending on what is included in the scope. For this metric, the authors of the paper found that setting revenue brackets were more helpful which could be assigned with a greater degree of confidence than the exact revenue figures. For example, if there are a very low number of annual reference plants, then it is possible to estimate that the market revenue for that particular technology is under $100 million per annum. Likewise, if the total technology revenues of one company is known, and this in itself pushes the technology into a higher revenue bracket, it allows for assignment of impact without knowing total revenue sales from all of the players.

Similarly, the technology is in the lowest impact level – Level 3 – when the annual market value is less than $100 million, in Level 2 when the value increases up to $500 million and in Level 3 when the value exceeds $500 million.

We set the following thresholds for each of the criteria:

- Level 1 impact – Unicorn Technologies
  - o Used in 1,000 or more reference plants
  - o Used in 25 or more countries
  - o Annual sales are $500M or more
- Level 2 impact – Lion Technologies
  - o Used in 100 or more reference plants, but less than 1,000 reference plants
  - o Used in 10 or more countries, but less than 25 countries
  - o Annual sales are $100M or more, but less than $500M
- Level 3 Impact – Horse Technologies
  - o Used in less than 100 reference plants
  - o Used in less than 10 countries
  - o Annual sales are less than $100M

In terms of assessing whether a technology had reached Level 1, the question arose as to whether it required the technology to cross all three hurdles, or just two out of the three, and if so, which two. It is proposed for this analysis, that if a technology meets Criteria 1 and Criteria 2, then it is deemed to have crossed over to the next level of impact and adoption. Criteria 3 then becomes an auxiliary criteria which is a helpful and meaningful auxiliary metric to provide additional context to metrics 1 and 2. It is not always possible to get accurate data on market size and interpretations of this vary, as to what is counted or measured as in-scope. In cases like MBBR, the scope of supply of media and associated control systems can make up just 20% of the total project cost. Also, some technologies are inherently more capital intensive than other technologies which can make it easier for them to reach higher market values for lower levels of deployment relative to a lower capital cost technology.

3. Method

Data was gathered on eleven case studies. The author contacted informed industry professionals in Australia, Japan, Europe and North America with detailed knowledge of these technologies and databases that tracked the technology deployment. The objective of the research interviews and email communications was: 1) to gather data on the number of full-scale installations for the case studies investigated in this chapter and 2) to assess whether the criteria used to define the different levels of disruptivity were robust and would be understood and usable in a consistent and objective way by water industry stakeholders. The target group from which we received the data for each technology were selected to provide representative coverage across key stakeholder groups, including consulting engineers, water treatment technology providers, academics, water utility end users and water technology investors, and on the basis of their extensive expertise in developing new water treatment technologies and implementing innovation. The author of this thesis conducted these research interviews and exchanged emails to gather data with multiple follow-ups between September 2015 and June 2020.

The interviewees were contacted by e-mail in advance and given standard background information on the purpose of the research interview and the disruptivity framework as outlined above. Some interviews took place on the phone whereas some were by email. The interviewees were asked for feedback on the criteria defining the three levels of disruptivity and discussions were conducted on how the different technologies investigated in this chapter fit the framework.

Naturally, a certain amount of time is required in order for a technology to achieve significant impact and adoption. This was addressed in the creation of the WaTA model, covered in a previous chapter. It was found that it took 17-24 years from when a technology was first introduced to when it reaches halfway through the Early and Late Majority. Thus, when using case studies to analyse market impact, technologies were selected which were first introduced over 17 years ago, except for one technology, Struvite Recovery, introduced 14 years ago. The timeframes at each stage of technology adoption were calculated as the average number of years taken to hit Criteria 1 and Criteria 2 for each specific level.

The availability of data to support the analysis was one factor that was used to determine which technologies were short-listed for analysis. In the absence of available historic data, it would not be possible to analyze the rate of technology diffusion. The technologies were also selected for being diverse geographically and across different types of treatment from drinking water to wastewater. Table 1 lists the technologies analysed and assessed for level of impact and adoption, in particular applications.

For UF membrane filtration, it was decided to focus on drinking water treatment only, as the application of UF membrane filtration in wastewater is covered under MBR and is a very different application.

While efforts were made to obtain the exact data in terms of total numbers of plants and total number of countries the technologies were used in, it was proposed that the classification system is based on more than, or less than, a pre-determined range of criteria. Finding the exact number of reference plants in existence can be difficult, particularly after the technology has been offered for many years by many different companies, however it is easier to estimate with a higher confidence interval that the total number lies within certain pre-determined ranges. This provides a model, which although a simplification of reality, makes the classification system easier to apply systematically in real world applications where approximations are available, which are accurate within the given range, but not precise.

Table 1: Technologies and the respective applications assessed for level of impact and adoption

No.	Technology name	Application studied
1	Ultrafiltration (UF) membrane	Drinking water treatment
2	Ultraviolet (UV) disinfection	Municipal wastewater and reuse and drinking water treatment
3	Membrane bioreactors (MBR)	Municipal and industrial wastewater treatment
4	Upflow anaerobic sludge blanket (UASB) reactor	Industrial wastewater treatment
5	Dissolved air flotation (DAF)	Industrial wastewater treatment
6	Moving bed bioreactor (MBBR)	Municipal and industrial wastewater treatment
7	Sludge thermal hydrolysis	Municipal wastewater treatment
8	THIOPAQ biogas treatment	Municipal and industrial wastewater treatment
9	Phosphorus recovery as struvite	Municipal and industrial wastewater treatment
10	Microbial encapsulation	Municipal wastewater treatment
11	Ceramic membrane filtration	Drinking water treatment

4. Results

Once the number of reference facilities, number of countries the technology was adopted in and the annual market value were gathered for each of the eleven technologies, the three criteria were then applied to determine level of market impact as outlined in the methodology above. The data are tabulated in Table 2-12 and the resulting level of impact assigned to each technology is summarised in Table 13.

Figure 1 represents the number of years that each technology spent in each level of market impact from when the technology was launched to the year 2019. For Dissolved Air Flotation (DAF) technology, the data was acquired from only one vendor, Nijhuis

Table 2: Data for ultrafiltration (UF) membrane technology – drinking water market

	Year	Number of reference plants	Number of countries adopted	Annual market value ($ million)
12	1985	1	1	
	1997	100	10	100
9	2000		25	
	2002			250
	2006	1,000		
13	2008			500
	2019			

Industries which accounts for less than 20% of industrial wastewater market share. Hence this technology has been excluded when calculating the average time required by a water technology to reach Level 1 market impact. Hence, considering only UF DWT, MBR, MBBR, UASB, and UV disinfection for wastewater and drinking water markets

Table 3: Data for ultraviolet (UV) disinfection technology – municipal wastewater and reuse, and drinking water treatment

	Year	Number of reference plants	Number of countries adopted	Annual market value ($ million)
	1983	1	1	
11	1987	100		
	1994		10	
	1997	1,000		
8	1999			100
	2002		25	
17	2019			500

Table 4: Data for membrane bioreactors (MBR) technology – municipal and industrial wastewater treatment

	Year	Number of reference plants	Number of countries adopted	Annual market value ($ million)
	1990	1	1	
	1996	100		
12	2000			100
	2001	1,000		
	2002		10	
4	2006		25	
13	2008			500
	2019			1,250

Table 5: Data for Upflow anaerobic sludge blanket reactor (UASB) technology – industrial wastewater treatment

	Year	Number of reference plants	Number of countries adopted	Annual market value ($ million)
11	1976	1	1	
	1987	100	17	
11	1988			100
	1998	1,000	52	
21	2019	1,700		250-300

Table 6: Data for dissolved air flotation (DAF) technology – industrial wastewater treatment by Nijhuis Industries

	Year	Number of reference plants	Number of countries adopted	Annual market value ($ million)
	1975	1		
12	1986		10	
	1987	100		
13	1988		25	
	2000	1,000		
9	2019			

