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Revised Draft Water Resources Management Plan 2019

Technical Report - Water supply resilience

Contents

1. Overview

This technical report details how we have identified appropriate water supply resilience considerations for inclusion within our Water Resources Management Plan 2019 (WRMP19).

The Defra *Guiding principles for water resources planning* ('guiding principles') and Environment Agency (EA) *Water Resources Planning Guideline*[1] stipulate a number of aspects of resilience that need to be considered within the plan. How these have been incorporated within our plan is described within this report.

> *"To assess the resilience of your supplies, we expect more thorough testing of vulnerability of water supply systems - not solely tests based on historic events but future events that could reasonably be foreseen – to enable you to better plan for, and respond flexibly to future uncertainties. You should also assess resilience to other hazards such as flooding and freeze-thaw impacts and the overall resilience of your network. Where appropriate, you should include options to improve your resilience in your plan."* – Defra guiding principles

Resilience has been defined as *"*the ability to cope with, and recover from, disruption, and anticipate trends and variability in order to maintain services for people and protect the natural environment now and in the future*"* by the UKWIR project report *Resilience Planning: Good Practice Guide* - 13/RG/06/2. This has been endorsed by Ofwat through the *Resilience Task and Finish Group* report and has thus become the industry standard definition.

The above UKWIR report includes a reasonably comprehensive identification of potential hazards that could affect water supply resilience. The key hazards that exhibit the highest risks to our supply system have been selected from the fuller list for further review; the remaining hazards would only be considered on a case by case basis where a particular asset is known to have exposure to the hazard. This selection of key hazards has been achieved through a review workshop considering historical incidents, near misses and investments that have been made, or considered, to manage significant resilience risks. Some of these selected hazards have been considered at a system level and some against individual assets, depending upon the expected scope of the hazard.

In the context of the Water Resources Management Plan, we have taken the following key steps to incorporating water supply resilience into our thinking:

- Consideration of the effects of a **severe drought** upon our ability to maintain adequate water supplies, as an extension of the traditional 'dry year' assessment. This is detailed in Sections 4.4.8 and 6.3.1 of our *Revised Draft WRMP19* main report, with further detail in our *Revised Draft WRMP19 Technical Report - Supply forecasting*;
- Consideration of the effects of a **severe freeze-thaw** (driving peak demand) upon our ability to maintain adequate water supplies (Section 4.3.1 of this document);
- Identification of any water resources options that we are considering to reduce the risk of water supply failure associated with other resilience hazards, as assessed through our Wholesale Risk and Asset Planning (WRAP) process[2], including flooding, power, and critical asset failures (Section 6); and
- Tested our preferred plan for wider resilience benefits, specifically in the context of the peak demands associated with a major freeze-thaw event (Section 7).

The identification of resilience risks and the prioritisation of options to manage these risks is an ongoing element of our WRAP process and has not been included within the scope of previous Water Resources Management Plans. This means that in this plan we report the results of our risk assessments, and identify potential solutions to our biggest risks. For the future, we are working to define a programme of resilience investment to be delivered at a pace customers support and can afford.

[1] Environment Agency and Natural Resources Wales - Water Resources Planning Guideline: July 2018 has been referenced when writing this report

[2] WRAP is our company wide asset management process to identify risks and issues, identify and monitor strategic performance requirements, and prioritise risks and issues for investment or operational management.

We believe that our approach has provided a robust assessment of our water supply system's resilience to a range of credible hazards, which is significantly wider than traditional water resources considerations included within previous Water Resources Management Plans, as outlined in the Defra guiding principles. This has led to a more comprehensive identification of shocks and stresses that can present risks to our water supply system and will lead to a lower risk of service failure to the customers we serve than the traditional approach.

1.1 Changes from draft to revised draft Water Resources Management Plan

Change	Reason	Update(s)	Relevant section(s)
Major update with evidence and justification for selection of Manchester and Pennine Resilience solution following consultation	Customer/stakeholder engagement and consultation outcomes available; completion of cost-benefit analysis and solution appraisal; confirmation of preferred plan	Full summary of decision-making process and evidence added to select preferred plan	Major updates to Appendix A – Manchester and Pennine Resilience Options Process, with minor position updates in Sections 6-9
Comparison of winter 2017/18 freeze-thaw event to modelled assessments	To validate the freeze-thaw resilience conclusions given recent events	Additional explanation of the 2017/18 winter event in context, with conclusions	Section 4.3.1 (with minor related updates in Sections 7-9) and Appendix B – Extreme Demand Peak Week Review (2018)
Comparison of summer 2018 peak demand event to modelled assessments	To validate the peak demand resilience conclusions given recent events	Statement of position covering the 2018 summer peak demand event to date	Section 4.3.1 (with minor related updates in Sections 7-9) and Appendix B – Extreme Demand Peak Week Review (2018)

2. Scope of report

This report provides some technical detail to describe our approach to incorporating wider water service resilience risks into our Water Resources Management Plan 2019, as a distinct element from the traditional dry year assessments. We describe the process that we have followed to identify our current baseline risks associated with a key set of priority hazards. We then describe the process for option identification and selection. Since publication of our draft Water Resources Management Plan, we have completed the option selection process for addressing our highest priority resilience risk. This was not available at the time of issuing the draft plan, because it required further customer research and consultation. Other resilience risks will be considered as part of our ongoing business as usual prioritisation of investment.

Two "all system" approaches have been delivered for assessing water supply resilience to extreme drought and to freeze-thaw. The results of the specific resilience system modelling studies into extreme drought are provided in separate technical reports[3], and summarised in our *Revised Draft WRMP19* main report as described earlier. The summary results and approach for the freeze-thaw assessment are included within this report. These results demonstrate the baseline and forecast interruption risk profile under key resilience shock conditions. The resilience risks and associated options are identified through our Wholesale Risk and Asset Planning (WRAP) process, and are prioritised for investment over time as part our business planning processes. The largest and most significant water service resilience risk, known as Manchester and Pennine Resilience, is associated with a potential failure of a major strategic aqueduct. This has been subjected to a detailed risk assessment process and has undergone a comprehensive option selection and appraisal process, described in our *Revised Draft WRMP19* main report and this technical report. It is also a major component of our Business Plan submission to Ofwat covering the 2020-2025 investment period.

[3] *Revised Draft WRMP19 Technical Report - Supply forecasting* for position of drought risk, plus *Revised Draft WRMP19 Technical Report - Options Appraisal* for consideration as part of options appraisal and stress testing of the plan.

In addition, we are actively evaluating potential programmes of work for 2020-2045 associated with our strategic aqueduct system, and certain critical water treatment works and trunk mains that could impact upon our water resources balance. This would typically be through improved reliability affecting our outage position over time, but also through some additional resource development (see Table 1) where this is the most effective balance between risk reduction and bill affordability. This programme would target a significant reduction in the water supply interruption risk for many of our customers.

For our preferred plan at the draft Water Resources Management Plan stage, we also tested system resilience with water trading in place. This was to ensure that resilience under extreme demand conditions observed during a company-wide freeze-thaw event would still be achieved under water trading based plan. This was carried out through the same system modelling approach as for the baseline freeze-thaw assessment, an approach detailed later in this report. For our revised draft Water Resources Management Plan, water trading is no longer part of the preferred plan position, but retained in an adaptive pathway. The previous resilience assessment is therefore still considered representative for this purpose.

3. Overview of methodology

Figure 1 summarises the approach that we took to assessing water service resilience, and identifying areas where the risk to customers (of failing to have a reliable, wholesome water supply) needed to be reduced. We have used a range of techniques to identify specific resilience risks and associated options to resolve them. The approach for the assessment and relative ranking of resilience risks and their associated options is also described below.

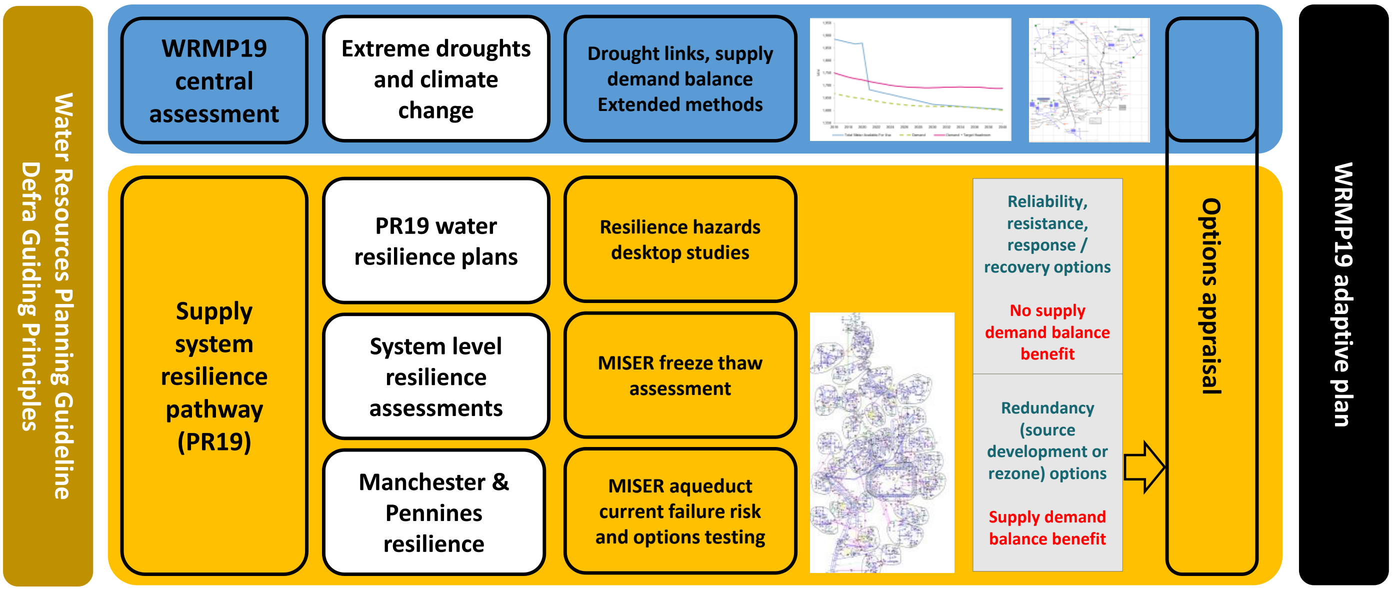


Figure 1 High level schematic of the WRMP19 resilience methodology demonstrating how resilience risks and benefits are assessed

4. Resilience risks identification

The identification of resilience risks for inclusion within the Water Resources Management Plan and wider business planning processes was through a number of different techniques, which are briefly described below.

4.1 Hydraulic network assessments

These studies were based upon hydraulic models and were focused around individual water treatment works and their associated water supply zones. Each study identified potential shortfalls in the current ability to supply customers in the event of a long duration[4] outage of a water treatment works. Each study included a review of engineering options to provide alternative supplies from a different source to the customers at risk of losing supply. Some of these study options have been delivered during the current 2015-2020 investment period and others will be prioritised for delivery during the coming periods 2020-2045. The nature of resilience solutions means that they alleviate constraints at a local water supply zone level, rather than a water resources strategic level, relevant to dry year assessment in the Water Resources Management Plan. However, we will consider where any asset interventions influence the supply-demand balance at each planning cycle. These studies can be used to model the consequences of a wide variety of different resilience hazards upon a local element of the supply network, such as flooding, power or critical asset failure.

4.2 All hazard resilience workshops

These workshops were essentially a “source to tap” asset review and have been used to identify a wider range of vulnerable assets than the hydraulic network assessments, such as service reservoirs, pumping stations and trunk mains. Examples of the types of risks that have been identified through these workshops were pollution events in rivers or reservoirs, or potential catastrophic raw water asset failures.

The risk assessment process gives a structured way to quantify risks associated with resilience hazards that are both shocks and stresses. Resilience shocks are relatively short duration events that provide extreme demands upon a system; most of the key hazards that we have reviewed could be classified as resilience shocks. Resilience stresses are hazards associated with a more gradual change in context that typically erodes the capacity of a system to manage shocks. Consequently, the assessment of resilience stresses would typically be alongside shocks. The most significant example of a stress clearly relevant to the water service is drought. Droughts can affect service on their own, but also reduce the capacity of a system to respond to any other shock event, such as a critical asset failure.

Whilst these reviews have been focused upon the identification of resilience risks, rather than solutions, inevitably some risks have solutions that may have been previously identified through other bottom up risk processes or through the options identification process in the Water Resources Management Plan (relating to dry year supply-demand drivers). Examples of additional sources that may be considered for development to meet long term water supply resilience objectives rather than dry year supply-demand considerations are included in Table 1 below.

Table 1 Example water resource options for water supply resilience

WR Option ID	Description
WR120	New boreholes at treated water storage (Wirral), new 15 Ml/d water treatment works, revocation of existing abstraction licences at Gorston, Springhill and Hooton
WR047b	New abstraction from the outfall of the Milwr tunnel at Bagillt, new c.18km raw water transfer main, new raw water pumping main to inlet of Sutton Hall Water Treatment Works
WR117	Increased abstraction from the Ribble Carboniferous aquifers, treatment to potable standards and transfer to treated water storage in Strategic Resource Zone
WR102a	Reinstate abstraction from 11 Widnes boreholes, reinstate Cronton Booster, new raw water main to Prescot Water Treatment Works, modified water treatment works process for additional 52.3 Ml/d
WR105a	Decommission existing Lymm Water Treatment Works, utilise both existing boreholes at Lymm at 9.1 Ml/d, convert treated water main to raw water main to new water treatment works located at Sow Brook (near Lymm), utilise existing treated water main to Manchester Demand Management Zone.
WR107	Reinstate Aughton Park and Moss End boreholes (Bickerstaffe) at 10 Ml/d, new raw water main to existing Royal Oak Water Treatment Works, modified water treatment works to allow for additional volume

[4] The studies considered water treatment works’ outages of three different durations: less than 12 hours, 5 days and greater than 5 days.

The workshops were focused in each of our 33 Demand Management Zones (DMZ) and included a facilitator, an asset manager, and typically a production manager and appropriate network staff. The focus of the workshops was to evaluate any known single point of failure or other significant perceived resilience risk. Approximately 100 individual resilience risks were identified through the workshops. There was a substantial overlap with the hydraulic assessments in the identified risks. Each water treatment works identified via the hydraulic assessment was also identified via the workshops, however, further non water treatment works risks were recorded. The output from these workshops became the basis for our register of "single point of failure" resilience risks.

The UKWIR report 13/RG/06/2 defines an "all hazards" approach to resilience assessment. The general approach is to consider appropriate hazards that may result in a service failure, in this case customer supply interruption. We evaluated the full list of hazards identified through the UKWIR report in an internal workshop to generate a targeted, more focused list for general resilience assessments. The approach taken was to review each hazard and to consider whether this hazard had ever materialised within either our company or the wider UK water industry, or was deemed credible in our system. This enabled us to identify the primary hazards that contribute most significantly to water supply risk. The hazards considered for water service supply service failure risks are described in Table 2 below. These were evaluated in addition to the systems approach for freeze-thaw and drought (see Section 4.3).

