sustainability

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Commentary

A Resilient and Sustainable Water Sector: Barriers to the Operationalisation of Resilience

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Abstract: Global threats such as climate change, increasing urbanisation, and rapid population growth will continue to pose major challenges for the water sector over the coming decades. Questions over supply, delivery and demand, all form a central part of this argument with the themes of sustainability and resilience often included in the response. Recent events, along with reactive changes to national legislation and policy, have resulted in a need for the notion of resilience to develop from a theoretical concept to a tangible operational method. This commentary discusses barriers to the operationalisation of resilience in the water sector of England and Wales. The current privatised governance structure of the water sector is first discussed before the three main barriers to operationalisation—lack of agreed definition, metrics and the measuring of resilience—and the need to further acknowledge the 'socio' in socio-technical systems, are further explored. A deeper understanding of the notion of resilience in the context of the water sector, and how it can be successfully and effectively applied and implemented at an operational level, are crucial if the sector is to manage and respond to the aforementioned global challenges.

Keywords: resilience; sustainability; operationalisation; socio-technical systems; water

1. Introduction

The privatisation of the ten Regional Water Authorities (RWAs) of England and Wales in 1989 brought with it a new regulatory regime that was centred on promoting economic efficiency, whilst simultaneously improving drinking water and environmental quality [1]. Following privatisation, despite multiple changes in regulatory and operating environment, and recent renewed calls for nationalisation, the core focus of the water industry remains the same—cost efficiency, water and effluent quality and environmental protection. However, the conditions in which the sector must operate are now more challenging than ever.

Global water systems continue to face increasing threats and challenges in relation to future uncertainties and pressures regarding operating conditions and environments [2]. As stated by Makropoulos et al. [3], such threats can be found at:

(a) The supply side (quality and quantity), due to hydro-climatic variability;
(b) At the delivery side, as current infrastructure and treatment methods continue to age and become less reliable in an ever-evolving context of limited investment and increased regulation;
(c) At the demand side, as demographics and socio-economic trends alter demand levels whilst customer expectations for quality of service and value for money increase.

Independent of such internal and external pressures and threats, water companies and service providers must continue to find ways to not only operate but maintain performance and provision of services in such variable and extreme conditions. It is therefore now agreed that significant systemic changes and a substantial shift in paradigm is required [3–6] if organisations and the water sector as a whole are to achieve the reliable, sustainable, and resilient service necessary for to meet and exceed required performance.

The concept of resilience and the broader framework of sustainability have undoubtedly seen their share of inclusion in policy rhetoric during recent times. Both resilience and sustainability are, and will be, heavily involved in the future direction and operation of water sectors, both globally [7] and more locally focussed to England and Wales [8]. The notion of resilience can be perhaps seen as the 'new kid on the block' as its popularity across academia, industry and wider society has increased exponentially of late [9,10]. However, before discussing resilience, its increase in popularity, and its relevance to the water sector in England and Wales, it is important to first consider it within the broader framework of sustainability.

As stated by Leigh and Lee [11], sustainability is a normative concept that refers to physical and institutional practices that meets the needs of the present without compromising the ability of future generations to meet their own needs [12]. For a system to be considered 'sustainable', a delicate balance and interplay between the requirements of the social, environmental and economic must be achieved. Similar to the notion of resilience, discussion and debate around sustainability criteria and the definition continue, with a precise definition remaining elusive [13,14]. Sustainable development and the creation of sustainable systems is fundamentally based on the achievement of a balance between environmental, economic and social objectives over dynamic time and spatial horizons [13]. The sustainability paradigm therefore requires multidisciplinary action and the involvement of multiple stakeholders from all levels and areas of the system. Sustainability is now recognised as the most widely used framework in natural resource management and is often depicted as a triangular model that balances the three competing interests of society, economics and the environment, as shown in Figure 1 [11]. Leigh and Lee's [11] work highlights this interplay and how the concept can be, and is applied to urban water systems.

The top of the triangle represents social justice priorities (cost equitability, distribution and democratic decision making processes), the lower right economic priorities (economic efficiency for adequate provision of quality and quantity whilst ensuring water security), with the lower left depicting environmental priorities (long-term viability and regeneration of supply and flow). Managing the triangle of 'people, profit, planet' [4] and the complex interplay and interactions between the three can perhaps be viewed as the central task of the water industry. However, as previously stated, the-ever increasing, unknown threats that the sector is now facing is making the management of an already complex nexus, ever more challenging.

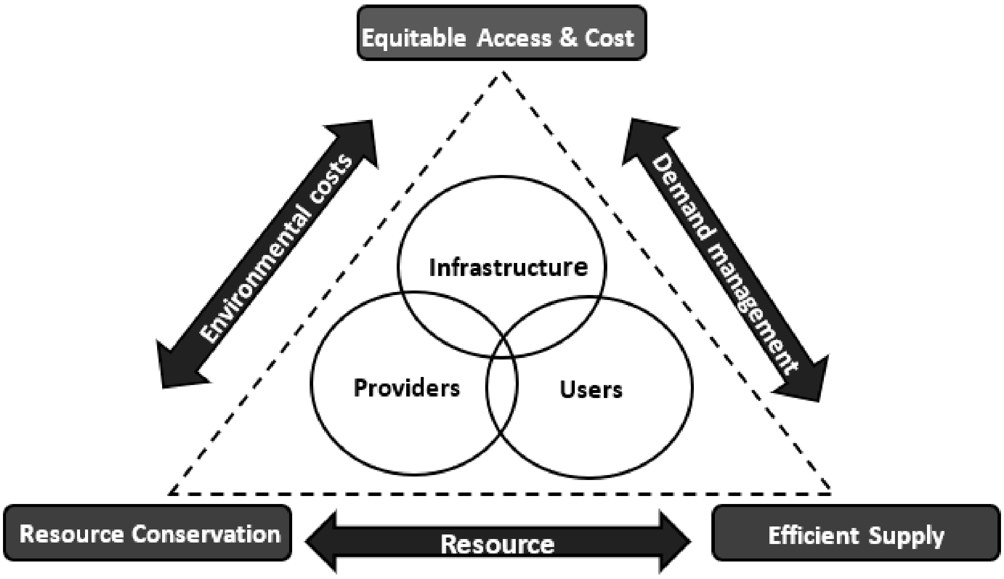

Figure 1. The triangular model of urban water sustainability. From Leigh and Lee [5] (p 4).

Criticism of the sustainability model is often based around the idea that it suggests a static balanced system rather than one that embodies the continuously altering and reshaping tensions and priorities that result from both internal and external pressures [11]. It is therefore suggested that sustainability is better seen as a journey or trajectory rather than a fixed state [4,15]. As highlighted by Butler et al. [4] , the goal of a sustainable system is "therefore to continue functioning over the long term, balancing agreed societal goals".

Along with maintaining basic functioning, water systems are also required to adapt to changing operating conditions and environments, deal with internal and external disturbances whilst maintaining a required level of performance.

Not only are systems in general, and in this instance water systems, required to be able to maintain function over the long term, they are also required to adapt to changing operating conditions and environments, and deal with internal and external disturbances whilst maintaining the required level of performance. In other words, systems must be both sustainable and resilient, with resilience first being required before sustainability can be considered [4].

In recent years, the term 'resilience' has seen a sudden and marked increase in use and application, in both academia, and policy discourse, with the term now in common parlance across many facets of society. In general terms, resilience is understood to be the ability to withstand shocks and stresses, whilst continuing to maintain key functions and or structures [16]. Many researchers agree that the etymological roots of the term stem from the ability of a system to 'bounce back' [17–19]. Such an explosion in prevalence of the word 'resilience'[19] has resulted in resilience evolving into a multidisciplinary and multifaceted term [20,21], one which has been adopted by and used in a range of academic fields. Use of the term ranges from a metaphor linked to sustainability and the governance of risk, to a property of a dynamic model, to a measurable quantity that can be assessed and applied in the field [22,23]. Application of the word resilience can be seen in the form of a noun, verb, and adjective, with the multitude of interpretations highlighting the richness of the concept, as well as presenting challenges with its application in systems at an operational level [24].

Like many sectors and fields, resilience and its associated properties have seen a marked increase in popularity across fields of global environmental research as a whole [25] as well as more specifically in water management and governance [6,26–29], with both resilience and sustainability following similar trajectories in their rise in application and popularity. A study conducted by Rodina [16] found 149 papers related to water resilience published in the first six months of 2017, with zero publications matching the search criteria in 1982. The increase in use and popularity of the term resilience, specifically in relation to environmental resource governance, are attributed to its focus on the ability to manage complexity, emergence and change , which appeals to systems worldwide that are facing ever-evolving, complex threats and challenges [16,30].