Table 7: Data for moving bed bioreactor (MBBR) technology – municipal and industrial wastewater treatment provided by AnoxKaldnes and Headworks

	Year	Number of reference plants	Number of countries adopted	Annual market value ($ million)
	1990	1	1	
8	1997	100		
	1998		10	
	2006		25	
17	2008			100
	2015	1,000		<500
4	2019			

Table 8: Data for sludge thermal hydrolysis – municipal wastewater treatment

	Year	Number of reference plants	Number of countries adopted	Annual market value ($ million)
	1996	1	1	
23	2007	14	9	<100
	2008	20	11	<100
	2019	98	24	<100

Table 9: Data for THIOPAQ biogas treatment – municipal and industrial wastewater treatment

	Year	Number of reference plants	Number of countries adopted	Annual market value ($ million)
	1990	1	1	
20	2002	25	10	<50
	2009	95	20	<50
	2010	111	23	<50
9	2012	148	25	<50
	2019	<500		<50

Table 10: Data for phosphorus recovery as struvite – municipal and industrial wastewater treatment

	Year	Number of reference plants	Number of countries adopted	Annual market value ($ million)
	2006	2	2	
13	2015	41	9	<50
	2016	47	10	<50
	2019	60	11	<50

Table 11: Data for microbial encapsulation – municipal wastewater treatment

	Year	Number of reference plants	Number of countries adopted	Annual market value ($ million)
	1991	1	1	
	2008	29	4	<100
28	2009	31	4	<100
	2016	40	5	<100
	2019			

Table 12: Data for ceramic membrane filtration – drinking water treatment

	Year	Number of reference plants	Number of countries adopted	Annual market value ($ million)
	1996	1	1	
22	2011	100		
	2018		10	
1	2019	<1,000	<25	30

Table 13: Technologies and their level of impact as of 2019

Level 1 Impact: Unicorn Technologies	1. Ultrafiltration (UF) membrane – drinking water treatment 2. Ultraviolet (UV) disinfection – municipal wastewater and reuse, and drinking water treatment 3. Membrane bioreactors (MBR) – municipal and industrial wastewater treatment 4. Upflow anaerobic sludge blanket reactor (UASB) – industrial wastewater treatment 5. Dissolved air flotation (DAF) – industrial wastewater treatment 6. Moving bed bioreactor (MBBR) – municipal and industrial wastewater treatment provided by AnoxKaldnes and Headworks
Level 2 Impact: Lion Technologies	7. THIOPAQ biogas treatment – municipal and industrial wastewater treatment 8. Ceramic membrane filtration – drinking water treatment
Level 3 Impact: Horse Technologies	9. Sludge thermal hydrolysis – municipal wastewater treatment 10. Phosphorus recovery as struvite – municipal and industrial wastewater treatment 11. Microbial encapsulation – water and wastewater markets – municipal wastewater treatment

(and excluding DAF) as Unicorn Technologies, the average time required from the very beginning to when it reached Level 1 market impact was 21 years and the average number of years spent at Level 2 prior to hitting a Level 1 market impact was 10 years. The average time at Level 3 market impact for these same technologies was 11 years. That means it took 11 years to reach over 100 plants and to be used in ten countries thus indicating a much faster market adoption as this number is well below the 17-24 years average time period required for the technology to reach halfway through the Early and Late Majority of the Water Technology Adoption (WaTA) model (O'Callaghan et al., 2018).

THIOPAQ and Ceramic Membranes DWT were the two Level 2 Lion Technologies as of 2019, studied in this chapter. These two technologies separately took less than 24 years to move to the Level 2 status during their adoption history (Figure 1), which is in line with the WaTA model where a technology on average takes 17-24 years to reach halfway through the Early and Late Majority, representing 50% of the total market adoption.

Three of the technologies studied are currently categorized as Level 3 Horse Technologies (Figure 1): microbial encapsulation, thermal hydrolysis and phosphorus recovery as struvite, but this could change over time. Notably in the cases of thermal hydrolysis sludge pre-treatment and microbial encapsulation, they have remained at Level 3 for 23 and 28 years, respectively. Struvite recovery was first adopted 13 years ago and is below the 17-24 years average time required for the technology to reach halfway through the

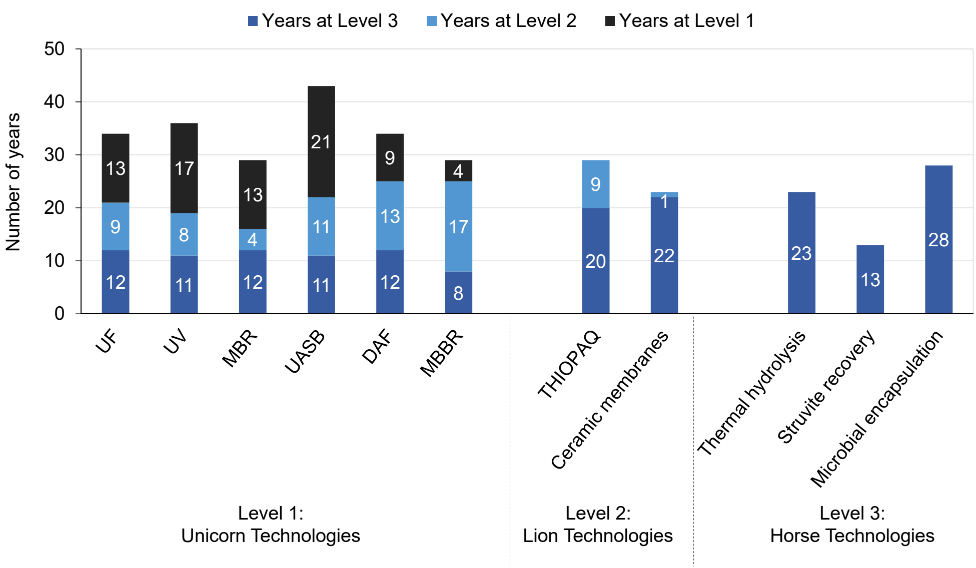

Figure 1: Timelines for each technology to reach different level of market impact.

Early and Late Majority of the WaTA model. Hence, there is a possibility that this technology will reach Level 2 in a few years. Also, if struvite recovery were to become crisis/need driven, by a new piece of legislation for example, then it would be more likely to move into Level 2 or Level 1 impact.

5. Discussion

Many who are involved in the realm of technology development are familiar with the term "Unicorn Company" (Simon, 2016; Dellerman et al., 2017). This term is widely recognised as referring to a privately held startup company whose market capitalization exceeds $1 billion. It is a goal of many researchers, entrepreneurs and investors to develop technologies that will result in the creation of unicorn companies. A review of data provided by BlueTech Research found that no such companies exist in the water technology space, with the exception of large conglomerate companies that offer multiple different solutions and which have grown by acquisition (BlueTech Research Intelligence Platform at inside.bluetechresearch.com, accessed June 20th, 2020).

A particular technology class (as opposed to an individual company), however, can represent a total market value that is worth more than $1 billion per annum (as opposed to market capitalisation). Whether this would be an useful threshold to measure market impact was tested and it was found that for many water technologies, this was setting the bar too high. There are relatively few individual water technology markets, such as Reverse Osmosis Seawater Desalination, Activated Carbon Water purification, Ion Exchange Resins, that represent more than $1 billion in annual sales (Global Water Intelligence (GWI), 2017). Thus, in a real world scenario, the threshold of $1 billion is not appropriate for the water technology sector for individual technology classes. $500 million per annum was selected as an appropriate threshold to quantify a Level 1 impact.

