MRes Thesis – An approach to assessing the resilience of the water service in England and Wales – Can we answer the question: is the service resilient or brittle?

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> "A chain is no stronger than its weakest link; but if you show how admirably the last few are united together, half the world will forget to test the security of the equally essential parts which are kept out of sight."
> (The Cornhill Magazine, 1868)

Synopsis

This research considers the concept of resilience and the extent to which the resilience of a water supply system can be assessed. A method of assessing water service resilience is developed and tested for the water service in England and Wales. This is done by analysis of service performance data over time and by examination of one particular system. As part of this, a group of features which you would expect to see as part of a resilient water supply system is explained and defined. The research concludes that it is possible to arrive at a view of the level of resilience of service by looking at performance data and processes and systems against a set of criteria. The research also concludes that there is more evidence to support the argument that the water service in England and Wales is more resilient than in the past. Some further areas for research into the resilience of the water service are noted, and ideas for how a more in-depth analysis of resilience might be carried out are suggested.

Introduction

1.1. Research aims

This research explored methods for assessing the resilience of a water service, and sought to assess the degree to which the water service in a region of England and Wales can be said to be resilient. The aim was to develop a method of assessing the resilience of the water service, apply this method to an area of England and Wales, and arrive at conclusions about how far the resilience of a complex system which covers a large geographical area can be assessed.

Delivery of the **water service** is measured through a number of key performance indicators in companies and by regulators. The most important of these relate to the 'guaranteed standards of service' which customers are entitled to receive. These guaranteed standards relate primarily to water pressure, interruptions and customer contact[1]. Customer contact covers issues like appointments and response to correspondence which is not in the scope of this work. In addition to the guaranteed standards of service there are also guaranteed drinking water standards which customers are entitled to[2]. This research focuses on the delivery of the three key elements of those guaranteed standards:

- The supply of potable water to domestic customers on demand and without interruption.
- The supply of potable water to domestic customers at adequate flow rate and pressure; i.e. at a minimum rate of 9 litres per minute and a minimum pressure of 0.7 bar.
- The supply of potable water to domestic customers which complies with the European Drinking Water Directive standards as specified and enforced by the Drinking Water Inspectorate: i.e. those set out in schedule 1 of the Water Supply Regulations 2000 (as amended).

Although guaranteed standards also cover expectations of the sewerage service, that has not been considered in this study. The research also does not focus specifically on the service provided to non-domestic customers, i.e. business and industry. However it is clear that the services are interlinked and some time has been devoted to examining differences in the levels of resilience of the service delivered to domestic and non-domestic customers.

The research examined the ability of the existing systems in the water sector to maintain supply, pressure and water quality in the context of the risks of external changes in circumstances. In recognition of the fact that it is impossible to eliminate all risks to service, and that small-scale, low materiality service failures are a recognised and accepted part of the current

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[1] For more information about guaranteed standards of service see The Water Supply and Sewerage Services (Customer Service Standards) Regulations 2008 (SI 2008/594).

[2] For more information about the standards required of a potable water supply see The water supply (Water Quality) regulations 2000 (SI 2000/3184).

national water service, the focus was on resilience to service failures which affect more than just a handful of properties or which have high consequences, such as public health impacts. This work therefore excluded investigation of issues like small-scale pressure interruptions, planned interruptions or non-harmful discolouration.

The research sought to determine the degree to which current infrastructure arrangements, business-as-usual practices, capital maintenance regimes, emergency planning and staff, skills, equipment and institutional arrangements can be said to minimise the risks to service and therefore make the water service resilient.

Some observers, such as the think-tank DEMOS have argued that our society as a whole in the UK is brittle and that this is primarily because of our reliance on dense networks to provide us with water and other services. DEMOS have asserted that “Our everyday lives and the national infrastructure which they rely on operate in a fragile union, vulnerable to even the smallest disturbances in the network.” (Edwards, 2009). Similarly professional bodies such as the Institution of Civil Engineers (‘ICE’) have made numerous calls for step-changes in activity with the aim of increasing service resilience in areas such as water. For example, with regard specifically to flooding the ICE have stated that “Economic and regulatory forces have reduced investment in new infrastructure to the point where there is no longer any spare capacity available to provide alternative sources of power or water treatment should key utilities be compromised by flooding.” (ICE, 2010).

On the other hand, service performance information collected by regulators suggests that the water service is actually much more resilient than in the past. Risk-based approaches to asset operation and maintenance and precautionary pro-active investment in areas such as water quality have led to demonstrably higher standards, stable serviceability and substantial headroom. Wide-scale service failures are relatively rare and the regulator Ofwat has stated that “services are… safer, better and more secure than ever before” (Ofwat, 2010).

Since this diversity of opinion might lead to some uncertainty, it becomes necessary to seek a reliable method by which to determine the extent to which the water service is resilient and whether this has improved or deteriorated over time.

1.2. Research objectives

The aim of the research was to investigate whether it is possible to assess the resilience of the water service in England and Wales. The objectives to meet this aim were to apply and evaluate a top-level analytical approach and develop and test a qualitative method of assessing water service resilience. Through doing this, the research sought to generate some ideas on useful ways to approach an assessment of current resilience as a first step to setting longer-term targets for resilience.

The research was split into three phases:

1. Literature review.
2. Analysis of data on service failures and empirical failures of resilience.
3. Development and testing of an approach to assessing existing service resilience.

The first phase was the literature review which was necessary to frame the question and research aims and establish what had already been done on the subject. The focus of this phase was to reach a usable definition of resilience, describe the state of knowledge in the sectors and analyse existing approaches to assessing resilience.

The second phase looked at national information about the number of service failures experienced by customers over the past two decades and presented some analysis of how patterns of service disruption have changed over the past twenty years. Based on this data the research also discussed historic events in England during the last 40 years where the water service as defined above has failed on a significant scale. This helped establish a range of the plausible external hazards which can reduce the water service and provided an insight into how able the whole sector is to learn from service failures and increase overall resilience in response to actual failures.

Phase three of the research focussed on developing an assessment approach for resilience by looking at principles of resilience and developing expectation criteria. This assessment approach was then tested by applying it based on a study of infrastructure arrangements, operational practices, case studies and emergency plans at one water company. This included a study of the company’s strategic business plan, water resource management plan, climate change adaptation plan and internal process documents, reports and discussions with company representatives.

2. Phase 1 – Literature Review

2.1. Approach

A literature review on the subject of resilience turns up a broad and diverse range of research across many different academic disciplines. It is a term used in psychological health, economics, social sciences, ecology, engineering and emergency planning. Whilst its meaning in all these contexts is similar, it is not the same. The first step of the review was to establish a definition which is workable and applicable to the water sector. The second step was to look at any methods for assessing resilience which have been used and whether these had been applied to a water service.

2.2. Definitions

Resilience has been variously defined and its conceptualization in recent years has been called “fuzzy and contested” (White, 2010). It shares similarities with ‘sustainable development’ in that it is frequently used as an umbrella concept to describe a broad array of interrelated issues (Dovers and Handmer, 1992). For example the breadth of research interests evidenced by the ‘Resilience Alliance’ - a body of multi-disciplinary academics promoting and linking research on “social-ecological systems in order to discover foundations for sustainability” (Resilience Alliance, 2011) gives some impression of how wide-ranging a subject resilience is considered to be. In order to usefully define resilience for the water sector it is necessary to look at its origins and the current academic uses of the term. Perhaps more importantly, it is also necessary to look at the current applications of the term in policy and applied fields.

The term resilience in its modern sense has its roots in ecology and was defined by CS Holling in 1973 as a property of an ecological system which “is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist.” Holling separates resilience from 'stability' so that an ecosystem may be resilient but not stable. This definition relies on defining the system under examination and understanding the links between that system and the functions and processes which might affect it. These are the links which need to be examined in order to assess resilience.

There are a host of academics who have attempted to arrive at workable definitions of resilience for use when considering socio-ecological systems like a water supply system. For example, after a lengthy review of the various uses of the term, Klein arrived at a definition of resilience as the amount of disturbance a system can absorb and remain within the same state and the “degree to which that system is capable of self-organisation”; self organisation meaning not requiring external influence to maintain the system, for example government interference (Klein, 2003).

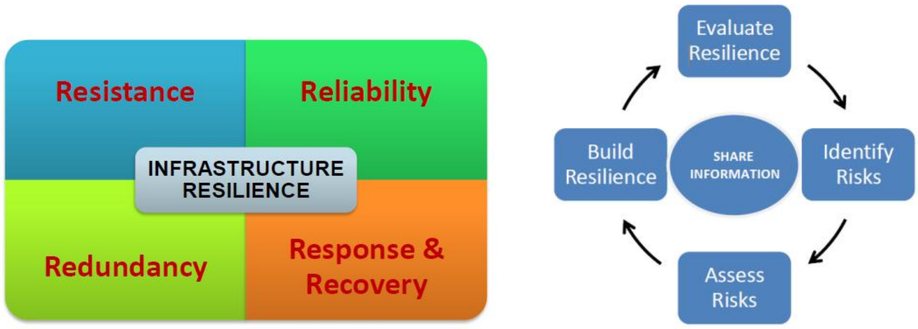
Building on the work of Klein and others (for example Adger, 2000 and Pelling, 2003) resilience can be defined as a measure of the ability of a system to absorb changes whilst performing its intended functions. If such a system's functions are compromised due to a change in circumstances, it may be deemed not resilient enough to cope with whatever the change was that caused the failure. This means that the concept of resilience links very strongly with risk management, but that it is "a lesser function within the risk framework" (White, 2010). What is meant by this is that resilience is dependent on risk and is one factor which affects the risk borne by a system. The degree of resilience which a system might require is actually a contingent question, depending on risk and risk appetite. To investigate the resilience of a *service* therefore requires an investigation of the systems required for the delivery of that service and the risks associated with these systems. These systems include the infrastructure networks themselves, the practices and procedures of the operators, the critical external dependencies and relevant institutional arrangements. Therefore studying resilience can be treated as an application of systems theory, as explored by Bertalanffy (1963) and others since.

The concept of resilience has been further broken down into two streams, which have been termed the "equilibrium" and "non-equilibrium" paradigms (Pickett et al, 2004). Put simply, these views are that resilience is either the ability of a system to 'bounce-back' after a disturbance or the ability of a system to absorb gradual changes in circumstance (White, 2010). Hollnagel et al. (2006) argue that resilience encompasses both of these streams and that organisations would be successful if they were able to "recognise, adapt to and absorb variations, changes, disturbances, disruptions and surprises". In these terms, resilience means not simply being able to react well, but also proactively anticipating and acting to cope with potential risks.

The definition used by the Government Cabinet Office in its most recent work on national infrastructure however tends towards the 'equilibrium' definition. Its definition is that "Resilience is the ability of assets, networks and systems to anticipate, absorb, adapt to and / or rapidly recover from a disruptive event." (Cabinet Office, 2011). Use of the term 'disruptive event' shows that what is in mind when resilience is being discussed is not a gradual change in circumstance, but rather specific event hazards. In this policy context the 'non-equilibrium' definition is more commonly referred to as 'adaptation'. Adaptation and its links with resilience are explored in more detail later on.

Current understanding in the water and sewerage sectors in England and Wales is based on the Cabinet Office definition with the additional proviso that resilience actions are those which aim to protect the *service* from the effects of hazards that are predominantly beyond the control of the water companies who control the water supply systems (Ofwat, 2010). A hazard is defined as any type of event which disrupts the normal activities of human society and natural habitats (Balica et al, 2009). The focus on service is important because it means that resilience is not just focused on the ability of individual system components to function as intended. The Cabinet Office explains that resilience is the sum of four main system characteristics shown in figure1: **resistance, reliability, redundancy and response** (2011). Resistance is specific protection such as flood walls, redundancy consists of spare capacity such as backup systems, and reliability consists of designing system components such that they can operate in a wide range of circumstances. Response activity consists of emergency plans, and ensuring the right corporate culture and skills exist to be able to react in the event of a hazard.

Figure1: Cabinet Office classification of resilience characteristics and the 'resilience cycle'.



Source: Cabinet Office 2011

There are however, other points of view on this subject and in technical terms resilience is usually defined more narrowly. Its technical uses tend to be more closely in line with the original dictionary definition as "the act of springing back"; so in mechanical engineering it relates to the energy absorbed by a material at its elastic limit (OED, 2011). Hashimoto et al, (1982) and Bogardi and Kundzewicz (2002) define resilience as a measure of how fast a system is likely to return to a satisfactory state. They therefore separate it from reliability and vulnerability. In their work on water resource systems resilience is a specific conditional probability that a satisfactory state will return in a given time period. These uses are more niche technical definitions of less common usage at the level under investigation in this research. For that reason the wider definition, incorporating the four system characteristics as set out above, has been used here. These categories have been used to structure the research described in the work plan below.

Brittleness as a term has less provenance than resilience but can be defined simply as its opposite. It has been used in this sense in the literature, particularly with regard to ecological systems (for example see Gunderson and Holling, 2001) and by Fiering with regard to water resource systems (1982). A brittle service is one which is stopped or substantially deteriorated by even small changes in external circumstance. A brittle service cannot be maintained when subjected to external hazards and challenges to its normal operation and is less able to return to a satisfactory state.

It is possible to conceive of brittleness and resilience as two ends of a scale, with a fully brittle system only able to operate under completely static conditions and a fully resilient system able to operate under any circumstances. A highly-sensitive, controlled, scientific experiment might therefore be said to be highly brittle, where as a bitumen road is relatively, much more resilient.

2.3. Links with other branches of study

The degree of resilience in a system is determined by a range of attributes, systems, processes and norms and it therefore links very strongly with many areas of study where the concept is sometimes not overtly considered. Resilience does share some similarities with the concept of sustainability, the meaning of which has never been specific enough to form the basis of a commonly-accepted methodologically-based assessment. This is partly because, as with resilience, its exact meaning is significantly influenced by the education, experience and culture of the individual who seeks to apply its principles (Filho 2000). However, unlike for resilience, engineering companies and policy makers have developed a range of methods which seek to assess the 'sustainability' of projects and infrastructure; for example Arup's 'SpeAR' (2011) and the BREEAM environmental assessment (2008) advocate the use of a mix of qualitative and quantitative assessments against sets of given criteria. As discussed later a similar approach might be possible for assessment of resilience.

Fields of study in asset management are a very important area of overlap since in providing a water service the configuration, condition and operation of the various assets are fundamental in determining reliability, resistance and redundancy. Considerations in good practice asset management are explained in detail in BSI PAS55 (2008). Examination of good practice in asset management suggests that resilience is one objective of asset management (although it may not be considered as such), to be balanced alongside other objectives such as cost efficiency and regulatory compliance. Related to the assets in the system, obvious areas of importance in a resilience context are the specific tolerances, allowances and safety factors. The design specifications of assets and their performance against these specifications plays a big role in determining the resilience of the system which relies on those assets. There is extensive technical research on these subjects, both relating to the general concepts and the specifics associated with assets in use in the water service but a review of this work was out of scope for this research.

Resilience is very closely related to the fields of risk assessment of management, subjects on which there has been a great deal more research. As Blackmore et al. (2008) note there are intuitive similarities between risk assessment and resilience concepts and it is therefore important to understand the research which has been done in this area in order to begin to look at how resilience might be assessed. Assessing and managing risk is an inherent part of any human activity and there has been detailed academic study into the practice of assessing risks and processes for managing risks for decades (see for example Lowrance, 1976 and Rowe, 1977). In engineering contexts over the past few decades, managing organizational risks, and particularly health and safety risks to employees has led to lots of research into methods of reducing risks in complex systems, often driven by national policy (Reason, 1997). As a consequence of the great body of research into the nature and management of risks, and an almost unanimous recognition by policy-makers and regulators that risk-based approaches tend to lead to more stable service and more efficient solutions than a reactive approach to failures (see for example ISO 31000, 2009), complex risk assessment and management approaches have become common practice in the water sector[3].

The key differences between risk management and resilience have been explored in the literature. Blackmore et al. (2008), argued that the key hallmark of a ‘resilience approach’ to systems analysis as opposed to a risk-based approach is that it is a holistic approach which considers whole-of-system performance. Blackmore et al. describe a number of ways in which a purely risk-assessment driven approach might be more limited than a risk-based approach. However, as explained above, resilience is really a sub-component of risk and ‘resilience approaches’ have a number of shortcomings, most notably the fact that overall system resilience is much more difficult to quantify and validate than any individual risk. Logically, one way of assessing resilience would be to carry out a comprehensive risk assessment relating to the system under discussion. In doing this you would be developing an understanding of what the threats to that system are and what mitigants already exist which help deal with those risks (Hollnagel, 2004). A comprehensive risk assessment should therefore be a ‘resilience approach’ as Blackmore et al. define it. However it is clear that for any complex system this is inevitably a very difficult and time-consuming exercise.