In general, environmental resource governance is currently going through a period of change, in which the focus is no longer on managing for efficiency and optimisation, but is instead centred on the ability of systems, independent of their character, to be flexible, adapt and reorganise during periods of stress [16], thus embodying a range of theorised resilience principles. Despite a range of criticism, some of which will be discussed in following sections of this paper, the concept and notion of resilience continues to be a relevant and highly debated topic, with an ever-growing body of literature working to situate resilience within the complex realities of resource governance, resource management, and environmental change [9,16,19,31].

Although such an increase in popularity has brought with it widespread admiration, the range of merited critiques that resilience receives is largely centred around the broadly elusive nature of the concept and the poor operationalisation of previously identified resilience principles.

As highlighted by Bhamra, Dani and Burnard [21], early resilience-based work found within the literature tends to focus on conceptual work aimed at developing a static knowledge base through the establishment of fundamental concepts and principles [26,32,33]. Following the popularisation of the term by Holling in 1973 [32], efforts have primarily been focussed on adapting the term and associated principles to a range of fields or systems of enquiry. Although this has in turn resulted in a diverse literature base, the concept of resilience has in general received little systematic and empirical work dedicated to proving or putting into action any theories suggested. Such efforts have culminated in the literature becoming saturated with resilience theory, whilst in need of work related to and based on interventions and their implementation.

Other resilience-based criticisms also exist surrounding resilience and its relationship to sustainability [34,35]. Although both are undoubtedly highly interrelated concepts, it is considered important to note that at times the objectives of resilience may conflict with those of sustainability [11]. Interventions that intend to achieve resilience at one temporal or spatial scale may negatively impact or affect sustainability goals at another [36]. It is therefore recommended that all potential resilience-based interventions and actions must also be viewed in the context of sustainability.

Despite the criticisms surrounding the term resilience, in an England and Wales context, recent changes to legislation, specifically the Water Act 2014, resulted in the Water Services Regulation Authority (Ofwat), the sectors economic regulator, being provided with a primary duty to further its resilience objective within the water sector. The amendment to the Water Act 2014 now requires water companies to:

(a) Secure the long-term resilience of water undertakers' supply systems and sewage undertakers' sewage systems as regards environmental pressures, population growth and changes in consumer behaviour, and
(b) To ensure that undertakers take steps for the purpose of enabling them to meet, in the long term, the need for the supply of water and the provision of sewerage services to customers. [37].

Such changes have resulted in a sector legally required to implement resilience-based actions and interventions across its operations, whilst global cross sector debate continues to question whether resilience ideas are in fact able to foster radical change [18].

Based on this premise, reflection on the concept of resilience and its relevance to the water sector in England and Wales is proposed in this paper, focussing on the current ability to operationalise resilience. More specifically, three potential barriers to operationalisation of resilience are explored. This paper is comprised of five main sections. Section 2 provides an introduction to the water sector in England and Wales, and the governance structures that are currently in place. Section 3 reviews the definition of 'resilience' in the context of the water sector. Section 4 discusses resilience metrics and the concept of measuring resilience. Section 5 explores the role of the 'social' in the socio-technical systems that makes up the water industry. Finally, a conclusion to the commentary is provided in Section 6.

2. Water Governance in England and Wales

The global water sector faces a host of climate- and population-related challenges and threats in the 21st century[4,38]. Climate projections for the UK indicate significant rises in average summer temperatures, with winters becoming wetter and summers drier, with an increase in significant extreme weather events [38]. It is estimated that by 2045, the UK population will have increased from 65 million in 2015 to 76 million in 2045 [39]. Such a rise in population, coupled with increases in summer temperatures and decreases in rainfall, results in predictions of repeatedly increased long- and short-duration droughts [40]. Perceived threats to the industry are not only centred around physical climate-related threats such as supply of natural resources and the reliability of engineered infrastructure, but also include social pressures seen across wider society, including changing demographics and labour markets, and concerns over cyber security [41]. The rapidly evolving nature of such threats and pressures enters new levels of complexity when coupled with the reducing customer tolerance of failure to meet required levels of performance [41].

2.1. Development of water sector structure

Water supply and governance in England and Wales has undergone significant change during recent history. Prior to the 1960s, water supply and sewerage services were mostly covered on a city or town basis through regional municipalities which had developed on an ad hoc basis. This resulted in more than 1000 bodies involved in the supply of water and 1400 bodies responsible for sewerage and sewage disposal [42], with provision of services remaining separate from planning. During the 1960s, water planning was moved to a national level due to the establishment of a statutory water resources board which was subsequently abolished during the 1970s–1980s [42]. Following this, planning was moved to catchment-based water authorities under control of local government. It was the catchment-based structure that was taken forward for the start of the privatisation process in 1989 [43], as highlighted in Figure 2. It is important to note that the water sectors in Scotland and Northern Ireland did not undergo the process of privatisation and therefore their governance structures remain separate, and differ considerably, from that of England and Wales.

Privatisation of the water sector in England and Wales in 1989 not only created new opportunities for operating and investing, but also a new tightly monitored regulatory environment in which the publicly listed companies must now operate, as shown in Table A1 in the Appendix. In the years following privatisation, multiple additional pieces of legislation have been introduced which have modified the legal environment in which the companies operate. This is shown in the Table A2 in the Appendix.

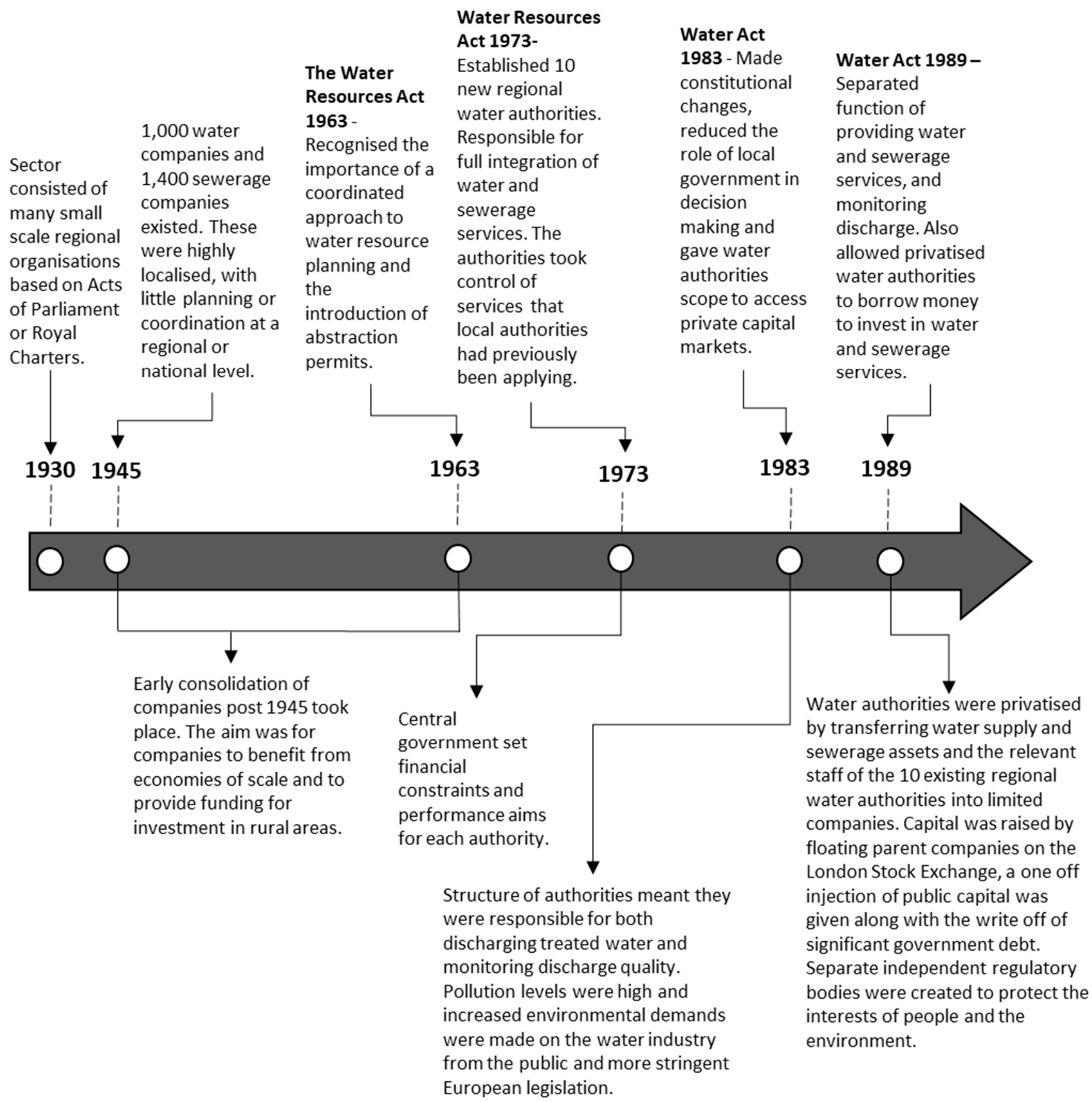

Figure 2. Water sector overview—pre-privatisation. Adapted from Ofwat, [43].