Table 2 Water service resilience hazards assessed

Hazard	Description
Power outage	This is modelling the impact of losing power to a facility from a third party supply, which may be due to any root cause. This failure mode is not for failure of our assets on site, but failure of the external power input. Only assess this failure mode for powered assets or where power failure may lead to loss of supply.
Fire	This is looking at the risk of a fire on site. This risk is primarily associated with High Voltage (HV) assets and is modelled specifically against HV transformers.
Critical asset failure	Critical asset failure is included for civil, mechanical and electrical (M&E), and ICA (Instrumentation, Control and Automation), as well as infrastructure assets such as mains and aqueducts. This is primarily used where the failure of a single critical asset could lead to the loss of supply or loss of treatment. Many resilience needs can be assessed primarily against this failure mode.
Flood	This models the potential for flooding based upon Environment Agency fluvial and coastal flood modelling zones.
Malicious damage	This models the expected risk from 3rd party malicious damage. Historically this work has largely been considered under the Security and Emergency Measures Directive (SEMD) programme.
Contamination	Source contamination or infiltration of contaminants into the water process or network. Typically this will include for river contamination, impounding reservoir algal blooms and service reservoir infiltration.
Human factors failure	Any potential failure that is associated with a non-asset related issue. Typical examples could include a failure to calibrate or verify the operation of an instrument, a chemical delivery to the incorrect tank, running processes in manual rather than auto or general changes to a system or process carried out in a way that leads to the system failure. This failure mode should always be included for resilience needs.
Cyber failure	Any potential supply failure associated with the failure of a telemetry or control or monitoring signal. This failure mode should be included for all resilience needs where telemetry is available for the assets associated with the need.

Resilience risks identified from the existing WRAP process were screened to identify those which could have a material effect upon the supply-demand balance; principally those that may lead to the development of new sources and those which may lead to the capability to move existing water supplies in strategically significant ways and therefore have additional benefits to the supply-demand balance in times of water stress. The preferred options to resolve these risks were then compared to the unconstrained Water Resources Management Plan dry year options list and it was confirmed that they were included for assessment under the core Water Resources Management Plan options identification process.

Resilience risks identified through workshops, facilitated by Arup Engineering, focused around each of the current 33 Demand Management Zones (DMZs) and involved the appropriate asset managers and various operational managers with familiarity of the DMZ. Operational response and recovery capability was included in the risk identification process, primarily by excluding risks where a network rezone or water tankers could ensure the ongoing provision of a safe water supply to all customers who would otherwise be affected.

A total of approximately 100 resilience risks were identified through this process across all 33 DMZs. This list has been continually reviewed and updated as the delivery of additional interventions has helped to reduce either the probability, expected duration or credible consequence of the risk.

The assessment of the resilience risks has been through a standardised methodology to ensure consistency in their ranking and subsequent prioritisation.

4.3 System level testing

We carried out system wide assessments of the ability of the network to respond to extreme demand scenarios. The particular scenarios tested included relatively short duration shocks such as a freeze-thaw event, where demand would be unusually high due to high volumes of bursts and hence leakage, and also longer duration stresses such as an extreme drought, where water resources would be very constrained and demand is typically higher. This was particularly specified in the Defra guiding principles.

4.3.1 Freeze-thaw

Peak demand deficits due to freeze-thaw events have been considered. As this is a fairly short duration event that can have very local effects, the existing Aquator™ model[5] used throughout the wider Water Resources Management Plan process (i.e. to assess dry year 'stress'), with a monthly demand profile, was considered to be less appropriate to demonstrate the current and future risk associated with short duration freeze-thaw "shock" events. A different modelling tool, MISER, was used for this assessment, largely because of the greater resolution of the supply system represented in the existing MISER model build.

For the freeze-thaw assessment, a suite of simulations was carried out utilising the most severe historical freeze-thaw demand profile with data available, from the winter of 2010/11. The winter of 2010/11 included three separate freeze-thaw events; each was modelled using weekly time steps and the latest available MISER model was configured to represent all three potable resource zones[6] at the expected configuration with the Thirlmere transfer in place in future[7]. The specific updates to the model that reflect changes from the previous network configuration at the date of the simulation (summer 2017) are primarily the following:

- Various maintenance projects that are due to have the effect of restoring peak production capacity at a number of water treatment works including, for example, Oswestry and Franklaw;
- The completion of the Southport projects designed to ensure sufficient peak capacity during summer months, including the completion of the Royal Oak Water Treatment Works; and
- The completion of the Thirlmere transfer project that brings West Cumbria into the Strategic Resource Zone with the completion of a new water treatment works.

For each of the events, five demand scenarios were simulated, equating to the historic peak demand, and four incremental uplifts, each of 5%. Deficits for each time step in each DMZ were identified and recorded. It should be noted that the MISER model doesn't include local storage so that the effect of short duration or relatively small deficits in the model can usually operationally be managed with existing service reservoir storage.

A review of peak week demand during the March 2018 freeze-thaw event and an initial review of the extended dry period in summer 2018 has been carried out since publication of the draft Water Resources Management Plan for consultation. The results of the review are included in Appendix B of this revised report.

4.3.2 Extreme drought

Please see our *Revised Draft WRMP19 Technical Report - Supply forecasting* for an explanation of work to develop severe and extreme drought scenarios, and results from testing of risk in this area. Our *Revised Draft WRMP19*

[5] The model build in Aquator™ represents the supply network at relatively high-level for the purpose of water resources modelling.
[6] The fourth small non-potable Barepot water resource zone is covered in the assessment process, but has not currently been identified as containing priority water service resilience risks.
[7] The modelling was completed at draft plan based on the expected latest date for completion of the Thirlmere transfer scheme from WRMP15, of March 2022. Although at the time of writing the revised draft WRMP19 submission delivery is expected a year earlier, this is immaterial for the purposes of the modelling assessment.

Technical Report - Options appraisal explains how options appraisal and stress testing of the plan has included severe and extreme drought resilience as an integral component of decision-making.

4.4 Interruption risk studies

These studies used the mass balance representation of the supply system held within MISER to enable credible failures and constraints to be modelled to understand the current and future risk profiles, with and without mitigation options. Studies have been carried out to identify the effect of specific, large scale changes or events to the supply system. An example of one of these studies was the impact assessment on the potential failure of assets associated with the Manchester and Pennine Resilience risk (see Section 6.1.2).

We have used the same models to help to demonstrate that the introduction of a future potential large-scale water trades should not bring additional, unacceptable risk to the water supply system (when supported by appropriate options as part of the plan). This was demonstrated through the assessment of any demand deficits associated with the network including potential trades and the requisite enabling works as described in Section 7.

4.5 Reservoir risk assessment

We own a large number of dams and reservoirs, and a key priority is managing the associated risks in line with Health and Safety Executive guidance. We have a well embedded risk assessment process and supporting systems to evaluate, track and manage the societal risks associated with these assets. The primary focus of our investment programmes across the next 25 years will be to reduce the risk that people and infrastructure in the North West are exposed to from our reservoirs. We are committed to a long-term programme of risk reduction.

We are focused on reducing the risk of dam failure, an event which would cause great damage and distress to people, and major cost to our business. Our future programmes of work are aimed at reducing the risk of a catastrophic incident and improving our source reliability. We are making our reservoirs and dams more resilient to hazards such as extreme flood events through improving reservoir capacity as well as reducing the risk of failure by erosion with other measures.

5. Customer research summary

The key elements of customer research that we have used to inform our approach to managing our overall water service resilience are summarised in Figure 2.

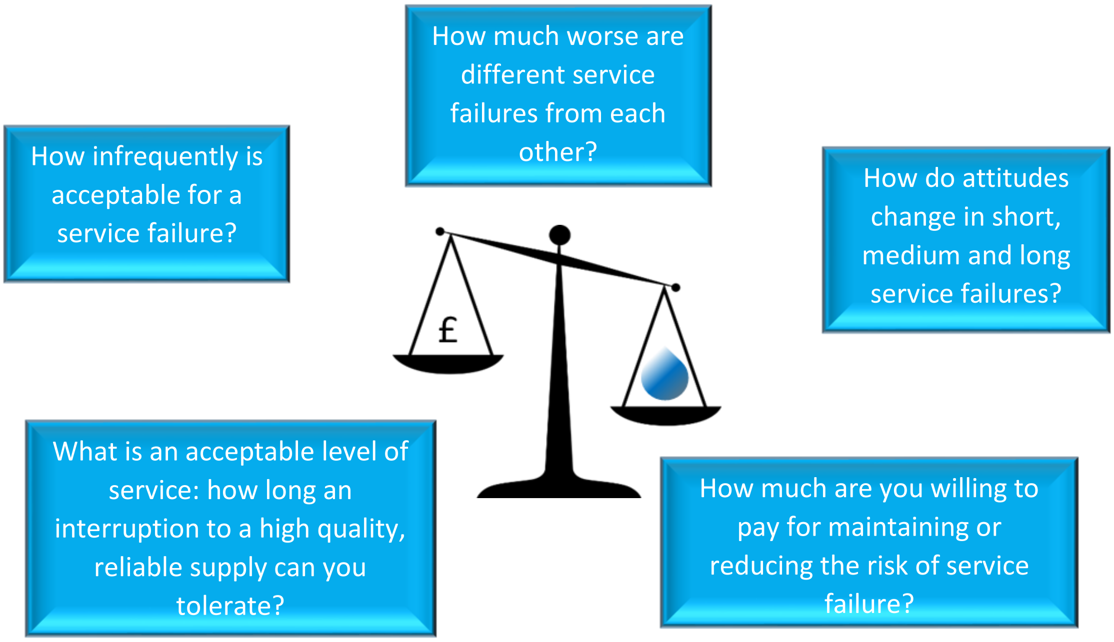


Figure 2 Key water service resilience questions

The customer research and approach to evaluating the responses to these questions is described more fully in our *Revised Draft WRMP19 Technical Report - Customer and stakeholder engagement* (Section 4). The overall value for avoiding a long term interruption has been assessed as £290/day. The relative weightings for different types of service failure were assessed from research carried out with customers affected by our major water quality incident in the Fylde area during 2015.

As previously stated, using our customer research we have evaluated relative weights for different types of service interruption. These are generally assessed as interruption risks, but in the case of the Manchester and Pennine Resilience project, where a more comprehensive assessment of potential impacts has been carried out (Appendix A, Section A.7), we have used specific weightings for water quality service risks in any failure mode where these could be expected.

6. Resilience option assessment

All resilience needs were assessed by either their expected impact upon the risk of interruption to supply or their potential to lead to a water quality incident. In some cases, the interruption would be due to poor water quality, rather than loss of supply directly. We have chosen to assess both of these outcomes against a common metric of interruptions of service. Where it has been possible to identify the expected outcome and differentiate between a water quality or interruption consequence, we have converted water quality consequences to “equivalent interruption days” with the weightings as outlined in Table 3.

There were two different approaches to the assessment: a desktop version where no system model is available that can reflect the risk, and a system model. In each case, the output is comparable and is defined as an annualised risk of interruption. The system model has been used extensively in the assessment of the Manchester and Pennine Resilience project risks and options.

Table 3 Water service relative impacts

Customer impact	Relative Weighting
No water – service interruption	1.0 (default)
Discoloured water (safe to drink)	0.6
Taste or odour issues (safe to drink)	0.6
Boil water notice	0.35
Do not drink	0.8
Do not use	1.0

6.1 Options identification and appraisal

6.1.1 Overall approach

All resilience risks had option assessment carried out through the WRAP. The process was varied for different priority risks, with those which were assessed to be the most complex and highest priority getting the most in-depth option and costing assessments. A series of network contingency models and associated option identification reports were commissioned for each water treatment works to document a current view of required network activities in the event of long term failure of the works. This led to the confirmation of resilience risks associated with specific water treatment works failures. This work has also formed the basis of cost and scope estimates for options to address some of the identified resilience risks.

The identification of options to manage resilience risks is typically managed through our standard WRAP process. Central to the WRAP process is a series of “risk and value” gateways where the need and potential options are challenged by our strategy and engineering teams. Prior to each gateway, we consider a full range of potential options we can use to manage the risk. We ensure that we have covered all credible options by reviewing the risk against our Generic High Level Solutions (GHLS), see Table 4 below. This challenges us to think about all potential risk management approaches and to consider ways to manage the risk without a “new build” solution.

Table 4 WRAP Generic High-level Solutions

Generic High Level Solution (GHLS)			Resilience 4 R's
1	**Monitor and Respond**	Accept the risk and plan to respond in an agreed way if the risk arises with a contingency plan	Response and Recovery
2	**Operational Intervention**	Return relevant assets to their original performance through one off maintenance, coupled with an agreed contingency plan	Reliability
3	**Optimisation**	Improve relevant asset performance by changing operational and maintenance regimes, possibly coupled with one off investment to increase the capability of the existing assets	Reliability
4	**Refurbishment**	Capital investment on relevant assets to prolong asset life and restore their performance to the original design	Reliability
5(a)	**Replacement**	Replace the relevant assets on a like for like basis where refurbishment is unlikely to be economically viable	Resistance, Reliability
5(b)	**New Asset**	Capital investment on new or additional assets to meet new performance standards, enhanced reliability or a more cost beneficial solution	Resistance, Reliability, Redundancy
6	**Partnership**	Collaborative investment shared or wholly provided through a third party with costs and benefits shared across all parties	Any of 4 R's

This process has been externally audited as a robust methodology by Arcadis Consulting.

6.1.2 Options identification and appraisal – Manchester and Pennine Resilience

For the Manchester and Pennine Resilience risk we have developed a similar process, but more specifically tailored to the complex interaction of resilience risks. The long distance water transmission pipelines have been the subject of investigation and refurbishment since the 1990s. Considerable planning and investment in enabling works was required to undertake two outages of one of our major strategic aqueducts supplying Manchester, a 109 km pipeline commissioned in the 1950s. The findings of the second outage, completed in the winter of 2016, indicate that there are both water quality risks and water supply risks. These risks have been assessed as the highest ranked water supply resilience risks when assessed in accordance with the company resilience risk assessment process.

Key failure modes were identified to represent the greatest resilience risks, and probability and consequence was determined for each failure mode. We developed multiple options to reduce the resilience risk to an acceptable level. This process follows the Cabinet Office guidance for the four R's of resilience; aiming to offer solutions across the four R's.

Additionally, we are undertaking operational interventions and optimisation through:

- On-line monitoring and enhanced laboratory analysis of water samples;
- Installation of rapid-response ultraviolet treatment units for biological contamination;
- Automated facilities that divert short term deterioration of water quality to waste;
- Agricultural land management to reduce pathogens entering water supplies; and
- Assessment of additional supply, re-zone and alternative water supplies.

We have also already committed a project to address the highest risk tunnel section of the aqueduct system. Following publication of our draft Water Resources Management Plan, we completed customer research to understand the level of support for further risk mitigation to improve the resilience of the aqueduct system. The five alternative solutions that we selected for consultation and customer research are presented in Section 6.4.4 of our *Revised Draft WRMP19* main report. They are detailed further in Appendix A of this technical report, which also explains the process for identifying options and solutions to manage the risk, and sets out the evidence gathered through the consultation period to select a preferred solution.

6.1.3 Reservoir Resilience Programme

Our reservoir investment programmes are delivering improved reliability through more proactive interventions. By being proactive we are able to improve scheduling and carry out work at lower risk times. Much of the industry operates a reactive approach to safety concerns, leading to unplanned emptying of reservoirs to take them out of service. It is typical that an affected reservoir is operated with major constraints upon yield for up to a year whilst investigations and any remedial work is carried out.

By proactively carrying out risk reduction interventions (such as improving flood capacity, or installing filters to prevent internal erosion) the period out of service can be planned to avoid interruptions, and with the work programmed and scheduled to be efficient and timely. Proactive risk reduction is safer for downstream communities than 'fix on fail', and less likely to lead to supply interruptions for customers.

The risk reduction measures we are undertaking often involve increasing the capacity of the dam to resist floods, ice loading, or earth movement, making the supplies to customers more resistant to interruption in the event of a challenging incident.