Emergency management is another area where there is a clear overlap particularly with the response element of resilience. This field is also known as business continuity planning and there are clear and consensus-driven principles and systems associated with this concept which have been established in the UK in recent years (most notably by the BSI in BS 25999:1, 2006 and BS 25999:2, 2007). Some sections of the literature focus entirely on this response element and how it can be assessed and improved in a complex system (for example the work of Knott and Fox, 2010). Research in this field has been used to develop the resilience of systems by increasing the effectiveness of a system’s response to hazards.

As noted in the section on definitions, resilience also has very strong links with the concept of adaptation, and is particularly closely associated with adaptation to climate change. Indeed adaptation can be seen as simply another term for the ‘non-equilibrium’ definition of resilience. The concept of adaptation has gained in importance over the past few years as the predictions of increasing climate risks have become widely accepted by politicians, by the public and in the academic communities operating outside climate science. Consequently there has been a burgeoning literature on this subject during the last decade and in much of this improving overall system

[3] For example every water company in England and Wales applies the principles of the capital maintenance planning common framework, which was developed by UKWIR in 2002 and advocated by Ofwat, in its maintenance planning. Further examples of risk-based approaches include the drinking water safety plans and the adaptation reports produced by all companies in response to a Defra direction in 2011. All these approaches involve assessing risks and planning proactive interventions based on the nature of the risks assessed and the social and company risk appetite.

resilience is equated with ‘adapting’ (see for example UKCIP, 2010). Adaptation has been defined as “adjustment in natural or human systems in response to actual or expected climate stimuli or their effects which moderates harm or exploits beneficial opportunities” (Adger et al, 2007). This definition clearly shows why resilience is an important part of the picture. If a system is made more resilient to existing risks which are expected to increase, it should be expected to better cope with future climate change than otherwise. Alternatively, if a system is brittle now, it may be expected to fail more often if it faces increased stimuli in the future. Climate change is a “risk multiplier” (GOS, 2011) and hence in the context of climate change, a system which is resilient now might not necessarily be so in the future. It is important to bear this in mind when considering the historic information considered in phase 2 of the research.

2.4. Legislative Context

A brief exploration of the overall policy context is important in order to understand the research context. The basic responsibilities and expectations associated with the water service derive from the Water Industry Act 1991 (as amended). It is from this legislation and its accompanying statutory instruments that the basic definitions of satisfactory water service are derived. These legislative requirements cover the three aspects of service detailed in the research aims. Some of these standards are intended to be immutable (such as drinking water safety). The most recent piece of legislation related to service resilience is the Civil Contingencies Act 2004, the provisions of which are still being implemented. That Act effectively drove the working definition of resilience at the national policy level, defined key national responsibilities and created new powers designed to improve national resilience. The provisions of the act included powers and responsibilities for ‘category 2 responders’, which includes water companies.

The most important thing to note for the purposes of this research is that the legislation does not set standards of protection, or standards of risk management which the water service is expected to meet. Indeed some subjectively defined exemptions exist in statutory instruments related to external hazards such as ‘severe weather’ (‘The GSS Regulations’, 2008). However there are statutory obligations which require water companies to ensure they have certain processes in place or meet certain requirements in emergency situations. The Security and Emergency Measures Direction is the most relevant of these (‘The SEMD Direction’, 1998). Under this the water companies are required to have independently certified plans in place to deal with any unavoidable failure of the piped water supply by providing a minimum supply of water by alternative means. The plans should include provision to maintain piped water supply as long as possible, by any means considered to be reasonable and practicable, for example by installing temporary links with neighbouring systems or at a pressure lower than normal with due regard to ensure that the water supply remains wholesome and fit for human consumption. The plans should aim at commencing the distribution of water by alternative means as soon as possible after the failure has occurred with a view to providing at least 10 litres of water per person per day to all those affected within the first 24 hours and maintain this supply until the piped supply is restored.

This is the absolute minimum baseline level of protection which companies strive to meet in emergency situations. But against this legislative background it is largely left to ad-hoc interpretation and agreement between the companies, customer bodies, regulators and government departments as to how resilient service should be in different times and places.

2.5. Methods of assessing system resilience

As explained earlier, resilience is related to both physical and socio-political characteristics and is driven by design, location, build, operation and maintenance (Coaffee and Bosher, 2008[4]). This means it is impossible to understand resilience on a “product-by-product basis” – focusing on individual assets or groups of assets – as this will only give part of the picture; examination of the context of the system is required (Little, 2004). This makes resilience a very broad subject for study and perhaps as a consequence there are relatively few methods which have been applied for assessing system resilience. Those which exist tend to have been carried out with a low amount of detailed scrutiny. One reason for this is perhaps that it has only come into common use in the policy arena during the last decade (for example see a BBC article from March 2004) and as such the demand for reliable assessments of resilience have been limited. Much of the focus on improving resilience in Government and the water industry as an aim in and of itself was prompted by the Pitt Review of the 2007 floods which contained 92 recommendations for action (Pitt review, 2008), all of which were accepted by Government. This catalyst prompted a significant amount of debate on the subject during the last water sector price review in 2009. A second possible reason for the limited number of applied examples may be that resilience is too broad a concept to be a feasible object of focussed research. The success or failure of this research should at least tell us something useful in answer to that question. Potential methods for testing resilience include process checklists, risk assessments (as explained above), event exercises, interviews and modelling; some examples are explored in this section.

There have been very few academic studies of the overall resilience of water supply systems in the way defined here. There has been focus on the general resilience of urban environments (e.g. White, 2010 and Graham, 2009) often linking with wider sustainability considerations but these studies tend to focus on only the most material high-level risks and disasters facing cities and towns, although they do usually include both threats to water supply and quality and urban flooding risks. The approach taken in these examples is to review the available research and policy landscapes and discuss in general

[4] Coaffee and Bosher also make an interesting point that aesthetic design choices can often conflict with resilience (e.g. glass buildings can represent a significantly higher risk in the event of terrorist hazards) but in the water sector aesthetics is rarely a driving feature of modern asset design, underground or otherwise.

terms the relative importance of different high-level risks facing the urban system and the feasibility of potential solutions to these risks. Similar approaches have been taken by national and international bodies in studies on the resilience of water supply services in the face of climate change (e.g. WHO, 2009).

There have been attempts to arrive at quantitative assessments of resilience. The work of Hashimoto et al. (1982) sought to develop indices related to how a system would recover from short-term supply shortages and is frequently cited as the first such attempt. Building on this model some researchers have developed resilience indices which in theory could be used to comparably assess resilience across time or between systems. Prasad and Park (2004) for example developed a *network resilience index* in an attempt to quantify what they called system reliability. In most cases these index approaches have been applied only to specific external hazards which might affect the system (such as flooding in the cases of Balica et al, 2009), or particular system attributes (such as pipe internal energy dissipation thresholds in the case of Todini, 2000). In these contexts the formulas required can be kept relatively simple. However taking this sort of approach is at odds with the definition of resilience derived above and given by Hollnagel et al. (2006), because it requires limited focus and therefore cannot represent the whole context of the system.

Wang and Blackmore (2009) propose a systems analysis approach for water supply systems which derives quantitative results. However they were only able to provide an example of this method in use for a very limited water supply system – a single tank supplying a single property. Modelling approaches have also been attempted, for example Reca et al. built on the work of Todini (2000) to attempt to develop a model for assessing the reliability and cost implications of different water distribution network approaches (Reca et al, 2008). Like the index approaches, such modelling approaches have tended to confine themselves to small theoretical networks and have explored only a few network characteristics. They are therefore somewhat detached from reality and remain very difficult to apply to large complex networks. As such these methods are unlikely to be particularly useful for assessing resilience of water service on a national scale in line with the definition given above.

Qualitative approaches based specifically on assessing processes have been used, for example Caralli et al. (2011) proposed a ‘Resilience management model’ which is focussed on process improvement. The point of this approach was to draw together a list of actions which can be done to increase resilience of a system and then use that list to assess where shortcomings in a particular system are and where improvements could be made. The focus in this approach is firmly on people, information, technology and facilities. Therefore these sorts of process approaches only offer part of the picture and tend to focus on the response and redundancy elements. Similar approaches have been trialled for assessing adaptation, such as that developed by Wilby and Vaughan (2011) and the NI188 indicator which was used to assess local government adaptation progress (Defra, 2008). Most recently the Cabinet

Office has given an explanation of the steps a company is expected to have been through in order to have understood and improved its resilience (Cabinet Office, 2011). However there are no applied examples in the literature where assessments against these notional best-practice approaches have been done.

Probably the most comprehensive assessments which give a view on the resilience of service have been carried out by water companies themselves, rather than academic researchers. And it is therefore in work by these agencies where the most promising approaches to assessing resilience of the water service probably lie. For example, on drinking water quality the policy direction has placed a firm emphasis on comprehensive risk assessment and management encompassing “all steps in water supply from catchment to consumer” as the means of securing safe drinking water supplies (Bartram et al, 2009). The production and evaluation of drinking water safety plans is one approach to providing an assessment of the resilience of the system with regards to drinking water quality.

Finally, a difficult and resource-intensive method of testing aspects of resilience which has also been applied is through exercises and drills. These are used frequently in the water sector to test responses to local risks (for example the potential escape of ozone at treatment works or the detection of cryptosporidium oocysts in the water supply) and have been used in recent years as a means of testing resilience to national risks. For example the Government’s ‘Watermark’ exercise, which took place in March 2011 was a simulation of a national flood event designed to test the command and communication protocols at the national level. The focus of such exercises is inevitably on the response component of resilience but it is a useful way of discovering potential problems and shortcomings of resilience and the components of a system which weaken the resilience of the whole (Environment Agency, 2011).

2.6. Conclusions

The most appropriate definition of resilience to use in this context is a measure of the ability of a system to perform its functions in the face of perturbations in its operating conditions such as environmental variability. This means that some risks which a water service faces, such as asset failure resulting from ‘wear and tear’, were not included. The definition used in this research was based predominantly on the current parlance in the sectors which were under investigation, where it has recently gained in prominence and it is clear that this has a solid (but not unanimous) basis in the academic literature. This definition has been used in order to avoid confusion in the research process and to produce conclusions which are intelligible for decision-makers in the sectors.

Different methods for evaluating resilience in these terms have been explored in the academic literature but there is no single best-practice approach. Furthermore, an assessment of water service resilience has never been systematically attempted. There is also the fact that resilience will vary over time and between regions due to the wide range of factors which determine how resilient a system is and the inherent nature of risks. As a consequence it is difficult to establish a consensus on whether the resilience of the water service in England and Wales needs to improve or not. Some useful approaches have been suggested in the literature but not been practically applied. In industry there had been progress, for example in the 2009 business plans, but the coverage has been fragmented or covers only one or two hazards – e.g. fluvial and coastal flooding. Ideally there would be some middle way between detailed index-based or risk-assessment methods (which in practical terms can only explore one attribute or risk), and the high-level, low-detail assessments. The remainder of this research seeks to develop an example of such an approach which can be built on in the future.

3. Analysis of data on service failures

3.1. Introduction

A straightforward means of assessing current and historic resilience is to look at national and regional data on service disruptions. The reasoning behind this is that a resilient service should have fewer service disruptions over time than a brittle one. This approach is commonly used to assess the success of measures in the water sector and improvement over time, for example Bridgeman (2011) looked at drinking water quality compliance and performance against service indicators at an industry level and concluded that in most areas of service, key performance measures show a clear improvement trend.

There are three main provisos to consider when using this approach.

- Reliable and comparable information about service has only become available over the last twenty years as monitoring and reporting has improved. Given that some hazards (for example rainfall events exceeding the sewer design capacities) are estimated to occur with less than 0.5% probability in a year this period may be considered a small sample size.
- Various accounting, political and reporting conventions, many of which have changed over time, may mask actual performance. For example, the method of reporting ‘low pressure’ events and the criteria under which fluctuations in a customers’ pressure service level may be excluded from publicly reported data have changed over time as discussed later in this section.
- Data of this kind may not reflect the fact that external circumstances (and the associated nature of the risks) change over time – for example the data are unlikely to reveal resilience to risks under circumstances of future climate change. Therefore this approach can only demonstrate resilience to events which have a precedent.

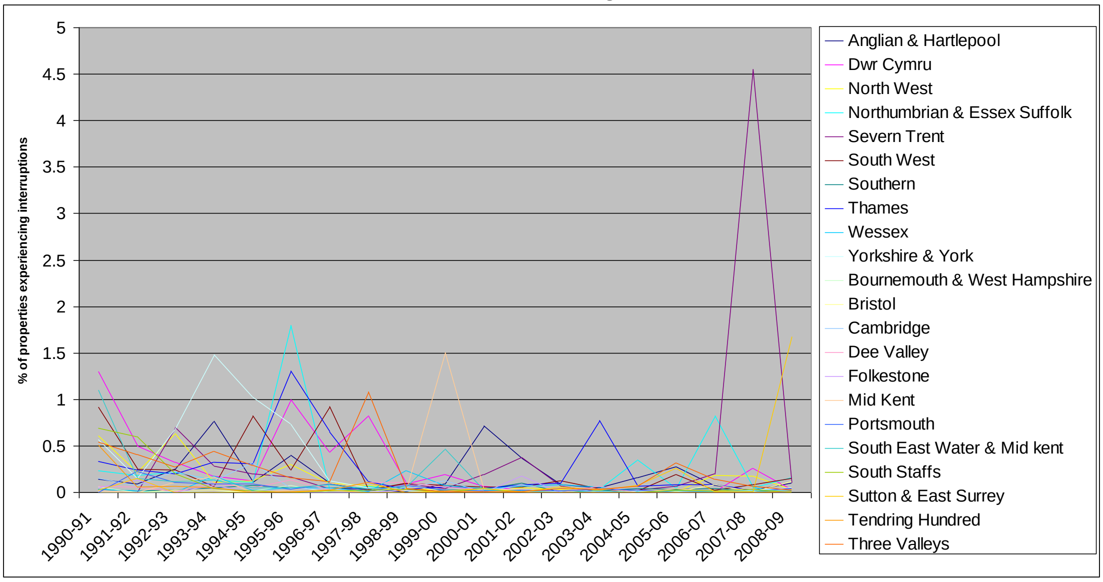
As explored in the literature review, resilience is highly likely to change over time as risk and vulnerability vary. Also many of the external hazards to which we might expect a water service to be resilient may be of a frequency less than the period for which data are available. Many of the possible hazards have never materialised during the period. As such, this is an imperfect approach to measuring a present level of resilience.

The analysis below focuses on the three key aspects of water service described in the introduction: supply interruptions, drinking water quality and pressure incidents. The information presented is drawn from water companies' annual regulatory reporting submissions for the years 1990 to 2010. Information is provided both in data tables and in commentaries on specific points of data.

3.2. Unplanned interruptions to supply

Figure 2 shows the % of properties served in each water companies' region experiencing supply interruption above 6 hours between 1990 (when this measure began to be consistently collected) and 2009. This data does not include legal supply restrictions ("hose pipe bans") which are covered in section 3.3. As this data shows, almost every company has seen one or more years during the period where there have been significant increases in the number of customers experiencing supply interruptions. However the percentage of properties generally remains below 2% and only exceeds this on one occasion for one company.

Figure 2 – Unplanned water service disruptions over 12 hours from 1990-2009 as a % of each water company's customers



The following table presents the most significant single events of service disruption identified in the data presented above. Table 1 describes events where water supplies were interrupted for more than 0.5% of a company's water service customers for over 12 hours or more.