A typical venture capital investor seeks to invest into companies whose technologies lead to Level 1 impacts, and the typical investment time horizon for a venture capital fund is under 7 years between investments to exit. This analysis provides data to underpin the observation that it is not likely to achieve Level 1 impacts in the time horizon sought by venture capital investment groups, if we measure time from inception of a new company and the first installations. As found in the analysis above that the average timeframe for a Unicorn Technology to reach Level 1 impact is 21 years. Similarly, when the same technologies are analyzed at each level of market impact separately, it can be seen that on average these remain 10 years at Level 2 and 11 years at Level 3 market impact, respectively. This implies that once the technology gets into the mainstream market, it can grow relatively quickly. This in turn implies that if a venture capital firm were to invest into a water technology company that is just transitioning from Level 3 up to a Level 2, that it is possible to move from Level 2 to Level 1 in about 10 years.

The data shows that Microbial Encapsulation technology, which is a Level 3 Horse Technology, remained at this level for 28 years to date. This technology was first used for wastewater treatment in Japan in 1991, whereas the first wastewater treatment pilot plants in the United States was in 2015 (Microvi Biotechnologies – BlueTech Research interview with Microvi, March 12th 2020). Ceramic Membrane Drinking Water Filtration, Level 2 Lion Technology, remained at Level 3 market impact for 22 years and only just crossed over into Level 2 in 2019. Similarly to Microbial Encapsulation, this was first used in drinking water treatment in Japan, and was slow to be adopted outside of Japan. These two examples illustrate that a technology can have an impact in terms of market adoption in one country and this can be isolated.

The THIOPAQ technology, while it reached Level 2 impact, remained at Level 3 – Horse Technology – for 20 years. This is at least partly related to the fact that its adoption is value driven. This underpins the challenges in pushing forward value driven innovation, particularly linked to resource recovery and circular economy, when the market is nascent, and the quantities produced are not significant enough to get the attention of the mainstream suppliers in the value chain. It is also noteworthy in the case of THIOPAQ that there was originally, and still remains today, the only one company offering the technology in oil and gas and municipal applications. The company Paques offers the technology to treat biogas from anaerobic digestion, while a licensee, the company Paquell, offers the technology in oil and gas applications. It has been noted by other researchers, notably Parker (Parker, 2011), that having a competitor is a common factor associated with successful new technology introductions. Our research and analysis uphold this finding. This may seem somewhat counterintuitive to investors and start-up companies who often seek out what are termed 'Blue Ocean' markets, which do not exist today, where demand is created, rather than fought over and the market is not crowded out with competitors. Our research and analysis provides clear evidence that creating a market is hard work, requiring patience, tenacity and capital reserves to sustain a company for many years until the market takes off. Any perceived first mover advantage is offset by the heavy investment of time and money required to single handedly create a new market. This often leads to companies creating a market for someone else, or others, who will follow in their footsteps, piggy backing on their initial investment. The analogy would be of a marathon runner who runs 25 miles alone, only to have a sprinter enter the race and overtake them on the last mile. Often these sprinters, or fast-followers, are industry incumbents who have the ability to catch up quickly. The African proverb, "If you want to go fast, go alone. If you want to go far, go together", may be apt in the water sector, where it is often the tortoise, and not the hare, that wins the race; where patience and tenacity are rewarded over speed and agility.

The ideally balanced scenario in introducing a market creating technology would appear to have 2-3 companies active at the same time. This accelerates innovation cycles, competition drives down price, further accelerating adoption and the heavy effort of educating the market is divided between 2-3 players. This then reduces the burden on others and also avoids the need for a client to sole-source a solution, which presents challenges where a competitive bid tender is often a requirement of the procurement process. There is therefore a synergy and collective benefit to having 2-3 competitors all pushing simultaneously to open a new market.

The fragmented nature of existing technologies in the water sector may serve as a buffer against disruption in much the same was as diversity in a gene pool confers greater resistance in the population to the rapid spreading of a new disease. Certain technologies appear to have remained at Level 3 for longer time periods that can be simply explained by comparing this with the timelines in the Water Technology Adoption (WaTA) model. This would suggest that a dimension other than time is the rate-limiting factor throttling the level of impact and adoption. Identifying why these technologies remain limited in impact, may help serve to de-bottle neck these areas and anticipate what factors may limit adoption of future technologies.

Thermal Hydrolysis is still at a Level 3 impact 23 years following its first launch into the market. It has, however, had a much higher level of impact in the United Kingdom, with an estimate that over 40% of all sewage sludge in the United Kingdom is processed using Thermal Hydrolysis. There is 800 kt of installed design thermal hydrolysis capacity from one supplier alone – Cambi (Personal Communication with Cambi, June 29th 2020). Approximately 1.5 Mt of sewage sludge is produced in the United Kingdom each year (Woods et al., 2006).

How can a technology achieve such dominance in one market and not in another? If we were to assess the level of impact of Thermal Hydrolysis on the UK market only, then it has had a high level of adoption. The UK water utility market has a number of unique distinguishing characteristics, being a privatized regulated market with a dozen or so large PLC water companies providing water and wastewater services. As such, it is less fragmented and relatively consolidated. In addition, the prevailing practice in the United Kingdom, in accordance with the Safe Sludge Matrix, is that enhanced sludge treatment is required for many agricultural uses, which can be achieved using Thermal Hydrolysis (Farm Advisory Service, 2001).

Differences in local market structure, and legislative drivers can account for these different levels of adoption. Ceramic Membranes are widely used for drinking water treatment in Japan, but much less so much globally. The data shows that Criteria 1 – total number of plants – was achieved quite early for ceramic membrane drinking water treatment, but took a lot longer to have a global impact.

It is possible to achieve localized impacts in terms of adoption in particular markets, as is seen with Ceramic membranes and Microbial Encapsulation in Japan and Thermal

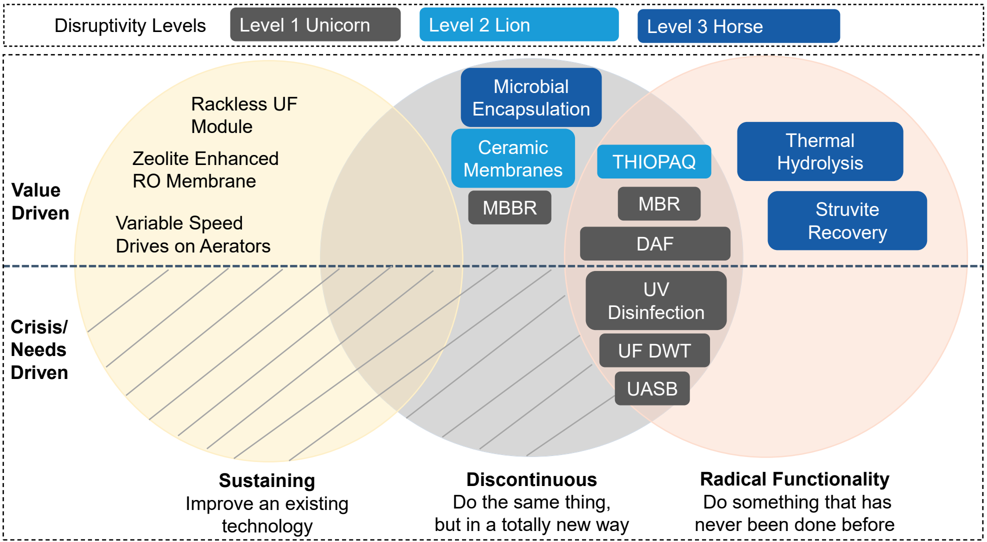

Figure 2: Technologies classified according to level of market impact, type of innovation and innovation driver, i.e. value driven or crisis/needs driven.

Hydrolysis in the United Kingdom, which are anomalies or outliers when viewed in the context of the global impact and adoption levels of these technologies.

The author posits that as market or technology conditions change, such as legislative drivers, or improvements in the technologies that improve their competitiveness, this can have the effect of driving technologies forward that had hitherto remained stalled at Level 3.

Crisis/need drivers enable water technologies to advance to Level 1 Unicorn status: UV disinfection, UF drinking water technologies, and UASB are all examples which were driven by crisis and need advanced to Level 1 Unicorn status (Figure 2).