At the time of privatisation, the government stated the much-needed injection of capital, and high levels of debt as the key driving force. Infrastructure was of poor quality with high levels of environmental pollution occurring. Since 1989, the industry has seen infrastructure and services investment totaling approximately £130 billion [43], with improvements seen across the sector.

The independent regulatory structure that was created alongside privatisation has undoubtedly influenced the relative success of the industry over the past 30 years, with the initial aim to prevent monopoly abuse [44], and the suggestion of the potential to develop market competition. Although market competition has only opened for non-household customers in 2017 [45], the use of regulatory price controls and financial incentives for companies to be cost efficient whilst investing and improving customer services by Ofwat has, in general, balanced the interests of customers with shareholders [46]. However, debate still exists surrounding the role of large-scale multinational corporations in the provision and access to a necessary commodity. In particular with regards to the scale of shareholder dividends alongside poor company performance on leakage and pollution, with calls for the renationalisation of the industry in national politics and the mainstream media becoming ever more regular [47].

2.2. Water governance in England and Wales

Recently, the profile of environmental hazards in the UK has repeatedly been pulled to the forefront of public consciousness as extreme climate-related threats and their associated impacts become more frequent. The changes and evolution on how and where threats are presenting themselves (seasonality, geographical location, magnitude and duration) has resulted in a perceived society wide acknowledgement for the need to 'do more'. With the majority of large-scale events that have occurred in the UK over recent years involving either floods or droughts, conversations around the water sector and its more specific roles and responsibilities have again risen to the forefront of national discussion.

An independent review, by Sir Michael Pitt, in response to the devastating UK summer floods of 2007 [48], highlighted a number of suggestions and recommendations on actions the UK in general could take in order to minimise future vulnerabilities and maximise future response to such threats. With the concept of increasing the resilience of the UK's critical infrastructure forming a central narrative of the report. Following the publication of the Pitt Review there were a number of other legal and policy documents released in the UK outlining the need for 'resilience' if the country was to deal with the ever-increasing list of threats that it was now facing [49]. In 2011, the Cabinet Office published a report titled 'Keeping the Country Running' which focussed on increasing the resilience of the UK's critical infrastructure networks. The report was the first time that the UK government defined the term resilience, with multiple subsequent policy documents related to resilience adopting this definition. In 2014, the term 'resilience' was entered into water-related legislation for England and Wales [37], thus creating a legal duty for water companies to *'secure long-term resilience'* and providing Ofwat, the industry's economic regulator, with a primary duty to enforce this.

Although Ofwat is the sector's economic regulator, their role extends beyond basic economic regulation. Every five years they are responsible for a review of sector prices and outline a methodology for controlling the prices that water and sewage companies can charge as well as incentives they can secure and service packages that customers receive. The aim of the Price Reviews (PRs) is to balance customer and company views and interests whilst assuring that the sector is not only able to finance operations and services but also meet required legal, environmental and social duties [50]. Once the initial methodology is set by Ofwat outlining challenges that must be tackled, and expectations of the sector as a whole, each company is required to submit a business plan stating their planned activities and financial requirements for the upcoming five-year regulatory period. The PRs determine the regulated planning, operation and performance of the water sector and therefore heavily influence and control the actions of water companies in England and Wales. Following the previously outlined changes to legislation and regulation, PR19, which sets the methodology for the regulatory period of 2020–2025, highlighted resilience as one of the four key themes for the upcoming regulatory period. Although a methodology [51] and supporting documents were provided by Ofwat [41], which outlined and cemented the need for the operationalisation of resilience within the sector, companies were able to respond to the challenges and shape their business plans in their own way.

3. Defining Resilience

The notion of resilience and therefore the use of the term has a rooted background in fields ranging from psychology and disaster management, to engineering and ecology, with increasing application in business, economics, and technology [31,52]. Although the term resilience was first used in the fields of psychology and psychiatry in 1940s [53] with regards to the individual, the concept of resilience for systems was fully established and popularised in the field of ecology by Holling in 1973 [54]. Following Holling's initial work with regard to ecological systems, the meanings of the word resilience expanded to include engineering, social and economic fields [53]. With the main difference between the two referring to resilience as occurring by recovering to a previous or improved stable state (engineering) [53] and resilience which is achieved by moving towards a different system state (ecology) [53,55]. As outlined by Cimellaro et al. [53], resilience has been defined within the context of the speed that systems go towards equilibrium [56], their capacity to cope and/or bounce back [57], and to be inherently strong, flexible, and adaptive [58].

The multitude of, at times, contradictory definitions, often within the same field of study or industry sector, has resulted in the view that 'resilience' has become little more than a buzzword with a lack of collective understanding [59–61]. Pizzo [62] suggests that the multiple sub meanings that are embedded within how one term is understood leave the concept open to large margins of ambiguity and resulting confusion. Linkov et al. [59] and Smith and Fischbacher [63] suggest that although the ever-present debate around meaning and definition continue to be of interest to the academic community, it can have serious implications for both the design and implementation of resilient systems, and the need for a transition into an operational paradigm for system management [18,34,42].

How resilience is understood and defined within the field and sector that it is to be applied in is agreed by many to be the critical first step in how it is used. First defining the system and its focus is imperative to all aspects of its application. As with all definitions of resilience, the approach that is taken is dependent on the sector or field, the theoretical underpinning or standpoint, and the overall aim of a study or aspect of practice.

3.1. Resilience and a Water Sector Definition

Traditionally, the water sector and its partners have approached the subject of resilience from the view point of risk management linked to a historical perspective of 'building better' and creating systems that are 'fail safe' [3,64]. This resulted in the industry first defining the term resilience using an engineering theoretical underpinning, with Ofwat initially aligning themselves with the thinking outlined by the UK Cabinet Office [49], and defining resilience as *"the ability of a system to withstand shock and continue to function"* [4]. Following Ofwat's new primary duty awarded in 2014, an independent Task and Finish Group was commissioned to advise the regulator on what resilience meant for the wider water sector. The group was made up of members from across the water sector including industry, academia and regulation, and agreed on ten suggestions relating to furthering its new resilience duty. One of the main outcomes was to develop a definition of resilience for the water sector.

"Resilience is the ability to cope with, and recover from disruption, and anticipate trends and variability in order to maintain service for people and protect the natural environment now and in the future" [65].

It is this definition that Ofwat adopted and now use, which fits more with the engineering definition of resilience, with the requirement of a system to return to a previous or improved stable state [53]. The report produced by the Task and Finish Group was designed to feed into Water 2020 which formed the structure for Ofwat's preparations for PR19. Outputs from the Task and Finish Group highlighted occasions when a lack of definition have hindered progress around resilience in the water industry, citing Ofwat's 2011 focus groups on resilience and climate change, and customer research as part of PR14 [65]. In 2017, Ofwat published a document titled 'Resilience in the Round' [41], as part of the PR19 methodology, with the aim of providing water companies with suggestions on how they could respond to the resilience challenge. The document introduced the notion of 'resilience in the round' and defined the terms corporate, financial and operational resilience as well as suggesting the need for, and positive aspects of, adopting a systems thinking approach to companies preparations. However, although the document was produced as part of the PR19-related materials, it states that it is not a 'rule book' [41] and that it is instead hoped that companies will use the guidance as 'food for thought'. Despite the Task and Finish Group recommending that the industry "agree on a shared definition of resilience for the sector" [65] in 2015, at the time of writing this paper, this is yet to happen, with Ofwat instead allowing individual companies to choose how they define and understand the term 'resilience' for the PR19 process. A lack of singular definition and confusion around the term resilience has the potential to, and has previously been found to hinder progress made around furthering resilience in the sector [65]. Submissions of company business plans to Ofwat for the PR19 process confirmed the lack of singular definition to be adopted by the industry as although 'resilience' formed one of the core themes of the PR process, water and sewerage companies in England and Wales continue to define and understand the term differently.