By reducing the probability of dam failure we are also protecting the property and infrastructure that lies downstream of our dams (including homes, schools, hospitals, and transport and utilities infrastructure), preventing the damage to infrastructure that would occur in the event of a dam failure. Whilst people could be evacuated in the event of a slowly developing dam failure, built infrastructure could not be relocated and the disruption to normal life and the economy that loss of infrastructure causes cannot be overstated. Reducing the risk of dam failure is therefore improving the resilience of the entire community, not just for those living immediately downstream of the dams.

7. Testing the preferred plan

7.1 Draft plan

In our draft Water Resources Management Plan, the preferred plan, which included options to facilitate a potential water trade, was evaluated to ensure that there would be no deterioration to the overall water supply system resilience. The approach taken for this test was to utilise the previously developed MISER "all system" model that was used to test the supply system against extreme freeze-thaw events.

The selected enabling works for a water trade were defined and modelled within the MISER model. The principal changes were the inclusion of the additional sources or reduced demand, plus some reconfiguration of strategic trunk mains in the south-west part of our region.

The model was then run with the same extreme freeze-thaw demand profiles previously utilised for modelling the baseline risk of the system against this hazard. This equates to simulating each of the three historic freeze-thaw events during the winter of 2010/11 five times at 5% increments of increasing demand. A total of 15 simulations were therefore produced to test the plan.

The results of the extreme demand analysis test against the proposed plan showed no deterioration against the baseline risk. The first deficits appear when the demand is increased by 15% against the WRMP19 baseline demands, with observed maximum historic peaks, in the two most stressed demand management zones. This is a high percentage increase relative to these historic maximum.

7.2 Revised draft plan

For the revised draft Water Resources Management Plan, water trading is no longer within the preferred plan as it has not been selected by other water companies in their respective plans. However, given that the potential for future water trading will continue to be strategically explored towards WRMP24, we have retained an adaptive pathway (separate from the preferred plan) which shows what a future water trading plan could look like. For this purpose, the resilience assessed completed at the draft plan stage is still considered representative and demonstrates that our strategic approach protects water supply resilience.

The preferred plan for revised draft Water Resources Management Plan includes further enhanced leakage reductions and interventions to address the Manchester and Pennine Resilience risks. These can only improve the system level resilience to events such as freeze-thaw from the baseline position tested, and thus no further testing was required of system resilience for the preferred plan for the revised draft Water Resources Management Plan.

8. Water supply resilience plan

We are planning to continue to reduce the largest identified water service risk during the upcoming investment period from 2020-2025 at a pace and to a level supported by our customers and other stakeholders. This relates to the aforementioned Manchester and Pennine Resilience and following a comprehensive assessment of solutions we have selected solution D as our preferred plan. Solution D involves rebuilding all single line sections of the major aqueduct supplying these areas. This is explained in further detail within Appendix A.

This solution does not change the supply-demand balance position, noting that it is being taken forwards to address a different resilience driver.

9. Conclusions

The Water Resources Management Plan has been subject to detailed assessment of both drought and non-drought resilience. The plan has been tested against credible, stretching, demand scenarios that simulate a range of extreme system wide freeze-thaw events. The preferred plan results in interventions to further improve resilience, and for the water trading adaptive pathway testing has been previously completed to show how resilience is protected under that potential future. The preferred plan includes the strategic choice for water service resilience, which is to continue to reduce the Manchester and Pennine Resilience risk and this choice is supported by the evidence gathered through the consultation period on our draft Water Resources Management Plan.

10. References

Department for Environment, Food and Rural Affairs, 2016. Guiding principles for water resources planning.

Environment Agency and Natural Resources Wales, 2018. *Water Resources Planning Guideline,* s.l.: s.n.

UKWIR, 2013. Resilience Planning: Good Practice Guide [13/RG/06/2].

Appendix A – Manchester and Pennine Resilience Options Process

A.1 Overview

Our largest and most significant water service resilience risk, known as "Manchester and Pennine Resilience" (M&PR) is associated with a potential failure of a major strategic aqueduct. This has been subjected to a detailed risk assessment process and is currently undergoing a comprehensive option selection and appraisal process. This appendix describes the risk assessment and options appraisal process.

A.2 Understanding the risk

The aqueduct in question has been subject to inspection in 2013 and 2016. During these inspections a range of data was collected. We further investigated the system risk and resilience by three key elements. They consist of:

- A condition assessment model for the aqueduct;
- Assessment of the consequences of failure, both for water quality and loss of supply; and
- A system risk curve, identifying all relevant failure modes with an assessment of probability and consequence.

A failure mode describes the specific manner or way by which a failure occurs in terms of failure of part of a defined system under investigation. In this assessment, failures modes are the ways or means that the aqueduct, or associated assets, can fail resulting in a negative impact on customers leading to loss of supply or changes in the quality of the water supplied. There may also be other societal consequences such as flood damage.

We undertook an assessment of the aqueduct as a linear supply system using information gathered during the 2013 and 2016 outage investigations to develop a comprehensive list of potential failure modes. Failure modes fall into two prime consequence categories: water quality and loss of supply. Initial identification gave circa 60 failure modes to be assessed; this was reduced to 17 by combining section failures with a common or similar consequence and removing any duplication in hazards, assets and consequences. This included removing any modes that incorporated 'double jeopardy' where this results in significantly reduced likelihood of the consequence materialising.

Our regional supply network is a complex and highly integrated system. Different failures of different assets which make up the system will have varying impacts on water supply depending on the prevailing conditions in the system. Demand, raw water availability and asset capabilities all vary over time. In order to fully understand the system risk, we have undertaken detailed supply-demand modelling to consider the different events and their impacts.

To quantify the security of supply risk, we have adopted our existing production planning mass balance model, MISER, as the basis of our assessment approach. The existing model contains all water treatment works (WTWs), large diameter trunk mains (LDTMs) and strategic service reservoirs. We have extended the MISER model to account for upstream hydrological constraints that may be impacted from longer duration failure events. For the first time, we have combined both our water resources Aquator™ and production planning tools to use MISER in this way.

For the purposes of Manchester and Pennine Resilience, we commissioned Servelec Technologies who have a proven track record in carrying out complex modelling analyses in the water industry, to work with us on the consolidation of our MISER model and its use in the assessment of security of supply risk.

The impact of each of the failure mechanisms has been tested under four potential scenarios:

Failure Occurrence Conditions	Starting in April	Starting in October
Normal Year	Normal year demands Normal year hydrology applied (1978/79)	Normal year demands Normal year hydrology applied (1978/79)
Dry Year	Dry year demands Dry year hydrology applied (1995/96)	Dry year demands Dry year hydrology applied (1995/96)

Normal and dry years account for the variation in both demand and hydrological conditions under a normal and dry year. A failure occurring in April and lasting 6 months captures the impact on our supply system during the summer demands. Similarly, a failure during October and lasting 6 months takes account of winter freeze-thaw events.

For coherence, the underlying conditions and assumptions used in the MISER model have been aligned with our Water Resource Management Plan, which is appropriate for the purposes of Manchester and Pennine Resilience.

Because failure events are unpredictable and impacts are dependent on a range of factors such as the time of failure, the supply-demand position and water storage among others, we have accounted for a range of hydrological and demand conditions within our MISER model. These are summarised in the table below.

Criteria	Detail
Demand Data	District Meter Zone (DMZ) level weekly demand data Normal Year (Average) and Dry Year (Peak) demands applied Based on WRMP demand forecast
Leakage / Losses	Included within DMZ level demand figures Separate allocation of losses to our network of large diameter trunk mains
Water treatment works capacities	Consistent with WRMP supply assessment as the maximum sustainable capacity Min, Max and initial business as usual starting flows apply
Raw Water Components (based on the Aquator™ model used for dry year assessment)	Raw Water Inflow sequences – historic inflows into raw water impounding reservoirs (IRs) used
	Abstraction Licences – Annual (Ml/y) and Daily (Ml/d) raw water abstraction constraints apply
	Impounding Reservoir control curves – operational policies that ensure year round availability of raw water storage
	Impounding Reservoir capacities and starting levels – Historic impounding reservoir storage sequences used
	Emergency Storage – Accounts for c.20 days' supply and stops at assigned 'dead water level'
	Hands-off flow (HoF) – minimal river flows below which abstraction cannot take place
	Compensation flows – Fixed Ml/d release requirements from our impounding reservoirs, typically for environmental provision
MISER Optimisation	Week by week – management of resource to meet demand on a week by week basis
Raw Water + Process Losses	Losses in raw water transfer mains up to the water treatment works and losses as a result of the treatment process at the water treatment works are accounted for
Enabling Works	Account for network re-configurations we would need to undertake in the event of losing the aqueduct

In the case of catastrophic failure events leading to long duration outages of the aqueduct, we would operate under a set of conditions appropriate to these unique circumstances; these conditions would not form a part of our business as usual approach, but would be our 'emergency' response to such events.

A series of mass balance models of the supply system, have been produced (in MISER) for the scenarios below to enable credible failures and constraints to be modelled to understand the current consequences, in terms of demand deficits, both with and without mitigation options.

Criteria	Assumptions Under Failure
Enabling	Strategic and emergency valves are made available in the model
Water Treatment Works Capacity	Treatment works ramp up linearly from their starting flows to available max capacity
MISER Optimisation	Week by week approach – this is how we would manage our supply system in the event of a failure
Raw Water	In an emergency, we would relax operation against our impounding reservoir control curves and make available our emergency storage Regulatory constraints and licences still apply (Abstraction licences, hands off flow and compensation flows)

A deterioration model has been used to assess concrete lining deterioration in the potable water aqueduct. For the purposes of the deterioration model, a Hoek and Brown calculation has been used to determine a critical lining thickness after which further wear is assumed to present lining failure risk. The data used in the model included the tunnel construction method; concrete core sample strengths and depths of worn and unworn concrete; locations of water quality failures (exceedance over prescribed concentration or value, known as PCV) from sampled ingress during the outage; and identified structural areas of concern recorded during both outages. The model produces a probability of failure for catastrophic liner failure due to wear, and consequent water quality or catastrophic structural failure, and can be used to forecast the change in risk of catastrophic liner failure assuming that the liner continues to degrade at the average historic rate.

The results of all this analysis has been combined into an overall system risk curve. This is a common approach in the quantitative assessment of risk. It is usually shown as a plot of cumulative frequency or probability against consequences. In some fields the consequences are expressed as number of fatalities (N) and therefore the plot is commonly referred to as an "F-N curve". However, we have expressed the consequence in a common measure of "customer days lost" (the number of properties affected, multiplied by the number of days affected).

The system risk curve is a useful tool to understand how the risk arises from different parts of the system and we have used it to identify and select appropriate options to mitigate the risk. For the purposes of customer research and consultation, we have simplified the system risk curve into three indicative events to represent the overall baseline system risk over a future 10 year period:

- 65% probability that 1.2 million properties could be affected by water quality problems for at least one week;
- 35% probability that that 120,000 properties could be affected by supply interruptions for up to three months; and
- 10% probability that 240,000 properties could be affected by supply interruptions for up to two weeks.

These represent the baseline risk in the absence of any options which are discussed in the following sections. It includes the impact of deterioration in the aqueduct condition from the outage into the 2020s, and works already planned to mitigate the current risk. The baseline risk ranks highly when assessed alongside other water assets in accordance with the company risk assessment process.

We have already committed a project to address the highest risk tunnel section of the aqueduct, and the benefits of this are included in the indicative events listed above. Options to further reduce the risk are considered in the following section.

A.3 Range of options considered

We have considered a broad and innovative range of intervention options to mitigate the resilience risk posed by the aqueduct system. This process began with the understanding of failure modes and risk described above. The system risk curve served to focus our attention on the wide range of potential options to address identified risks to customer supply. By identifying individual potential options, which could be later combined together to comprise overall solutions, we were able to remain open-minded and a broad list was developed rather than focusing in on a number of specific solutions.

The initial list of 434 options comprised both operational interventions such as increasing the outputs from existing water treatment works, and capital investment interventions which ranged from duplication of tunnelled sections of the aqueduct, through to construction of new water treatment works and demand management from multiple parts of our water supply network. The range of options proposed is shown in the table below and demonstrated through the subsequent sections.

Option category	Unconstrained options
Demand management	38
Distribution	115
Operational intervention and optimisation*	35
Quality	125
Resource	121
Total	**434**
*This includes a wide range of operational response / recovery options to allow us to respond effectively if the risk arises and return relevant assets to operation, coupled with an agreed contingency plan	

High-level costs for each of the initial options were subsequently estimated for comparison, in order to determine the most cost effective ones to take forward.

Following the initial identification and high-level costing of options, we continued the optioneering process in three major stages, as described below and summarised in Figure A1.

Stage 1 (coarse option screening)

We discounted options based on several factors, such as estimated value for money, environmental impacts, technical feasibility (including water quality) and whether or not the risk reduction objectives were met. We reviewed each option to identify the extent to which that option benefits the environment or whether the environment suffers from the implementation of the option. Examples of options that have a positive impact on the environment include leakage reduction options, as less leakage means reduced requirement to abstract and treat raw water. At this stage, we also considered whether the proposed option had the potential to impact on Special Areas of Conservation and/or Special Protection Areas. These decisions were supported by calculations of the cost per megalitre for each of the different options to determine which would offer the best value for money for customers whilst comparing their relative geographical locations, as well as assessing how applicable these options were in addressing the failure modes being identified. At this stage, the number of options had reduced from 434 to 143 options (Figure A1).

Stage 2 (option grouping & coarse solution screening)

The remaining options were then grouped together to form solutions, directly addressing each of the failure modes identified. At this stage, we grouped the number of options together into 79 solutions. This work was supported by an ‘Option Solution Failure Design Tool’. This tool was used for recording and controlling the data associated with the grouping of options to solutions and failures mode. Once grouped together, an indicative overall cost for each solution was generated.

Following this, we undertook a secondary option screening process to discount options that had not yet been grouped into a solution.

The coarse solution screening considered the risk reduction (improvements in customer days lost) for each of the 79 solutions, against cost (totex, NPV, bill impact) to inform the selection of the solutions taken forward to customer research.

Stage 3 (final solution screening)

Once a shortlist of five candidate solutions were found, we undertook customer engagement to inform the selection of the preferred plan, including through consultation on our draft Water Resources Management Plan. We considered these results alongside other factors, including an environmental appraisal and an economic appraisal, to select our preferred solution. Further detail is provided in Sections A.7 to A.9 below.