The Upward Flow Anaerobic Sludge Blanket (UASB) reactor technology represented advancement in industrial wastewater treatment. Prior to this, the alternatives were either aerobic biological systems, which were not practical due to the high-energy consumption required to drive aeration and the generation of excess waste activated sludge, or anaerobic treatment systems, which required large footprints, which were often not available at industrial sites. The UASB technology provided a low energy and lower sludge generating technology when compared to aerobic biological and lower footprint and higher rate, when compared to existing anaerobic biological treatment systems. As such this innovation provided radical functionality. It was driven by the need to treat high organic strength industrial wastewater and was a market creating innovation as it enabled this treatment to be provided by overcoming the limitations of previously available biological treatment methods. UV and UF initially created new markets. Ultimately in time, they could offset something in new green field sites, but they were add-ons, retrofit additional elements that were added to an already existing treatment train. This ability to create new markets and be added on, may be a key factor that influences the level of adoption. MBR provided high quality treatment at a small scale, and helped create a product that enabled on-site water reuse.

None of the technologies outlined in this chapter would be classified as sustaining innovation. Sustaining is defined as improvements to an existing technology to enhance its performance (O'Callaghan et al., 2020). Sustaining innovation can also be defined with reference to the exclusion of characteristics associated defining other types of innovation, such as not using new components, not creating new value chains. The author posits that the water sector adopts sustaining innovation at much higher rates than for other types of innovation, such as discontinuous and radical functionality. Examples of sustaining innovation include the Rackless UF module, variable speed drives on aerators and use of zeolites as an additive in RO TFC membranes (Jeong et al., 2007; Lind et al., 2009; Hoek et al., 2011). Sustaining innovations are generally introduced by existing companies to existing technologies, and as such the barriers to adoption are low and the market is primed and ready to adopt the next generation of an existing technology.

6. Conclusion

A novel framework for assessing the impact of water technologies on the market is proposed in this paper. Three levels of impact are defined based on the total number of reference plants, the total number of countries the technology is adopted in and total annual market value. Level 3 represents the lowest level of market impact with Level 1 being the highest. Technologies that hit Level 1 are referred to as Unicorn Technologies. For those technologies that reached Level 1 impact, the average time required to do this from the year of the first installation was 21 years. It was noted that once these technologies hit Level 2, they could on average move up to Level 1 within 10 years. This indicates that once a technology gains Level 2 market impact, it can move with momentum forward to high Level 1.

It was also observed from the data that there appears to be a synergy and collective advantage to having competitors pushing simultaneously to open up a new market. This shares the investment required to educate the consumer and prime the market and it drives competition, which accelerates continued innovation and cost reduction. The fragmented nature of the water sector presents a buffer against disruption and higher levels of impact were observed in consolidated markets. Certain technologies can remain stalled out at Level 1, in some cases for over 20 years and it is posited that in the absence of some fundamental change in either the technology or the market drivers, certain technologies may never graduate on to have higher levels of market impact.

This paper focused on applying a set of criteria to technologies that have already been fully developed. The objective being first of all, to establish a set of meaningful criteria that could be applied in practice and secondly, to then measure how long it took these technologies to cross over the various different hurdles and levels of impact and adoption. Now that these criteria have been described, then these can be used during the development phase to dynamically track rates of impact and compare these against other reference cases.

The authors believe that if during the development phase, we can look at common innovation typologies and characteristics of new technologies and market drivers for adoption and compare these with similar, fully developed analogues, then this could potentially help one to understand which technologies have a high potential to disrupt the market.

6

Chapter 6

General Discussion

1. Contributions / key ideas

A Water Technology Adoption Model (WaTA) was developed to track technology diffusion. This model can be used to objectively track progress in the development and adoption of emerging new innovative water technologies. Certain criteria were defined that can be used to classify the stage on the adoption model of a particular technology. Based on applying the model to a series of case studies, average timelines associated with the movement through each stage of the model were identified. This model can be used by researchers and various stakeholders to set realistic expectations on how long it takes to develop and introduce a new technology to market. This can help to ensure that a realistic amount of capital and time is budgeted. Often technology developers run out of time and funding, and patience dwindles, as goals are not realized as quickly as anticipated. Conversely, technologies can sometimes be funded for far too long when there are no clear signs of progress and they remain zombie technologies and consume a disproportionate amount of time and capital without delivering any real value.

The author posits that if the time taken to bring a technology through the WaTA model takes significantly longer (circa >25% longer) than the average timelines for each stage, the probability that it will either stall-out, or fail, is increased. Analogous to an airplane taking off, the time to reach cruising altitude is an important metric to track. Any delay in reaching cruising altitude raises a cause for concern and may indicate that there is a deeper underlying issue that should be addressed. The greater the deviation from these typical timelines, the higher the probability that the technology will not make it through to next stage and will remain stalled out indefinitely, or until there is a fundamental change in either the technology, the market, or both. Conversely, technologies which make their way rapidly through the initial stage of the WaTA Model may have a higher probability of making it all the way through the adoption cycle in a time efficient way. As such, we posit that velocity through the stages of the model is an important and valuable heuristic to measure and track that can be correlated to the probability of success.

The rates of technology diffusion and adoption are influenced by different innovation drivers. Analysis of the rate of diffusion of different technologies revealed that certain technologies moved faster through the WaTA model than others, and it was observed that this could be correlated with two different types of innovation drivers. One innovation driver was classified as needs / crisis driven innovation, where the technology was solving an acute problem. The second type of innovation was classified as value driven innovation, where the main driver for adoption was that it delivered additional value compared to solutions currently deployed. It was observed that technologies that could be identified as crisis driven innovation, moved through the adoption cycle almost at twice the rate compared to technologies whose adoption was value driven. The author suggests that it is useful to consider at the outset, if the technology is value driven, (i.e. creating additional value, through efficiency, improved performance etc.) when compared to existing solutions available or whether it is responding to some form of need or crisis that exists.

The author posits that when compared with crisis driven innovations, that value driven innovations pose lower risk, but take longer to diffuse into the market, whereas crisis driven innovations, pose often higher risk as they are dependent on external forces such as legislation to be passed and enforced to drive adoption but when they move, they move at a faster rate.

The existence of competition appears to be a key factor associated with successful technology introduction, particularly in the regulated municipal utility market. It has been noted by other researchers, notably Parker (Parker, 2011), that having a competitor is a common factor associated with successful new technology introductions. Our research and analysis uphold this finding, and found that in the case of technologies, which reached higher levels of market impact, including MBBR, MBR, UV and UF, there were at least two strong competitors working to introduce the technology during the Early Adopters Stage.

This may seem somewhat counterintuitive to investors and start-up companies who often seek out what are termed 'Blue Ocean' markets, which do not exist today, where demand is created, rather than fought over and the market is not crowded out with competitors. Our research and analysis provides clear evidence that creating a market is hard work, requiring patience, tenacity and capital reserves to sustain a company for many years until the market takes off.

The regulated water utility market in particular, often requires the ability to obtain multiple bids in an open tender. It also takes a considerable effort and bandwidth to educate the market on a new innovation so that it is primed and ready. Having more than one company is important, particularly for a value-driven innovation, where it is more of a push, than a pull, into the market.

It takes considerable bandwidth and effort to evangelize for and educate the market for the existence of and benefits from using this new innovation. Having more than one company active is in effect competition where the burden of education and marketing is distributed.

Any potential first mover advantage associated with being the only technology provider, is negated by the heavy investment of time and money required to single handedly create a new market. This often leads to companies creating a market for others, who will follow in their footsteps, piggy-backing on their initial investment. An analogy would be of a marathon runner who runs the first 23 miles alone, only to have a sprinter enter the race and overtake them on the last section of the race. Often these sprinters, or fast-followers, exist as large industry incumbents who have the ability to catch up quickly.