Ofwat's initial assessment of the business plans submitted for PR19 found only two out of seventeen companies to be making 'good progress' with regards to the 'securing long-term resilience' objective [66] and overall stated that performance from companies in this area 'falls short'.

4. Metrics and the Measurement of Resilience

The measurement of resilience, and applying a value or scalable quantity to its presence in a system can be found throughout the literature, and after the definition of the term, is one of the most popular areas of inquiry [17,67–71]. Metrics, much like definitions, span multiple fields and sectors and operate at varying scales and levels of complexity.

In 2015, the Resilience Task and Finish Group suggested 'developing benchmarking, standards and metrics' as one of its ten recommendations for the advancement of resilience in the water sector in England and Wales [65]. The Task and Finish Group stated that both Ofwat and water companies need to develop metrics that are capable of "comparing resilience, reflecting customer views, local context, the environment and company ownership of plans" [65], along with the development of a resilience standard. The report also suggested that companies should report against a set of resilience criteria, which should be qualitative and ensures that all company boards have properly assessed resilience in a way that goes beyond their existing risk register [65]. Such a suggestion to measure resilience via qualitative methods differs from the traditional engineering view of resilience typically adopted by the water sector, in which quantitative methods are more commonly adopted and promoted. As part of the PR19 process, Ofwat suggested the use of metrics and a standard method of reporting to help aid comparison between companies [51].

The use of metrics and indicators has become standard across all levels of government and organisations as a way to simplify decision making, compare performance and track progress. Sustainability indicators in particular, have increased in popularity and use in recent years, as the demand for unbiased metrics for rational decision making and the ability to track and evaluate large-scale trends increases [14]. Like sustainability, interest in resilience metrics has also increased, as system operators and managers search for indicators of the resilience of their systems, or their presumed ability to perform whilst under stress, along with the ability to compare types of system.

The Oxford English Dictionary define an indicator as something that 'points out, or directs attention to, something' [72], with metrics defined as 'a system or standard of measurement; a criterion or set of criteria stated in quantifiable terms' [73]. Typically, a number of metrics contribute to overall indicators, with the primary goal of indicators considered to link cause with outcome [14]. Causal models are considered to provide the greatest insight into the relationships between indicators and outcomes. However, the complexity of distinguishing operating conditions from stresses, determining relationships and measuring the capacity of a system to respond is highly complex [14]. Yet, it is the system's capacity to respond and adapt that remains the most likely to lead to resilience, and therefore indicators that highlight such an ability are considered most likely to reflect the current level of resilience present in a system.

4.1. Metrics for the Water Sector

Recent submissions to Ofwat of company business plans for the PR19 process indicate the current status, view and understanding of resilience metrics within the industry. Multiple companies approached metrics from a quantitative traditional risk management-based view, by first identifying possible threats, shocks or stresses then measuring how current systems would respond to them pre and post identified interventions.

The resilience metrics methodology prepared for United Utilities [74] by Arcadis, for their PR19 submission, was considered an example of 'good practice' by Ofwat and was awarded a B grade for all three resilience test areas [66]. The approach that they took was focussed on a risk-based assessment and included calculating a numeric resilience value for identified systems against identified hazards. First, risk was calculated using,

$$\text{Risk} = \text{C (consequence)} \times \text{V (vulnerability)} \times \text{T (threat likelihood)} \tag{1}$$

resilience was then calculated using,

$$\text{Resilience} = \text{Risk} \times \text{Control factor.} \tag{2}$$

The report states that a score for 'control factors' "is achieved by defining common questions in line with the 4Rs of resilience" [74], which are redundancy, response and recovery, resistance, reliability, and are taken from the Cabinet Office's guidance on resilience [49].

Question sets, with multiple choice answers, were drawn up for each of the categories or 'risk factors', as referred to in the report. For example, one question for impact and duration to calculate a consequence score, two questions to assess the likelihood, and one for vulnerability. One question was then asked for each of the 'control factors'. Each answer had a numeric value associated with it between 0 and 1 depending on the option selected. Linear, logarithmic and exponential scoring was used depending on the question and the choice of answers provided. The report states that this approach was taken with the aim of applying an 'appropriate' weighting for each response [74]. A numeric resilience score by system and hazard, for example, water treatment works and flood, was then calculated using the above equations, with an overall company score calculated at the end. The report suggests that the company score can be used for comparisons across the industry and used to see improvements over time [74].

The approach taken by this methodology incorporates some qualitative assessment, as recommended by the Task and Finish Group [65] and allows for comparison between systems, e.g., asset types, and companies at a sector level. However, the approach is undoubtedly risk and reliability focussed, with assessment only done against known or predicted hazards and threats. The recent increase in popularity of the term resilience is linked with its ability to go a step further than risk management, which is dependent on the identification of the threat or hazard, with failure often occurring within known boundaries. The focus of resilience is instead considered to be the maintenance of performance [64] or system function, and the management or reduction of impacts and consequences, independent of the threat type or hazard. As the specifics of the scale of many of the challenges that the water sector will face in the future (with regards to supply, demand and delivery) remain relatively unknown, solely assessing a system against known threats, only addresses a small part of the problem. Although such methodologies provide an alternative approach to risk management with the inclusion of the assessment of response and recovery, and redundancy, the need to approach resilience metrics independent to risk assessment remains. Such approaches support the notion that perhaps current metrics used for resilience in the water industry of England and Wales are based on what can and is measured, rather than what should be measured.

The need to break systems down into smaller parts that make up the whole can be linked to the concept of reductionism and our desire as humans to understand system functions at the micro through to the macro. Such an approach suggests that by analysing and studying the micro functions of the system, the macro will be understood. However, this often depends on more simple linear cause–effect interactions and relationships. By applying a value to the levels of resilience considered to be found within, or possessed by the system, the status of resilience can be more readily reported and compared across systems and organisations. In many cases, such a view focusses on measuring the individual properties or parts of the system in question, rather than the overall performance, again giving rise to the notion that the whole can be understood by the lesser components.

Despite the large number of studies that are dedicated to the primarily quantitative focussed measurement of resilience, the field of resilience engineering argues that it is not possible to measure resilience at all and more specifically via quantitative methods, as, if the resilience of a system is defined in terms of its performance, resilient performance is not something that the system has or possesses but is instead something that it can be [75,76]. Again, this refers to the idea that a focus on measuring individual properties in isolation is not sufficient for measuring overall system resilience, and that instead focus should be shifted to how all individual functions are connected and mutually dependent, with the ultimate focus being on how the system performs as a whole. Hollnagel [70] suggests that instead of considering what resilient performance is, efforts should instead be shifted to exploring what enables resilient performance. Instead of metrics, indicators of resilient performance, whether these are in quantitative or qualitative form, should be recorded and analysed.

Due to the nature of the water industry, in which each company differs due to regional geographic characteristics, as well as age and condition of infrastructure, demographics and densities of population served, and specific metrics for direct comparison may not be suitable. Instead, more generalised indicators of resilience performance, as suggested by Hollnagel [70], have the potential to be more well suited.

Molyneaux et al. [77] provided a review of how different disciplines seek to measure and build resilience whilst discussing the theoretical underpinning which each discipline bases its understanding of resilience on and therefore the methods used to measure it. Their work [77] outlines the tendency of the field of ecology to focus on highlighting the roles that diversity, redundancy and system capacity play in increasing system resilience. This is in comparison to the field of psychology, that tends to approach situations with an increased level of pragmatism regarding the inevitability of ups and downs. The field of psychology therefore focuses on protective capacities, which are either present or absent, and that are likely to increase the coping capacity of an individual. These capacities include latent ability, education, social support and financial capacity, which Molyneaux et al. [77] argues are similar to adaptive capacity in ecological resilience and that similarities are merely masked by differences in terminology used by different disciplines. Such work highlights that how resilience is measured is very closely linked to the definition adopted by that system, and again helps emphasise the need for a clear definition and understanding of the term from the offset.

Shin et al. [78] reviewed 21 quantitative resilience measures developed for water infrastructure systems and compared them against a set of 11 resilience-based criteria. The authors highlight a number of gaps that exist within the reviewed metrics including a failure to address cascading damage to/from interconnected systems and the rapid detection of system failures. Challenges to the broader development of quantitative resilience metrics for the water sector are also highlighted, with the authors suggesting the need for integrated measures to address the multiple performances of a water infrastructure system and to identify trade-offs between them. Such analysis emphasises the rigidity of quantitative metrics that are developed for the analysis of engineered infrastructure systems, and the inability of quantitative measures to include all resilience criteria for complex systems [78]. Metrics that fail to acknowledge the interdependencies and trade-offs in large-scale socio-technical and socio-ecological systems risk failing to provide accurate or useful results.