Table 1 – Significant supply interruptions since 1994

Year (April to March)	Water Company	Cause	Number of properties without supply and length of the period
1994-95	Thames Water	Low winter temperatures caused a high frequency of bursts.	4600 over 24 hours.
1995-96	Welsh Water Thames Water	Both companies cite severe winter temperature causing a high numbers of bursts. Thames Water also cite severe summer temperature highs in July 95 caused more bursts.	7000 properties over 24 hours 10000 properties over 24 hours
1997-98	Three Valleys Water	Burst on a strategic 21 inch diameter main in Harlow, followed by two further bursts following the repair.	3000 properties over 24 hours; Over 12000 properties for more than 12 hours.
2001-02	Severn Trent	Strategic main burst interrupted supplies to around 15,500 properties.	10700 properties for over 24 hours
2001-02	Anglian Water	Bursts in Daventry causes as a result of scraping and relining mains previously when replacement would have been more advisable but more costly.	2500 properties for over 24 hours
2003-04	Thames Water	Three major atypical events (trunk bursts) in London at Enfield Road, Brent Cross and Peckham adjacent to a storage reservoir.	13000 properties for over 24 hours
2004-05	Northumbrian Water	Flooding incident at Hexham - two strategic mains crossing a river catastrophically failed. (note that if only one had failed service would not have been affected).	>6500 properties over 24 hours
2005-06	Three Valleys Water	Severely hit by a single burst main incident, causing loss of supply.	over 3000 properties for over 24 hours
2006-07	Northumbrian Water	Failure of 18" main at Middlesborough and Bedlington.	>8000 properties for over 24 hours
2007-08	Severn Trent	Flooding of Mythe Treatment works during summer floods.	130,000 properties for up to 17 days
2011-12	Thames Water	Burst main repair complicated by damaged nearby gas main.	50,000 properties for unknown nr hours.

Source: Analysis of annual regulatory return data and commentaries and queries to individual companies concerned.

There were only 11 occasions in the 15 years from 1994 to 2009 where more than 0.5% of any company's customers were without supply for more than 12 hours at one time. The most frequent cause of such events is strategic mains failures. Explanations for failure of these include inadequate maintenance, severe winter weather and fluvial flooding. It is arguable that there is some inherent bias in the nature of the explanations in some of these cases. For example there existed little incentive for a company to write detailed explanations of any shortcomings in company procedures or responses which may have contributed to the nature of the service failure. This is due to the fact that in this context the company was explaining its performance to a regulator in the context of defined regulatory outputs, which are enforceable by negative penalties on the company. Investigating these biases further and the nature of the political relationships driving this would be a useful area for further research.

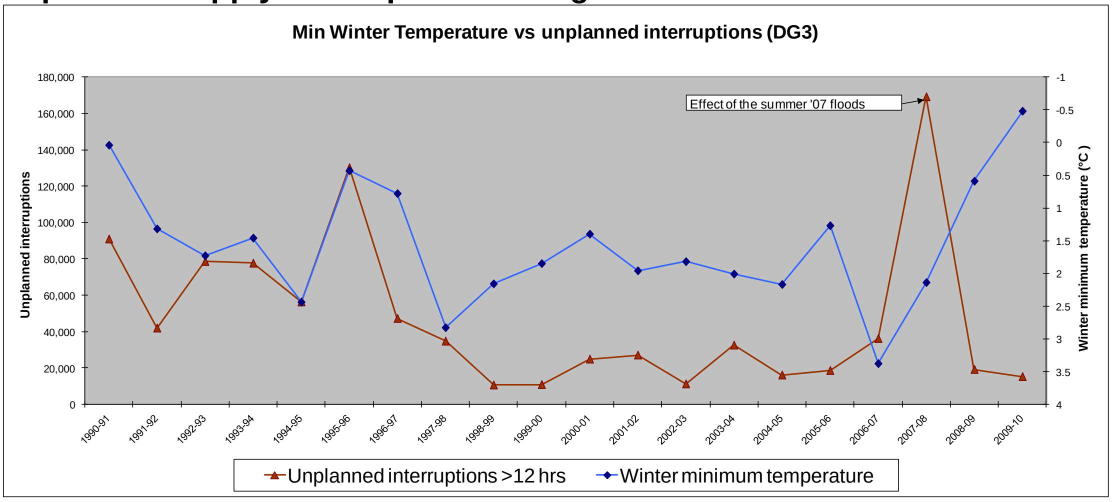
It is noteworthy that failures at non-infrastructure assets (treatment works, service reservoirs, pumping stations) have never caused significant disruption to supply (excluding quality failures), except in the case of the 2007 floods.

Of the drivers for these events, only cold weather and flooding can be considered ‘external hazards’ as defined in section 2. These are discussed in more detail below.

3.2.1. Cold weather

A relationship between cold minimum temperatures and unplanned supply interruptions is shown in figure 2.

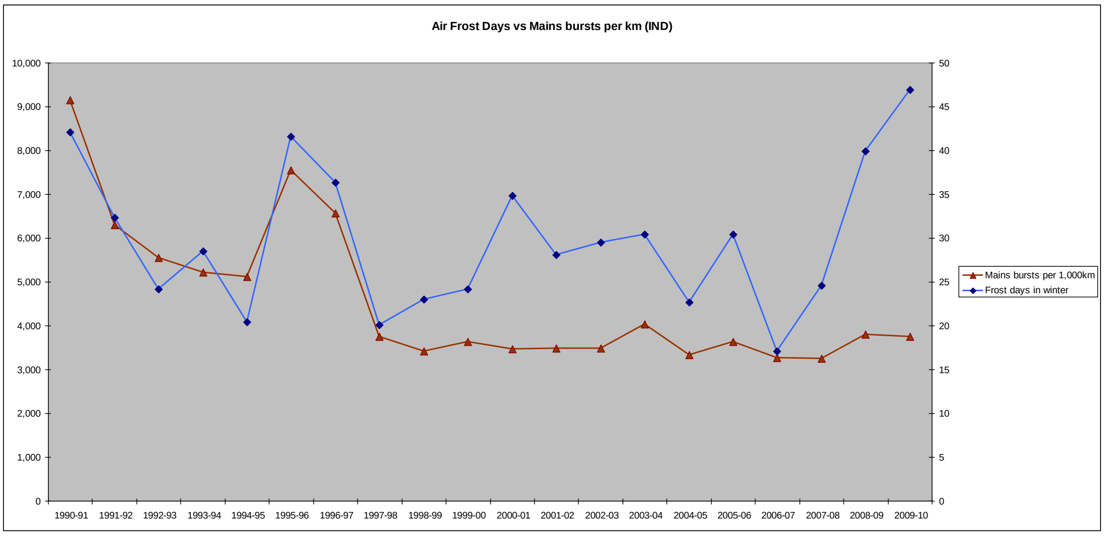
Figure 3 – Minimum annual winter temperature shown with number of unplanned supply interruptions in England and Wales 1990-2010



Source: June Return Data and Met Office Publicly-available Weather Data

The cold spell in 1995-96 affected two companies particularly badly. After that the effect of cold weather on interruptions to supply, even on occasions where situations were comparable to 95-96 such as 2008-09 and 2009-10, appears to be negligible. This indicates that cold weather *per se* is less of a significant driver of service failures than it has been in the past. The same is true of infrastructure asset performance. For example, figure 4 below shows number of air frost days (the number of days where the air temperature dropped below 0 °C during the day) against bursts per 1000 km of mains. The two appear closely correlated, particularly at the points where winters were coldest, up until the start of the 21st century. From this point the level of bursts has stabilised, suggesting that the network (in terms of underground infrastructure assets) have become more resilient to cold weather than in the past.

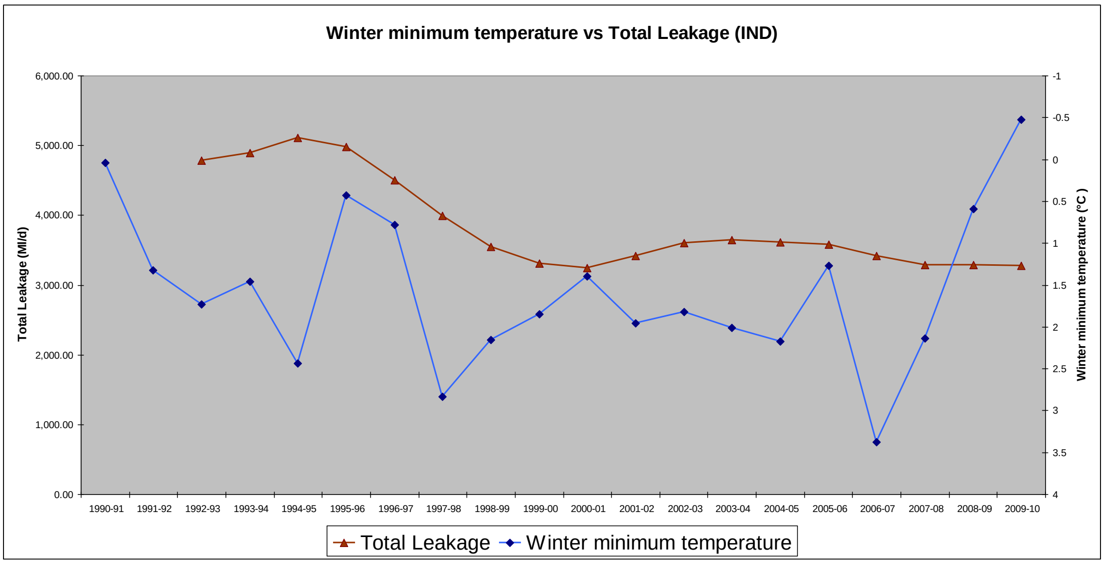
Figure 4 – Air frost days and total mains bursts per 1000 km in England and Wales 1990 to 2010.



Source: June Return Data and Met Office Publicly-available Weather Data

Given that the analysis above shows that pipes are bursting in response to cold weather, we also investigated whether they were still fracturing due to cold weather – but less obviously (i.e. the pipe was failing but not in as identifiable a failure mode) and if they were, whether these fractures were being addressed more quickly. This can be represented by leakage, as data on leakage is readily available. Figure 5 shows leakage levels against minimum temperature and demonstrates that there is little correlation between cold years and overall leakage levels. This is particularly obvious when we compare data for 2009-10, which included a very cold winter. Despite this, leakage levels remained stable.

Figure 5 – Winter minimum temperatures shown against total leakage levels



Source: June Return Data and Met Office Publicly-available Weather Data

These data suggest that companies are more resilient to cold weather than they were in the past. However, it may also suggest that other factors play a bigger role in driving the level of leaks and bursts than the cold weather.

Having said this, as indicated above, the winters from 1998 to 2009 were all milder than the climate average (as measured from the 30-year period from 1970 to 2000), so the occurrence of cold weather events which actually affect the assets to a significant extent has been lower in all these years. This analysis (based on the available weather data) also cannot directly indicate other environmental factors such as ground movement or rainfall which more directly influence levels of bursts and leaks. It is also likely that asset failure is more closely related to certain critical thresholds being exceeded (for example absolute minimum ground temperature below a certain threshold) rather than average air temperature over a month. This effect cannot be revealed from the high level data presented here.

The high-level data suggests that companies have reduced their vulnerability to cold weather; either through improved assets or improved asset management, (for example specific winter contingency plans). There have been no major incidences in recent years where service has deteriorated outside the normal range (about 2SD from the mean) as a result of cold weather.

It was possible to draw conclusions about the current resilience of the network to cold weather from the effect on service of the cold December in 2010. This was the December with the coldest average temperature of all Decembers since 1900 and the coldest single month since privatisation. It was also notable because temperature fluctuated to cause freeze-thaw events in a relatively short space of time of the type, which affect infrastructure networks in particular (Met Office, 2012). Information from the companies suggests that there was a large increase in the amount of contacts and repair activity during the 2010 Christmas period. In one region there was a 330% increase in burst mains and in another region the water being put into supply peaked at 600 Ml/d (35%) higher than the average for that time of year[5]. This resulted in more than 50,000 properties suffering an unplanned interruption to supply lasting more than 12 hours compared with 15,000 in the previous year. However, in England and Wales there were no analogous events to the situation which arose in Northern Ireland during the same period, where the service impacts were much more significant, with 46,000 people being completely without water for over 12 hours at one time. Northern Ireland Water reported they were putting 40% more water into supply than normal[6]. Given the population differences between Northern Ireland and England and Wales, it is clear that the companies in England and Wales were more resilient to the weather event that occurred during that time than Northern Ireland. However it must be noted that the temperature average in Northern Ireland was 0.5°C colder than in England and Wales so the hazard was

[5] CC Water Regional Meetings 2011; Minutes available from http://www.ccwater.org.uk/server.php?show=nav.819 (accessed July 2012)
[6] NI Water press notice (29 Dec '10)

marginally more severe. An area for further work would be a more in-depth comparative analysis of the Northern Ireland water service failures. This would likely generate a number of useful conclusions about water service resilience and how it can be improved. This has not been covered in more detail here as the research focus was on England and Wales.

3.2.2. Flooding

Since privatisation, the most severe cases of service failure arose as a result of flooding. As shown in table 1 there was a significant water supply disruption for 130,000 customers for over 13 days. This was due to a number of extreme rainfall events following a period of consistently high rainfall in the summer months of 2007. This resulted in flooding of several critical water company assets, most notably the Mythe water treatment works.

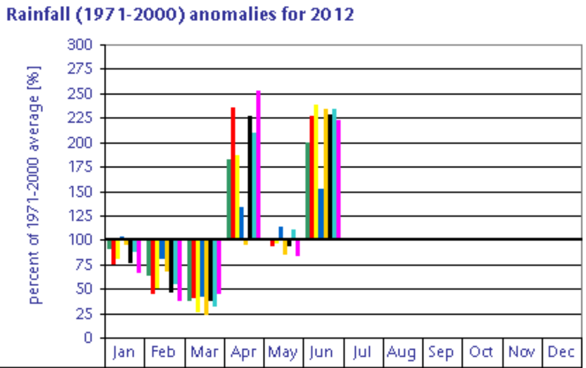
This event highlighted the vulnerability of large numbers of customers supply to disruption of large critical assets, particularly treatment works and hence a lack of resilience of these assets to extreme events. The consequences of that event have not been re-analysed in detail but this research considered the multiple learning points on network flexibility, flood defence and emergency planning which came out of the event and the following investigation (Severn Trent, 2007). The recommendations and features have been incorporated into the methodology explained in section 4.

It has been identified that over 900 clean water pumping stations and water treatment works (>50% of those in England) are within EA flood risk areas, and the majority of these are assessed as being in “significant” flood risk regions (Environment Agency, 2009). This is because most water treatment works (and associated pumping assets) are sited near to a raw water resource (often the rivers identified as being the source of flood risk). Despite this, on a proportional basis it is a very small proportion of works which have been flooded.

It should be noted that the more frequent cause of supply disruption resulting from flooding has been the impact on critical mains, rather than treatment works, such as the Hexham disruption in 2004-05 when flooding caused the failure of large trunk mains located at waterway crossing points. Although these events are more common, they usually result in disruption for fewer customers for a shorter period of time partly as they are more straightforward to rectify.

More recently the abnormally high rainfall in April, June and July 2012 (illustrated in figure 6) caused significant localised flooding. However there has been minimal impact on the water service across England and Wales, with most critical supply assets remaining operational. Although the severity and quantity of rainfall has been marginally less severe than in 2007, this suggests an increased level of resilience to flood risk.