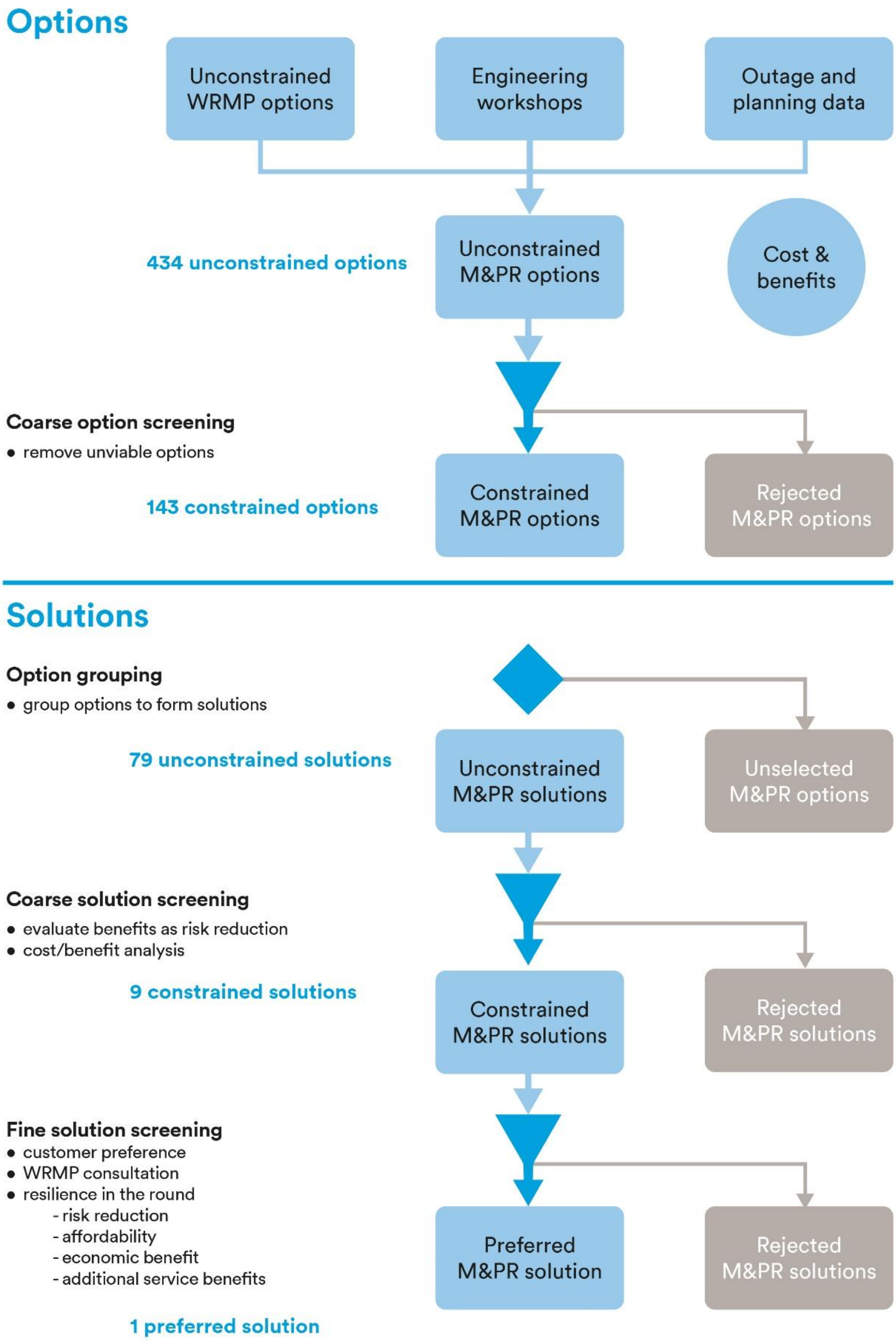


Figure A1 The optioneering process

The Manchester and Pennine Resilience options have been developed in conjunction with the Water Resources Management Plan supply-demand options. Similar assumptions were used in developing and screening options, and the same document templates have been used. Relevant options from the WRMP19 supply-demand 'pool' (i.e. those associated with the aqueduct and supplied areas) have been included in the Manchester and Pennine Resilience options list.

Multiple benefits were achieved between both Manchester and Pennine Resilience and the WRMP19 supply-demand options. These include the development of more robust options during the optioneering process, as these were developed from a multi-disciplinary and multi-driver approach. Knowledge sharing between the options sets was also undertaken during the optioneering process, to ensure that key factors were taken into consideration which would be useful for both the resilience driver and the supply-demand driver.

We have focused on the four R's of resilience (namely *Resistance, Reliability, Redundancy* and *Response & Recovery*) throughout our optioneering process to propose options that span each of these four areas, to be considered. Figure A2 highlights examples of options considered under each 'R'.

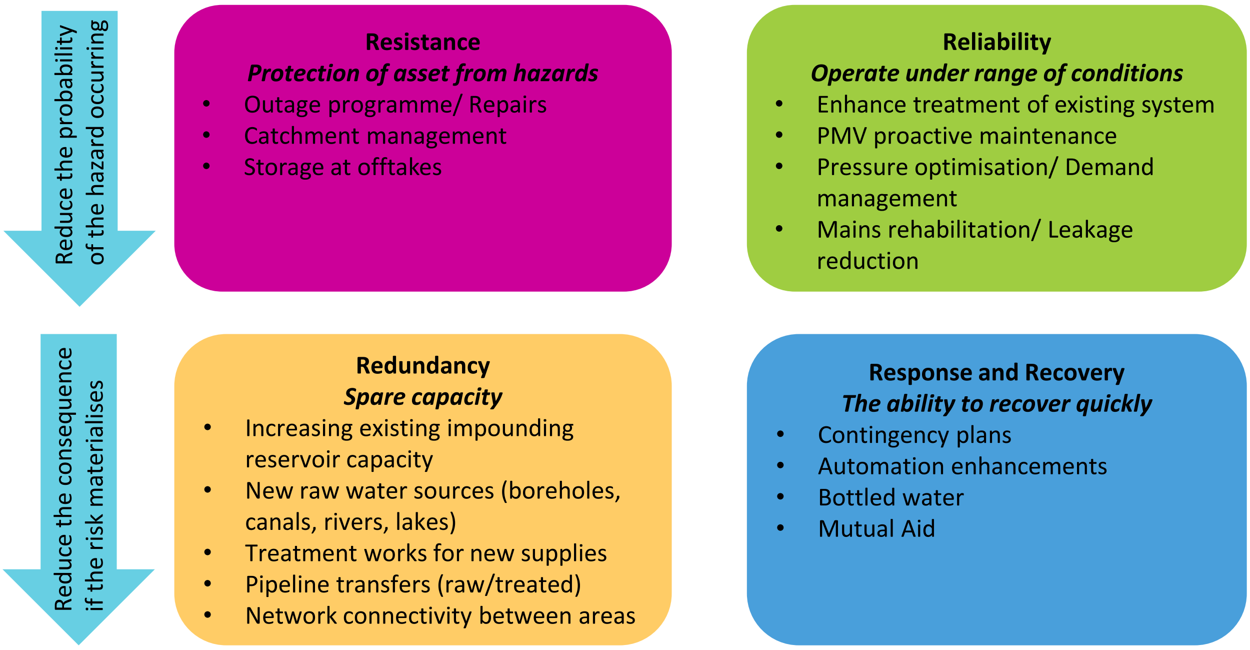


Figure A2 Demonstrating resilience through optioneering

Options considered ranged from a new treated water aqueduct, enhanced use of existing raw water sources, enhanced outputs from existing treatment works, new raw water sources and treatment works and enhanced use of existing and new network improvements. We also investigated the use of novel treatment technologies such as reverse osmosis. The range of options considered are summarised below.

<u>Enhanced use of existing raw water sources</u>

In order to improve overall resilience, we have considered increased abstraction from existing water sources. We have investigated a number of options, including relocating the treatment of the majority of Manchester's water supply from its current position in Cumbria, to a location just outside Greater Manchester. A key benefit of this is protection against potential ingress of contaminants into the aqueduct to ensure a consistent supply of clean drinking water to customers in Manchester and surrounding areas.

We have a number of existing abstraction licences, where raw water is taken from rivers and transported to a water treatment works for treatment, before being put into supply. In some cases, the actual abstraction rate is currently below the consented value. Work has been done to assess the feasibility of increased abstractions, hence increasing the availability of raw water for subsequent treatment and supply to customers.

Enhanced existing treatment works capabilities

We have also investigated options to improve the capability of existing treatment works. One such option is upsizing the capacity of a water treatment works, which is not directly fed by the aqueduct. In order to do this, additional treatment is required and work has been done to assess whether this can be incorporated into the existing treatment works.

Another study which has been undertaken is looking to relocate some treatment units, from the current location on the outlet of a reservoir, to a nearby water treatment works. This reduces the likelihood of contamination and provides a more robust process for consistently providing clean drinking water. Other options which we have considered include reinstatement of an existing water treatment works that is not currently in use and carrying out improvement works on disinfection equipment, to reduce the chance of contamination entering into supply.

Enhanced use of existing network improvements

In order to improve overall resilience, we have developed a number of options that utilise the existing water supply network. A key benefit of these options is that they would minimise or eliminate the need to install new network or transfer pipelines, ensuring continuity of supply during an aqueduct outage.

In some options, uprating the flow from the West East Link Main (WELM) and Rivington was reviewed to avoid installation of new raw water pipelines.

A review of leakage reduction has been conducted in various District Metered Zones (DMZs) in order to minimise an amount of water loss. Reducing the level of leakage prevents the need to develop new water resources, thereby minimising environmental impacts. It would also mean lower costs, hence providing the best value for money for consumers.

In another study, we reviewed the use of a canal and river to transfer raw water downstream and reduce the total length of new pipeline. The major benefits of utilising a river/canal for a raw water transfer are reduced extent of construction work, land purchase requirements, engineering assessments and planning permission applications. This would result in lower costs overall and reduce the impact on a number of both urban and rural roads. An additional study involved searching for abandoned pipes and boreholes that could be brought back into service to improve aqueduct resilience. However, no suitable combination of abandoned pipes and boreholes were identified.

New raw water sources

The use of new raw water sources would reduce the reliance on the aqueduct to supply water. One route which is available to increase supply is through borehole extractions. A small proportion of Manchester's current water supply is provided by boreholes; however, there is a possibility to increase this through tapping into new sources. We have examined abstraction points within Greater Manchester, as well as locations further afield. Another major opportunity exists in identifying new river abstractions which are not currently being utilised. We have identified potential river sources throughout the catchment, and studies have been carried out to assess the feasibility of increasing supply.

An innovative option that we have explored is to engage in water sharing with other UK water companies. There has been some discussion between ourselves and a neighbouring water company, with the possibility of installing a pipe capable of transporting water in either direction. In an emergency situation where one company has a shortage of supply, water can be sent into the network in which it is required.

We have also explored some more unconventional solutions to increase the availability of clean water. Examples include installation of a reverse osmosis plant designed to treat wastewater effluent and the use of graphene for water treatment.

New treatment works

There is a possibility that a number of new water treatment works could be built to improve resilience. In the past five years, there have been two aqueduct outages, where we have isolated flow through the aqueduct in order to assess its condition. To be able to do this, we have had to ensure maximum capacity of our reservoirs, thereby ensuring a continuous supply during the outage. However, this only gives a short window of time to inspect the condition of the aqueduct. We have undertaken studies to assess the benefit of building new water treatment works, which can treat river-source water, at various points along the route of the aqueduct. The advantage of this is two-fold, as it provides an alternative source of water if the aqueduct were to fail, and allows for longer outages to be planned than has been the case previously.

Another option under consideration is increasing the flowrate of an existing abstraction, and re-routing the additional flows to a new treatment works, capable of supplying the Manchester network. Through additional connectivity, overall resilience would improve, as the source of raw water could be selected based on prevailing conditions in the wider network.

New network improvements

Several network modifications were proposed and investigated due to the following scenarios:

- The existing network is not capable of supplying additional flow to the proposed/existing destinations; and
- No existing water pipeline or network near the alternative water source and/or treatment works.

In some options, a new connection would also be required between the existing water take-off point and new treatment works. Addition of new pipelines would improve aqueduct resilience and wider water supply security.

A.4 Additional benefits delivered

Manchester and Pennine Resilience options were developed alongside wider business needs. This is highlighted particularly with aqueduct repair, and other resilience schemes.

A joint working group was set up, between the teams working on supply-demand and resilience options, to ensure that the project solutions were mutually compatible, were not competing for the same raw water resources and were not building insufficient or excessive resilience into the system.

This resulted in one potential option being considered where a combined solution could be used for supply-demand, Manchester and Pennine Resilience, and wider resilience needs. This was a hybrid solution where the initial scopes of solutions were modified. Environmental benefits would be seen from reducing the number of raw sources, new water treatment works, the length of new pipework, and overall energy requirements.

There is another associated benefit which may result from the implementation of an upgrade to the West-East Link Main (WELM): it would give added flexibility for supplying west to east, should it be needed for other reasons. This would be particularly the case if, in the future, additional sources of water need to be developed in the western part of the supply system. This might be the case, for example, to meet other resilience drivers. The additional water would then also provide benefit to the eastern part of the supply system.

A.5 Impact on probability, consequences of failure and impacts on service

We engaged with customers on the topic of resilience, the aqueduct risk and the relationship between risk mitigation and cost. In order to effectively communicate this, we determined a range of viable solutions that reduce risk to different levels and calculated the associated bill impact. To determine the viable solutions, we undertook a cost-benefit analysis (CBA). The cost-benefit analysis outputs clearly showed the relationship between solution cost and benefit (at this stage, benefits were equal to the level of risk reduction). This allowed a set of solutions to be identified based on the lowest cost solutions to deliver a range of residual risks (i.e. higher cost solutions which gave the similar benefits were discounted at this stage). The solutions that were chosen to represent a choice between residual risk and bill impact for customer research and consultation are summarised below.

A.6 Solutions short list

This section shows the detail of the solutions that have been selected as alternatives for consultation and customer research. Flows for each of these solutions were determined based on historical flows and/or MISER modelling.

Solution A: Target repairs of the two tunnel sections that are in the worst condition

This solution focuses on addressing the highest remaining risk to water supply. New sources would be required to supply some customers during the rebuild, and these would also provide some alternative water supply for the future. The scope includes:

- Repairs to be undertaken during longer duration outages. Offtake points would require alternative water supplies for the outage period;
- New 5 Ml/d water treatment works in Rossendale fed from a new abstraction on the River Irwell (similar to water resources option WR141);
- Isolation valves added to the two sections being repaired;
- Uprate West-East Link Main to 150 Ml/d;
- Leakage reduction across various Demand Management Zones (note that this is not additional to the leakage reduction already included in WRMP19 alternative plans 2, 3 and 4); and
- Rezoning in Rochdale Demand Management Zone.

The new abstraction would be used intermittently to support outages of the aqueduct to enable repairs.

Solution B: Rebuild the tunnel section that is in the worst condition and provided targeted treatment for water quality

This solution addresses the highest risk to water supply. It also addresses the highest water quality risk. The scope includes:

- Install additional treatment for metals and ultraviolet disinfection at all 12 bulk supply points along the aqueduct;
- Install additional treatment for metals and increased ultraviolet disinfection capability at the Manchester end of the aqueduct;
- Leakage reduction across various Demand Management Zones (note that this is not additional to the leakage reduction already included in Water Resources Management Plan 2019 alternative plans 2, 3 and 4);
- New tunnels to replace the two highest risk tunnel sections of the aqueduct; and
- Four week outage of the aqueduct to install connections.

Solution C: Build 5 new water treatment works

This solution will treat impurities that could enter the water supply when it is flowing through the aqueduct. The scope includes:

- Re-designation of the aqueduct as a raw water aqueduct;
- New two-stage 450 Ml/d water treatment works near Bury;
- New 80 Ml/d water treatment works near Kendal;
- New 60 Ml/d water treatment works in the Bowland area;
- New 50 Ml/d water treatment works in Hyndburn;
- New 20 Ml/d water treatment works in Rossendale;
- New connections, mains and pumping stations to supply all areas fed from existing bulk offtakes from the new water treatment works; and
- Four outages of the aqueduct to install connections.

Solution D: Rebuild all tunnel sections

This solution addresses all water supply and water quality risks associated with the tunnels. The scope includes:

- Construct new sections of tunnel parallel to the existing aqueduct;

- Construct new wells adjacent to the existing wells; and
- Outage of the aqueduct to allow connections between the old and new wells.