Canadian struvite recovery company, Ostara, enjoyed first mover advantage, but they did not get far enough nor were fast enough, to become profitable and now there are many me-too competing technology offerings in the marketplace. In effect almost Ostara single handedly created the phosphorus struvite recovery market and are now competing in a Red Ocean for a slice of what is a small and finite market. The total investment into developing this technology exceeds USD$50M and the company today is valued at fractions of this.

The African proverb, "If you want to go fast, go alone. If you want to go far, go together", may be apt in the water sector, where it is often the tortoise, and not the hare, that wins the race; where patience and tenacity are rewarded over speed and agility. The ideally balanced scenario in introducing a market creating technology would appear to have 2-3 companies active at the same time. This accelerates innovation cycles, competition drives down price, further accelerating adoption and the heavy effort of educating the market is divided between 2-3 players. This then reduces the burden on others and also avoids the need for a client to sole-source a solution, which presents challenges where a competitive bid tender is often a requirement of the procurement process. There is therefore a synergy and collective benefit to having 2-3 competitors all pushing simultaneously to open a new market.

The thesis shows us how we can differentiate between different types of innovation and how different innovation theories can be applied to water to help us to do this. The application of Innovation Diffusion theory, and development of a system of nomenclature that goes beyond the simple use of the word innovation as a generic term, allows various stakeholders to consider the innovation characteristics of the technology or solution and categorize it. This recognizes that there are many different types of innovation. It recognizes particularly the limitations of Disruptive Innovation theory, which is based on an impact on the market that can only be quantified after the technology has had an effect on the market. The ability to classify innovation typology based on a characteristic of the technology, allows typology to be assigned early on in the development lifecycle. Based on analyzing case studies of the type of strategy employed to bring different types of innovation through the WaTA model and the success they have had, or have not had, may help others to identify the development strategies that are tailored to and best suited to particular innovation typologies. For example, it can be discussed that venture capital investment is best suited to support the development of discontinuous innovation and radical functionality as opposed to sustaining innovation, which are best left to incumbents.

Sustaining Innovation

Sustaining Innovations are best suited to be diffused by industry incumbents as opposed to new entrants, unless the efficiency gain is greater than 30% over an incumbent technology. The author suggests that for researchers the best route to market for sustaining innovations which offer the potential for an efficiency gain of less than 30%, is by licensing the technology to an incumbent. It is not possible to rely on the value of the innovation itself to enable a start-up company, or new entrant, to obtain a significant market share from incumbents. A business strategy, separate to the innovation, may enable companies to succeed, but this needs to be analyzed independently from the technology.

Radical Functionality

An innovation with radical functionality is generally introduced by a new entrant, as opposed to an existing player. This was also the case with the introduction of the Membrane Bioreactor, offered by a start-up company Zenon, from Canada, and Memcor, from Australia. Both companies subsequently were acquired circa 1997 by GE and US Filter, respectively. In the case of the Membrane Aerated Biofilm Reactor (MABR), a new technology, this is being offered by a start-up company, Oxymem, now acquired by DuPont, as well as a larger industry player, Suez WTS, though in the case of the latter, the technology was originally conceived by start-up company, Zenon and many of the original Zenon team members are still involved with the MABR technology.

Discontinuous Innovation

Discontinuous Innovations have the potential to disrupt existing markets. As such, they need to be carefully monitored by incumbents. A good example is the development of electric vehicles in the automotive industry to replace fossil fuel powered cars or the introduction of digital photography, which took over from film photography. The introduction of discontinuous innovations requires a shift in the value-chain as it involves the use of different components and technical standards. Examples of discontinuous innovation in the water sector include the use of ceramic membranes, as opposed to polymeric membranes, or the use of UV LED light for disinfection, as opposed to mercury amalgam lamps. The introduction of ceramic membranes and UV LED in the water sector, have been led predominantly by new players, not existing industry incumbents. Examples of companies that have been active in the early stage development and introduction of UV LED water technology include Aquisense, RayVio, Water Sprint, Crystal IS and Acuva. Notably, none of these companies are mainstream UV companies. Companies active in the development and technology diffusion of ceramic membrane filtration include Metawater, Nanostone, PWN Water Technologies, Purifics, Ceraflo. None of these companies offer polymeric ultrafiltration membranes. This would uphold the general observation that discontinuous innovation is more often led by new entrants. This bias on behalf of incumbents towards existing solutions, creates a risk of obsolescence. A clear example was the impact on the film photography company Kodak, when its business was taken by digital photography. The author posits that a way to mitigate this bias on the part of incumbents is to have a separate part of the business focused on developing innovations that are disruptive to the main-stream business, using strategic investment as a way to take a position in companies that are developing such technologies. Otherwise they could simply watch and wait, and acquire at the right time in the WaTA diffusion model, ideally when the technology has achieved a Level 2 impact and has de-risked the technology and is poised for growth.

The thesis provides a simple model that can be applied consistently to measure 3 different levels of disruptive market impact. A model to measure and quantify the level of market impact was developed and applied. Having evaluated various different metrics, the author identified two key metrics and one auxiliary metric that could be used to place technologies into three different levels of impact. It was then possible to also analyze how long technologies spent at each level. Some technologies failed to reach the highest level of impact within the timelines studied and the author suggests that this is linked to the interaction of the innovation typology and market drivers. As such by studying what types of innovations have had the greatest market impact and how long it took to achieve this, we are better placed to evaluate new innovations based on their own innovation typology and use this as a benchmark to predict their likely impact.

Localized higher-level impacts in particular countries were observed that do not replicate themselves more widely in other markets pointing to the fragmented nature of the water sector. This is seen with ceramic membranes and microbial encapsulation in Japan and thermal hydrolysis in the United Kingdom, which are anomalies or outliers when viewed in the context of the global impact and adoption levels of these technologies. Thermal hydrolysis is still at a Level 3 impact globally, 24 years following its first launch into the market. It has however enjoyed a much higher level of impact in the United Kingdom, with over 40% of all sewage sludge in the United Kingdom processed using Thermal hydrolysis. Ceramic membranes were deployed for drinking water filtration in Japan in the early 1990's, and yet this application of ceramic membranes to drinking water treatment remained quite limited to Japan for the next two decades. Microbial encapsulation was demonstrated and applied at various wastewater treatment plants in Japan again in the 1990's but it would be many more years, before a similar approach was trialed and demonstrated at a full-scale plant outside of Japan.

How can a technology achieve such dominance in one market and not in another? If we were to assess the level of impact of thermal hydrolysis on the UK market only, then it has had a high level of adoption. Differences in local market structure, and legislative drivers can account for these different levels of adoption. The author posits that market conditions can change and that this will drive technologies that remain stuck at Level 3, to move forward with the help of new legislative drivers, or improvements in the technologies that enhance their competitiveness.

Fragmentation may act as a buffer to disruption. The fragmented nature of existing technologies in the water sector may serve as a buffer against disruption; in much the same was as diversity in a gene pool confers greater resistance in the population to the rapid spreading of a new disease. Conversely, if fragmentation could be removed, or reduced, this could remove one of the obstacles to disruption and accelerate the diffusion of new innovations. The topic of customer fragmentation in the US water utility market and its impact was discussed by Seth Siegel (Siegel, 2019).

The following are some examples of the many different forms of fragmentation which can be found.

Variations in size and scale

Firstly, there is fragmentation in terms of **size and scale**. A drinking water or wastewater treatment system in the municipal utility sector can vary in size over three orders of magnitude, from small systems designed for single households, to systems serving over ten million people. Technology is scalable and unit operations can be replicated, however such a wide variance in size presents challenges in terms of execution and deployment. Certain technologies are more suited to certain niches and operating envelopes in terms of capacity.

