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Understanding the costs of investigating coliform and *E. coli* detections during routine drinking water quality monitoring

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ABSTRACT

Bacteriological failure investigations are crucial in the provision of safe, clean drinking water as part of a process of quality assurance and continual improvement. However, the financial implications of investigating coliform and *Escherichia coli* failures during routine water quality monitoring are poorly understood in the industry. The investigations for 737 coliform and *E. coli* failures across five UK water companies were analysed in this paper. The principal components of investigation costs were staff hours worked, re-samples collected, transportation, and special investigatory activities related to the sample collection location. The average investigation costs ranged from £575 for a customer tap failure to £4,775 for a water treatment works finished water failure. These costs were compared to predictions for US utilities under the Revised Total Coliform Rule. Improved understanding of the financial and staffing implications of investigating bacteriological failures can be used to budget operational expenditures and justify increased funding for preventive strategies.

ARTICLE HISTORY

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KEYWORDS

Bacteriological monitoring; water quality; investigation costs

1. Introduction

Bacteriological quality monitoring is conducted to assure the safety of drinking water for consumers and to assess the performance of treatment processes. Water companies routinely collect samples from water treatment works (WTW) finished water, service reservoirs and customers' taps and analyse them for a range of microbiological parameters. Bacteriological monitoring in the UK and across Europe focuses on coliforms, *Escherichia coli*, Enterococci and *Clostridium perfringens*. Positive results in analyses for these microorganisms indicate environmental or faecal contamination of treated water and all four parameters have prescribed values of 0 cells per 100 ml (Council of the European Communities 1998). This work focuses on the investigation of water quality failures for coliforms and *E. coli*. Coliforms are a broad group of bacteria that can be found in soil, decaying vegetation, water and faeces. Their presence does not always indicate a threat to health, but could point to a problem with treatment operations or a breach in the distribution system. *E. coli* are considered to be exclusively faecal in origin and some strains are pathogenic (Standing Committee of Analysts 2002). When indicator bacteria are detected in water quality monitoring samples, water companies are required to investigate and take action to restore water quality as soon as possible (Standing Committee of Analysts 2002).

There are many potential causes of coliforms and *E. coli* in drinking water monitoring samples: raw water contamination overloading the WTW (Kistemann, Dangendorf, and Exner 2001; Passerat et al. 2011); extreme weather events, in particular rainfall (Curriero et al. 2001; Schets et al. 2005); compromised/damaged water treatment and supply infrastructure allowing ingress of environmental water (Besner, Prévost, and Regli 2011; Fricker 2003); biofilm formation and cell detachment (Berry, Xi, and Raskin 2006); and sample tap/sample point contamination (Eboigbodin, Seth, and Biggs 2008).

Whilst remedial works expenditure is generally well-documented within water companies and is determined on the basis of cost-benefit analyses (Lindhe et al. 2011), the actions taken and costs of investigating bacteriological failures are currently poorly understood (Ellis 2013). This study identified only one other report detailing the potential costs of the investigation phase of work following a bacteriological failure: the US Environmental Protection Agency's Revised Total Coliform Rule (RTCR) (US Environmental Protection Agency 2010). The RTCR has required US water utilities to investigate detections of coliforms and *E. coli* since April 2016. The RTCR replaced the Total Coliform Rule and is intended to confer greater public health protection through the investigation and remediation of bacteriological quality failures. To enable utilities to budget for the regulatory changes a detailed economic assessment was incorporated into the new guidance.

The aim of this paper is to explore and compare the financial implications of investigating bacteriological failures for five UK water companies. This will be achieved through a detailed analysis of the tasks involved in completing an investigation and assignment of costs to these elements. The calculated costs will be compared to the anticipated costs of the RTCR. The results will be useful for understanding cost implications of coliform sampling to utilities and as documentation of the investigation actions undertaken in practice, both of which could be linked to health outcomes research or sampling plan design and optimisation (to enhance methods such as those outlined in Cozzolino et al. 2011; Hart and Murray 2010; Speight, Kalsbeek, and DiGiano 2004).

2. Material and methods

2.1. Data sources

Five UK water companies provided data: Dŵr Cymru Welsh Water (DCWW), Essex and Suffolk Water (ESW), Northumbrian Water (NW), Scottish Water (SW) and Severn Trent Water (STW). The company details are summarised in Table 1.

When coliforms or *E. coli* are detected in samples collected as part of the routine water quality monitoring programme, the water company begins a process of re-sampling, archival data analysis and, where applicable, site investigations to determine the cause of the failure. The details of each of these investigations are contained within a failure report, and a summary of this report is sent to the relevant water quality regulator, either the Drinking Water Inspectorate (DWI) (for England and Wales) or the Drinking Water Quality Regulator for Scotland (DWQRS). The findings of the investigations are used to inform localised remedial activities and wider operational behaviour.