Figure 6 – 2012 Monthly Rainfall anomalies for 2012 compared to 1971-2000 climate average



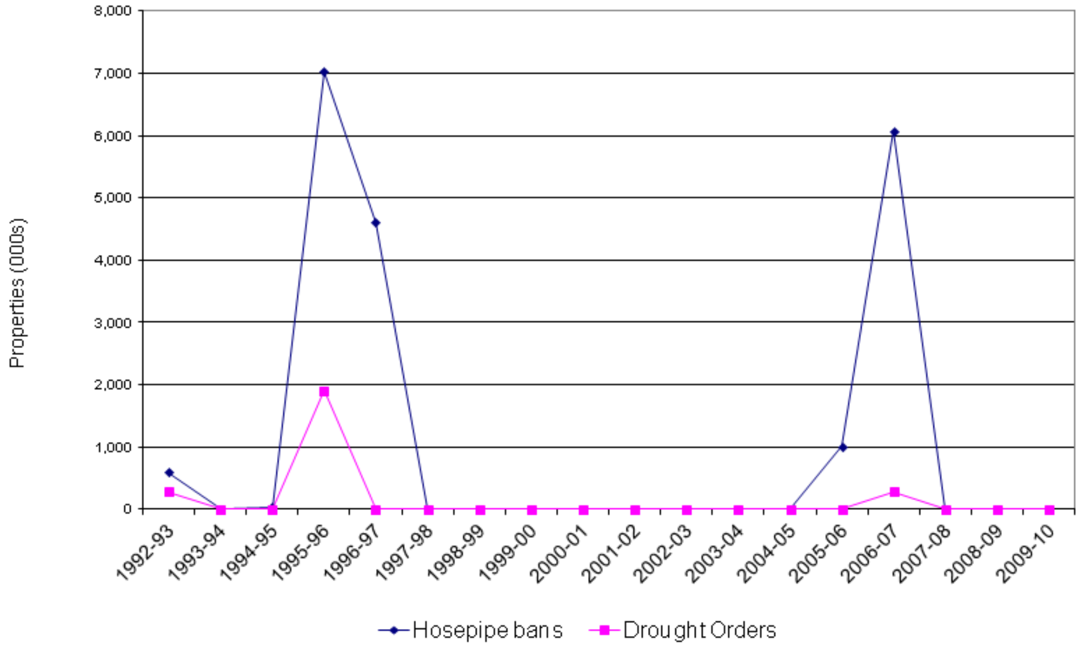
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UK	90	63	38	182	101	200						
England	75	44	40	236	94	227						
Wales	80	51	26	187	96	238						
Scotland	104	80	41	134	113	152						
N Ireland	95	68	23	95	85	235						
Eng and Wal	76	46	37	227	94	229						
England N	88	54	32	210	110	234						
England S	67	38	45	252	83	222						

(Met Office Data, Downloaded July 2012)

3.3. Supply restrictions and drought permits

Water companies have legal powers to impose temporary water use restrictions as a means of controlling demand where there is a risk to supply. These are usually employed where dry weather threatens the balance of supply and demand. Similarly, drought permits which allow special measures such as abstraction beyond normal regulatory limits, can be granted to companies where the Environment Agency is convinced that the weather is unusually dry. The number and extent of such restrictions and permits is therefore a useful indication of how resilient the service is to periods of dry weather. The % of customers subject to any supply restrictions in each year is shown in figure 7.

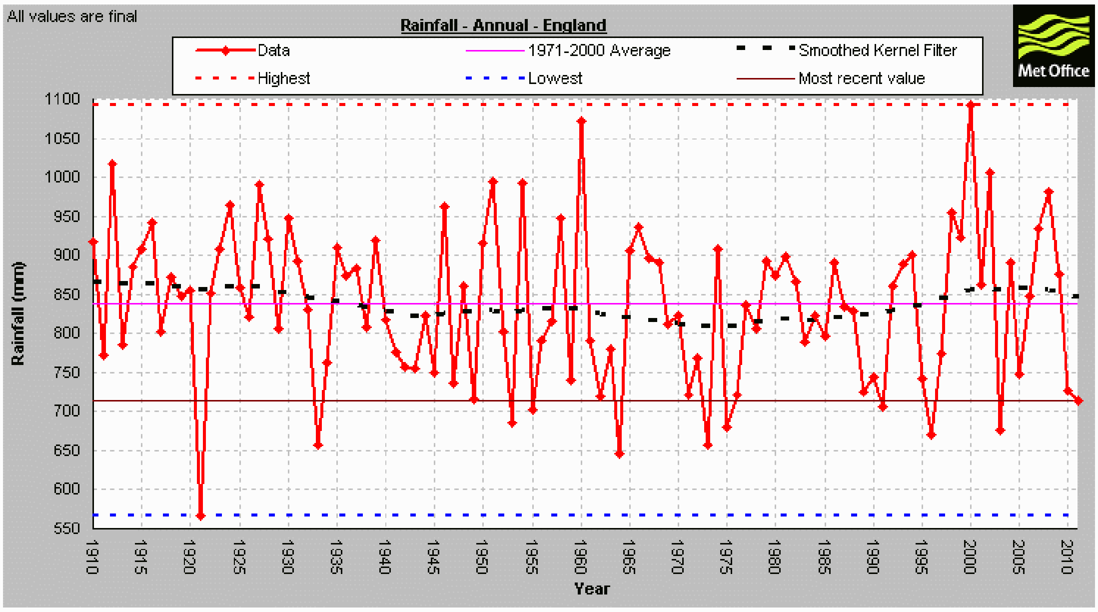
Figure 7 – Number of customers in regions subject to hosepipe bans or drought orders from 1992-93 to 2009-10.



Source: June Return Data

As this graph shows, supply restrictions due to drought do occur periodically and are still necessary during periods of dry weather. In the 2011-12 year there were a number of supply restrictions in the South-East (data has not at this time not been published on number of customers affected). It is noteworthy that the number affected by the dry weather between 2004 to 2007 (which drove the supply shortages in 2006-07) was lower than the number affected in the dry period 1995 to 1997, although this is partly reflected in the rainfall records which show a consistently drier three year period between 1995 and 1997 than was the case between 2003 and 2005. The rainfall records are shown in figure 8.

Figure 8 – Annual rainfall in England



Source: Met Office 2012: http://www.metoffice.gov.uk/climate/uk/

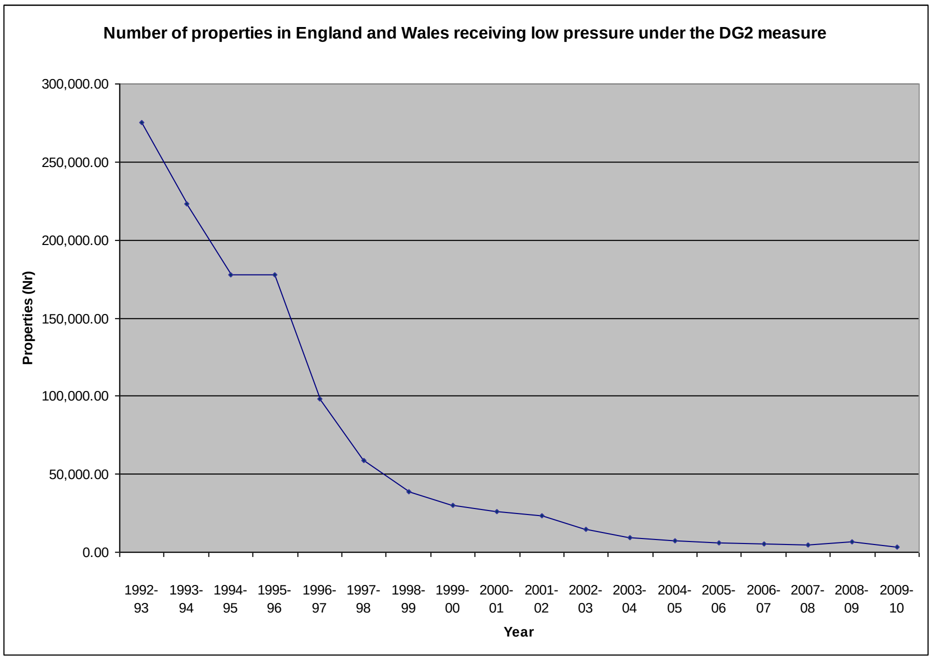
We may conclude from this that the water service, particularly in the south east is not fully resilient to the effects of dry weather prolonged over a number of months, and particularly persistent multi-year dry periods. Supply restrictions are unpopular and draw negative press attention so whilst service is not affected per se, they would not be deployed unless the risks to service were high. Supply restriction events as highlighted above do not mean that water customers' supply has been completely cut off or that pressure or drinking water quality decline. Drought permits and hosepipe bans can be seen as one measure within the water service which allows the reduction of service risk during dry periods.

3.4. Pressure

On pressure, the number of properties experiencing pressure below the 'reference level' of flow of 9l/min at a pressure of 10m head on the customer's side of the main stop tap has declined every year.

It is important to note that pressure at the property is often calculated using a surrogate measure and a factor (i.e. an accredited measurement of pressure is only taken at the mains not the tap).

Figure 9 – Number of properties receiving low pressure.

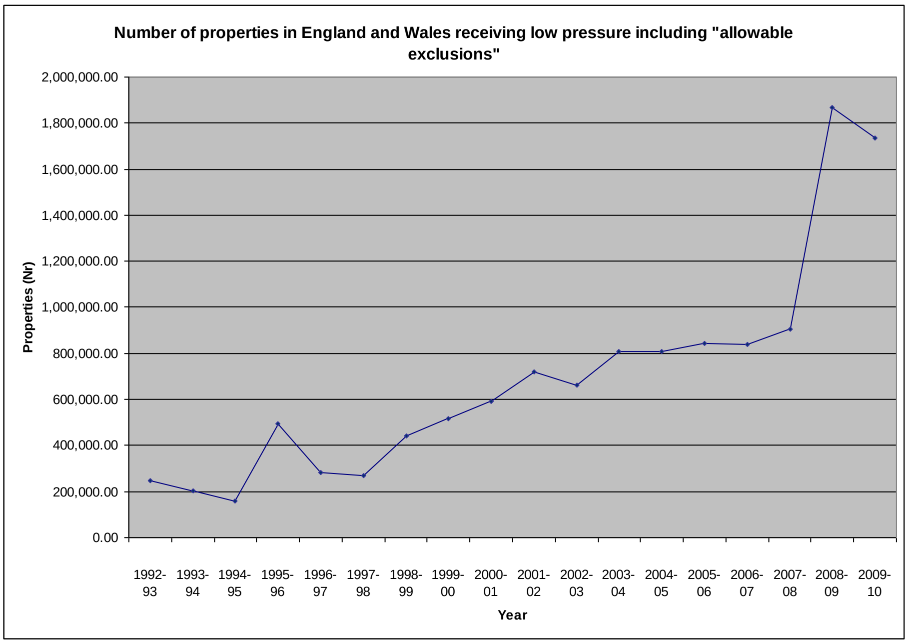


Source: June Return Data

This measure shows continual and steady improvement in the number of properties receiving low pressure. However the indicator used to track progress in the sector uses a number of "legitimate exclusions" which include the sorts of events to which companies might not be resilient. For example 'One-off incidents' which covers a number of causes of low pressure are excluded- these can include mains bursts, failures of company equipment (such as PRVs or booster pumps), fire fighting; and 'action by a third party' (Ofwat, 2009). Low pressure caused by maintenance can also be a legitimate reason for excluding from this measure.

The aim of these exclusions is really to focus efforts on what can be controlled without creating a perverse incentive to companies to deal with problems over which they have little control (such as customers' own pipework). However the effect of them is to mask the effect of failures of resilience in the reported statistics. Therefore we can conclude that this measure is not an ideal measure of historic pressure resilience. Figure 10 shows numbers of properties experiencing low pressure including those as a result of 'allowable' exclusions.

Figure 10 – Number of properties receiving pressure below the expected standard.



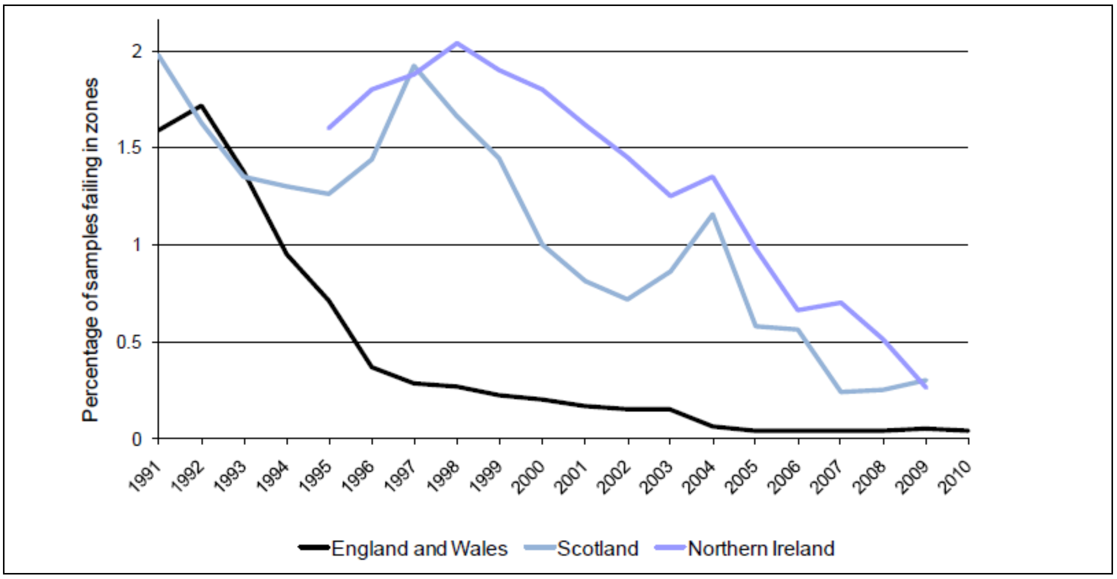
Source: June Return Data

Under this measure pressure failures have actually significantly increased over time, which suggests that companies have become less resilient. However, the research suggested that this was due to companies installing better monitoring equipment on their networks and picking up pressure fluctuations which previously went unrecorded. This is therefore not a comparable measure over time as an indicator of resilience. Another measure which could be used is the number of customer complaints driven by low pressure incidents, which would be a worthwhile area for further analysis.

3.5. Quality

Failures of drinking water quality are relatively rare and have been significantly reducing over time as can be seen by the quality regulation compliance performance over time (figure11).

Figure 11 - Percentage of tests failing to meet quality standards from 1991 to 2010



Source: DWI Annual Report 2010 (June 2011)

This strongly suggests increasing resilience on drinking water quality especially given the fact that standards for drinking water have been consistently rising over the last twenty years.

In cases where the Drinking Water Inspectorate believes the company is at fault under the Water Supply (Water Quality) Regulations, it has powers to take action. The number of occasions where it does take successful legal action may be used as one proxy measure for a company's business as usual and response and recovery processes. Successful prosecutions are shown in Table 2.

Table 2 - DWI successful prosecutions and fined amounts (actual prices)

Incident year	Successful prosecutions	Amount
1991	0	-
1992	0	-
1993	1	£1,000
1994	2	£125,000
1995	2	£9,500
1996	2	£15,000
1997	16	£164,500
1998	9	£130,500
1999	1	£15,000
2000	2	£33,000
2001	0	-
2002	1	£3,750
2003	0	-
2004	3	£65,000
2005	0	-
2006	3	£92,000
2007	0	-
2008	1	£7,500
2009	0	-
2010	0	-
TOTAL	**43**	**661750**

Source: DWI data available at: http://dwi.defra.gov.uk/about/annual-report/2010/index.htm

The trend to fewer prosecutions in recent years suggests that companies are becoming more resilient to risks causing quality failures. However it could be a result of other factors, e.g. reduced regulatory effectiveness, legal issues or issues going undetected.

Where quality failures do occur they are often the result of asset failure (usually burst mains) or inadequate monitoring and sampling. Operator error is a cause in some cases, most notably the Camelford incident in 1988 which highlights the importance of operating procedures and training in ensuring the system and service are resilient. The most common causes which can be classed as external hazards are upstream contamination, most frequently either cryptosporidium or pesticides and weather impacts on raw water quality (For example weather was cited 3 times as a contributing factor in the issues highlighted by the DWI in 2010). Another external hazard which has caused quality issues is power supply failure, due to network distribution failures or even from lightning strikes. In all these cases a resilient treatment process and supply network would be expected to cope with the change in external circumstances and deliver potable water.

3.6. Conclusions

Taking all these measures together gives us an impression of the overall level of resilience in the water service of England and Wales. The data suggest overall improvement in service resilience – particularly on quality and constancy of supply – over the past couple of decades. Against this context it would be difficult to argue that the service is not resilient in current circumstances without evidence that there will be in the future some significant change in the nature of the risks borne by the service or a decline in the resilience of the service. A study of the data in this way does not enable us to make conclusions about these two things because it is a retrospective analysis. The data here only indicates overall performance, affected by a range of different factors and not the ‘resilience’ attribute of the system. It is therefore a useful and necessary context in answering questions about the level of resilience but it doesn’t fully answer the question. The second informative element it was possible to take from this analysis are the clues about the types of external hazards which are most common and how the existing systems have generally responded to those hazards in the past.

4. Evaluating resilience through process assessment criteria

4.1. Introduction

Companies, regulators and stakeholder groups in the water sector have recognised that 'resilience' is a desired outcome for the water service (Ofwat, 2010). There have been attempts in the sector, most notably by the regulator at the 2009 price review, to arrive at a means of gauging companies' progress at meeting such outcomes which are not readily measurable by any consistently used approach (unlike, for example, leakage performance). Therefore a need was identified to arrive at a method by which resilience of a water system can be gauged which also might identify elements requiring improvement or additional resource.