Ofwat's response to the resilience metrics sections of the business plans submitted for the PR19 process was mixed with individual companies being praised, but overall stating the industry 'falls short' on securing long-term resilience. Analysis of the business plans submitted highlights the lack of consensus on, and issues surrounding, resilience metrics, with regards to both their understanding and use. Such findings highlight the need for further work in this area and the development of suitable systems-based resilience indicators.

5. Acknowledging the Socio-Technical

5.1. Development of Socio-Technical Systems

Similar to both resilience and sustainability, 'socio-technical' has also turned into something of a buzzword in recent times, with references to 'socio-technical', 'socio-technical systems' and 'socio-technical systems theory' in the literature all increasing over recent years [79]. Recent communication from Ofwat [41], and a new interest in the notion of systems-based thinking, has resulted in the 'socialising of resilience' not only making its way to the forefront of wider sustainable water and resilience-based research [18,80] but also water governance in England and Wales.

In general, the term socio-technical refers to the interactions between the social, and technical aspects of a system [81], with the majority of critical infrastructure, transport, manufacturing and health care systems now falling under the umbrella of 'socio-technical systems'. Research on socio-technical systems, and the interactions between humans and machines in working environments, dates back to work conducted by Trist in the early 1950s in the British Coal Mining industry [82]. In this piece of work, socio-technical analysis was carried out at three levels, "the primary work system; the whole organisation; and the macrosocial phenomena" [82]. As an industry historically reliant on manpower and traditional labour models, the mining industry underwent drastic changes in mechanisation and labour recruitment, in a period of post war industrialisation. A publication by Trist and Bamforth [83] that reported on their research in the coal mining industry was understood to be the first comprehensive application in an industrial setting of socio-clinical ideas [82]. The results of this and associated projects in which technical and social factors were included, were considered to constitute a new field of inquiry.

Since its inauguration, the field of socio-technical research has developed rapidly with 'socio-technical theory' now forming the basis of the field. Walker [79] considers socio-technical theory to be founded on two explicit principles. The first being that the interaction of social and technical factors create conditions for both successful and unsuccessful system performance. These systems comprise of partly linear cause-effect relationships, and partly non-linear unpredictable complex relationships, that highlight the challenges of combining the 'socio' with the 'technical'. Perhaps put more simply it is that the 'socio', does not behave like the 'technical' as not only do people not behave as machines, but as increasing levels of complexity and interdependence are added, the 'technical' also starts to exhibit non-linear behaviours [79]. The second principle of socio-technical theory is that often the optimisation of either the socio or the technical results in an increase in the quantity of unpredictable, 'un-designed' and non-linear relationships that more often than not, negatively impact the performance of the system. Walker [79] suggests that socio-technical theory is therefore centred on 'joint optimisation'.

5.2. Socio-Technical Systems and the Water Sector

When viewing the water sector as a complex socio-technical system, one that is reliant on the interplay of the social, technical and ecological systems that it is comprised of, it is necessary to acknowledge and recognise all parts of the system equally. Traditional focus on the risk management of the physical engineered technical systems that are required for the collection, treatment and distribution of water and wastewater, as well as the more recent emphasis on the status of ecological systems, has resulted in the social aspect of the system typically being viewed as a lesser addition. The answer to the question 'resilience for who, and to what?' has up until now rarely been addressed by making changes to the social aspects of the systems with a focus on disturbances by exogenous forces, often underplaying the internal social dynamics of the system in question [18]. With many sectors, including that of the water industry focussing their efforts on optimising the technical engineered parts of systems through the introduction of, and increased reliance on, automation systems such as SCADA—all of which further increase levels of complexity and interconnectedness in already complex systems, with many technological advances bringing new security threats and increasing levels of system vulnerability [84].

Research conducted by Baker et al. [85], which focussed on resilience learning for water sector culture change, in the UK, highlights the threats that poor leadership and changing staff profiles can have on the overall resilience of the system or sector. Interviews conducted with employees from a number of water companies and regulators identified interventions to aid the required shift in culture, necessary for the introduction of resilience learning.

Ofwat defines operational resilience in the 'Resilience in the Round' document as;

"the ability of an organisation's infrastructure, and the skills to run that infrastructure, to avoid, cope with and recover from, disruption in its performance" [41].

The document details several examples of how resilience can be improved at a corporate, financial and operational scale. However, the specific roles or effects that individuals or social groups and networks have on the overall performance, and therefore resilience of the system, are not referenced or recognised. Reference is made throughout to customers and the value that resilient systems will give to customers. However, there is no specific reference to the sector's workforce.

Analysis and use of the interactions that take place between social and technical systems highlight the dependencies and complexities that exist within such systems and the need for a change in paradigm with regards to their management. As stated by Woo [86], the implementation of the 'work to rule' campaigns in socio-technical systems often causes performance to come grinding to a halt as the ability to adapt, which is required by such complex and interdependent systems, is removed or shut down. For many social systems, the need for optimisation is a result or reflection of wider social requirements to continually 'do more with less'. The need to increase quality and productivity when faced with a reduction in resources has not only resulted in an increase in levels of complexity but also an increase in the occurrence of unanticipated events with the potential to threaten safety [86]. When analysing such events that have occurred within complex systems, it is here that traditional risk and safety based management practices fall short, as they are often based on the assumption that large-scale accidents appear unique, with a single cause of failure or 'root cause'. However, as stated by Cook [87] "catastrophe requires multiple failures—single point failures are not enough".

Examples of large-scale complex failures in the water industry can be seen through the analysis of the North Battleford and Walkerton events (Canada) [86], and the recent Southern Water event (UK) [88]. North Battleford and Walkerton are examples of large-scale drinking water quality failure events, with the Southern Water event providing an example of an environmental pollution event taking place within the governance structure of the water sector in England and Wales. The events relating to these examples did not result from one catastrophic failure but instead, multiple non-linear small-scale cascading failures, which can be linked to the ultimate breakdown in system performance. Through the analysis of such events, the un-designed non-linear relationships in socio-technical systems, as highlighted by Walker [79], can be seen. In such cases, an attempt to 'optimise' the system in one area resulted in large-scale system failures, with significant damage to public and environmental health. Here, a focus on a reduction in capital or operational costs and a failure to recognise the interactions between the social and technical system properties largely impacted overall system performance.

North Battleford, Walkerton and Southern Water events all highlight the affect that breakdowns and failures within the social aspect of the system can have on overall system performance. Such incidents highlight that system components cannot be optimised individually [82], with overall system performance instead resulting as a function of their interactions [89,90], again emphasising the need for the water sector in England and Wales to increase their focus and work on all aspects of the system with particular attention being paid to the social and the interaction with the technical.

The notion of 'operationalising resilience' is something that has already seen application in the field of community resilience [91–93]. As interest in what helps some communities continue to succeed whilst others fail becomes ever more sought after, studies into required capacities that make a community resilient highlight the need for strong social links and high levels of interconnectedness. Such work indicates that communities with required capacities are able to respond to challenges independent of the typology of the threat, and therefore successfully exist as dynamic and resilient human systems [94,95]. Community resilience is not about controlling the conditions that effect communities, but is instead about the ability of individuals and communities as a whole to respond to change [94]. Community resilience presents a topic of discussion around social difference and dynamics combining insights from human development, and can therefore be applied to a range of systems, most notably those of socio-technical and socio-ecological systems, with examples of use in the development of organisational resilience metrics already existing [67].

With regards to the water sector, there is increasing acceptance of resilience being viewed not as a means of controlling the conditions or threats that have the potential to affect a system, but instead as the ability of the system to respond to change and manage performance based on the scenario in which it is operating at the time [64]. Research conducted in the field of community resilience analyses issues of scale within systems and communities, looking at stakeholders at all levels and the effect they have on the performance of a system [96], emphasising that in complex systems especially, it is not solely external forces that pose a risk to performance and function but also internal forces.

Wilson [96] highlights the need to downscale and take into account that communities are comprised of individuals, households and stakeholder groups—all of which have their own resilience pathways which may differ to those of the community in which they live. Such observations are necessary when normative questions such as 'who is defining and measuring resilience?' and 'how the data will be measured?' come into play, so that it is made clear that methodologies to assess resilience are as inclusive as possible of different stakeholders views that exist within the community, organisation or system, if both communities and organisations are to understand their resilience strengths and weaknesses [67]. Wilson [96] goes on to state that implementation of resilience pathways can only find its most direct expression at the individual/ household level, as it is only the most local level that the outcomes of policy and higher level decision making can be turned into action with tangible effects. Such work indicates that for the concept of resilience to turn from a theorised academic principle to a tangible operational method in the water sector, specific attention must be made at the local operational scale, and more specifically with the people and the networks that exist at such a scale.