Localised needs and crises

The market is hyper-local and fragmented in terms of **needs and crisis**. Biological phosphorous removal was adopted very quickly in South Africa (Chapter 3), due to particular salinity issues with local water quality that favored its adoption over the use of chemical dosing. These conditions were not present in other parts of the world and hence chemical dosing was more widely adopted. Certain areas experience drought, whereas others have nutrient enrichment due to phosphorus and/or nitrogen. Mature markets have unaccounted for water due to ageing infrastructure and sludge disposal options. In addition to this, practices and economics vary widely, even from state to state in the United States and certainly from country to country. By contrast the need to disinfect drinking water continues to represent a clear homogenous need and this led to the widespread adoption of the use of chlorine in the treatment of water supplies. In the United States, within 10 years of the first application of chlorine to the treatment of drinking water, over 90% of all public water supplies had adopted the use of chemical disinfection (Siegel, 2019).

Technology fragmentation

Certain segments of the technology market are fragmented with no clear winning or **defining technology type**. Polymeric membrane ultrafiltration is a case in point. UF membranes can be flat sheet, or hollow fiber, the flow pattern can be inside out, or outside in, a range of materials can be used including Polyethersulphone (PES), Polysulfone (PS), Polypropylene (PS), Polyvinyl Difluoride (PVDF), manufacturing processes also vary from non-solvent-induced phase separation (NIPS) process to thermally induced phase separation (TIPS). By contrast, other segments are remarkably commoditized, such as sea water membrane desalination, by a particular chemistry like thin film composite or a particular form factor, spiral wound elements.

A crisis is required to achieve Level 1 adoption of technologies with radical functionality. The water market does not require new functionality unless it is required by legislation. As such, in the absence of legislation there is no driver that will encourage widespread adoption of a technology that can deliver a level of service above and beyond what is mandated if it requires additional investment. If the technology saves money, then it is value-driven. All of the Level 1 impacts of radical functionality innovations were associated with a market need/ crisis.

Market-taking technologies often involve a long waiting period for a component or something that needs to be replaced i.e. for a new plant or a plant upgrade or expansion. On the other hand, market-creating technologies such as UV and UF initially created new markets as they were added into an existing treatment train as an additional unit process. Ultimately as the market matured, they could offset certain unit processes in new green-field sites, such as chlorine disinfection or sand filtration respectively, and became market taking, but when first introduced, they were market creating, or rather responded to an acute need that created the new market.

The Membrane Bioreactor (MBR) technology was market-creating in that it enabled high quality treatment at a small-scale offering the potential for on-site water re-use in water scarce areas, such as at Golf Clubs in areas such as Florida and California. This required on-site treatment and had a ready outlet for the re-use quality water.

It is not possible to introduce low-end Disruptive Innovation into the regulated utility water sector. In Disruptive Innovation theory, as defined by Christensen, there are two key types of water technology innovation described, firstly low-end innovation and the second, market-creating innovation. The author posits that there is no room for 'low-end disruptive innovation' in the regulated municipal water utility sector. Technologies cannot just be '*good enough*' for low-end customers. All customers must meet the standards set by regulators.

There is an unmet need for low-end disruptive innovation in the industrial sector and in the provision of water services in the developing world to meet Sustainable Development Goal 6 (SDG6). In the industrial treatment sector, current treatment technologies can over-deliver on what is required. In the Oil and Gas and the Mining industry, end-users often lament the fact that the technologies used are over-kill for what they need. The water industry is often applying municipal solutions in an industrial setting. According to Abraham Maslows' law of the instrument, or law of the hammer, we have a cognitive bias to rely on familiar tools.

The Water Sector like many other sectors has a cognitive bias towards the use of existing tools. Maslow's first recorded statement of law of the instrument was "Give a small boy a hammer, and he will find that everything he encounters needs pounding" (https://en.wikipedia.org/wiki/Law_of_the_instrument). The extremely widespread and ubiquitous use of Reverse Osmosis (RO) treatment, wherever water re-use is required, is an example of this. Many industrial end-users and indeed some water utilities, note this is going a step further than is required, in effect "*burning the house to roast the pig*". There may be room for less expensive solutions that do not produce as high-quality water as RO, but produce water, which is fit-for-purpose, or '*good enough*', consistent with the Christensen definition of low-end innovation.

There is also room for low-end disruption in the developing world in the provision of both drinking water and sanitation. In the case of Sanitation, there is a large number of Water and Sanitation (WASH) startup companies that leapfrog the conventional collect system and treatment model employed in the western world. One example employed in Kenya by company Sanivation, involves the use of blue buckets, which are deployed in people's homes for the purposes of collecting urine and faeces to be converted into a solid fuel at a centralized facility. This is not as convenient as a flush toilet, but it leap-frogs the need to have centralized wastewater collection systems. This is vital to solving challenges in areas where it is not possible to invest in centralized infrastructure. Another example is the use of an Atmospheric Water Capture (AWC) device to provide water for basic needs in areas where there are no other viable alternatives. This is not as 'good' or convenient as conventional drinking water treatment and distribution infrastructure, but it overcomes the great difficulties that exist in providing underground water distribution systems in the developing world and also the challenges that exist when the water is simply not there to be collected and treated.

The greatest need for Innovation to solve global water challenges is at a systems level as opposed to a technology level. Applied Research and Development in the water sector is very much focused on developing technologies (whether they are discontinuous, radical functionality, sustaining), that sit on top of, or fit into, an existing system or the urban water cycle. The urban water cycle itself needs to be evaluated, as outlined in the works of David Sedlak and Glen Daigger (Daigger et al., 2019; Sedlak, 2014). This will lead to new systems that include groundwater recharge, rainwater harvesting, non-potable and potable water re-use, decentralised systems, off-grid water, use of non-conventional water sources, water-less technologies, source separation, resource recovery and alternative sanitation ideas such as the Re-Invented Toilet, which was supported by the Bill and Melinda Gates Foundation. Systems level solutions would also include wetland habitat rehabilitation to restore water balances and provide for natural filtration systems and planting trees to help to create rain.

Market creating innovations, which meet un-met needs, and address non-consumption, may be some of the most important innovations required. The major drivers for water innovation cannot be met by simply improving existing technologies or systems. Digital technologies, such as Internet of Things (IoT), Artificial Intelligence (AI), extracting value and intelligence from Big Data, all these open up new opportunities in the water sector to solve water challenges in new and exciting ways. For example, the use of satellite data from space to detect leaks in water mains on earth, the use of earth observation science to balance water needs at a catchment level or the use of data algorithms and software that optimize energy and water use withing commercial buildings. Financial innovations, such as micro-loans for the world's poorest people that enable them to become part of fixing their own problem are another excellent example of approaching these problems from a different angle. All these are non-traditional approaches to addressing water quantity and quality challenges.

2. Limitations of this work

One of the reasons why Clayton Christensen studied the evolution of the hard drive market was that it had short evolution cycles for change lending itself well to observation. In the early days of genetics, scientists studied fruit flies for similar reasons. In the water sector, gestation periods for new technologies are long, as we have seen and the lifespan of technologies is often decades. To look at case studies, required us to look back 30-40 years in some cases. These periods of time pre-dated the Internet. While there was peer reviewed literature available, we were heavily reliant on the personal records maintained by individuals who directly led the development and evolution of these technology markets to obtain data required. For this we are very grateful. Access to commercial data is always difficult, as companies have to protect proprietary information.

The field of study for the thesis was municipal and industrial water and wastewater treatment. There are other areas, such as the use of water in agriculture, that are not addressed in this thesis.

3. Suggestions for future research work

The author would encourage continued use of the frameworks outlined in this thesis to study emerging water technologies, and also emerging policies and business models. The author recommends combined use of the Technology Impact Framework outlined in Chapter 5, for assessing level of market impact, overlain with the innovation typology, described in Chapter 4 and the Water Technology Adoption model (WaTa) described in Chapter 2, to help understand the level of impact that the diffusion of a particular technology is likely to have and in what time frame.

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Appendix

Description of water technologies discussed in the thesis

Biological Phosphorus Removal (BPR): In the Biological Phosphorus Removal process, activated sludge is recirculated through anaerobic and aerobic conditions. This generates favorable conditions for poly-phosphate accumulating organisms (PAOs) and their uptake of phosphorus from wastewater and store it within their cells. The main advantage of BPR is that addition of chemicals for phosphorus removal are not required.