Solution E: Rebuild all tunnel sections and provide additional sources of water

This solution addresses all water supply and water quality risks associated with the tunnels. This solution would enable future tunnel maintenance by providing alternative water supply whilst work is being done. The scope includes:

- Construct new sections of tunnel parallel to the existing aqueduct;
- Construct new wells adjacent to the existing wells;
- Uprate West-East Link Main to 150 Ml/d;
- Leakage reduction across various Demand Management Zones (note that this is not additional to the leakage reduction already included in Water Resources Management Plan 2019 alternative plans 2, 3 and 4);
- New 33.5 Ml/d water treatment works in the Bowland area fed from existing licenced sources in the area;
- New 40 Ml/d water treatment works in Hyndburn fed from a new abstraction on the River Ribble (similar to water resources options WR049a and b[8]);
- New 5 Ml/d water treatment works in Rossendale fed from a new abstraction on the River Irwell (similar to water resources option WR141);
- New 40.5 Ml/d water treatment works near Preston fed from existing licensed sources on the Rivers Lune and Wyre;
- Outage of the aqueduct to allow connections to the above new sources.

The full capacity of the new abstractions would be only used infrequently as their purpose is to provide redundancy in the event of failures elsewhere in the system.

At this stage we have assumed that there is no material impact of solutions A to E on the supply-demand balance position, noting that these are being defined to address a different resilience driver. Their purpose is to provide redundancy in the event of failures elsewhere in the system, or for planned outages.

A.7 Customer engagement results

Engagement methodology

We have worked closely with YourVoice, our Customer Challenge Group, to engage effectively with customers on this issue. Due to the scale and complexity, it was recognised that it was especially important that customers fully understood the risks and that the engagement was designed in a way to avoid biasing the results. YourVoice appointed independent experts from the Centre for Regional Social and Economic Research at Sheffield Hallam University to review the reasonableness of the research and interpretation of the results. We addressed all of their feedback before the research was formally launched.

We engaged a specialist research company to undertake both qualitative and quantitative research: DJS Research Limited. Through an iterative review process, involving the YourVoice Customer Engagement Subgroup, their appointed experts and the specialist research company, the customer research materials were designed to ensure they were robust, understandable and articulated the risk at an appropriate level.

Through engagement with YourVoice and Sheffield Hallam University during the design of the customer research materials, we ensured that the information was not over-stating the risk or creating a bias for a particular course of action. Sheffield Hallam University validated that there were not any obvious shortcomings in the customer research approach, methodology and analysis that may indicate any undue unintentional research bias. Triangulation between the qualitative and quantitative findings provides confidence in the results.

[8] Note that for the supply-demand balance, options WR049a and b were screened out due to climate change uncertainty (Appendix G of the *Revised Draft WRMP19 Technical Report - Options identification*). For M&PR the option would be used in a different mode of operation so the climate change screening does not directly apply. Mitigation of climate change impacts on the solution will likely be possible, for example by changing the utilisation or considering the interaction with storage in the system.

In the research, customers were presented with the summary risks using a visual representation using "risk ladders" to benchmark against other unrelated risks. Risk ladders effectively help people anchor a risk to other, perhaps more familiar risks. They also act as a visual aid to understand the scale of possible risk reduction.

Through the customer research exercise, we engaged with 2,426 household and business customers across the region on water supply resilience and the likelihood and impact of service interruptions to the 2.5 million people whose drinking water comes from the aqueduct. Figure A3 illustrates the breadth and depth of the qualitative and quantitative research conducted.

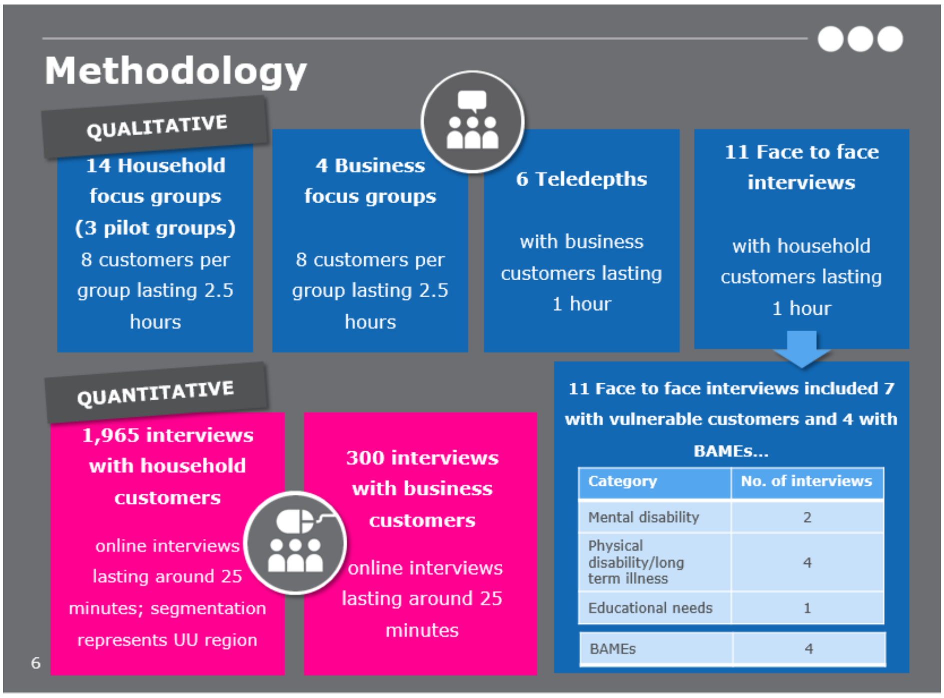


Figure A3 Customer engagement methodology for Manchester and Pennine Resilience research

Customer engagement results on the need to address the risk

A clear majority of customers (70%) in the survey said they had a high level of concern for the risk. A very high proportion (88%) chose an option to reduce risk over and above maintaining the status quo. This shows very clear support for the need to address the risk. Furthermore, Sheffield Hallam University validated that the research showed that both household and business customers had a strong preference for acting upon the current situation.

There is strong evidence from this research for us to act upon the current situation. There is support from both the qualitative and quantitative stages of customer research that action is essential. Additionally, the type of action was important to customers too. They expressed a clear preference for a robust long-term solution and did not just want a 'sticking plaster', as evidenced by analysis of supporting comments for option preferences.

Open responses from the qualitative surveys are shown in Figure A4.

Figure A4 Open responses from qualitative customer focus groups that support the need to act on the Manchester and Pennine resilience risk (DJS Research, February 2018)

Customer engagement results on the selection of a solution

Through the research exercise, we established that in addition to the support for the need above:

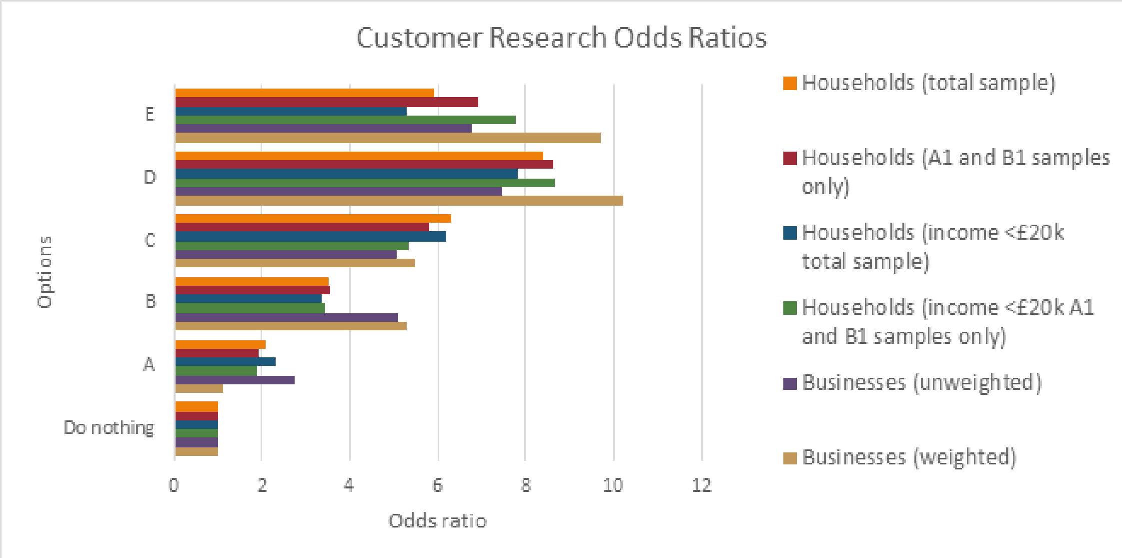
- Customers have a preference for durable, longer-term solutions that leave relatively low residual risk;
- Most customers are not willing to pay for temporary fixes that only partially reduce the risk;
- Customers support solutions to resolve the underlying issue of the deteriorating tunnel and conduit sections; and
- Customers showed a clear preference for the solution that reduced risk to relatively low levels and a household bill increase of £11. The relative preference for this solution was eight times higher than for the 'status quo'. Overall, both household and business customers have a statistically significant preference for this solution or a more expensive one with a greater risk reduction.

We varied the information presented to customers in order to understand the basis of their choices and to test the impact of context on their decision-making, as follows:

- We measured the influence of the risk values by halving the values with selected focus groups, and by creating appropriate test cells in the online sample to test the same effect in the quantitative survey; and
- We tested the influence of the option descriptions by removing description to just focus on risk and bill impacts in selective focus group discussions, and the addition of test cells with and without option descriptions in the online sample for the same purpose.

We shared the results with YourVoice and Sheffield Hallam University, and responded to their challenges to ensure that the conclusions were robust and defensible. We acted on their feedback by undertaking additional statistical analysis of the preferences expressed by lower-income customers. We also reassessed the business results with weightings so that small businesses are represented in line with the regional spread. Both assessments corroborated the overall customer views. Sheffield Hallam University concluded: "the research has been conducted in a rigorous manner; the results capture customers and are robust; the findings provide a sound basis for the recommendations made."

Customer responses from the quantitative research showing relative preferences for the five candidate solutions, relative to "do nothing" are shown in Figure A5.



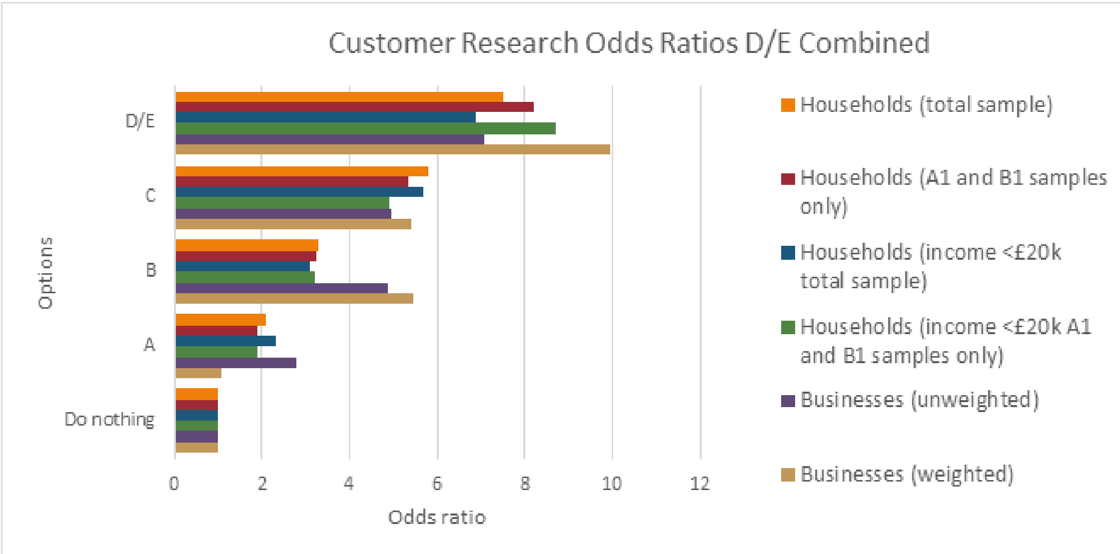


Figure A5 Customers' relative preferences for the 5 solutions or maintaining the status quo

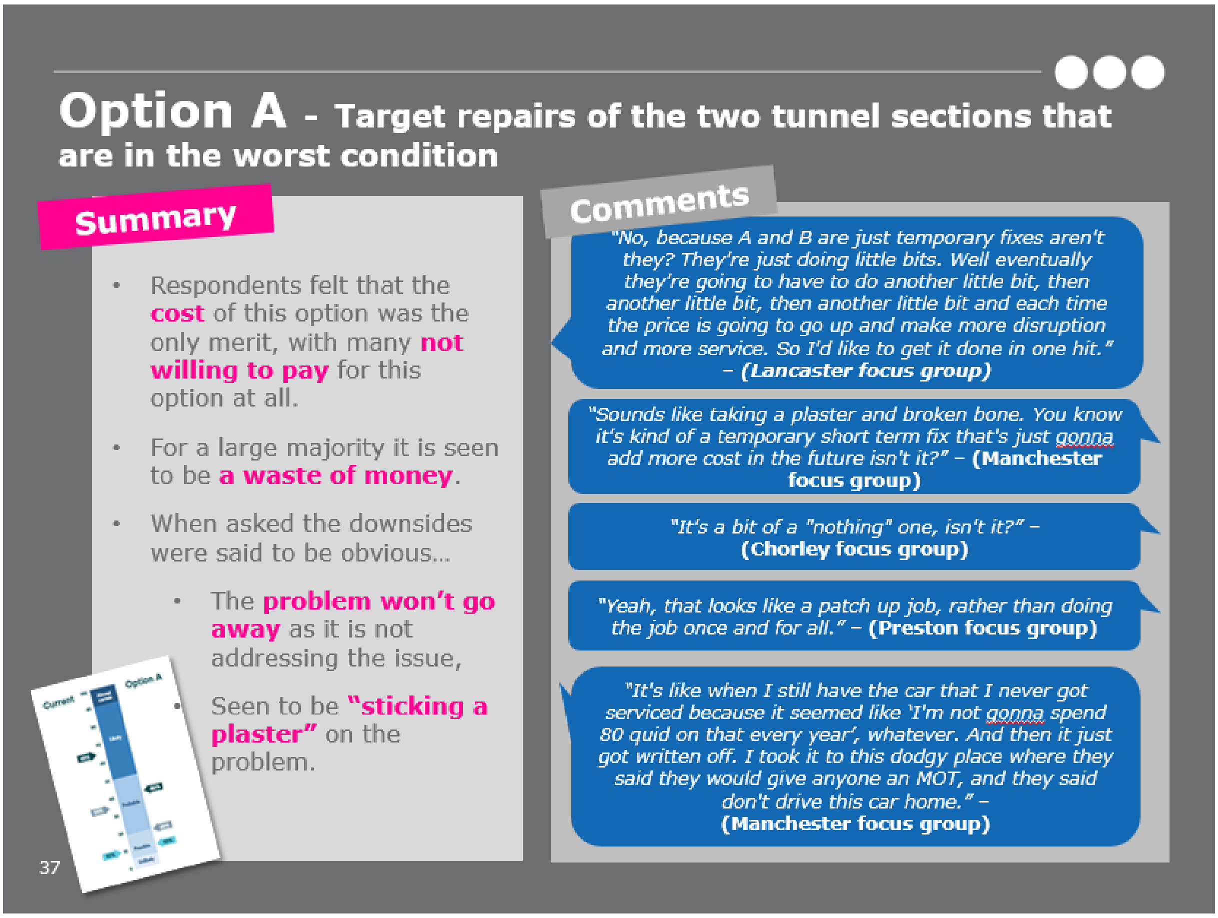
The features of the charts above, which show total sample and statistically significant responses, are explained as follows:

- **Odds ratios:** Odds ratios show the relative preference for each solution. Solution D, or solution D/E when combined, has the highest preference. There is a clear preference that action is required to avoid the 'do nothing' scenario.
- **Do nothing option:** We presented to customers the 'do nothing' option as the scenario for maintaining the current risk. As described in Section A.2, the 'current risk' is defined as the risk over the next ten years, taking into account the risk reduction from proactive activities (e.g. integrated contingency plans, operational improvements and targeted repairs to the highest risk section) and the increasing risks associated with future deterioration.
- **Option D/E combined:** A pair-wise choice experiment was used to look at the order of preference for each of the solutions using a customer utility preference score allowing a majority preference analysis to be undertaken. This showed that when tied preferences were included, the majority of household participants chose solution D in their top two choices (62%), and the majority of household respondents (including ties) also chose solution E (59.3%). When tied preferences were excluded from the analysis, solutions D and E

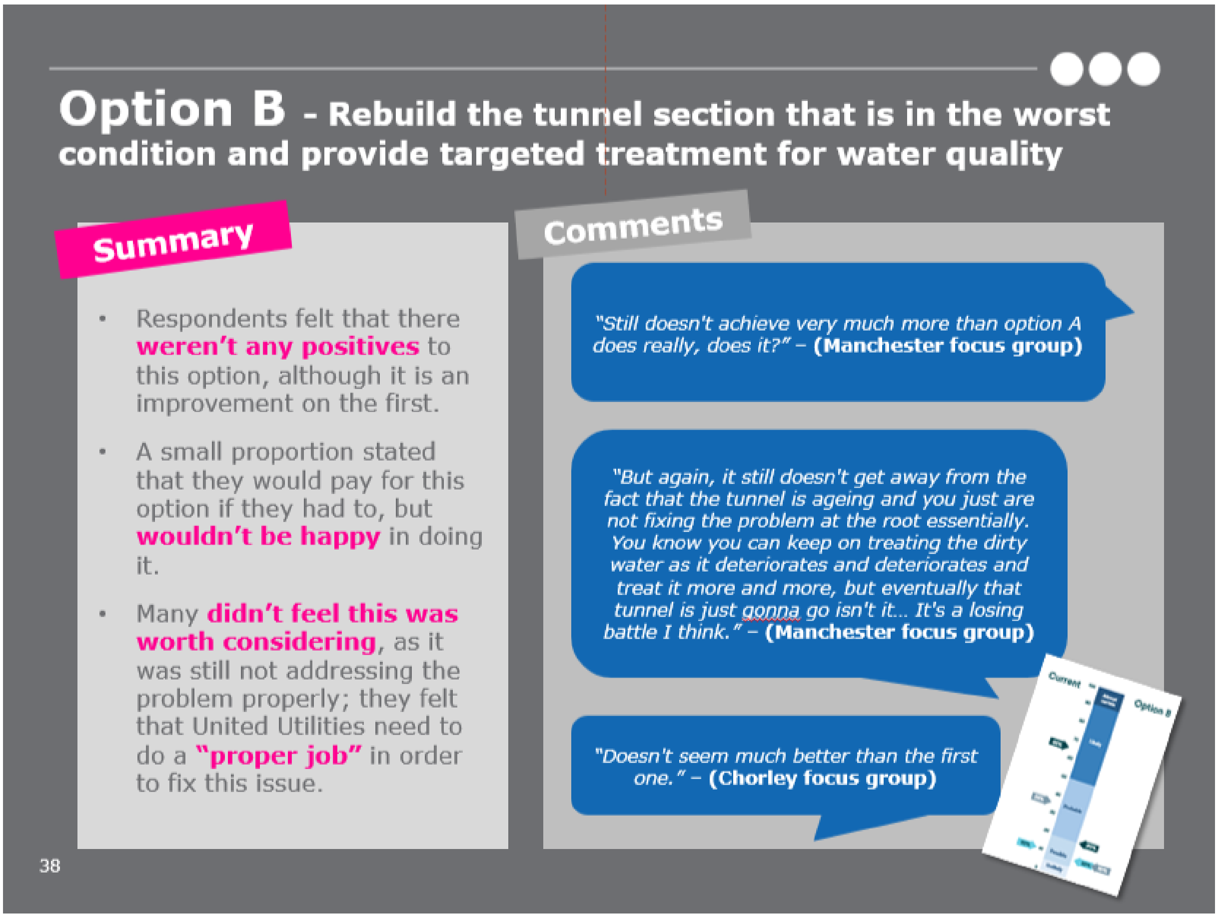
were again the top two choices (50% and 48% respectively). There was a high degree of cross-over between people who select solution D or E in their top two choices, and this indicated that combining solutions D and E is valid when comparing to preferences for the other options. This approach was validated by researchers at Sheffield Hallam University.

- For transparency, we illustrate above the customer responses with D and E separated, as well as D/E combined.
- **A1 and B1 samples:** Household samples were split into four sample groups: A1, B1, A2 and B2. Businesses were split into two sample groups: A1 and B1. Note that these are not socio-economic designations; they are the sample grouping designations reported by the research company. Information on risk and options was varied across the segments: sample A saw risk figures as per Figure 36 in our *Revised Draft WRMP19* main report, whilst sample B saw lower risk figures (approximately halved); sample 1 saw options descriptions as per Figure 34 in Section 6.4.4 of our *Revised Draft WRMP19* main report, whilst sample 2 did not see option descriptions, only risk reduction and bill impact. A statistical analysis of confidence intervals showed that the combined samples A1 and B1 reported clearer preferences based on a better level of information provided which was needed in order to make a more informed choice. This conclusion was validated by the independent experts at Sheffield Hallam University, who deemed this to be an innovative approach.
- **Businesses (weighted and unweighted):** The business sample was weighted to make it representative of the distribution of businesses by size of employer across our region. Odds ratios for business customers shows that solution D/E was also the favoured solution for both the weighted and unweighted samples. The confidence for intervals for solution D/E overlapped slightly with those for solution B and solution C for the unweighted sample; however, when the sample was weighted to be representative of the profile of businesses in our area the preference for solution D/E was statistically significant.

Customers told us they want a long-term solution to the problem that reduces the risk to minimal levels. Open responses from customers in the qualitative survey are shown below for the five solutions they discussed.



Option A - Target repairs of the two tunnel sections that are in the worst condition
Summary
Respondents felt that the cost of this option was the only merit, with many not willing to pay for this option at all.
For a large majority it is seen to be a waste of money.
When asked the downsides were said to be obvious…
The problem won't go away as it is not addressing the issue,
Seen to be "sticking a plaster" on the problem.
Current
Option A
Comments
"No, because A and B are just temporary fixes aren't they? They're just doing little bits. Well eventually they're going to have to do another little bit, then another little bit, then another little bit and each time the price is going to go up and make more disruption and more service. So I'd like to get it done in one hit." – (Lancaster focus group)
"Sounds like taking a plaster and broken bone. You know it's kind of a temporary short term fix that's just gonna add more cost in the future isn't it?" – (Manchester focus group)
"It's a bit of a "nothing" one, isn't it?" – (Chorley focus group)
"Yeah, that looks like a patch up job, rather than doing the job once and for all." – (Preston focus group)
"It's like when I still have the car that I never got serviced because it seemed like 'I'm not gonna spend 80 quid on that every year', whatever. And then it just got written off. I took it to this dodgy place where they said they would give anyone an MOT, and they said don't drive this car home." – (Manchester focus group)
37



Option B - Rebuild the tunnel section that is in the worst condition and provide targeted treatment for water quality
Summary
Respondents felt that there weren't any positives to this option, although it is an improvement on the first.
A small proportion stated that they would pay for this option if they had to, but wouldn't be happy in doing it.
Many didn't feel this was worth considering, as it was still not addressing the problem properly; they felt that United Utilities need to do a "proper job" in order to fix this issue.
Comments
"Still doesn't achieve very much more than option A does really, does it?" – (Manchester focus group)
"But again, it still doesn't get away from the fact that the tunnel is ageing and you just are not fixing the problem at the root essentially. You know you can keep on treating the dirty water as it deteriorates and deteriorates and treat it more and more, but eventually that tunnel is just gonna go isn't it… It's a losing battle I think." – (Manchester focus group)
"Doesn't seem much better than the first one." – (Chorley focus group)
Current
Option B
38

Option C - Build 5 new water treatment works

Summary

- Respondents felt this option was **better than options A and B** at first based on the risk reduction. However, when introducing what the option is, it quickly dropped in their estimations.
- Respondents felt option C **didn't solve the issues** raised with deterioration within the Haweswater Aqueduct.
- Due to **not tackling the potential risk to water supply**, a large majority said they would be **unwilling to pay** for this option.

Comments

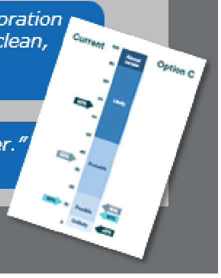
"It's like the elephant in the room isn't it; that you can't get away from this deteriorating tunnel… You can just keep doing these fixes, but the bottom line is the tunnel is broken whilst you're building these things." – **(Manchester focus group)**

"This is my least favourite. When you look at that, you have the same potential negative consequences as A, but for twice the cost. Exactly the same cons, nearly double the cost." – **(Crewe focus group)**

"Well Option C we're getting nothing. We're not getting anything really. We're already treating the water. " – **(Lancaster focus group)**

"… it doesn't address the issues of deterioration of pipes. It means if you get water it's clean, but you might not get it." – **(Chorley focus group)**

"I can't see the point of doing it whatsoever." – **(Crewe focus group)**



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Option D - Rebuild all tunnel sections

Summary

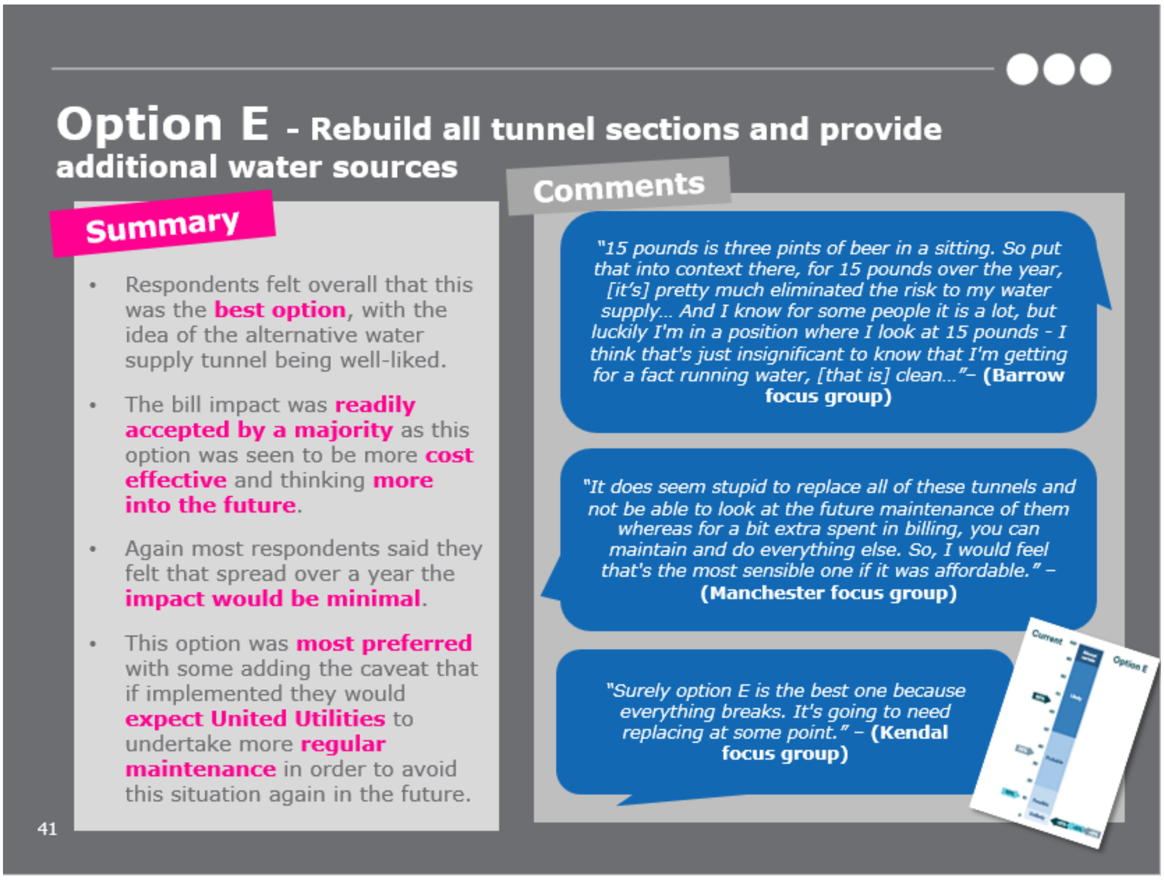
- Respondents felt this was a more **long term option** and **"makes more sense".**
- They understood it was a **big operation** to implement, however the general feeling was that they would get their **"money's worth".**
- The bill impact was seen to be **worthwhile**; a small price to pay for a **big enough outcome**.
- Most respondents said they would be **happy to pay for this**. They felt that spread over a year the impact would be **"mere pennies"**.

Comments

"Actually D is merely a pound a month, and I felt that that was a small enough impact on the bill for a big enough kind of outcome." – **(Manchester focus group)**

"It addresses the pipe deterioration and any water quality issues and there's only a small risk there, isn't there, to service failures to non-tunnelled sections? So it's not even like there's a high risk there. It's still small. There's not a lot you can do about those anyway." – **(Chorley focus group)**

40



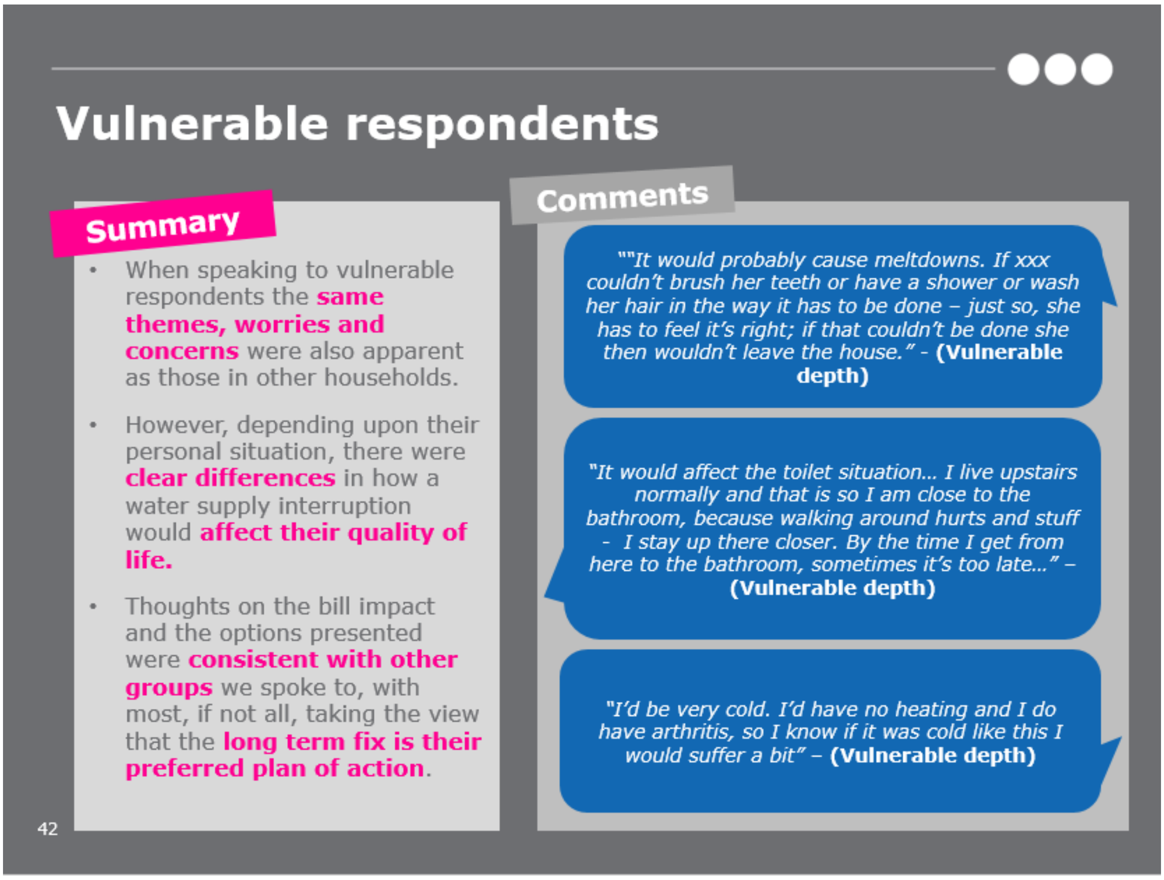


Figure A6 Comparison of customer opinions on the solutions they were presented during the customer research focus group. (DJS Research, February 2018)

A.8 Stakeholder consultation feedback

At stakeholder events during the consultation period we sought views on the preferred solution of those present. These included our draft Water Resources Management Plan consultation events or engagement activities, our regular public health liaison meetings and the Greater Manchester Green summit. This feedback was consistent with the customer engagement with solutions D and E being preferred most often and little support for lower cost, higher residual risk options.