Previous events, such as Walkerton, North Battleford and Southern Water, as referred to earlier, highlight the role that individuals can play in the performance of a system when the conditions in which it operates are tested, with the 'socio' aspect of the system able to both positively and negatively impact system performance, as outlined in the seminal work conducted by Trist and Bamforth [83]. The workforce of the water industry has the ability to largely impact the functioning and performance of its systems, and therefore the multiple resilience pathways that exist within the workforce must not only be acknowledged, but also nurtured, if water companies and organisations are to ever encompass the theorised resilience principles and be considered resilient.

As the water industry, like many others, continues to look for alternatives to large-scale capital infrastructure investments, and strives to continually increase its ability to adapt in the face of the unknown, there is an opportunity to further explore the role that the 'social' has in overall system resilience.

6. Conclusions

Within the water sector in England and Wales, recent large-scale events combined with high levels of uncertainty facing the industry, specifically in relation to supply, demand and delivery, have resulted in the acceptance of the need for resilience and its associated principles. However, although multiple positive steps are being made to further resilience across the industry, additional action is required if operationalisation is to be achieved. Changes to policy and legislation have so far provided a framework for the introduction of the concept of resilience to the water sector, with enthusiasm for the implementation of resilience across the industry. However, pathways to transfer this into action at an operational level are yet to be fully identified and acted upon.

Throughout the wider literature, the importance of a clear resilience definition is discussed. However, despite the recommendation from the Task and Finish Group, and Ofwat providing a definition, companies were still able to define resilience as they wish for the recent PR19 process. This resulted in varying degrees of success in relation to the 'resilience challenge', with confusion still surrounding the term and associated actions/interventions. The authors recommend a sector-wide consensus on the definition of resilience not only to aid understanding, but also help with regards to the development of resilience indicators and resilience-based interventions.

The development of resilience-based metrics and indicators not only forms a key part of Ofwat's PR19 methodology but also the wider resilience literature. However, issues surrounding the use of rigid quantitative metrics, especially those focussed on risk and the identification of a specific threat remain. Due to the complex nature of the interdependencies and connections that exist within systems such as the water industry, quantitative metrics are often unable to accurately portray the dynamic and adaptive nature of socio-technical systems that is central to resilient performance. It is therefore recommended that rather than specific infrastructure-based metrics, the water industry in England and Wales focus on the development of more generalised system theory based indicators of resilience.

Recent events in the water industry in relation to water quality failures and environmental pollution highlight the impact the 'socio' can have on the overall performance of socio-technical systems. However, this is still repeatedly either ignored or approached as an afterthought in the water sector, with Ofwat failing to acknowledge the role of the socio in both their definition of organisational resilience as well as the methodology for the most recent Price Review. Work conducted in the field of community and organisational resilience highlights the role that internal forces, and stakeholders at differing levels, can have on the overall performance of systems. The authors recommend that future work in the water industry focus on the further inclusion and acknowledgement of the 'socio' in socio-technical systems and the discussion around operationalising resilience.

This paper has highlighted the current status of resilience in the water sector in England and Wales and barriers that it is currently facing. The literature has been used to support the arguments made, with examples from other sectors and fields provided. Three potential barriers—a lack of definition, metrics and the measurement of resilience—and the current failure to fully acknowledge the social in socio-technical systems have all been discussed and further explored. It is hoped that efforts to remove such barriers will results in the further operationalisation of resilience in the identified water sector.

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Appendix A

Table A1. Water industry regulators in England and Wales.

Regulator	Industry Name	Description	Key Responsibilities
The Water Services Regulation Authority	**OFWAT**	A non-ministerial government department that is the economic regulator for the water and sewerage sectors in England and Wales. They are responsible for making sure that companies they regulate provide consumers with a good quality and efficient service at a fair price.	• Protect the interests of customers • Ensure companies carry out statutory functions • Where appropriate promote competition • Promote economy and efficiency
Environment Agency	**EA**	An executive non-departmental public body responsible to the DEFRA Secretary of State. They decide how much water can be abstracted from the environment and sets and enforces standards for the return of treated wastewater to the environment.	• Ensure environmental quality and pollution standards are met. • Provides licences for abstraction and discharge • Manage and enforce company work relating to flood and drought management
Drinking Water Inspectorate	**DWI**	Responsible for enforcing drinking water quality standards in England and Wales.	• Enforce drinking water quality standards
Consumer Council for Water	**CCW**	Represents customers interests relating to price, service and value for money. Investigates customer complaints about water quality.	• Represent customers • Investigate customer complaints
Department for Environment, Food and Agriculture	**DEFRA**	The UK government department responsible for water policy and regulations in England and Wales. Sets drinking water quality and environment standards which water companies must adhere to.	• Sets overall water and sewage policy framework in England • Works closely with Welsh Government who are responsible for overall water and sewerage policy framework in Wales. • Create special permits (e.g., drought orders) when required

Table A2. Water industry legislation England and Wales.

Year	Legislation	Key Points
1989	**Water Act**	Facilitated the privatisation of water and sewerage companies.
1991	**Water Industry Act**	Main powers and duties of newly formed water and sewerage companies replacing those that were set out in the Water Act 1989.
1991	**Water Resources Act**	Set out functions of the then National Rivers Authority (now Environment Agency) and introduced water quality classifications and objectives for the first time.
1992	**Competition and Service Act 1992**	Increased Ofwat's powers to determine disputes and increased the limited opportunities for competition in the industry.
1995	**Environment Act**	Restructuring of environmental legislation to promote efficient use of water by customers. Created the Environment Agency, a new body which took over the National Rivers Authority, Her Majesty's Inspectorate of Pollution, the waste regulation functions of local authorities and certain elements of the Department for Environment.
1998	**Competition Act**	Prohibits agreements between businesses that prevent, restrict or distort competition. Also prohibits any abuse of a dominant market position. Ofwat and Competition Markets Authority share enforcement powers.
1999	**Water Industry Act**	Made amendments to the Water Industry Act 1991 including; removing a company's right to disconnect household customers for non-payment of bills, limiting circumstances in which companies can start charging domestic customers on a metered basis and securing that companies could continue to charge customers on the basis of rateable value.
2002	**Enterprise Act**	Update of Water Industry Act 1991 to update the regime for the compulsory reference of certain mergers between water companies to the Competition Commission.
2003	**Water Act**	Changes to framework for abstraction licensing and corporate structure of economic regulation.
2010	**Flood and Water Management Act 2010**	Encourages use of sustainable urban drainage systems (SUDs), amended the Water Industry Act to modernise the list of activities that can be restricted by water companies in a drought, and made it easier for water companies to offer lower tariffs to certain groups.
2014	**Water Act**	Enables greater competition for non-household customers—limited to English water companies. Provision of statutory duty to Ofwat for resilience and new powers to make rules on charges and charges schemes as well as making provisions for flood insurance and drainage boards.