The research into past service standards and what makes a water service resilient enabled the generation of a list of expectations on features one might expect to see as part of a resilient water service. One institution which has responsibility for delivering water supply within a region of England and Wales was then assessed against these criteria. The core principles behind a resilient service and the details of the approach taken to evaluating against these criteria are explained in section 4.2. The results from applying this approach are described in section 4.3 and conclusions from this phase of the research are discussed in section 4.4.

4.2. Approach to evaluating resilience

Approaches which seek to measure the quality of a service where a quantitative evaluation is difficult or impossible have been used in the water industry in England and Wales. Such an approach involves establishing guidance or principles and then qualitatively assessing the success of a system or organisation in meeting those principles, usually based on a report or plan and questioning and answering processes. Regulators use such approaches where there is limited information available and where there is inherent uncertainty, for example assessing preparedness to future climate change. Examples include Ofwat's approach to assessing capital maintenance planning through an asset management assessment scoring system (Ofwat, 2009) and Government's approach to assessing 'adaptation' to climate change (Rance et al, 2012). Advantages of the qualitative approach include fewer requirements for data, less need for certainty about the future and low administrative burden. The biggest disadvantages are the high degree of uncertainty and subjectivity associated with the assessments and the perennial problems associated with attempting to measure actual performance and behaviour from stated processes and frameworks.

Some attempts at taking this approach for resilience in particular have been attempted recently. For example a questionnaire was provided to water companies early in 2012 by Mott Macdonald and the responses were analysed as part of their work to produce a report for Ofwat on principles for resilience planning (Mott Macdonald, 2012). This exercise provided a useful initial indication of some of the key tools and approaches used by companies and allowed conclusions on areas of potential weakness. It is therefore a useful starting point. However it does not give a clear picture of the level of resilience of the service in any particular system.

The method used in this research was similar. First a set of principles of resilience were explored, i.e. attributes and features of a resilient system. The principles arrived upon are described in section 4.2.1. The features of one geographic water supply system were then examined, using evidence from public documents and strategic business plans, internal processes and procedures and discussions with staff. There was no formal interview approach using a set of defined questions, although this would be one way to improve this element of the approach. In simple terms the process was to establish a list of the things that could be done to improve the resilience of a water system and then check whether these things are done. From this the intention was to enable an assessor to draw conclusions about how resilient a particular system is. The system under examination has been kept anonymous in this research because some of the information was deemed commercially sensitive. The study was intended to serve as an example of how this method could be applied to assess comparative resilience of different water systems and provoke ideas about how such a method could be applied and improved, rather than as an assessment of that particular system.

4.2.1. Principles of resilience

The purpose of establishing core principles of resilience was to enable some measurement of forward-looking resilience of a system, even if this was just in a binary way. The logic was that if these features are in evidence then the system is likely to be more resilient than one which does not have those features in evidence. This reasoning is similar to that employed with regards to capital maintenance planning. In the water sector the capital maintenance planning common framework is used as a basic set of principles and features which an optimal capital maintenance planning process should be able to evidence. The chances of making errors in risk assessment, project planning and capital delivery are judged to be lower if these features are in evidence. The common framework is fundamentally concerned with risk, primarily risks around asset deterioration and failure, and therefore this research sought to develop and apply a similar framework for ‘resilience’ planning which might overlap with an assessment of success against the common framework.

Outcomes from the literature review, from relevant government and regulatory guidance documents - for example PPS25 (DCLG, 2010) and Government guidance for category 1 and 2 responders (Cabinet Office, 2009) - and from a review of companies business plans, strategies and best practice guides were used to generate a long list of features and activities which are expected to be present in a resilient water supply system. The features and activities which were reached in the long list develop the general categories of resilience put forward by the Cabinet Office and were intended to be more relevant for the water service in particular. The long list of features which are expected in a resilient water system is shown in Table3.

Table 3 - Long list of features and activities you would expect to see in a resilient institution.

Category	Feature	Explanation
Strategy & Governance	A clear overarching strategy for service with concise, clear messages.	Important so staff and stakeholders (particularly contractors) understand the companies' priorities and to help justify business decisions directly in relation to service.
	Clear definitions and prioritisation	In resource-constrained world it is important that priorities are made clear so that resources are allocated in a proportionate way.
	Relevant key performance indicators	Provide the internal incentives to safeguard service and prompts the management pressure to reduce risks and react efficiently to issues. These should be closely and simply linked to states service priorities.
	Overall approach – a 'corporate resilience strategy'	Provides mandate to reduce risks and plan for failures. Without this mandate risks can go ignored and processes are not necessarily in place to cope with issues arising.
	Tolerances - what sorts of things the company is willing to accept and what are unacceptable.	Provides clarity which is important for risk management and resource allocation. If certain failures are tacitly agreed to be tolerable then this can lead to risks going unaddressed.
	Governance: Clear responsibilities for staff and others	Diffuse responsibility can lead to inertia ("not my job") or over-reliance on good will which can be unreliable. Clear responsibilities also themselves prompt action to understand and address risks in areas of responsibility.
	Appropriate (positive) incentives and penalties	True both internally and externally (e.g. Vandalism can cause significant service problems and the risk of censure is important).
	Clarity throughout organisation	Without clarity on service priorities responses to external hazards can be mixed or slower than otherwise. This is also true of clear responsibilities as diffused responsibilities can lead to ineffective action
Information and Data	Staff can communicate with each other	It is important that actions can be completed quickly, and this occurs more readily in a system where communication is clear, easy and efficient. Communication is important where a hazard arises so that action can be coordinated.
	Understanding of network and particularly where critical failure points are located	Allows a better identification and understanding of risks beforehand and a better diagnosis of problems when issues occur. This increases likelihood of resolving system problems to eliminate or reduce service failures.
	An integrated understanding of the network (not just isolated parts of the network).	It is possible to have a good understanding of the network but have this understanding diffused or split between areas. A wider understanding can help enable quicker resource shifting or enable more efficient solutions than would be possible using only a local approach.
	Good asset knowledge, reliable data (including of elements of the network out of control	Important in reliably identifying and assessing risks to service and will allow more targeted solutions if issues arise. This also increases the likelihood of optimised maintenance which reduces risks to service. An example would be understanding the condition and material of pipes further down the network and how they might be affected by a quality failure upstream at the works.
	Good forecasting of deterioration and risk.	Allows risks to be better prioritised and maintenance to be planned in a such a way as to reduce risks to service.
	Linked into weather forecasting services.	Allows earlier warning of external hazards and therefore increases the likelihood of pre-emptive action or timely remedial action.
	Linked into flood forecasting centre (available to national category 2 responders which includes water companies).	A specific example of the above - the flood forecasting centre can provide alerts to water companies at different risk levels days in advance and thus increase alertness allowing pre-emptive action or planning to reduce the time-scales of remedial action.
	Strategic and Regional Flood Risk Assessments analysed in relation to network	Allows companies to reliably identify and focus on areas of flood risk and hence plan work to minimise the risks or set in place specific processes to deal with the flood risks in that area.
	Good hydrological understanding of the network and its consequent service time thresholds (e.g. How long a particular service reservoir can supply a population before reaching low levels leading to service issues)	It is possible to have a good understanding network failure modes without understanding impacts on service, this is an additional set of knowledge needed across a range of groups to provide service resilience.
	Monitoring and alerts.	A system providing reliable early warnings of asset deterioration, asset failure, raw quality fluctuations or supply constraints all allow earlier action and therefore can help reduce risk of service failure. These systems are more efficient when part of an efficient telemetry network but they need not necessarily all be automatic, they can take the form of site checks or iterative surveys. Indeed periodic validation of monitoring equipment is a requirement of reliable understanding.
	Systems which react to alerts	Systems are needed which pick up alerts and notify the right person, otherwise they can go unnoticed.
	Reliable quality monitoring – e.g. on pH which can provide timely alerts.	A particular subset of the above it is important that water quality monitoring takes place to allow pre-emptive action on quality. Monitoring failures can lead to service issues downstream and may even necessitate supply restrictions.
	Network maps and knowledge available to relevant staff. (& up to date).	Linked to good asset knowledge, time can be wasted, and service risk multiplied where assets are unable to be geographically located by staff or contractors. Conversely risk can be reduced if locations are known and communicated.
Collaboration	Recognition of interdependencies with other organisations	External hazards might not necessarily affect the water system directly but might cause knock-on effects on a system on which the water system depends. There are risk reduction measures and contingency processes which can be deployed to mitigate risks arising in this way.
	Understand reliability of energy supplies	A key example of a universal interdependency risk, water supply systems rely inherently on energy. It is therefore sensible to understand the resilience of the energy supply system and put in place risk mitigants and procedures should it fail. A key example is backup generation.
	Contract provisions for calling on outsourced suppliers where necessary.	Some supplies and tasks are obtained from outside the water supply system, therefore a resilient system should prepare processes to call on outsourced suppliers at short notice where necessary, and include emergency provisions in contract arrangements if possible. This increases the chance of timely responses to arising issues.
	Engage with the regulators.	In the water sector regulators exercises a significant amount of control over water systems by setting price limits and regulatory targets. These are key factors determining available resources for companies. Where additional resources or certain service risks exist these should be discussed with regulators so that targets and price limits help balance risk rather than exacerbate it.
	Good relationships with external agencies and effective communication channels	When external risks materialise having good relationships and established communications channels with associated organisations can make it easier to enact mitigating action. Reciprocal aid arrangements can reduce the overall risk to the water system at minimal additional resource cost over the lifetime of the arrangement.
	Plan with others	Emergency planning is more likely to work when applied if it has been considered jointly with other organisations who may be involved. This increases the chance that snags can be addressed beforehand and thus enables more effective responses.
	Lobby effectively for others to reduce risk where there are reliances.	Many risks to a system are not within the control of the system controllers. However it is still possible to increase your own resilience by seeking to influence others who do control external risks to reduce those risks themselves. It is good practice to be sharing these sorts of risks where apparent
Risk	Identify risks to service	It is important that all the possible risks to service are considered at various points in a system. If some risks go unidentified this decreases the likelihood of them being effectively pre-emptively addressed or planned for. To remain valid this exercise should be iterative so that new risks are identified and considered.
	Consider external hazards which are infrequent	Risks which are infrequent, or indeed have never historically occurred can often be ignored. However it is good practice to identify risks which are feasible, even if infrequent and if this is not done the system is less likely to be resilient.
	Consider super-extreme risks - even though they are unlikely it is useful to consider them - are unexpected occurrences and can test systems.	Some risks are extremely remote, for example plane crashes into assets or earthquake disruption. However the cost of considering these risks momentarily is usually very low and whilst it might not be cost beneficial to address them, considering these sorts of risks can offer new perspectives on existing risks and processes. Considering extreme risks is also a good way to check the validity of contingency planning.
	Risk screening at a high level	Where risks are being identified in a resilient system there should be evidence that these risks are screened using some set of criteria so that they can be assessed and categorised depending on their nature.
	Risk assessment at company/business level	Risk screening itself will lead to a less tailored approach to risks and therefore it increases the chance of effective risk responses if the risks are assessed in more detail individually at business level.
	Risk assessment at asset level	Meaningful understanding of risks leading to effective responses is more likely at levels at which quantification and direct response are possible. Therefore the most resilient systems are expected to evidence understanding at granular levels of the system. This should be in evidence across the system and be related to the business-level understanding of risk.
	Risk management	A resilient system should have a process to follow through from risk assessment to risk responses.
	Iterative assessment	If risks are assessed as only a one-off exercise then it is likely the assessment will become less valid over time. It is therefore important that assessment is iterative. This also increases the chance that risks and processes will be front of mind.
	Risks shared	A system will not be resilient if a comprehensive risk assessment has been carried out but not communicated to those able to effect action. Therefore it is good resilience practice for risk assessments (or elements of them) to be shared with key agents in the organisation managing the system.

Category	Feature	Explanation
Interventions	Addressing risk where it exists	Evidence that where risks are highlighted as potentially affecting service that there are processes by which changes to the system can be affected to reduce those risk.
	Propose and carry out resilience improvements	Where risks to service exist, there should be evidence that the system is capable or working up practical risk reduction solutions which are then taken forward.
	Protected works.	A specific example of resilience improvements particularly relevant to the water industry, where threats to particular water treatment works and/or pumping stations have been judged to present risks to service, a resilient system should be able to organise itself to protect those works.
	Restricted access and security	It is important that malicious agents are kept out of critical areas to reduce risks. Whilst this has not caused significant disruption in the past the research found examples where metal theft and vandalism had caused asset disruption with consequent risks to service.
	Make and follow drinking water safety plans.	Plans for reducing all drinking water safety risks should be in place and there should be evidence that these are being followed. Companies are legally obliged to have drinking water safety plans so you would expect these plans to be in evidence.
	Addressing interdependencies	Relating to external risks, there should be evidence that engagement or intervention activity has taken place to minimise the shared risks.
	Solutions addressing multiple problems	A system is more likely to be resilient where there is evidence that solutions address multiple risks at once. This is likely to be more efficient and this feature would also suggest a better understanding of risks and the network.
	Quantifying differences made before and after interventions	If there is evidence of understanding of the difference which interventions have made to the risks to service, this puts organisations in a better position to reassess risks and take further action if necessary. If this is not possible the system may be subject to unforeseen risks and therefore be less resilient.
Maintenance (BAU): N.B. Since this is not a maintenance focussed method this covers the main elements you would expect from a maintenance regime relevant to the resilience of the system. As noted in section 2, the resilience of a system over time is deeply related to the effectiveness of the maintenance regime in place.	Responsive maintenance procedures (fix-on-fail)	A resilient water system will at least have proven fix-on-fail asset maintenance procedures with the aim of repairing assets before service is impacted. Evidence of this would be a minimum requirement of a resilient water system.
	Asset condition investigations	A resilient system should either evidence reliable asset knowledge or, where this does not exist, there should be rolling asset condition investigations so that risks can be spotted and addressed before they occur. This should inform proactive maintenance regimes and/or influence the provisions made for reactive maintenance.
	Proactive maintenance regimes. – service reservoirs, distribution, disinfection and treatment process control.	A resilient system should have proactive maintenance regimes with the aim of keeping the system perpetually in good working order by tackling assets before they fail and thus reducing risks to service. This includes replacement and repair activity but also general maintenance e.g. re-greasing, pipe cleaning, periodic disinfection.
	Provisions for maintenance in different conditions	For example cold weather, the resilience of a system can be expected to decrease if the maintenance planned and reactive can only occur in benign conditions. Risks to the maintenance regime can place risks on the service.
	Adequate equipment checks.	Business as usual in a resilient system should include consistent checks on equipment and service levels
	Stringent maintenance and operation procedures	As part of business as usual it is important that there are stringent operational procedures backed up by training and checking. This is important in minimising operator error and thus introducing risks to the system and to service.
Response and recovery	Procedures for emergencies – including extant manuals.	A n effective response to emerging risks relies on there being well-understood procedures for who should do what and when. These should be flexible enough to be applied in a range of circumstances but clear enough to avoid confusion in the response.
	Procedures tested through exercises	The procedures for emergencies are more likely to function correctly if and when they are needed if they have been tested with staff through exercises. This is an effective way to learn from and address potential snags in the procedure and hence improve the effectiveness of responses
	Backup capacity (personnel)	In order to react quickly and effectively it is important that the right resources are accessible and that there is provision for overtime working or secondment if necessary.
	Backup capacity (equipment and resources)	Certain equipment and resources may be needed to restore system service and it is important that these are accessible by prior arrangement, potentially with external parties for use in special circumstances.
	Plans specific to possible events	Whilst generic emergency procedures are better than no plan and make it easier to communicate, a more resilient system should have prepared plans particular to the different risks which it has identified in its risk assessment based on understanding of the system and how it might be expected to react.
	Communication protocols	In the event of service issues arising it is important that there are good communication protocols in place as part of the procedure to minimise confusion and ensure the correct methods are communicated externally. This includes clear chains of command with directions to staff made clear.
	Clear routes to notify others where there's a public health risk for example (PCT, DWI)	In certain failure events there are specific communications which are crucial to preserving the system. A resilient system should have communication routes for these sorts of priority communications planned out and resources in advance of any emergency occurring.
	Flexibility in the system.	The most effective responses to risks in a water system will involve reorganising the system operation so that service is not affected. This is dependent on the arrangements made in the system and the flexibility in operational possibilities. Procedures and processes for rearrangement along these lines are a feature of resilient systems.
	Spares.	Stocks or rapid access to spare parts can drastically reduce the time needed for repairs, and indeed maintenance, and can therefore reduce down time and risks to service.
	Backups (e.g. generators).	A resilient system should have backup supplies (i.e. Alternative sourcing routes and headroom in quantity) for crucial system inputs, for example electricity, diesel and treatment chemicals like ferric sulphate.
Cultural	Staff who care about the service and reputation of the business	The motivations of staff operating a system are important in determining how resilient it is. Where the staff are keen and focussed on service objectives under all circumstances the system is likely to be more resilient than where staff are unconcerned with service outcomes. Motivation is also a key determinant of speed in response to materialising risks.
	Flexible working to cope	A system is more likely to be resilient where the staff are willing to work at inconvenient times or for additional time in order to deal with risks arising.
	Pro activity - looking for risks	Risk identification and assessment is most likely to reflect reality and identify all feasible risks where it involves a wide range of people working across the system. Therefore a resilient system is more likely to result when risks are being flagged at every level and assessed and managed seriously.
	Honesty (e.g. About failures - escalating to the right level).	Honesty and transparency is also important so that risks are identified at the earliest possibility. In some circumstances where risks or issues are not communicated to staff working across a system this can cause threats to service which otherwise could have been address earlier.
Good practice	Good diagnostic procedure.	Procedures for identifying problems and snags are important in aiding corporate learning following service failures.
	Logs during incidents	It is good practice when service risks arise to track progress and issues which occur along the way. This allows good practice to be incorporates into future processes and procedures and allows problems and avoidable issues to be identified.
	Meaningful lessons learned and procedures changed	A method of improving resilience is to carry out meaningful analysis of service failures and consider improvements and changes to the system which would reduce risks to service.
	Incorporate changes in industry best practice	Adopting new technologies and processes which help improve the features outlines above is a way to improve system resilience over time.
	Assurance (process audit?)	Process and procedures can be subject to external scrutiny and offer recommendations and improvements for how they can be improved.