At the draft Water Resources Management Plan consultation events, we asked attendees to state their solution preference immediately after being presented the solution's description, level of risk reduction and bill impact. Results of voting at the consultation events are shown in Figure A7 as Round 1. We asked the question again after they were presented with a summary of the customer research feedback and the Strategic Environmental Assessment, Water Framework Directive assessment and Habitats Regulation Assessment that was completed for each of the five solutions and published alongside our draft Water Resources Management Plan. The answers to the same question when asked again are presented as Round 2. A single round of voting was carried out at the public health liaison event.

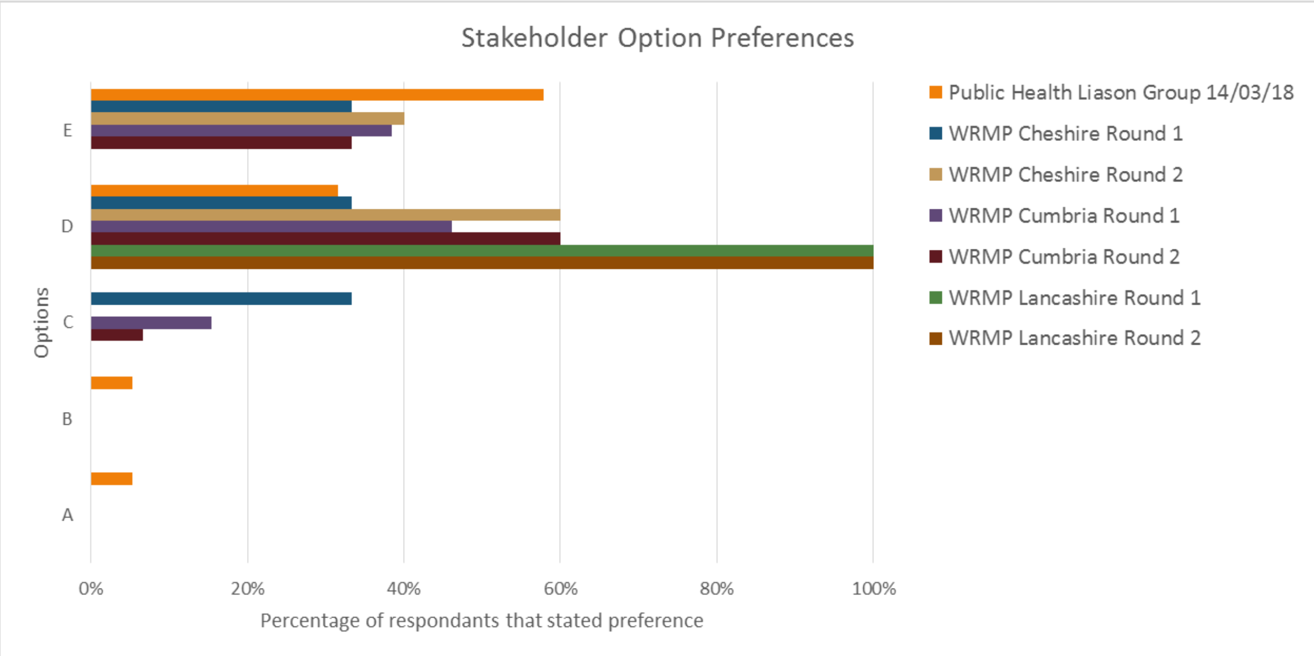


Figure A7 Results of feedback on preferred solutions gathered from Public Health Liaison Group and WRMP consultation events

In addition to the Public Health Liaison Group meeting and Water Resources Management Plan consultation events, we were present at the Greater Manchester Green Summit hosted by the Mayor of Greater Manchester, Andy Burnham. Our CEO, Steve Mogford, was invited as a key speaker at the event. We took the opportunity to hold a market stall where we spoke to delegates about the Manchester and Pennines water supply risk and asked them to vote on their preferred solution. The results of the voting at this events are presented in Figure A8.

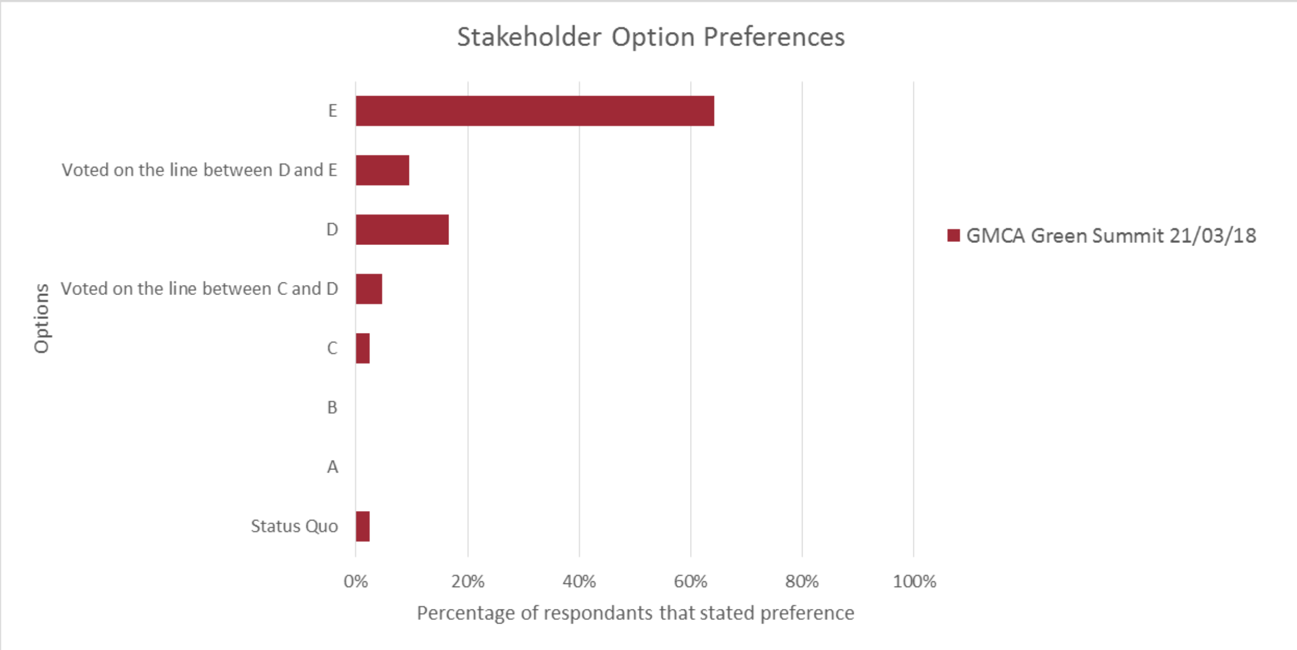


Figure A8 Results of feedback on preferred solutions gathered from the GMCA Green Summit

It is clear that the majority of people at these events supported the longer term solutions that bring the risk down to negligible levels. Solutions D and E were the most favoured.

Formal responses to the consultation were generally supportive of including Manchester and Pennines resilience in the preferred plan, although few respondents chose to express a direct preference for one solution or another. The Environment Agency raised some concerns about those solutions which included new or changed abstraction patterns. Natural England noted that the Strategic Environmental Assessment of the solutions suggests that solution D might be preferable in both greatest resilience and minimising environmental effects. YourVoice expressed support for taking forward either solution D or E. It said that consideration will need to be given to whether the additional £4 annual bill impact associated with solution E compared to solution D is justified by the extra reduction in risk that would follow.

In addition to formal consultation responses, following engagement with stakeholders we also directly received a number of letters relating to the issue. The Greater Manchester Infrastructure Advisory Group, the Greater Manchester Resilience Forum, and the Mayor of Greater Manchester all welcomed the priority given to the long-term resilience of water supplies and said that the preferred plan must provide an appropriate and long-term solution to the issue. The Mayor of Greater Manchester confirmed that the Greater Manchester Combined Authority (GMCA) formally endorsed his recommendation. The Lancashire Resilience Forum Local Authorities sub-group expressed support for the need to carry out the works and said that the group's preference was for solution D.

After we submitted evidence, the Drinking Water Inspectorate (DWI) wrote to us commending support for the proposals and confirming that the proposed scheme is consistent with the requirements of Defra's Strategic Policy Statement published in September 2017, and DWI guidance on principles for the assessment of drinking water quality provisions within the PR19 process. In particular, the DWI noted that "we are satisfied that the proposed scheme adopts a sound risk based approach to management of water supplies from source to tap using a water safety plan approach".

We are working collaboratively with Greater Manchester's Chief Resilience Officer to develop Manchester's Resilience Strategy under the 100 Resilient Cities initiative. 100 Resilient Cities, pioneered by The Rockefeller Foundation, helps cities around the world become more resilient to social, economic, and physical challenges that are a growing part of the 21st century.

Greater Manchester was selected to the 100-city global network in May 2016, gaining funding for a Chief Resilience Officer, resources to draft a Resilience Strategy, access to a variety of resilience tools, and membership of a global network of peer cities to share best practices and challenges. The resilience strategy incorporates water infrastructure and acknowledges the need for investment to secure resilience for Greater Manchester's water supply through the Manchester and Pennine Resilience scheme.

With this is mind, in March 2018, the Manchester and Pennine Resilience scheme was evaluated from a resilience perspective via a workshop facilitated by the 100 Resilient Cities team in collaboration with GMCA; this was the first time a utilities project was taken through this innovative process. The five solutions that had previously been used in customer research were evaluated with respect to seven resilience qualities: reflective, resourceful, robust, redundant, flexible, inclusive and integrated. The solutions were also considered with regard to their potential to impact shocks and stresses that would challenge a city's resilience.

Examples of feedback from the 100 Resilient Cities team are as follows:

"100 RC is delighted to contribute to UU's exploratory work. According to our experience internationally, it is unusual for utility providers to expand beyond their technical analysis and incorporate research and exploratory work to truly address the complexity of the challenge at hand. This approach is commendable and likely to create innovative and robust solutions that not only minimise negative impacts of the upgrading process but also captures potential opportunities."

"UU's approach to including multiple stakeholders in its process should be commended and in order to maximise the benefit of this approach it is suggested that inclusiveness is continued to be built throughout the process by maximising the communication with the communities potentially affected by disruption and construction works. Not only does delivering inclusivity require awareness, awareness also builds a shared knowledge that is required to safely implement significant pieces of critical infrastructure."

A.9 Economic and environmental appraisals

Following receipt of the feedback from the customer research, the subsequent steps in our process to determine the best solution for customers were:

- An environmental appraisal covering environmental and social costing, Strategic Environmental Assessment, Habitats Regulations Assessment and Water Framework Directive assessment;
- A detailed cost-benefit analysis, using specific and standard economic metrics; and
- A wider multi-criteria decision analysis looking at resilience in round covering metrics beyond those included within the cost-benefit analysis (e.g. non-monetised environmental effects), for which we developed multi-criteria analysis to support robust decision making.

As noted above, we shared the outputs of the environmental appraisal for consultation on our draft Water Resources Management Plan, but the economic and multi-criteria appraisals were not available in time to include in the consultation.

Therefore, to make sure we put forward a robust, low regret solution we undertook a cost-benefit analysis and a wider decision analysis. The principle we followed was to establish the most cost beneficial solution (using the cost-benefit analysis) and then confirm, when bringing in other wider considerations and sensitivity analysis, that this was the best solution and continued to perform well over the wider set of metrics, using our multi-criteria analysis. Correlating these two outputs and then also correlating them with the preferences of customers and of other key stakeholders allowed us to make sure our decision was a robust one.

Through the research, customers showed a clear preference for the solution that reduced risk to relatively low levels and a bill increase of £11. Overall both household and business customers have a statistically significant preference for this solution or a more expensive one with a greater risk reduction. Therefore, when using the cost-benefit analysis and the multi-criteria analysis, as well as considering the five solutions from customer research, we supplemented them with four additional solutions that fell within this range of customer preference. These solutions were C12, C15, C18 and C32. This gave an additional test to regarding the selection of the five solutions in the customer research, although in practice in the analysis none of these options outperformed solution D.

Environmental appraisals

We carried out a Strategic Environmental Assessment, Habitats Regulation Assessment and Water Framework Directive Assessment, using our Water Resources Management Plan methodologies. These were published for consultation alongside the draft Water Resources Management Plan. In addition, environmental and social impacts were valued and brought into the cost-benefit analysis.

Following consultation, for the revised draft Water Resources Management Plan, we have incorporated the results of the Strategic Environmental Assessment, Habitats Regulation Assessment and Water Framework Directive Assessment into an overall set of appraisals so that a cumulative assessment of the full plan is present.

The Strategic Environmental Assessment, Habitats Regulation Assessment, and Water Framework Directive Assessment were used to inform an assessment of environmental and planning risks for each candidate solution and informed the multi-criteria analysis. We reviewed the relative performance of each solution in relation to environmental and planning risks, determining how each solution may be viewed within the legislative frameworks provided by the Town and Country Planning Act and the Planning Act.

The Environmental and Planning Risk Appraisal used in the multi-criteria decision analysis comprised a high-level review of potential environmental constraints to each of the nine solutions. The area of search was based broadly on a 500 metre buffer extending beyond the potential boundary of new facilities and the alignment of new tunnel sections. Environmental constraints were considered to be natural and built assets protected by national or EU legislation, or influenced by national planning policy constraints. Such features were identified through a Geographic Information System mapping exercise, including Sites of Special Scientific Interest (SSSIs), Special Areas of Conservation (SACs) and Special Protection Areas (SPAs).

This was then corroborated against results from the Strategic Environmental Assessment (SEA).

The approach taken to assessing the environmental and social costs (impacts) of the resilience options and solutions is similar to that adopted for the assessment of the feasible water resources options considered in preparing the draft Water Resources Management Plan, which was an adapted cost assessment reflective of the Environment Agency's Benefits Assessment Guidance (BAG). The BAG allows a desktop analysis of environmental and social costs and benefits. It requires impacts to be described qualitatively and, where appropriate, monetary values attributed to those potential impacts. The BAG uses a benefit transfer approach, whereby information on environmental and social costs are taken from published data (for example, from willingness to pay studies) and applied to the option under consideration. The approach provided a robust set of costs, enabling options to be differentiated in terms of costs.