References

1. Saal, D.S.; Parker, D. The impact of privatisation and regulation on the water and sewerage industry in England and Wales: A translog cost function model. *Manag. Decis. Econ*, **2001**, *268*, 253–268.
2. *Global Water: Issues and Insights*; Quentin Grafto, R, Wyrwoll, P, White, C, Allendes, D., Eds.; Australian National University Press: Canberra, Australia, 2014. ISBN 9781925021660.
3. Makropoulos, C.; Nikolopoulos, D.; Palmen, L.; Kools, S.; Segrave, A.; Vries, D.; Koop, S.; van Alphen, H.J.; Vonk, E.; van Thienen, P.; et al. A resilience assessment method for urban water systems. *Urban Water* J **2018**, *15*, 316–328.
4. Butler, D.; Farmani, R.; Fu, G.; Ward, S.; Diao, K.; Astaraie-Imani, M. A new approach to urban water management: Safe and sure. *Procedia Eng* **2014**, *89*, 347–354.
5. Pahl-Wostl, C.; Jeffrey, P.; Isendahl, N.; Brugnach, M. Maturing the New Water Management Paradigm: Progressing from Aspiration to Practice. *Water Resour. Manag.* **2011**, *25*, 837–856.
6. Pahl-Wostl, C.; Sendzimir, J.; Jeffrey, P.; Aerts, J.; Berkamp, G.; Cross, K. Managing change toward adaptive water management through social learning. Ecology and Society **2007**, *12*, 30.
7. Johannessen, Å.; Wamsler, C. What does resilience mean for urban water services? Ecology and Society **2017**, *22*. doi:10.5751/ES-08870-220101
8. Bissel, J. Resilience of UK Infrastructure. Available online: https://www.parliament.uk/documents/post/postpn362-resilience-of-UK-infrastructure.pdf (accessed on 15 February 2020)
9. Brown, K. *Resilience, Development and Global Change*; Routledge: Oxon, UK, 2015. ISBN 9781134614189.
10. Xu, L.; Marinova, D. Resilience thinking: A bibliometric analysis of socio-ecological research. *Scientometrics* **2013**, *96*, 911–927.
11. Leigh, N.G.; Lee, H. Sustainable and resilient urban water systems: The role of decentralization and planning. *Sustainability* **2019**, 11, 918.
12. Bruntland, G. Report of the World Commoission on Environment and Development: Our Common Future; United Nations: New York, NY, USA, 1987.
13. Sahely, H.R.; Kennedy, C.A.; Adams, B.J. Developing sustainability criteria for urban infrastructure systems. *Can J. Civ. Eng*. **2005**, *32*, 72–85.
14. Milman, A.; Short, A. Incorporating resilience into sustainability indicators: An example for the urban water sector. *Glob. Environ. Chang.* **2008**, *18*, 758–767.
15. Butler, D; Davies, J. *Urban Drainage*, 3rd ed.; Spon Press: London, UK, 2010.
16. Rodina, L. Defining “water resilience”: Debates, concepts, approaches, and gaps. *Wiley Interdiscip. Rev. Water* **2019**, *6*. doi:10.1002/wat2.1334
17. Hosseini, S.; Barker, K.; Ramirez-Marquez, J.E. A review of definitions and measures of system resilience. *Reliab. Eng. Syst. Saf.* **2016**, *145*, 47–61.
18. Brown, K. Global environmental change I: A social turn for resilience? *Prog. Hum. Geogr.* **2014**, *38*, 107–117.
19. Meerow, S.; Newell, J.P.; Stults, M. Defining urban resilience: A review. *Landsc. Urban Plan*. **2016**, *147*, 38–49.
20. Juan-García, P.; Butler, D.; Comas, J.; Darch, G.; Sweetapple, C.; Thornton, A.; Corominas, L. Resilience theory incorporated into urban wastewater systems management. State of the art. *Water Res.* **2017**, *115*, 149–161.
21. Bhamra, R.; Dani, S.; Burnard, K. Resilience: The concept, a literature review and future directions. *Int. J. Prod. Res.* **2011**, *49*, 5375–5393.
22. Carpenter, S.; Walker, B.; Anderies, J.M.; Abel, N. Metaphor to Measure Resilience for What to What? *Ecosystems* **2011**, *4*, 765–781.
23. Welsh, M. Resilience and responsibility: Governing uncertainty in a complex world. *Geog. J.* **2014**, *180*, 15–26.
24. Ganin, A.A.; Massaro, E.; Gutfraind, A.; Steen, N.; Keisler, J.M.; Kott, A.; Mangoubi, R.; Linkov, I. Operational resilience: Concepts, design and analysis. *Sci. Rep.* **2016**, *6*, 1–12.
25. Pahl-wostl, C. A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Glob. Environ. Chang.* **2009**, *19*, 354–365.
26. Hashimoto, T.; Stedinger, J.R.; Loucks, D.P. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour. Res* **1982**, *18*, 14–20.

27. Muller, M. Adapting to climate change: Water management for urban resilience. *Environ. Urban.* **2007**, *19*, 99–113.
28. De Bruijn, K. *Resilience and Flood Risk Management, A Systems Approach applied to Lowland Rivers*; DUP Science, Delft University Press: Delft, The Netherlands, 2016; ISBN 9040725993.
29. Galaz, V.; Centre, S.R. Water governance, resilience and global environmental change – a reassessment of integrated water resources management (IWRM). *Water Sci. Technol.* **2007**, *56*, 2–10.
30. Marshall, N.A.; Marshall, P.A. Conceptualizing and Operationalizing Social Resilience within Commercial Fisheries in Northern Australia. *Ecol. Soc.* **2007**, *12*, 1.
31. Vale, L.J. The politics of resilient cities: Whose resilience and whose city? *Build. Res. Inf*. **2014**, *42*, 191–201.
32. Holling, C.S. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Sys.* **1973**, *4*, 1–23.
33. Holling, C.S. Engineering Resilience versus Ecological Resilience. Engineering Within Ecological Constraints. Available online: https://www.nap.edu/read/4919/chapter/4 (accessed on 15 February 2020).
34. Anderies, J.M.; Folke, C.; Walker, B.; Ostrom, E. Aligning Key Concepts for Global Change Policy: Robustness, Resilience, and Sustainability. *Ecol. Soc.* **2013**, *18*, 8.
35. Derissen, S.; Quaas, M.F.; Baumgärtner, S. The relationship between resilience and sustainability of ecological-economic systems. *Ecol. Econ*. **2011**, *70*, 1121–1128.
36. Chelleri, L.; Waters, J.J.; Olazabal, M.; Minucci, G. Resilience trade-offs: addressing multiple scales and temporal aspects of urban resilience. *Environ. Urban.* **2015**, *27*, 181–198.
37. Water Act (England and Wales) 2014 c.28 Available online: http://www.legislation.gov.uk/ukpga/2014/21/pdfs/ukpga_20140021_en.pdf (accessed on 11 August 2019).
38. Lowe, J.A.; Bernie, D.; Bett, P.; Bricheno, L.; Brown, S.; Calvert, D.; Clark, R.; Edwards, T.; Fosser, G.; Fung, F.; et al. UKCP18 Science Overview Report. Available online: https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf (accessed on 17 February 2020)
39. Office for National Statistics Overview of the UK population: March 2017 Available online: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/articles/overviewoftheukpopulation/mar2017 (accessed on 24 February 2020).
40. Defra Creating a Great Place for Living Enabling Resilience in The Water Sector; DEFRA: London, UK, 2016.
41. OFWAT. Resilience in the Round: Building Resilience for the Future; OFWAT: Birmingham, UK, 2017.
42. Hamilton, W.A.H. Resilience and the city: The water sector. *Urban Des. Plan*. **2009**, *3*, 109–121.
43. OFWAT. Water Sector Overview. Available online: https://www.ofwat.gov.uk/regulated-companies/ofwat-industry-overview/ (accessed on 14 February 2020).
44. Parker, D. Regulation of privatised public utilities in the UK: performance and governance. *Int. J. Public. Sect. Manag*. **1999**, *12*, 213–236.
45. OFWAT. Business retail market Available online: https://www.ofwat.gov.uk/regulated-companies/markets/business-retail-market/ (accessed on 16 February 2020).
46. Ogden, S.; Watson, R. Corporate Performance and Stakeholder Management: Balancing Shareholder and Customer Interests in the U.K. *Acad. Manag. J.* **1999**, *42*, 526–538.
47. Pickard, J. Labour to pay £15bn to renationalise water industry. Available online: https://www.ft.com/content/876e456e-6f42-11e9-bbfb-5c68069fbd15 (accessed on 24 February 2020)
48. DEFRA The Government's Response to Sir Michael Pitt ' s Review of the summer 2007 Floods Final Progress Report; DEFRA: London, UK, 2012.
49. Cabinet Office. Keeping the Country Running:Natural Hazards and Infrastructure; Cabinet Office: London, 2011.
50. Rodriguez, M; Lawson, E; Butler, D. Organisational Resilience Metrics: A study of the Resilience Analysis Grid method and its applicability to the water sector in England and Wales. *Water. Environ. J*. **2019**. doi:10.1111/wej.12539
51. OFWAT. Delivering Water 2020: Our final methodology for the 2019 price review; OFWAT: Birmingham, UK, 2017.
52. Tusaie, K.; Dyer, J. Resilience: A Historical Review of the construct. *Holis. Nurs. Prac.* **2004**, *18*, 3–8.
53. Cimellaro, G.P.; Renschler, C.; Reinhorn, A.M.; Arendt, L. PEOPLES: A Framework for Evaluating Resilience. *J. Struct. Eng*. **2016**, *142*, 04016063.
54. Gunderson, L.H. Ecological Resilience—In Theory and Application. *Annu. Rev. Ecol Syst.* **2000**, *31*, 425–439.