A simple scoring method was used against each of these features. The number of scoring options was kept to a minimum in an attempt to reduce subjectivity in the analysis. The possible scores are given in Table 4.

Table 4 – Simple scoring approach used against criteria.

Code	Description	Explanation	Example
4	Strongly evident	Multiple strong sources evidence the fact that this feature exists throughout the system. No conflicting sources to dispute this.	An up to-date process document covering the feature, numerical evidence in a business plan that it has been followed confidence from people that it is followed.
3	In evidence	Some evidence that this feature exists only in parts of the system or only a limited number of evidence sources available.	A business plan shows some risk assessments have been carried out and actions planned but some key areas are absent.
2	Partially evident	Some conflicting evidence – for example suggesting evident only in some parts of the system but not others or weakly embedded.	A process document exists but relevant members of staff have never heard of it.
1	No evidence	No reliable evidence that the feature is in evidence in the system. There may be evidence that it is not in evidence.	No process in evidence and no mention of the feature in documents or by staff.

It is worth noting that this approach might only indicate where further analysis is required not necessarily whether the feature is entirely absent. This is something to be aware of but does not diminish the approach as a way of identifying areas for further investigation and possible improvement.

4.3. Application of the approach

The following sections describe high-level findings from the investigation grouped under the categories alongside the scores we arrived at under each feature. Overall results are discussed in section 4.4. The commentary under each section does not give a full explanation of how each score was derived but merely highlights key examples and findings from the assessment and discusses the type of evidence which was found for each of the features.

4.3.1. Strategy & Governance

The water system we investigated showed strong evidence of clear strategies and priorities for service. The three key service criteria of pressure, supply and quality are all prioritised in company strategy documents and communicated strongly through the business. It was also found that these high level service objectives were strongly linked to individual performance reviews. These were themed around the ideas of “always on” and “good to drink”. Tolerances around these objectives were also made clear externally and internally and there were company key performance indicators, with monthly minimum and stretch targets, specifically on these aspects of service. These also tied very strongly to monetary incentives at all levels of the company. What was less clear from the research was whether there was a corporate resilience strategy, i.e. a long-term objective for the levels of risk borne by customers. Whilst this was arguably implicit in the overall strategy and performance monitoring, it was not clear that these standards were expected to be maintained ten or twenty years into the future. Thus in areas of the business focussed entirely on long-term objectives, for example strategic business planning, it was less clear the tolerances and service levels which were being aimed for.

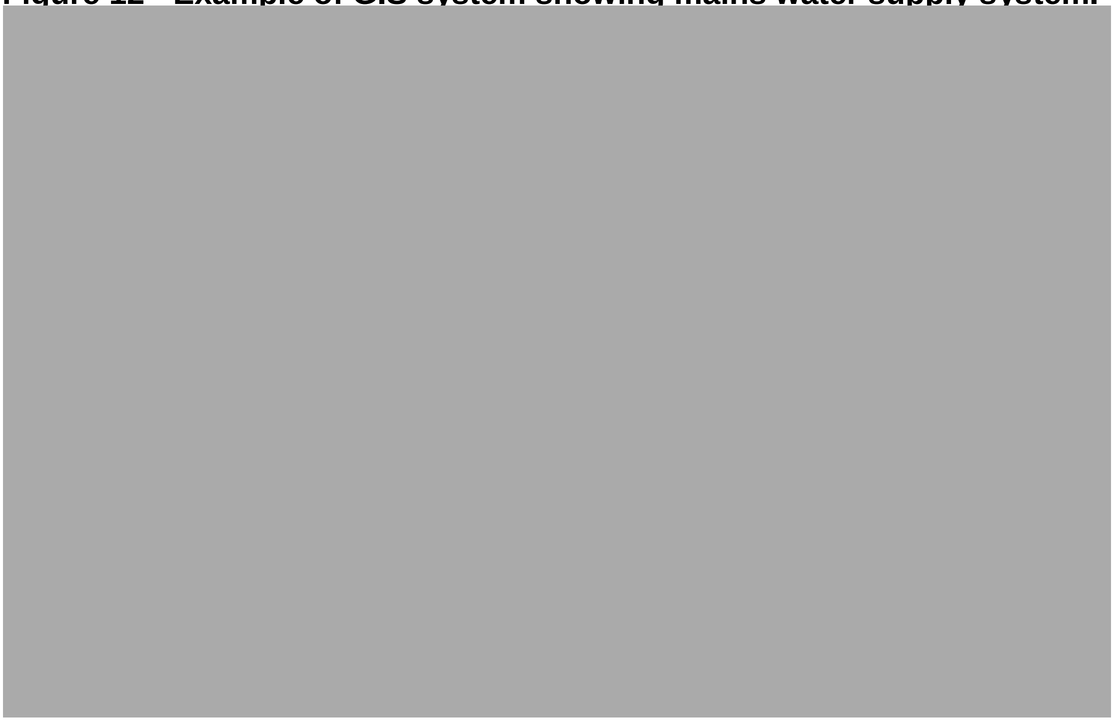
Feature	Score
A clear overarching strategy for service with concise, clear messages.	4
Clear definitions and prioritisation	4
Relevant key performance indicators	4
Overall approach – a 'corporate resilience strategy'	2
Tolerances - what sorts of things the company is willing to accept and what are unacceptable.	3
Governance: Clear responsibilities for staff and others	3
Appropriate (positive) incentives and penalties	4
Clarity throughout organisation	3

4.3.2. Information and data

An important component of resilience is having the right information and data to understand risks, understand issues which materialise in the network and, most importantly from a service perspective, to be able to prioritise solutions which protect or restore service in a timely manner. This means an understanding of the geographic network and local contexts, of external hazards such as flood risk and of the delivery of solutions, e.g. the process by which a mains burst repair is procured. It is particularly important that a company understands critical failure points, where service will be disrupted as a result of one point of failure (for example a trunk main). The speed of acquiring information and data is also important.

The research in this area suggested that water systems in England and Wales now deploy a wide range of information systems for storing and distributing information and data about their network and its performance. Many of these technologies have been adopted widely only within the last ten years with some only becoming embedded in business as usual practice within the last five. Examples include company-wide, live GIS systems and dynamic scheduling systems accessible to multiple parties across the organisation. However it is also clear that these systems do not increase resilience on their own – as they rely on people having the correct levels of understanding and using them effectively to assess risks and plan risk-reduction interventions or respond to issues as they arise. For example a replacement might be made which is different to that in the original plan (a MDPE pipe as opposed to a cast iron pipe). This might go unreported and result in the system being out of date. Companies recognise this as an issue and seek to establish processes for capturing updates and status changes on systems.

Figure 12 - Example of GIS system showing mains water supply system.



It was also clear that there was good understanding of the network and critical failure points in control centres and operating staff and that this knowledge was being constantly updated and disseminated to operators across the system. However there were fewer early warning systems and links to weather forecasting services and flood warnings than could have been possible. Some parts of the organisation were linked in to these warnings but there were not necessarily clear processes for communicating these warnings across the system. It was also found that there were sometimes delays or hindrances to staff communicating with each other and periodic system failures had historically caused problems with monitoring and alert systems in the past leading to service risks.

Feature	Score
Staff can communicate with each other	3
Understanding of network and particularly where critical failure points are located	4
An integrated understanding of the network over the whole geographic region of responsibility and an understanding of the networks in other neighbouring geographical areas (not just isolated parts of the network).	4
Good asset knowledge, reliable data (including of elements of the network out of control	4
Good forecasting of deterioration and risk.	2
Linked into weather forecasting services.	2
Linked into flood forecasting centre (available to national category 2 responders which includes water companies).	2
Strategic and Regional Flood Risk Assessments analysed in relation to network	2
Good hydrological understanding of the network and its consequent service time thresholds (e.g. How long a particular service reservoir can supply a population before reaching low levels leading to service issues)	4
Monitoring and alerts.	3
Systems which react to alerts	2
Reliable water quality monitoring	3
Network maps and knowledge available to relevant staff. (& up to date).	4

4.3.3. Collaboration

There is strong consensus in the literature and government guidance that a key feature of a resilient institution is one which recognises interdependencies with other systems and takes steps to reduce the risks to itself from those interdependencies (see for example Ofwat, 2010). Government guidance exists which details the types of steps category 1 and 2 responders are expected to go through with other agencies (Cabinet Office, 2009) and has initiated and supported a number of fora through which to do this, for example local resilience fora. Minimum expectations on collaborative resilience therefore centre around engagement with these mechanisms. A company operating a resilient water system should be expected to be considering where other bodies might be affected by external hazards and hence where this might affect the system. The research found that the system under investigation was an active member of several resilience groups whose purposes were to identify and discuss interdependencies and collaborate on emergency planning. Some stakeholders also expressed a view that water companies in England and Wales were leading other utility organisations in this area. Similarly there was strong evidence that water companies were engaging with regulators and local and national Government on resilience, including responding to consultations on the subject and communicating about risk and resilience schemes at local levels. However it was not clear that the whole system was aware of these groups or that their discussions and outputs were being used to effect system changes either within or outside the water system.

It is important that a resilient organisation understands its role in different incidents involving other parties, including ones where government is involved, such as wide-scale flooding. Evidence of this was found in multi-agency procedures and guidance documents but there was no strong evidence that all parties involved in an incident would be familiar with these procedures and it is likely that application of them would therefore be more ad-hoc than would be ideal. Procedures like this do give clarity where disputes or points of disagreement on responsibility may arise.

It was clear that water companies do share information about their network with relevant stakeholders, for example the Highways Authority and local councils. In some cases this information is live – for example a system accessed through an internet browser showing the water network, scheduled maintenance operations and supply disruptions. There were also found to be strong links between developers and water companies with the aim of ensuring the water network is not damaged or risks increased by accidental external interference or development changes which could affect service in parts of the network. Information and guidance was being shared to try and prevent this.
Potentially the most important area for collaboration in the water industry in England and Wales was found to be between water companies, who are ultimately responsible for delivering the service, and the large number and variety of companies to whom various critical functions in delivering the service are delegated, for example construction firms and leakage repair sub-contractors. The research highlighted that the trend in the water industry since privatisation has been for increased levels of activity carried out by outsourced companies, and over the past two years, there has been a trend towards a smaller number of bigger sub-contracts.

This means that the relationship between water companies and contractors is an important determinand in resilience of the system and it also means that to truly assess the resilience of the water service would require assessments of the resilience of the various suppliers on whom the water companies rely to deliver the service over a period of time. This is more difficult than carrying out a study of the public water companies because private contractors are – with the exception of health and safety – only very rarely required to publish information about their business planning, contingency planning and risk profiles, particularly in relation to their operations in certain geographic regions and for certain clients. This is a critical area for further investigation, as it may be found that there are many ‘hidden’ indirect risks to the water service originating or being only controlled in a limited way, within water companies’ supply chains. For example the quality of asset product being sold to and consequently installed and operated by companies might change over time in a way which is not apparent or communicated to the buyer. Without iterative checks and product testing this could lead to reducing resilience of the system over time.

There was some evidence of an understanding of the reliability of key supplies but in general it was found that there was an inherent and generally unquestioned assumption that supplies and suppliers would remain reliable. In general the risk assessments supported this assumption but it is one of those areas where systems can be caught out and a system constantly improving its resilience would evidence continuing questioning of its supply chain and driving improvements and backup provisions to reduce risks in this area. Energy was one area where there were strong back arrangements for relatively short periods of time at critical assets, but otherwise little risk management.

Feature	Score
Recognition of interdependencies with other organisations	4
Understand reliability of key suppliers	2
Contract provisions for calling on outsourced suppliers where necessary.	4
Engage with the regulators.	4
Good relationships with external agencies and effective communication channels	3
Plan in concert with other organisations	3
Lobby effectively for others to reduce risk where there is a reliance.	2

4.3.4. Understanding risk

A resilient water supply institution should be expected to understand the external hazards which can generate risks to the service. Therefore one would expect to see hazard analysis and risk assessment occurring on an iterative basis. Nationally, some of the relevant external hazards to water service are highlighted and assessed by government. The Government now sets out a national risk register which shows all the top risks to the UK. This includes those risks which affect essential services like water. Of these national risks, historically the water service has only been affected at a significant scale by severe weather (which includes a range of risks from very cold weather to windstorms), inland flooding, coastal flooding, and what might be classed as industrial accidents. Major attacks on water infrastructure have not occurred. This does not mean that they should not be considered when assessing the resilience of the service to external hazards. The research found that the industry was very strong at considering some of these national scale risks. For example reservoir flooding from dam failure is identified as a national-level risk by the Government and the water companies are responsible for risk assessment and asset management of many dams. In all the investigated areas it was found that dam risk assessment and management was approached with a large amount of resources and risk assessment and management was operated with very tight tolerances (i.e. there is a very low risk appetite in evidence). Lower-scale risks were being identified and assessed by the system itself on a routine basis and identification exercises in particular often involve expertise and experience form a wide range of backgrounds, thus ensuring a wide range of risks are captured and considered and progressed to risk management stages. However the research highlighted some minor shortcomings in communicating these assessments across the whole system, and particularly to external agencies, even in circumstances where risk sharing might be of use in enhancing interdependency resilience.

In general, risks to the water service which are conceivable but very unlikely and which have never occurred in England and Wales within the last century such as earthquake, plane crash and meteor strike were generally discounted and not included in company risk assessments.

Apart from assessing and managing risks during operation of the system it is important that risks are considered in the design stage when changes are made to the system. System changes offer both opportunities (to reduce existing risks) and threats (to introduce new risks to service or exacerbate existing ones) and interventions can therefore increase or decrease the resilience of a water supply network. In asset design it was found that a wide range of different changes in contextual circumstances in and around the particular asset to be created and the consequences to service of possible changes to those circumstances were being considered, but not in all design changes. Methods for doing this included design risk assessments, access studies and Hazard and Operability studies. One shortcoming was identified where standards were being followed without corroborating risk assessments for the particular circumstance.

Whilst these processes were generally discovered to be robust and effective when applied, it was clear that best-practice risk assessment was not being carried out in all circumstances. Examples were found of service failures which had occurred as a result of risks which would have been identified if a dedicated risk assessment and pre-emptive risk management process had been carried out following the commissioning of certain assets.