The BAG categories relevant to the resilience options included: property-based disamenity, informal recreation, formal recreation, angling, in-stream recreation, land-take (works), land-take (reservoir), landscape, heritage, archaeology, traffic, carbon (energy and climate change) and biodiversity. The environmental and social costs were calculated for each of the five solutions presented to customers, and the same methodology was applied to four other solutions that could deliver a similar risk reduction at a similar price to the options preferred by customers. The net present value of environmental and social impacts of each of the nine solutions was calculated and incorporated into the cost-benefit analysis, which became one of six equally weighted economic measures included within the cost-benefit analysis.

A risk rating based on the outcome of the environmental and planning risk appraisal and the environmental and social costings incorporated into the cost-benefit analysis are presented in Figure A9.

Solution	Environmental and planning risk rating (Level 1 = Low, 5 = High) incorporated into the multi-criteria analysis	Environmental and social costs incorporated into the cost-benefit analysis (NPV)
A	Level 1/2	£821,100
B	Level 3	£355,958,700
C	Level 4	£35,968,100
D	Level 2/3	£20,795,500
E	Level 4/5	£26,746,500
C15	Level 4/5	£125,932,000
C12	Level 4/5	£278,372,300
C32	Level 4	£53,959,300
C18	Level 4	£54,836,000

Figure A9 Environmental and planning risk rating and environmental and social costings

Cost-benefit analysis

An economic cost-benefit analysis was developed to inform selection of the best value decision. This looks at costs and benefits over an 80-year period, discounted using the Social Time Preference Rate. The conclusion of this work was that solution D is the most cost beneficial option for us to deploy.

This analysis included the following economic factors:

- Benefit to households estimated using willingness to pay to avoid supply interruption – based on recent United Utilities research;
- Benefit to non-households estimated using willingness to pay to avoid supply interruption – based on recent United Utilities research;
- Cost of alternative water supplies in the event of interruption, i.e. provision of bottled water for drinking and Arlington tanks refilled by Alternative Supply Vehicle;
- Cost of repairs in the event of failure;
- Environmental and social costs of solution delivery; and
- Solution capex and opex.

We also considered including the cost of damages (e.g. caused by flooding due to a failure of the aqueduct's structure). Our flood risk assessment suggested that very low number of properties would be affected by flooding caused by a breach of the aqueduct and on this basis, the potential costs were deemed insignificant in the overall cost-benefit analysis and thus were excluded. Costs to be incurred by us (for example fines, compensation and outcome delivery incentive penalties) were excluded from the analysis as they represent transfers of value within the economy rather than an economic loss.

The completed cost-benefit analysis gives the results shown in Figure A10, reported relative to the "do nothing" baseline scenario. The cost-benefit analysis was also developed with sensitivity analysis, as shown in Figure A11. Based on these results, we therefore conclude that solution D is the most economically cost beneficial option.

£m 80 year NPV	Solution								
Solution ID	**B**	**C12**	**A**	**C32**	**C**	**E**	**C15**	**C18**	**D**
Benefit to households	4,445	6,304	5,024	5,833	5,791	6,591	6,874	6,198	6,570
Benefit to non-households	184	250	200	239	238	277	275	258	276
Avoided relief costs	46	65	52	60	60	68	71	64	68
Avoided reactive repair costs	120	166	133	156	153	173	181	163	171
Total benefits	4,795	6,785	5,409	6,287	6,242	7,109	7,400	6,683	7,085
Solution Totex	(671)	(1,916)	(406)	(1,163)	(706)	(1,651)	(1,791)	(1,097)	(965)
Environmental Costs	(356)	(278)	(1)	(54)	(36)	(27)	(126)	(55)	(21)
Total Costs	(1,027)	(2,194)	(407)	(1,217)	(742)	(1,677)	(1,917)	(1,152)	(986)
Net benefits	3,768	4,591	5,002	5,070	5,500	5,432	5,483	5,531	6,100

Figure A10 Results of cost-benefit analysis

		Repair and remediation cost (central)			Repair and remediation cost (high)		
		Non-household (low)	**Non-household (central)**	**Non-household (high)**	**Non-household (low)**	**Non-household (central)**	**Non-household (high)**
All failure modes	**Household (high)**	D	D	D	D	D	D
	Household (central)	D	D	D	D	D	D
	Household (low)	C	C	D	D	D	D
Excluding water quality failure modes	**Household (high)**	D	D	D	D	D	D
	Household (central)	D	D	D	D	D	D
	Household (low)	C	C	D	C	C	D

Figure A11 Most cost-beneficial solution in a range of sensitivities

Multi-criteria analysis

In addition to the cost-benefit analysis, we considered resilience in the round measures as follows: risk reduction, bill impact, economic impact, environmental impact, and willingness to pay benefits for other related service attributes (as used in our corporate investment prioritisation) and the customers' stated preference. These parameters were evaluated through the use of a multi-criteria decision analysis to compare the solutions.

Each parameter is considered to have an influencing contribution towards the selection of a preferred solution and can be weighted accordingly in terms of its relative importance to solution selection. Carrying out the analysis in this manner gave us the ability to weight and test sensitivity of each parameter's influence on the optimal solution. This can be thought of as a form of robust decision making and here we consider which solution is most robust to uncertainties and variances in the weighting of parameters.

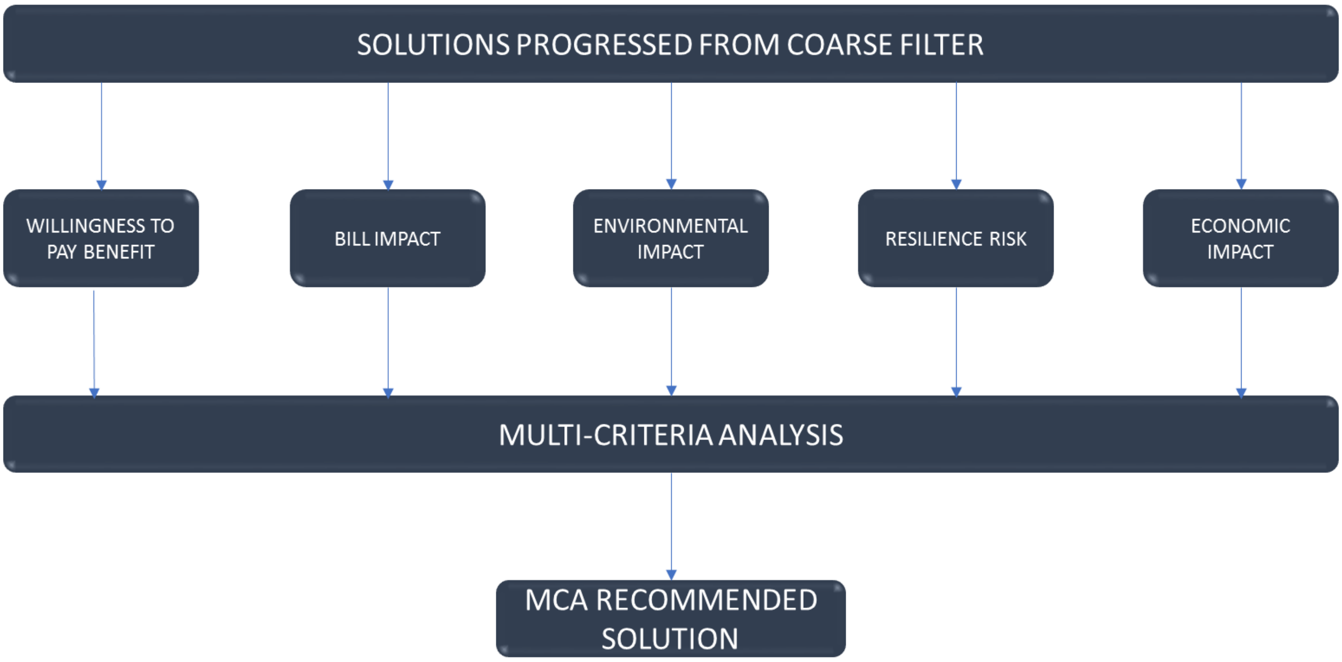


Figure A12 Metrics used in the multi-criteria decision analysis

The flow chart above (Figure A12) illustrates the components of the multi-criteria analysis. A description of the parameters evaluated in the determination of the most robust solution is outlined below:

- **Benefit (Willingness to Pay assessments)** - The benefit of each solution was generated using our 'Optimus' system and willingness to pay assessment included 14 measures, for example supply-demand capacity and drinking water safety plan risk score. The output from the data is a monetised value (£NPV).
- **Bill Impact** - The output from the data is a monetised value (£).
- **Economic Impact** - The monetised economic impact was provided by using the cost-benefit analysis with the addition of direct costs such as fines, compensation and other costs (not relevant in a pure cost-benefit analysis as they are transfers within the economy) (£NPV).
- **Resilience Risk/Days Lost Delta** - The Days Lost Delta was calculated through risk assessments and failure mode analysis (see previous sections). The output from the data is a number (£NPV).
- **Environmental Impact** – An environmental impact and qualitative planning assessment (qualitative assessment beyond the monetised costs of delivery included within the cost-benefit analysis).

Here we recognise that there is uncertainty in the assessment of each of the factors considered in the multi-criteria analysis and also that it impossible to precisely weight the different factors into an overall objective function that can be used to determine an "optimal" solution. Instead we considered which solution was most robust to uncertainties in these parameters. The weightings for the decision parameters would need to change by a significant amount to make the analysis select a different solution. This is demonstrated in the tables below (this is also summarised in Section 6.4.4 of the *Revised Draft WRMP19* main report).

Figure A13 shows that solution D is the preferred solution when all metrics are weighted equally. It also shows that under scenarios applying greater weights to various metrics, this solution remains as either first or second choice. Figure A14 demonstrates the robustness of solution D. This shows the weighting that would need to be given to each individual metric before an alternative solution is selected (keeping all other metrics weighted equally). Once the tipping point is achieved then the same solution remains selected as in each case they are the top performers against the metric. If the weightings are further increased, solution D remains in second place for all metrics apart from bill impact (C becomes second choice at 64.29% weighting) and environmental impact (A becomes second choice at 66.39% weighting).

We therefore conclude that solution D (C11) is the most robust solution.

Scenario	Decision Metric Weighting					Result (1st)	Result (2nd)	Difference (1st - 2nd)
	WTP Benefit	Bill Impact	Economic Impact	Resilience Risk	Environment-al Impact			
Equal Weightings	20.0%	20.0%	20.0%	20.0%	20.0%	D	E	13.37%
Bill Impact	12.5%	50.0%	12.5%	12.5%	12.5%	A	D	8.98%
Economic Impact	12.5%	12.5%	50.0%	12.5%	12.5%	D	E	8.10%
Resilience Risk	12.5%	12.5%	12.5%	50.0%	12.5%	D	E	7.98%
Environment Impact	12.5%	12.5%	12.5%	12.5%	50.0%	D	A	3.03%
WTP Benefit	50.0%	12.5%	12.5%	12.5%	12.5%	E	D	0.61%

Figure A13 Multi-criteria decision analysis outputs showing preferred option with different weightings applied

Metric	Tipping Point	
	Weighting %	Selected Solution
Bill Impact	42.53%	A
Economic Impact	78.72%	C15 [9]
Resilience Risk	94.41%	E
Environmental Impact	54.55%	A
WTP Benefit	48.72%	E

Figure A14 How far each metric would need to change before a solution other than solution D is selected

A.10 Selection of preferred plan

In summary, we found that:

- Customers showed a clear preference for solutions that reduced the risk to a relatively low level. Solution D had the highest odds ratios, and taken together the statistics show that customers support either solution D or E;
- Stakeholders prefer a long-term solution to the problem, for those who expressed a preference generally indicating a preference for solution D or E;
- Environmental appraisals show that solutions A and D generally have the lowest environmental risks. In consultation, the Environment Agency raised some concerns about those solutions which included new or changed abstraction patterns (i.e. solutions A and E);
- Cost-benefit analysis shows that solution D is the most cost beneficial and remains so under a range of sensitivities; and
- Multi-criteria analysis shows that solution D remains the most robust solution to a range of decision making criteria.

Looking at all these results in the round, it is clear that solution D represents the best solution for customers and the environment to provide resilient water supplies for the long-term. Therefore, we are selecting solution D as part of our preferred plan.

[9] Solution C15 is similar to Solution E, but includes more water resource options to enable long duration aqueduct outages so that the existing aqueduct can have a new concrete lining installed, rather than constructing new parallel tunnels. It does not perform well in other appraisals and was not considered suitable for inclusion in the short-list for consultation and customer research.

Appendix B – Extreme Demand Peak Week Review (2018)

The freeze-thaw modelling that was carried out as part of the draft Water Resources Management Plan (as described in Section 4.3.1), demonstrated that our system was resilient to average daily demands in a peak week of up to 2340 Ml/d with the expected distribution of demand seen in a typical extreme event. For the revised draft Water Resources Management Plan, we have since reviewed the recent events in 2018 against our previously modelled assessment. These are:

- The freeze-thaw event in March 2018 resulted in substantial numbers of customers across the UK losing water supplies for extended periods[10]. Despite elevated mains burst rates and extremely high demand, customers in the North West were not affected by a lack of strategic supplies. Our review against our previous modelling demonstrated that this event was a very similar severity to the baseline freeze-thaw event in the winter of 2010/11 used in the model, with average daily demand in the March 2018 peak week reaching a roughly equivalent level to the previous simulation of the peak week demand of the 2010/11 event, some way under our critical case. The local demand distribution was similar across each demand zone, with only the Vale Royal demand zone significantly exceeding the baseline model due to changes in network configuration since 2010.

- The prolonged dry weather in summer 2018 saw an exceptionally high demand for water compared to similar periods experienced over the last decade. This resulted in multiple weeks of sustained very high, peak week demands. However, initial analysis shows that these did not exceed the demands experienced during the winter 2010/11 freeze-thaw event used in the baseline case for testing, or exceed the modelled extreme event capability of our system. Locally, to date, this demand exceeded the limiting case by more than 1 Ml/d in four of our 33 demand zones. One of these was the Vale Royal demand zone, where the difference is largely down to network configuration changes since 2010. The second demand zone affected was Eden, where the extended dry period has led to higher demand in this largely agricultural area, with this extra demand being met through the local groundwater sources. The other two demand zones most severely affected were Southport and Manchester. The Southport demand zone has a large transient summer population and the newly commissioned Royal Oak Water Treatment Works (WTW) is our proactive response to the previously identified risk during peak demand periods; this site, combined with new supporting groundwater source availability, will support peak demand needs in future. Manchester is our largest demand zone and the variation to the limiting, modelled case is less than 3% as a proportion of the zonal demand; the Manchester demand can be flexibly met through regional resources, as long as overall company demand does not exceed production capability for extended periods.

Overall, the extreme events of 2018 have demonstrated that our freeze-thaw modelling of peak demand, based on the 2010/11 events, has been an appropriate basis for testing our system to extreme demand events and has further demonstrated the value of specific, proactive interventions such as the commissioning of the Royal Oak WTW to support the transient demand across our Southport demand zone in future. Further work is required to explore the summer 2018 dry weather event later in the financial year (i.e. post-event) using reconciled demand data in line with the Annual Water Resources Management Plan process review of dry year average demands, as described in the *Revised Draft WRMP19* main report.

[10] Out in the cold: Water companies' response to the 'Beast from the East' https://www.ofwat.gov.uk/publication/cold-water-companies-response-beast-east/