The investigation process comprises eight key stages:

- reporting a failure;
- opening an investigation;
- re-sampling;
- sample analysis;
- archival data collection and analysis;
- report compilation;
- completing the report and recording the root cause of the failure; and
- reporting to the regulator.

These stages were used as the basis for developing the cost calculation. The following data were collected from the failure reports: the number of re-samples collected; the location of the failure; the teams involved in the investigation and the respective office locations; and details of any additional investigation activities, such as draining and internally inspecting a service reservoir. Staff were interviewed to obtain the numbers of hours worked at the different stages of the investigation.

2.2. Investigation cost calculation

The investigation cost (*I*Cost) was calculated using equation (i), modified from the calculation in Ellis (2013).

$$I\text{Cost, } \pounds = (S_n * S_c) + (Dr_n * Dr_c) + (Hr_n * Hr_c) + X \quad (i)$$

Where: S_n = number of re-samples collected, S_c = cost per analytical suite, including materials, operation and maintenance of the laboratory, licensing/accreditation, etc., \pounds , Dr_n = number of miles driven, Dr_c = cost per mile driven, \pounds , Hr_n = number of hours worked by staff involved in the investigation, including travel time, Hr_c = hourly rate, \pounds , X = additional investigation costs, including ferry or flight fares for sampling on islands or remote areas, reservoir drain down and inspect operations, etc., \pounds

The number of miles driven (Dr_n) between the sample point and the appropriate laboratory and/or regional office was determined using Google Maps (2012–2015), taking the fastest route whilst avoiding toll roads. Dr_n took into consideration transport to or from air or ferry ports for samples collected on islands or in remote locations. The number of hours worked was estimated following staff interview and summed (Hr_n).

The cost per mile driven (Dr_c) used was £0.45/mile (HM Revenue & Customs 2012). In 2012, the average hourly rate in the UK was £12.62, excluding over-time (Office for National Statistics 2011). The hourly rate used in this work was £20.00/h (Hr_c), which attempted to account for overheads (pension, training, over-time, etc.). The cost per analytical suite was estimated at £5.00/suite (S_c) (Ellis 2013). Additional investigation costs (X) were provided by the water companies; ferry and flight details applied to SW investigations only and costs were estimated based on their sampling programme.

Table 1. Pertinent information relating to the five UK water companies involved in this research. Note: Year of Formation relates to the single water company formation from multiple regional water authorities and not the start-up of new water suppliers.

Water company	Company type	Year of formation	Population served	Size of supply area	Business type	Regulator	Source
Dŵr Cymru Welsh Water	Water and sewerage	2001	3 million	20,779 km ^{2(a)}	Not-for-profit	DWI ^(b)	Dŵr Cymru Welsh Water 2015
Essex and Suffolk Water	Water-only	1989	1.8 million	2,892 km ²	Private	DWI	Northumbrian Water Ltd. 2015
Northumbrian Water	Water and sewerage	1989	2.7 million	9,422 km ²	Private	DWI	Northumbrian Water Ltd. 2015
Scottish Water	Water and sewerage	2002	5 million	78,000 km ²	Government	DWQRS ^(c)	Scottish Water 2014
Severn Trent Water	Water and sewerage	1989	8 million	21,000 km ²	Private	DWI	Severn Trent Water 2014

Notes: (a) This is the area of Wales. A central part of Wales is served by Severn Trent Water, and a small part of England is served by Dŵr Cymru Welsh Water; (b) Drinking Water Inspectorate (for England and Wales); (c) Drinking Water Quality Regulator for Scotland.

2.3. Full-time equivalent calculation

In the UK, employees who work five full days a week are entitled to 28 days paid leave (GOV.UK 2014). Thus, there are 232 working days per year ((5 days * 52 weeks) – 28 days). The total number of hours worked by each water company on all investigations was divided by the number of years of data, and then by 7.5 h to give the total number of days worked, and finally divided by 232 working days. The result is an indication of the number of full-time equivalent (FTE) staff required for investigating coliform and *E. coli* failures at each company per year.

3. Results

3.1. Overview of bacteriological failures

Drinking water quality compliance for coliforms and *E. coli* was very high at all five water companies; the compliance figures are summarised in Table 2 by microorganism and sample point. Some water samples failed for both coliforms and *E. coli*: three at DCWW, 21 at SW and 11 at STW during the study period. Investigation reports are completed on a per sample rather than a per failure basis and thus a total of 737 reports were studied to determine the cost of investigating bacteriological failures: 124 from DCWW; 80 from ESW; 17 from NW; 326 from SW; and 190 from STW.