Feature	Score
Identify risks to service	4
Consider external hazards which are infrequent	3
Consider super-extreme risks - even though they are unlikely it is useful to consider them as doing so can provide a helpful check on systems and processes..	2
Risk screening at a high level	4
Risk assessment at company/business level	4
Risk assessment at asset level	2
Risk management	3
Iterative assessment	3
Risks shared	2

4.3.5. Interventions

A resilient organisation should be taking action to address risks it has identified. If this is not occurring then the service can be said to be deteriorating in resilience as the likelihood of one of the risks to service materialising increases. Success on this area cannot be measured purely by the money spent justified under a resilience driver (so called “inputs” rather than outcomes). There are also clear overlaps with other areas of expenditure. For example if a company is spending very little on proactive maintenance (as discussed in section 4.3.6) the likelihood of assets failing in such a way as to affect service would be expected to increase.

Evidence was found of extensive interventions in companies’ business plans for the period 2010-2015 based on risk assessments carried out and driven by the need to address risks to service presented by external hazards and improve resilience. Key examples included asset-specific protection such as flood walls, electronics raised beyond flood levels, security measures and purchase and installation of spare capacity such as pumps and generators as well as much larger schemes such as construction of transfer links between different resource zones. There were also examples of engagement actions, for example instituting or extending water import arrangements with other water system operators in neighbouring geographic regions. Additionally there was strong evidence that in some cases resilience needs had influenced maintenance programmes, for example the research saw cases of pumps identified as critical single points of failure which on failure could impact service being prioritised for refurbishment even over pumps which might have been prioritised based on age and condition but which entailed a less critical effect on service if they were to fail. This evidence gives confidence that a wide range of types of solutions are being considered and that risk assessment was carried through to risk management. However the assessment does not go far enough to allow conclusions to be drawn about whether individual interventions are optimal, efficient and effective or not. This would require more detailed individual studies.

One area of weakness was in quantifying differences in risk before and after interventions. This exercise was carried out in so far as it was necessary to get support from internal financial oversight groups but it was not clear that following project delivery the risks were again quantified and success assessed. There were also examples of some identified service risks being accepted without intervention and it was not clear that these risks would be reviewed in the future.

Feature	Score
Addressing risk where it exists	3
Propose and carry out resilience improvements	4
Protected works.	3
Restricted access and security	3
Make and follow drinking water safety plans.	4
Addressing interdependencies	2
Solutions addressing multiple problems	3
Quantifying differences made before and after interventions	2

4.3.6. Maintenance

A large amount of time and resources are spent on maintaining the water network in ordinary conditions. This research did not analyse all aspects of maintenance as they are covered through other assessment methodologies. In general maintenance procedures are well-established and well-resourced which increases the resilience of the system. However the research highlighted specific cases where oversight of existing assets and procedures had led to deteriorating resilience in certain respects and consequently supply failures. This was found to have occurred where there was a lack of a maintenance regime on existing kit or an abandonment of existing techniques. For example, during the AMP4 period (2005-2010) one company did not operate a proactive maintenance regime for cathodic protection equipment – which can be used to effectively protect metal pipes from corrosion in certain ground conditions. This resulted in failure of pipes and service effects which would otherwise not have occurred. Reinstating this programme after 2010 was found to reduce corrosion-related bursts on the protected mains significantly. Whilst it involved some additional up-front costs (capital and operational) there was a significant reduction in risk to service as a result – and hence an increase in service resilience. This example highlighted the point that increasing resilience often requires additional cost and therefore involves a trade off between cost and risk. This entails subjective decisions as explored in more detail in the research conclusions.

Feature	Score
Responsive maintenance procedures (fix-on-fail)	4
Asset condition investigations	2
Proactive maintenance regimes. – service reservoirs, distribution, disinfection and treatment process control.	4
Provisions for maintenance in different conditions	3
Adequate equipment checks.	3
Stringent maintenance and operation procedures	3
Asset condition	3

4.3.7. Response and Recovery

Response and recovery performance can be improved by having plans and provisions in place for specific extreme events and testing these plans, as observed during the Mythe flooding. There was good evidence in the system of contingency plans both specific and generic, including multi-agency planning. However there were only a limited number of examples of dry runs and exercises for each of these plans, which can help improve plans and train and prepare staff for event occurrences. Evidence of response and recovery resilience features can be found by looking at reactive maintenance performance, which were generally found to be improving over time through concentrated programmes aimed at improving the response times, increasing the effectiveness of responses and placing the focus on end-service rather than assets themselves. The number of different risk response options available to operators in different areas has increased adding flexibility and this combined with the focus on end-service rather than simply specific asset performance has likely increased the resilience of the system.

Some shortcomings were identified with staff availability. For example the research highlighted examples where the combined effect of the limited number of staff and statutory limitations on working hours, as set out in the working time directive, had led to risks over certain time periods where not enough staff would not have been available if a risk had occurred during that period. Similarly in some cases backup capacity in terms of equipment was found to be in shorter supply than desirable for a more resilient system and backup generators were only being rolled out across some sites because of resource limitations. In both these cases resilience could manifestly be increased but it would involve additional resources.

Feature	Score
Procedures for emergencies – including extant manuals.	4
Procedures tested through exercises	2
Backup capacity (personnel)	3
Backup capacity (equipment and resources)	2
Plans specific to possible events	2
Communication protocols	3
Clear routes to notify others where there's a public health risk for example (PCT, DWI)	4
Flexibility in assets	3
Flexibility in the network	3
Spares.	2
Backups (e.g. generators).	2

4.3.8. Cultural

The culture, motivations and enthusiasm of the people operating and influencing the water system has a strong impact on how resilient that system is. In some cases service failures have been caused by negligence, for example the Camelford incident mentioned in section 3, although this is rare. It is important from a resilience perspective that an institution maintains good staff morale and is made up of individuals who value the service and will work to protect it for customers. This is hard to measure but can be partly assessed through questionnaires and an assessment of the types of features present in the key organisations. The research found evidence of clear roles and responsibilities, clear lines of communication and positive attitudes. Working practices and management procedures also generally allowed for flexibility and open-handed approaches to problems and risks, which encourages honesty in raising problems and issues.

Feature	Score
Staff who care about the service and reputation of the business	4
Flexible working to cope	3
Pro activity - looking for risks	3

Honesty (e.g. About failures - escalating to the right level).	3

4.3.9. Good practice and learning

From a resilience point of view it is important to learn from service failures over time and innovate to reduce risks. The research found examples of this behaviour for example after the management of incidents dedicated projects had been established following service failure events or near-misses to learn lessons and institute improvements. There were also examples of sharing learning and in some cases companies had established dedicated resilience fora where practice can be shared. However with time and resource pressures it was not clear whether this is receiving priority over more immediate concerns. The general inertia in the water industry for adopting new technologies and processes observed by the Cave review and others (Cave, 2009) was evident in this area (many design standards remain unchanged even where more robust alternatives are available on the market) but this isn’t necessarily a bad thing from a resilience point of view because there was evidence that new, untried technologies can introduce new risks to the system. In general the system approach was to carry out extensive risk assessment and testing of newer technologies in controlled environments in order to trial new technology without reducing service resilience in the system. Another area of potential weakness was a lack of assurance on emergency planning and on post-event reports. This reduces the level of confidence and may be an action which could improve resilience.

Feature	Score
Good diagnostic procedure.	4
Logs during incidents	4
Meaningful lessons learned and procedures changed	3
Incorporate changes in industry best practice	3
Company-led innovation	2
Assurance – for example process audits	2

4.4. Discussion of results

The overall results for all features are drawn together and shown in figure 13 and figure 14 shows equivalent spider diagrams showing the score for each criteria within each sub-category. This is an example of how the assessment could be presented and used comparably with different systems. This would help enable quality checks of the assessment but would also enable good practice to be identified and shared for different features of resilience.

Figure 13 – Scoring spider diagram showing average score for each category

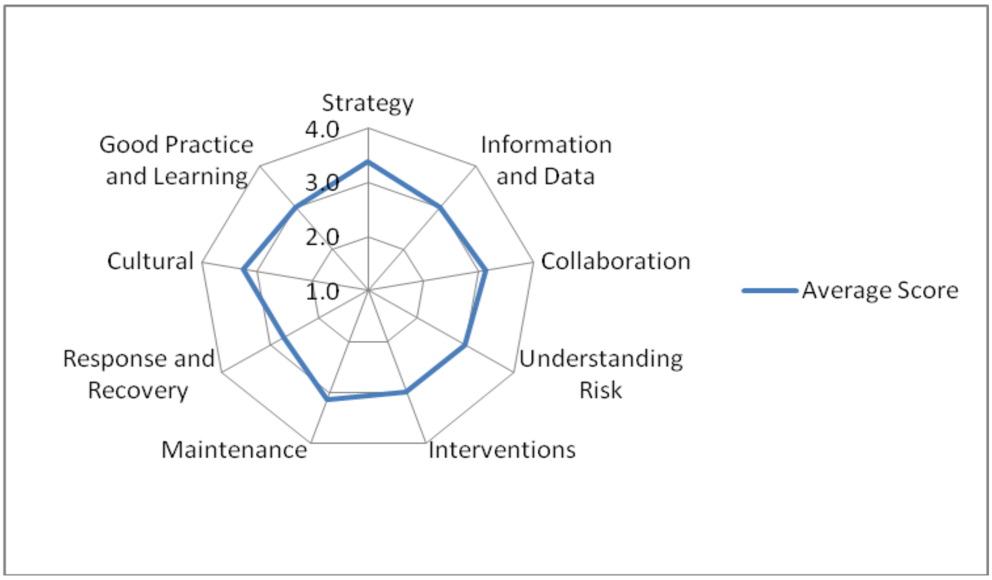
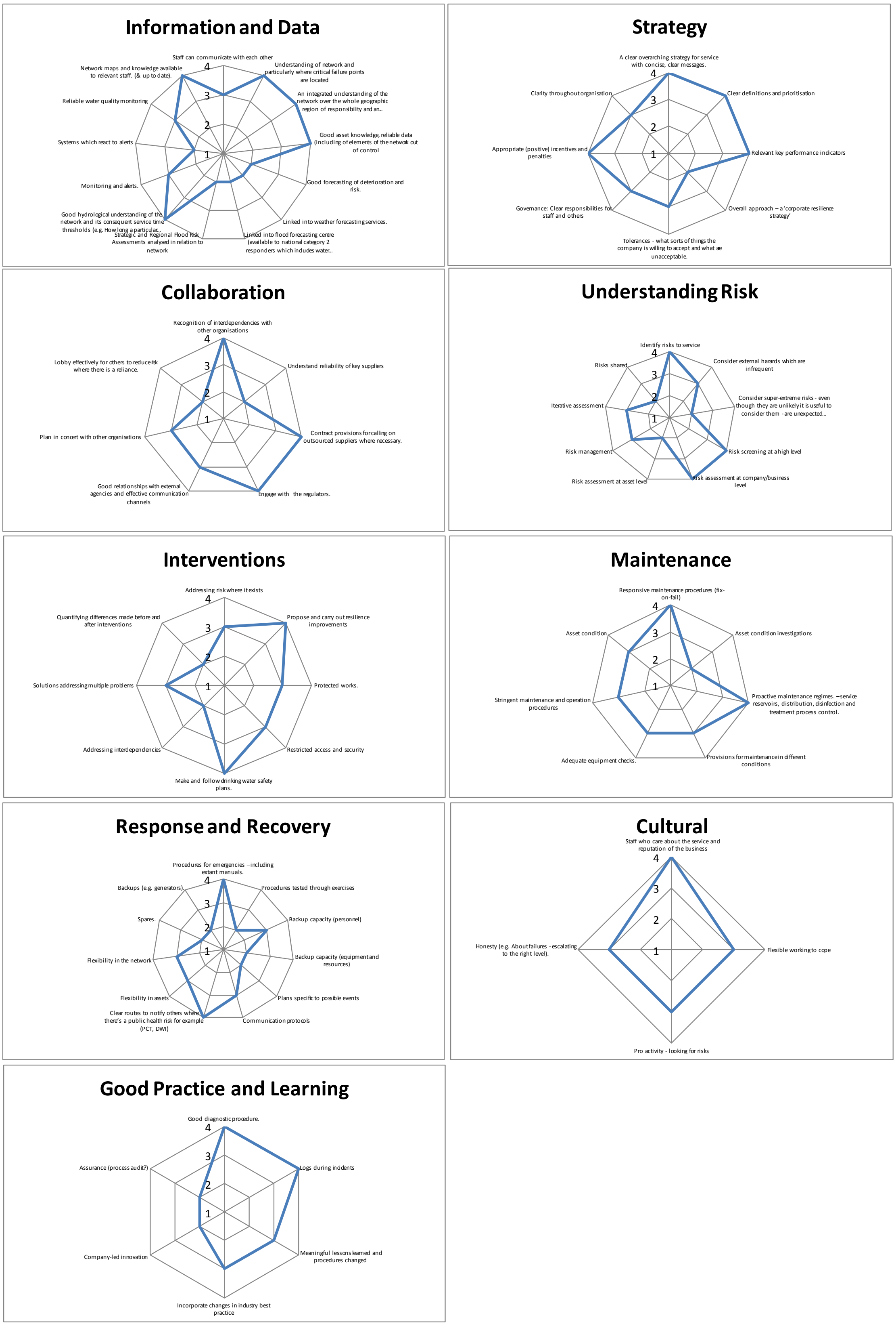


Figure 14 – Scoring spider diagrams for each resilience category.



This methodology and presentation approach also enables an assessor to identify and suggest areas of improvement to the system. For example, figure 14 indicates that the organisation could improve its links to weather and flood forecasting services. The assessment suggested that resilience could be improved if risk assessments were shared more readily and that more exercises and spare and backup operational equipment would help the system become more resilient. As noted in the strategy section one area for improvement would also be to set a company target for the level of risk to service expected after a period of time and establishing ways to measure and monitor improvements over time. However, doing this is recognised as a difficult exercise and must involve some subjective value judgements as discussed in section 5 and complex engagement with regulators and stakeholders about what is the desirable level of service and what customers would be willing to pay to achieve different levels of resilience. It is worth noting that such areas for improvement are suggested independently of any consideration of cost or equity considerations and also environmental considerations, but it is clear that the assessment can offer a way to highlight low cost measures of improving resilience (for example sharing risk assessments). Some resilience improvement measures have significant environmental impacts, such as the embodied greenhouse gases involved in the manufacture and transportation of concrete for conventional flood defences which must be considered and balanced in the sector.

As the research progressed it was found that some of the original criteria needed to be amended or additional criteria added, so it is likely that if this method were applied more widely, the criteria, and particularly the definitions might be expected to change over time. An additional exercise which would add value and make the method easier to apply would be to gather and add examples for each level of scoring under each criteria in a more robust way than has been done in this research. This would enable greater comparability of results.

It would be possible to use this assessment approach to measure change over time, by revisiting the same system after a period of time and assessing it on the same basis. This would be particularly useful in assessing the degree to which a system has improved following a particular hazard. As noted earlier the Mythe flooding events in 2007 prompted a number of changes in the sector, the degree of which can be assessed using this approach. An example for some of the features from the resilience principles is given in table 5 below. The first score was given based on a view of performance against the criteria from before July 2007, judged from an historic view of the company's systems and processes. Whilst the second score represents a view of performance against the criteria as of 2012, taking a judgement based on existing systems and processes.

Table 5 – Example of assessment at two points in time

Feature	Score – pre 2007	Score - 2012
Addressing risk where it exists	2	3
Propose and carry out resilience improvements	2	4
Protected works.	2	3
Restricted access and security	3	3

In this case the study showed clear examples which justify an improved score, for example the institution of a programme of asset-specific risk screening and assessment and the specific inclusion of asset protection schemes in the company's five year business plan. However in some areas, in this case security, there was little evidence of a significant change.

Clearly this method is highly subjective and to be applied rigorously would require multiple assessors and comparability between different systems. The development of examples of scoring under each criteria would also be helpful in enabling consistent assessment. However it demonstrates how an approach which might be used to judge how resilient a particular system is compared to another, whether its resilience has improved over time, whether there are particular weaknesses which can be rectified and improved and possibly in the event of a failure of resilience such as assessment could suggest where some of the causes of failure lay.

5. Measuring resilience – conclusions

Key Conclusions

- Analysis of service performance data is an important starting point in assessing resilience.
- Qualitative analysis of systems and processes and the degree to which they affect the resilience of the water service is possible.
- The outcomes of this research suggest a service generally improving in resilience over time.
- More evidence was found to support the argument that the water service in England and Wales is resilient as opposed to Brittle.
- An approach based on service performance analysis combined with a qualitative assessment of processes and systems could be used to suggest ideas for improvements and assess changes in resilience over time.
- These approaches are subject to a number of limitations and uncertainties.
- A fuller understanding of service resilience would require a complimentary assessment of risks to the system.