Ceramic membrane filtration: Ceramic membranes are an alternative to hollow fiber ultrafiltration membranes. As opposed to polymeric compounds in UF membranes, ceramic membranes are made from inorganic materials (e.g. silicon carbide, titania or alpha-aluminium). Pore sizes usually range between 0.1-1 µm. The main advantages of ceramic membranes are their flux stability, mechanical durability and robustness in harsh environments (e.g. corrosive wastewater).

Dissolved air flotation (DAF): Dissolved air flotation is a solid-liquid separation process. The process includes the formation of micro bubbles (diameter 30-60 µm), which move organics and other relatively buoyant material to the surface of the water. Compared to conventional settling processes (e.g. sedimentation), DAF has a smaller footprint. DAF is used in municipal drinking and wastewater as well as industrial applications.

Granular activated sludge: The granular activated sludge process is a variation of the conventional activated sludge process, in which the biomass is manipulated to form spherical sludge granules. The granules have aerobic, anaerobic and anoxic layers and thus perform simultaneous nutrient removal. Advantages to the conventional activated sludge process are better sludge settling, biomass retention, and smaller footprint and reduced energy requirements.

Membrane aerated biofilm (MABR) reactor: The membrane aerated biofilm reactor is an advancement of biological wastewater treatment. The technology includes a gas permeable membrane through which oxygen is delivered directly to the microorganisms that form a biofilm on the membrane surface. This increases the oxygen transfer efficiency, which leads to less aeration energy requirements and increased nitrogen removal. MABR reactors can be retrofitted into existing wastewater treatment plants.

Moving bed bioreactor (MBBR): The moving bed bioreactor is an alternative to the conventional activated sludge process. Cylindrically shaped plastic media are suspended in the reactor and serve as biofilm formation sites (i.e. attached growth). MBBRs can reduce the footprint, increase treatment capacity compared to conventional biological treatment, do not require sludge recirculation and can be retrofitted into existing systems. MBBRs are applied in municipal and industrial wastewater treatment applications.

Membrane bioreactors (MBR): Membrane bioreactors combine biological treatment with micro-/ultrafiltration membranes to achieve secondary and tertiary treatment in one system. MBRs provide nutrient removal and effluent polishing of wastewater in one system and therefore can reduce the required footprint compared to conventional treatment systems.

Microbial encapsulation: Microbial encapsulation is the practice of concentrating beneficial microbes used in water and wastewater treatment processes into polymer "cages" or capsules. The value proposition of microbial encapsulation is limited or no sludge production, increased treatment capacity, protection of the microbes from competing organisms, shock loads or toxicity. Application can be in drinking and wastewater treatment, especially for nitrogen removal.

Phosphorus recovery as struvite: Traditionally, phosphorus was removed from the wastewater stream and recovered in the form of sewage sludge, which was directly applied to arable land. Phosphorus from the sludge de-watering streams can be recovered as a solid mineral product, known as struvite (magnesium ammonium phosphate, $NH_4MgPO_4 \cdot 6\ H_2O$), through precipitation or crystallization. Struvite can potentially be marketed as a high value slow release fertilizer.

Polymeric hollow-fiber membranes: Polymeric hollow-fiber (HF) membranes were developed to achieve particle removal beyond conventional depth media filtration. The use of polymeric HF membrane filtration provided an absolute filtration cut-off point in terms of the size of particles that were excluded. These membranes are widely used especially in drinking water treatment.

Sequencing Batch Reactors (SBR): A Sequencing Batch Reactor (SBR) is a wastewater treatment technology based on the activated sludge process that uses suspended bacterial growth in an aerated reactor to achieve BOD removal. The key innovation of the SBR technology was the use of timed cycles to enable solids separation to be achieved by allowing a quiescent phase in the aeration basin where solids were allowed to separate and were removed from the bottom of the tank using a decanter. The ability to perform multiple unit processes in a single tank using a timed control sequence provided a number of valuable advantages over conventional activated sludge technology such as reduction in capital costs and reduced footprint by eliminating the secondary clarifier.

Sludge thermal hydrolysis: Sludge thermal hydrolysis is a sludge pre-treatment process. It uses high pressure and temperatures (100-180°C) to achieve cell lysis of activated sludge. This makes organic compounds easier available for anaerobic digestion and thus increases the yield of biogas. The main potential of thermal hydrolysis is the increased conversion of sludge volatile solids to methane gas (i.e. biogas) during the anaerobic digestion process.

TFC reverse osmosis membranes: Thin film composite (TFC) membranes were developed in the late 1970s to replace cellulose acetate as the dominant membrane chemistry used in reverse osmosis seawater desalination. TFC membranes consist of thin layers of polyamide and polysulfones. Existing companies using existing manufacturing techniques handled the change in chemistry.

THIOPAQ biogas treatment: THIOPAQ is a technology used for the removal of hydrogen sulphide from biogas through biological oxidation to elemental sulphur. This technology enables the extraction of biosulphur from natural gas, landfill gas or biogas. The biosulphur is suited for use as fertilizer or fungicide as it is more bioavailable to crops than chemically produced sulphur. The technology originates from the company Paques that offers THIOPAQ to treat biogas from anaerobic digestion. Its licensee Paquell offers the technology in oil and gas applications.

Ultrafiltration (UF) membrane: Ultrafiltration is a separation technology for fine particulates, bacteria and viruses. In commercial products, pore sizes range between 0.01 and 0.02 μm (i.e. 10 to 20 nm). UF is used for virus removal in drinking water, pre-treatment in reverse osmosis processes and surface and groundwater treatment.

Ultraviolet (UV) water disinfection: Ultraviolet water disinfection is an alternative to chlorine disinfection. UV light at wavelengths between 240 and 280 nm inactivates microorganisms (such as bacteria, viruses and protozoa) by irreversible damages to the DNA. UV light provides a means of inactivating *Cryptosporidium* oocysts and Giardia cysts which are resistant to chlorine disinfection. The properties of UV light provides a means to disinfect water without chemical addition and formation of disinfection by-products.

Upflow anaerobic sludge blanket (UASB): UASB is an anaerobic treatment process operated in an upward flow. These flow conditions generate a granular sludge blanket and anaerobic conditions. In this environment, organics in the wastewater are digested to biogas while the wastewater is treated. The main advantages of the UASB process are a high organic removal rates, low sludge production and high treatment capacities. Main application areas are in industrial wastewater treatment.

Summary

Water scarcity is driving change and innovation in the water sector. This will require new thinking and new approaches. The water challenges are presented in **Chapter 1**, highlighting the need for a better understanding of the water innovation process to contribute towards more effective and efficient use of capital in research and development (R&D) and a higher rate of successful innovation diffusion. The rate of innovation and technology uptake in the water sector is often reported as being relatively slow due to the conservative nature of the industry. The field of water technology is explained in this chapter with the help of the 'water technology taxonomy' developed by BlueTech Research. The purpose of this thesis is to give the scientific community and the community of global water professionals and policy makers, a framework for shared discussion. The challenges faced by such stakeholders i.e. an investor or an end-user and how this thesis can benefit them is also explained. The main objective is to examine the area of water technology innovation, using empirical data, and to adapt and build models specifically for the water industry.

A key output of **Chapter 2** is the development of detailed definitions for each stage of Water Technology Adoption (WaTA) model: Applied Research, Pilot Stage (Innovators), Demonstration (Innovators), Early Adopters, Early and Late Majority and Maturity Stage. The proposed model, including the criteria for assigning a technology to a specific stage, activities undertaken in this stage, objectives and outcomes, duration of this particular stage and the corresponding stage in other models i.e. Technology Adoption Life Cycle TALC (bell curve), are suitable for the study of water technology adoption. This will be foundational for future analysis of different types of water technologies. One of the key findings is that it is possible to develop generalized timelines for successful technology commercialization. Analysis indicates that from the year that pilot testing commences to when the technology is moving into the Early Majority section of the market and is commercialized, can take in the region of 11 to 16 years. This needs to be considered by any companies that are actively seeking to introduce a new technology to the water market. Having established timelines that are reasonable and typical, the author believes that this sets an important benchmark against which velocity, or rate, of progress can be measured. Another important conclusion arising is that velocity, or the rate, at which technologies move through the process of dissemination and adoption is an important metric to track and analyze, and that the extent of any deviation from these industry averages can be an indication of potential failures in this process. Because of the nature of the definitions, there will be a degree of subjectivity in the use of this model, and it is possible for a technology to straddle adjacent categories.