55. Handmer, J.W.; Dovers, S.R. A typology of resilience: Rethinking institutions for sustainable development. *Organ. Environ.* **1996**, *9*, 482–511.
56. Adger, W.N. Social and ecological resilience: Are they related? *Prog. Hum. Geogr.* **2000**, *24*, 347–364.
57. Comfort, L.; Wisner, B.; Cutter, S.; Pulwarty, R.; Hewitt, K.; Oliver-Smith, A.; Wiener, J.; Fordham, M.; Peacock, W.; Krimgold, F. Reframing disaster policy: The global evolution of vulnerable communities. *Environ. Hazard.* **1999**, *1*, 39–44.
58. Tierney, K.; Bruneau, M. Conceptualising and Measuring Resilience A Key to Disaster Loss Reduction. *TR News* **2007**, *250*, 14–18.
59. Linkov, I.; Bridges, T.; Creutzig, F.; Decker, J.; Fox-Lent, C.; Kröger, W.; Lambert, J.H.; Levermann, A.; Montreuil, B.; Nathwani, J.; et al. Changing the resilience paradigm. *Nat. Clim. Chang.* **2014**, *4*, 407–409.
60. Lundberg, J.; Johansson, B.J. Systemic resilience model. *Reliab. Eng. Sys. Saf.* **2015**, *141*, 22–32.
61. Davoudi, S.; Shaw, K.; Haider, L.J.; Quinlan, A.E.; Peterson, G.D.; Wilkinson, C.; Fünfgeld, H.; McEvoy, D.; Porter, L. Resilience: A Bridging Concept or a Dead End? "Reframing" Resilience: Challenges for Planning Theory and Practice Interacting Traps: Resilience Assessment of a Pasture Management System in Northern Afghanistan Urban Resilience: What Does it Mean in Plan. *Plan Theory Pract.* **2012**, *13*, 299–333.
62. Pizzo, B. Problematizing resilience: Implications for planning theory and practice. Cities **2015**, *43*, 133–140.
63. Smith, D.; Fischbacher, M. The changing nature of risk and risk management: The challenge of borders, uncertainty and resilience. *Risk Manag.* **2009**, *11*, 1–12.
64. Butler, D.; Ward, S.; Sweetapple, C.; Astaraie-Imani, M.; Diao, K.; Farmani, R.; Fu, G. Reliable, resilient and sustainable water management: The Safe & SuRe approach. *Glob. Chall.* **2017**, *1*, 63–77.
65. OFWAT. Resilience Task & Finish Group Final Report; OFWAT: Birmingham, UK, 2015.
66. OFWAT. PR19 initial assessment of plans: Summary of test area assessment. OFWAT: Birmingham, UK 2019; p. 132.
67. Lee, A. V; Vargo, J.; Seville, E. Developing a Tool to Measure and Compare Organizations' Resilience Developing a Tool to Measure and Compare Organizations' Resilience. *Nat. Hazard. Rev.* **2013**, *14*, 29–41.
68. Cumming, S.; Barnes, G.; Perz, S.; Schmink, K.E.; Sieving, J.; Southworth, J.; Binford, M.; Holt, R.D.; Stickler, C.; Holt, T. Van An Exploratory Measurement Empirical Framework of Resilience. *Ecosystems* **2005**, *8*, 975–987.
69. Schipper, E.L.F.; Langston, L. A comparative overview of resilience measurement frameworks analysing indicators and approaches. *Overseas. Dev. Inst. Work Paper.* **2015**, *422*, 30.
70. Hollnagel, E. RAG—Resilience Analysis Grid. Available online: https://erikhollnagel.com/onewebmedia/RAG_introduction.pdf (accessed on 26 February 2020).
71. Matin, N.; Taylor, R.; Forrester, J.; Pedoth, L.; Davis, B.; Deeming, H. emBrace: Mapping of social networks as a measure of social resilience of agents. Available online: https://www.researchgate.net/publication/306259479_ReportMapping_of_social_networks_as_a_measure_of_social_resilience_of_agents (accessed on 17 February 2020).
72. OED Online "indicator, n." Available online: www.oed.com/view/Entry/94420 (accessed on 17 December 2019).
73. OED Online "metric, n.1 and adj.1." Available online: www.oed.com/view/Entry/117657 (accessed on 17 December 2019).
74. Arcadis. *Measuring Resilience in the Water Industry*; Arcadis: Zuidas, The Netherlands, 2017.
75. Hollnagel, E. How Resilient Is Your Organisation? An Introduction to the Resilience Analysis Grid (RAG). Available online: https://hal-mines-paristech.archives-ouvertes.fr/hal-00613986/document (accessed on 17 February 2020).
76. Park, J.; Seager, T.P.; Rao, P.S.C.; Convertino, M.; Linkov, I. Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Anal.* **2013**, *33*, 356–367.
77. Molyneaux, L.; Brown, C.; Wagner, L.; Foster, J. Measuring resilience in energy systems: Insights from a range of disciplines. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1068–1079.
78. Shin, S.; Lee, S.; Judi, D.R.; Parvania, M.; Goharian, E.; McPherson, T.; Burian, S.J. A systematic review of quantitative resilience measures for water infrastructure systems. *Water* **2018**, *10*, 1–25.
79. Walker, G. Come back sociotechnical systems theory, all is forgiven. Civ. Eng. Environ. Syst. **2015**, *32*, 170–179.
80. Brown, R.; Keath, N. Drawing on social theory for transitioning to sustainable urban water management: Turning the institutional super-tanker. *Aust. J. Water Resour.* **2008**, *12*, 73–83.

81. Appelbaum, S.H. Socio Technical Systems. *Manag. Dec*. **1997**, *35*, 452–463.
82. Trist, E. The Evolution of Socio-Technical Systems: A Conceptual Framework and an Action Research Program. Available online: http://sistemas-humano-computacionais.wdfiles.com/local-files/capitulo%3Aredes-socio-tecnicas/Evolution_of_socio_technical_systems.pdf (accessed on 26 February 2020).
83. Trist, E; Bamforth, K. Some social and psychologicl consequences of the longwall method of coal-getting. *SAGE Soc. Sci. Collect.* **1951**. doi:10.1177/001872675100400101.
84. Luiijf, E.; Ali, M.; Zielstra, A. Assessing and improving SCADA security in the Dutch drinking water sector. *Int. J. Crit. Infrastruct. Prot.* **2011**, *4*, 124–134.
85. Baker, K.; Tang, S.; Sweetapple, C.; Ward, S.; Staddon, C.; Bishop, T.; Bulmer, P.; Butler, D. Resilience learning for water sector culture change. *Eur. Water Assoc.* **2018**, *6*, 6–26
86. Woo, D.M.; Vicente, K.J. Sociotechnical systems, risk management, and public health: Comparing the North Battleford and Walkerton outbreaks. *Reliab. Eng. Syst. Saf.* **2003**, *80*, 253–269.
87. Cook, R.I. How Systems Fail How Complex Systems Fail. Available online: https://web.mit.edu/2.75/resources/random/How%20Complex%20Systems%20Fail.pdf (accessed on 24 February 2020)
88. OFWAT. OFWAT's Final Decision to Impose a Financial Penalty on Southern Water Services Limited. Available online: https://www.ofwat.gov.uk/wp-content/uploads/2019/06/Ofwat%E2%80%99s-final-decision-to-impose-a-financial-penalty-on-Southern-Water-Services-Limited.pdf (accessed on 17 February 2020).
89. Saurin, T.; Patriarca, R. A taxonomy of interactions in socio-technical systems: A functional perspective. *Appl. Ergon*. **2019**, *82*, 2020.
90. Hollnagel, E. *Cognitive Reliability and Error Analysis Method CREAM*; Elsevier Science Ltd: Oxford, UK, 1998;
91. Pfefferbaum, Rose L; Pfefferbaum, B.; Van Horn, R.; Klomp, R.; Norris, F.H..; Reissman, D. The Communities Advancing Resilience Toolkit (CART): An Intervention to Build Community Resilience to Disasters. *J. Pub. Health Manag. Pract*. **2013**, *19*, 250–258.
92. Cabinet Office Community Resilience Development Framework; Cabinet Office: London, UK, 2019; pp. 1–17.
93. International Federation of Red Cross and Red Crescent Societies. *Road Map to Community Resilience: Operationalizing the Framework for Community Resilience—Brief summary;* International Federation of Red Cross and Red Crescent Societies: Geneva, Switzerland, 2016.
94. Magis, K. Community resilience: An indicator of social sustainability. *Soc. Nat. Resour.* **2010**, *23*, 401–416.
95. Folke, C.; Colding, J.; Berkes, F. Synthesis building resilience and adaptive capacity in social-ecological systems. In *Navigating Social-ecological systems: Building resileince of complexity and change*.; Cambridge University Press: Cambridge, UK, 2003.
96. Wilson, G.A. Geoforum Community resilience, globalization, and transitional pathways of decision-making. *Geoforum* **2012**, *43*, 1218–1231.