The research developed a method of assessing water service resilience and tested that approach – using high level service data for the industry in England and Wales and then by studying one particular system in relation to a set of features which you would expect to see as part of a resilient water supply system. It was found that it is possible to arrive at a view of the level of resilience of service by looking at performance data and processes and systems against a set of criteria. However this view is still clearly imperfect as it is subject to a number of key limitations. Foremost amongst these limitations is that such an assessment does not actually tell us very much about the risks to the system, it only indicates how likely it is that risks have been understood and addressed.

Recently the regulator has suggested measuring progress towards a generally defined 'outcome' by assessing whether a company has met certain milestones (Ofwat, 2012). This may be an approach regulators could adopt in the absence of better information. It would be an improvement in levels of understanding about the resilience of service in different areas. Milestones could be set and tracked in a similar form to that explored in section 3, looking at historic service failures over time and in relation to certain extreme events. One would expect there to be a correlation between good performance against the criteria explained in section 4 and a resilient system. However, further work would be required to apply the framework to a number of companies and assess its validity over time in relation to service information analysed in a similar way to that explored in section 3. In terms of analysis of service levels and the hazards which cause failures, further work could be done comparing service failures with hazards at increasing levels of granularity. This analysis gives strong clues about how resilient a particular system is, and can be applied at various different levels. The smaller the focus of the assessment, the more insight can be gained into historic risks and failures.

It must be noted that this research has tried to leave out of account cost and equity considerations and value judgements on what the 'appropriate' level of resilience might be. A crucial element in resilience planning must include setting an aim. It is therefore impossible to answer the question – is the water service resilient *enough* – without some value judgements about what enough is. This requires concerted discussion and understanding about the costs of increasing or decreasing resilience and the levels of service which customers are willing to bear.

Finally, whilst this research has shown that the UK water service can certainly improve in terms of resilience, the research strongly suggests that the current service in England and Wales is perhaps as resilient a water service as has ever existed. It is possible therefore to give a qualified answer to the original research question and conclude that there is very little evidence to support the argument that the water service in England and Wales is ‘Brittle’.

Certainly, compared to other areas of the world customers in England and Wales bear very little risk of water supply disruption (World Health Organisation, 2009). More work could be done to establish the most optimal paths to a resilient water service in countries which have not yet achieved stable and safe drinking water supplies. Conversely more work could also be done to establish whether there are other water services which have achieved even lower levels of disruptions than in England and Wales and how we could learn from improvements there.

A number of areas for further work were identified throughout the research. These are collected and summarised below:

- Supplement the service failure analysis above using numbers of customer complaints rather than recorded service failures.
- Investigating potential biases in company explanations of failure events and the nature of the political relationships driving this.
- Carry out a more in-depth comparative analysis of the Northern Ireland water service failures.
- Investigate the resilience of systems and organisations within the water companies' supply chains, within which lie many less-well understood risks.
- Apply a similar resilience assessment framework to other water supply systems in England and Wales to enable comparative analysis.
- Apply a resilience assessment framework to one system at multiple points in time to test whether it is an effective way to reveal changes over time.
- A more in-depth comparison of service failures with hazards at increasing levels of granularity.
- A study of optimal paths to resilience.
- International resilience analysis; how does England and Wales compare with the service in other countries and are there more resilient water services elsewhere in the world?

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References

Adger W N, Agrawala S, Mirza M M Q, Conde C, O'Brien K, Pulhin J, Pulwarty R, Smit B and Takahashi K, 'Assessment of adaptation practices, options, constraints and capacity' Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds.), Cambridge University Press, Cambridge, UK

Arnell N, 'Global Warming, River Flows and Water Resources' (Institute of Hydrology, Wiley, 1996)

Arup – SPeAR® - Sustainable Project Appraisal Routine (2011), Information available from: http://www.arup.com/Projects/SPeAR.aspx (accessed June 2011)

Balica S F, Douben H, & Wright N G, 'Flood vulnerability indices at varying spatial scales' Water science and technology volume 60, number 10, 2009, pp 2571-2580.

Bartram J, Corrales L, Davison A, Deere D, Drury D, Gordon B, Howard G,

Rhinehold A, Stevens M, 'Water Safety Plan Manual : Step-by-step risk management for drinking water supplies', World Health Organisation, (2009b)

BBC News, 'National resilience: Duck and recover' (22 March 2004) available at: http://news.bbc.co.uk/1/hi/magazine/3557611.stm (accessed June 2011)

BBC News, 'Brixton Hill water supplies return after burst main' available at: http://www.bbc.co.uk/news/uk-england-london-14059127 (accessed June 2012)

Blackmore J M, and Plant R A J, 'Risk and Resilience to Enhance Sustainability with Application to Urban Water Systems' (2008)

Bogardi, J.J. and Kundzewicz, Z.W. 'Risk, Reliability, Uncertainty, and robustness of Water resource systems' (Cambridge Uni. Press, 2002)

BREEAM, 2008, available at: http://www.breeam.org/page.jsp?id=66 (accessed July 2011)

Bridgeman J, 'Water industry asset management in England and Wales: Successes and challenges', Water and Environment Journal, volume 25, number 3, (September 2011) pp318-326

British Standards Institution, 'BS 25999 Business continuity', BS 25999:1, 2006 and BS 25999:2, 2007

Cabinet Office (2011) 'Guide - Keeping the Country Running: Natural Hazards and Infrastructure' consultation. Available at: http://www.cabinetoffice.gov.uk/resource-library/consultation-keeping-country-running-natural-hazards-and infrastructure (accessed July 2011)

Cabinet Office (2009), 'Expectations and Indicators of Good Practice Set for Category 1 and 2 Responders'. Available at: https://update.cabinetoffice.gov.uk/sites/default/files/resources/expectations_set-parts1to3.pdf
(accessed July 2012)

Caralli R A, Allen J H, White D W. 'CERT Resilience Management Model – a maturity model for managing operational resilience'. (December 2010)

Cave, M, 'Independent review of competition and innovation in water markets – final report', (April, 2009) Available at: http://archive.defra.gov.uk/environment/quality/water/industry/cavereview/documents/cavereview-finalreport.pdf
(accessed August 2012)

Charlie Edwards - DEMOS, 'Resilient Nation', (Lecturis, Eindhoven, 2009) Available at: http://www.demos.co.uk

Chenoweth J & Bird J eds. (2005) 'The business of water and sustainable development', Greenleaf, Sheffield, UK

Chi-hsiang Wang and Blackmore J.M., 'Resilience concepts for water resource systems' Journal of water resources planning and management 135: 6, pp 528 -536 (November 2009)

Coaffee J and Bosher L, 'Integrating counter-terrorist resilience into sustainability', Proceedings of the ICE – Urban design and planning 161 June, 2009 pp75-83

Cole J - Interoperability In a crisis 2 Human Factors and Organisational Processes RUSI occasional paper June 2010 available at: http://www.rusi.org/downloads/assets/Interoperability_2_web.pdf (accessed July 2011)

'De Foe's Novels', Cornhill Magazine, 17:99 (1868:Mar.) p.293 Available at: http://gateway.proquest.com/openurl?url_ver=Z39.88-2004&res_dat=xri:bp:&rft_dat=xri:bp:article:e942-1868-017-99-005754 (accessed January 2011)

Defra, NI 188 Guidance (2008)

Rance, J., Wade, S.D., Hurford, A.P., Bottius, E. and Reynard, N.S., UK CCRA - Climate Change Risk Assessment for the Water Sector (January 2012) available at: http://randd.defra.gov.uk/Document.aspx?Document=CCRAfortheWaterSector.pdf
(accessed June 2012)

Dovers S R, and Handmer J W, 'Uncertainty, sustainability and change' Global Environmental Change, Volume 2, Issue 4, December 1992, pp262-276

Environment Agency, 'Flooding in England: A national Assessment of Flood Risk' (2009), Available from: http://publications.environment-agency.gov.uk/PDF/GEHO0609BQDS-E-E.pdf (accessed August 2012)

Environment Agency 'Exercise Watermark Interim Report' (June, 2011), Available from: http://www.exercisewatermark.co.uk/media/49180/interim%20report_final.pdf (accessed July 2011)

European Environment Agency, 'Safe water and healthy water services in a changing environment', EEA Technical report No 7/2011 (2011)

Faber M H, and Stewart M G, 'Risk assessment for civil engineering facilities: critical overview and discussion', Reliability Engineering & System Safety Volume 80, Issue 2, May 2003, pp173-184

Filho L., (2000) 'Dealing with misconceptions on the concept of sustainability', International Journal of Sustainability in Higher Education, 1:1, 9-19

Gheorghe A. 2005 Integrated Risk and Vulnerability Management Assisted by decision support systems. Relevance and impact on governance. Springer, Dordrecht.

GL Group 'Treatment Works Resilience', Available at: http://www.gl-group.com/en/water/TreatmentWorksResilience.php (accessed 20 June 2011)

Graham S (ed) 'Disrupted Cities - When Infrastructure Fails' (Routledge, 2009)

Gunderson L. & Holling C.S. (eds) 'Panarchy: understanding transformations in human and natural systems' (Island Press, 2001)

Hamilton, Denis, Crossley, Stephen (2004) Pesticide residues in food and drinking water – human exposure and risks (John Wiley & Sons)

Hashimoto, T., D. Loucks, and J. Stedinger (1982), Robustness of Water Resources Systems, Water Resour. Res., 18(1), 21-26.

Hashimoto, T., J. Stedinger, and D. Loucks (1982), Reliability, Resiliency, and Vulnerability Criteria For Water Resource System Performance Evaluation, Water Resource Research, 18(1), 14-20.

HM Treasury Orange Book - Management of Risk - Principles and Concepts (October 2004) Available at: http://www.hm-treasury.gov.uk/d/orange_book.pdf (accessed July 2011)

Holling C.S. 'Understanding the complexity of Economic, Ecological and Social Systems' Ecosystems (2001) 4: 390–405

Holling CS 'Resilience and stability of ecological systems', Annual Review of Ecology and Systematics. Vol 4 :1-23. 1973.

Hollnagel E. 'Barriers and accident prevention' (Ashgate, 2004)

Hollnagel E., Woods D. D., Levenson N. ‘Resilience engineering: Concepts and precepts’ (Ashgate, 2006)

Institution of Civil Engineers, ‘Flooding: Engineering resilience’ (May, 2010), Available at: http://www.ice.org.uk/getattachment/cdcdd467-8863-49b7-9e19-393a39eff02f/Flooding--Engineering-resilience.aspx (accessed July 2011)

Kjeldsen T. R. & Rosbjerg D. ‘Choice of reliability, resilience and vulnerability estimators for risk assessments of water resources systems’, Hydrological sciences journal, 49: 5, pp755-767 (October 2004)

Klein R J T, Nicholls R J and Thomalla F, 'Resilience to natural hazards: How useful is this concept?', Global Environmental Change Part B: Environmental Hazards Volume 5, Issues 1-2, 2003, Pages 35-45

Knott, G and Fox A, ‘A model of sustainable risk management’, Emergency management - The Magazine of the Emergency Planning Society, (August 2010).

Little R. ‘Holistic strategy for urban security’, Journal of infrastructure systems, 10, no. 2, 55. (2004)

Lowrance, W.W. 1976. Of Acceptable Risk: Science and the Determination of Safety. Los Altos, CA: W. Kaufmann.

McDaniels T, Chang S, Cole D, Mikawoz J & Longstaff H, ‘Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation’, Global Environmental Change Volume 18, Issue 2, May 2008, pp310-318

Met Office (2009) Vision 2030: The resilience of water supply and sanitation in the face of climate change - Climate change projection study. Met Office/DFID, Hadley Centre, UK

Mott Macdonald, ‘Resilience - outcomes focused regulation. Principles for resilience planning’, report produced for Ofwat, (May 2012). Available at: http://www.ofwat.gov.uk/sustainability/climatechange/adapt/rpt_com120503mottmacresil.pdf (Accessed June 2012)

Myron B. Fiering ‘A screening model to quantify resilience’, Water resources research, 18:1, pp27-32, (1982)

Ofwat ‘MD 161 Maintaining serviceability to customers’ (April 2000) available at: http://www.ofwat.gov.uk/legacy/aptrix/ofwat/publish.nsf/Content/maintainingserviceability.html (accessed May 2011)

Ofwat, ‘Delivering Sustainable Water – Ofwat’s strategy’ (March 2010) available at: http://www.ofwat.gov.uk/aboutofwat/reports/forwardprogrammes/rpt_fwd_20100303ofwatstrategy.pdf
(accessed January 2012)

Ofwat, ‘Resilient Supplies – how do we ensure secure water and sewerage services?’, (November 2010) available at:
http://www.ofwat.gov.uk/sustainability/climatechange/prs_web_1011resilience

(accessed July 2011)

Ofwat, Final business plan information requirements 2009 (Sections B6 & C8) Available at: http://www.ofwat.gov.uk/pricereview/pr09phase2/ (accessed July 2011)

Ofwat, 'Capital maintenance and Asset Management Assessments (AMA) for draft determinations – technical note' Available at: http://www.ofwat.gov.uk/publications/pricereviewletters/ltr_pr0932_capmaintex (accessed June 2012)

Pahl-Wostl C, Kabat P & Möltgen J, 'Adaptive and Integrated Water Management – Coping with Complexity and Uncertainty' (Springer, 2008)

Pickett S T A, Cadenasso M L and Grove J M, 'Resilient cities: meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms', Landscape and Urban Planning Volume 69, Issue 4, October 2004, pp369-384

Pinsent Masons (2010) Pinsent Masons Water Yearbook 2010-2011 (12th Ed.)

Porteous, A. (2000) *Dictionary of Environmental Science and Technology*, 3rd edition, John Wiley & Sons

Reason J.T. 'Managing the risks of organizational accidents' (Ashgate, 1997)

Reca J., Martinez J., Banos R., Gil C., 'Optimal design of gravity-fed looped water distribution networks considering the resilience index', J. Water Resour. Plng. and Mgmt. 134:3 (May/June, 2008) 234-238

Rees J. A. (2002) TEC Background Paper No 6: Risk and Integrated Water

Resources Management. Global Water Partnership, Stockholm

Resilience Alliance. 2010. Assessing resilience in social-ecological systems: Workbook for practitioners. Version 2.0., Available at: http://www.resalliance.org/3871.php (accessed May 2011)

Rockstrom J. ' Resilience building and water demand management for drought mitigation' Physics and chemistry of the earth 28 (2003) 869-877.

Rowe W.D., 'An Anatomy of Risk'. (John Wiley & Sons, 1977)

Severn Trent, Gloucestershire 2007, 'The impact of the July floods on the water infrastructure and customer service final report' (December 2007)

The Government Office for Science, London ("GOS"), 'Foresight International dimensions of climate change – final project report', (July, 2011)

The Pitt Review 'Learning lessons from the 2007 floods' (June 2008)

Tversky, A., and Kahneman D. 1974. 'Judgment under uncertainty: Heuristics and biases'., Science 185(4157):1124-1131.

UKCIP 'A changing climate for business' (Metcalf G., Jenkinson K., and Johnstone

K., Eds.) 3rd Edition (June 2010)

UKCIP, ‘Climate adaptation: Risk, uncertainty and decision-making’, (R. Willows and W. Connell, Eds.) (May 2003)

White I, ‘Water and the City: Risk, Resilience and Planning for a Sustainable Future’ (Routledge, July, 2010)

Wilby R L, and Vaughan K, ‘Hallmarks of organisations that are adapting to climate change’, Water and Environment Journal 25 (2011), pp271-281

World Health Organisation (2009a) Vision 2030: The resilience of water supply and sanitation in the face of climate change – Technical report. WHO / DFID, Geneva, Switzerland. Summary report available at:
http://www.who.int/water_sanitation_health/vision_2030_9789241598422.pdf
Accessed July 2012.

‘The GSS Regulations’ (2008) The Water Supply and Sewerage Services (Customer Service Standards) Regulations 2008, Available at:
http://www.legislation.gov.uk/uksi/2008/594/made (accessed June 2011)

‘The SEMD Direction’ (1998), The Security and Emergency Measures (water and sewerage undertakers) Direction 1998, Available at:
http://www.cabinetoffice.gov.uk/sites/default/files/resources/semd98.pdf (accessed July 2011)