Chapter 3 focuses on measuring the rate of adoption either measured as the number of full-scale plants built per year or cumulative installed capacity over time. Six water technology innovations in the last 30 years are studied with the aim of analysing the respective timelines for moving through various stages of water technology commercialisation. These technologies are then categorised either as crisis/need driven adoption or value driven adoption category. The three Crisis / Needs Driven innovations – Ultraviolet Disinfection, Biological Phosphorus Removal and Ultrafiltration Drinking Water – had a crisis or market need to accelerate adoption, whereas Sludge Thermal Hydrolysis and THIOPAQ had an inherent advantage over the existing technologies used, based on factors such as capital cost savings, operational cost savings, smaller footprint, and life-span of the technology. An exception is the Sequencing Batch Reactor (SBR) technology, which could be viewed as a combination of both Value Driven and Need Driven Adoption because the technology had an advantage over incumbent technology, and there was a regulatory driver for nutrient removal that favored the use of SBR technology as a method of achieving nitrification and denitrification. In the water sector, the adoption of a water technology that is driven based on its value proposition takes in the region of 12.4 years to move through the Innovators and Early Adopters stages of the market and reach the Early and Late Majority. In the case of a technology whose adoption is driven by a crisis or market need, such as a new piece of legislation, or an urgent health or environmental issue, the time timeline can be half of this, in the region of 6.5 years.

The fragmented nature of the global water market, long replacement cycles for existing technologies and the market growth dependence on population increases and new regulation all contribute to the slow technology diffusion rates and low disruption in the water sector. **Chapter 4** is a critical review to the fact that innovation is required in water, that innovation as it relates to water is understudied, and that the concepts behind Disruptive Innovation Theory have lost their meaning due to overuse, mainly out of context, and that a practical framework is required to facilitate meaningful academic and industry discussion. If certain types of innovation have led to market disruption and market creation, other innovation frameworks like the Innovation Diffusion Theory which is more practical and useful than the Disruptive Innovation Theory should be used as analogues when evaluating the potential of new technologies. Three types of innovation are defined: sustaining, radical functionality and discontinuous, where sustaining innovation take market share away from existing technologies and the later two create new markets and unlock non-consumption. This framework is proposed to inform investment strategy in water and provide a clear and objective basis and framework for academic discussion of water technology innovation.

A novel framework to measure level of market impact for water technologies is presented in **Chapter 5**. Three levels are defined, with the highest level being Level 1 – Unicorn Technologies, the lowest being Level 3 – Horse Technologies, and in between Level 2 – Lion Technologies. These levels are measured using three criteria: total number of reference plants in operation, total number of countries in which the technology is used in and total annual market value that the technology represents. Eleven technology case studies are investigated against this framework to understand each technology's impact on the market. The Water Technology Adoption (WaTA) model in Chapter 2 found that it could take 17–24 years for a technology to move from the Innovators section of the market adoption curve to when it is in the middle segment of the Early and Late Majority. The findings of this chapter, that quantify levels of market impact, are in keeping with this timeline. It is possible to measure level of market impact comparatively across different water technologies using the proposed framework and this will facilitate objective conversation and discussion around the disruptive effects of new water technologies in terms of rates of adoption and impact.

Chapter 6 summarizes and discusses the contributions and key ideas of Chapters 2 to 5. Important to those who invest in developing innovations is the link between the innovation and the market. Understanding these links helps innovators, researchers, adopters and investors to understand the likely commercial impact, how it should be commercialized and diffused, the typical time required, investment required, who is best placed to take on technology diffusion, and relative rates of success and risks associated with bringing these innovations to market. Each of the three types of innovation, Radical Functionality, Discontinuous and Sustaining, can be assigned to a technology based on the innovation characteristics prior to technology diffusion. The Innovation type can however then be compared to other analogues for this type of innovation to set realistic expectations as they are all very different from one another.

Dedication
Acknowledgements

Dedication

To everyone in water sector, who works tirelessly in a committed way to provide access to water and sanitation for all and safeguard our environment. Human beings derive happiness from working together towards a common, shared goal. I can think of nothing better to be a part of than helping provide access to, and safeguarding, our most precious resource.

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About the Author
List of Publications

About the Author

Paul is a water scientist, thought-leader and documentary film producer.

Following completion of a Bachelor of Science in Bio-Chemistry at University College Cork, Paul travelled across Asia and volunteered for World Wildlife Fund (WWF) in Malaysia, where he became interested in the relationships between forests and water. This experience inspired Paul to take a Masters degree at Edinburgh Napier University where he studied Water Resource Management. After successfully completing this Masters degree, Paul's first role was for the Body Shop working alongside the pioneering environmentalist Anita Roddick. Her vision for corporate sustainability was well ahead of its time and Paul worked on a "Living Machine" project designed to purify water naturally. Paul subsequently returned to Malaysia to work on a research project that investigated how deforestation was impacting water quality.

Paul's next role was working for Atkins, a leading global engineering management consultancy renowned for its pioneering approaches to projects. It was while working as an environmental scientist on pilot testing of new technologies, that Paul first noticed how extraordinarily long it took to get water technologies to market, which gave him the initial idea for BlueTech Research.

Paul relocated to Vancouver, Canada in 2002 and worked with leading technology company, Noram Engineering and up and coming water technology start-up company, Ostara. Paul founded a consulting practice, O_2 Environmental, focused on advising early stage water technology companies on go-to-market strategy, carrying out due diligence studies for venture capital investors and ultimately providing merger and acquisition support and strategic advice on portfolio synergies for large water technology firms.

BlueTech Research was founded by Paul in 2011, to provide actionable intelligence in the field of water technology markets and is now a global leader with Blue-chip clients on 5 continents representing leading water utilities, Fortune 500 Corporates, Technology firms, Investment groups and research institutes.

The desire to gain deeper insights into the dynamics of water technology innovation provided the impetus for Paul to undertake his PhD in Water Innovation at Wageningen University.

Paul's latest project is a documentary film called "Brave Blue World." The film is designed to increase awareness of existing solutions to the water crisis and Paul co-produced this groundbreaking film, which has attracted support from a host of A-list celebrities. It is now available to view globally in 29 languages on Netflix.

He advises global Fortune 500 corporates such as L'Oréal, Coca Cola, Unilever and Proctor and Gamble on their water strategy policies. He has also guest lectured on water at Harvard and Cambridge Universities and addressed a live audience of 15,000 people alongside Jaden Smith at Web Summit 2020 in Lisbon.

Paul divides his time between the BlueTech Research offices in Vancouver and Cork where he lives fittingly by the sea with his wife Jean and his three children – Eoin, Katie & Rosie. In his free time, he is a keen pianist and enjoys kayaking, ocean swimming and free diving.

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Cover image: **Stepwell**, Gujarati **vav**, Hindi **baoli** or **baori**, subterranean edifice and water source, an architectural form that was long popular throughout India but particularly in arid regions of the Indian subcontinent. For centuries, stepwells—which incorporated a cylinder well that extended down to the water table—provided water for drinking, washing, bathing, and the irrigation of crops. They also served as cool sanctuaries for caravans, pilgrims, and other travellers during the heat of day or overnight. Commissioned by royal, wealthy, or powerful patrons, they were complex engineering feats and stunning examples of both Hindu and Islamic architecture.

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