Table 2. Total number of coliform and *E. coli* tests and the number of failures detected in the period of study: (a) by microorganism and (b) by sample point. Note: NWL only includes failures at customers' taps.

a	Years studied	Coliforms		<i>E. coli</i>	
		No. tests	No. failures	No. tests	No. failures
Dŵr Cymru Welsh Water	2010 - 2014	178,828	124	178,831	3
Essex & Suffolk Water	2009 - 2014	82,423	80	-	-
Northum- brian Water	2011	6,500	16	6,500	1
Scottish Water	2013 - 2014	184,920	326	184,988	21
Severn Trent Water	2008 - 2011	254,630	187	254,629	13

b	WTW Finished Water		Service reservoir		Customers' tap	
	No. tests	No. failures	No. tests	No. failures	No. tests	No. failures
Dŵr Cymru Welsh Water	87,245	17	191,210	53	79,204	57
Essex & Suffolk Water	22,506	11	32,168	26	27,749	43
Northum- brian Water	-	-	-	-	13,000	17
Scottish Water	107,404	53	206,180	173	56,324	121
Severn Trent Water	125,120	16	227,796	69	156,343	115

3.2. Costs of bacteriological failures

Customer tap failures were the cheapest failures to investigate at each company and they were also the least variable (Figure 1). It was anticipated that WTW finished water investigations would be the most costly due to the larger possible area of impact from a contamination problem. This was not the case: costs for WTW were similar to those for service reservoirs and they were not always the most expensive investigations. SW's WTW finished water investigations cost significantly less (within 1.0 standard deviation) than those at DCWW. DCWW's customer tap investigations cost significantly more than those at any of the other water companies. The reasons for these similarities and differences are explored in Section 3.3.

3.3. Contributory factors to the investigation costs

3.3.1. Hours worked

The total number of hours worked represented the greatest part of the investigation cost regardless of water company or sample point. There are three main investigation stages: (1) re-sampling and analysis conducted by samplers and scientists (tasks a, c and d, as identified in Section 2.1); (2) operations team site visits, to WTWs, service reservoirs and customers' properties (tasks e and g); and (3) generating and sharing the report (tasks b, e, f, g and h). There is some overlap between stages 2 and 3, as personnel involved in the report generation often attend site visits to WTWs and service reservoirs; in these results their hours worked are recorded as report generation.

Time spent sampling and testing in the laboratory was very variable; however, the differences between sample points and water companies were not significant (Figure 2). The minimum number of hours was 0 h for SW's sample points where no re-samples were taken because an obvious fault had been identified and they focussed their efforts on remediation. The maximum number of hours was recorded at ESW (392.0 h). This investigation was from a WTW finished water which had previously failed for coliforms and a large sampling survey was conducted to resolve the cause and direct remedial efforts.

The time invested by operations/regulations inspection teams per investigation was less variable than for sampling and testing, but there were significant differences (within 1.0 standard deviation) between some of the water companies (Figure 2). At customers' taps, DCWW spent more time than ESW and SW; they also invested more time than SW at service reservoirs; but, they spent less time than all other companies for failures at WTW finished waters. Regulations inspectors were not sent to every customer property following a detection of coliforms or *E. coli*; Operations teams were sent to most failures at WTWs and service reservoirs, the principal exceptions were failures where a fault was identified before the bacteriological results were obtained (ESW and SW) or where there was an incident at the laboratory which was known to have affected several samples (SW).

The number of hours spent in report generation and sharing represented the greatest proportion of investigation time for all companies and sample points except for ESW: at service reservoirs they invested more time on operations team inspections and at WTW finished waters more time was spent collecting and analysing re-samples (Figure 2).

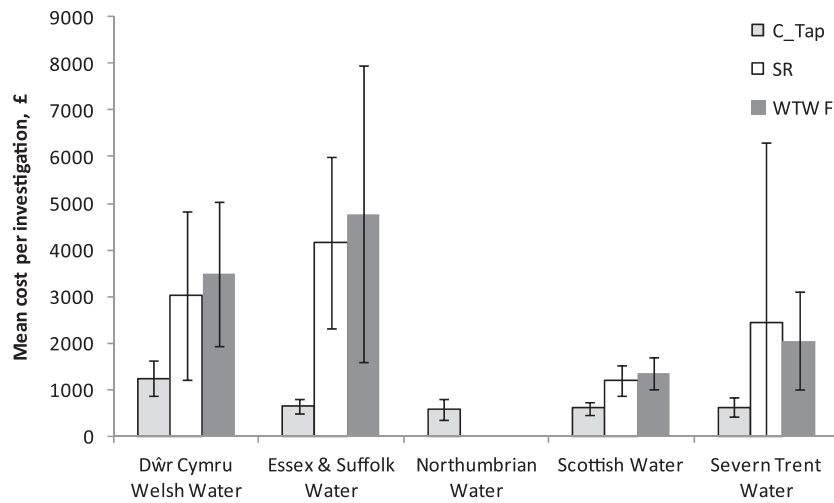


Figure 1. Mean costs for investigations at Customers' taps, Service reservoirs and WTW finished waters for DCWW (2010–2014), ESW (2009–2014), NW (2011), SW (2013–2014) and STW (2008–2011). Standard deviation shown. C_Tap = Customers' taps; SR = Service Reservoirs; WTW F = WTW Finished Waters.

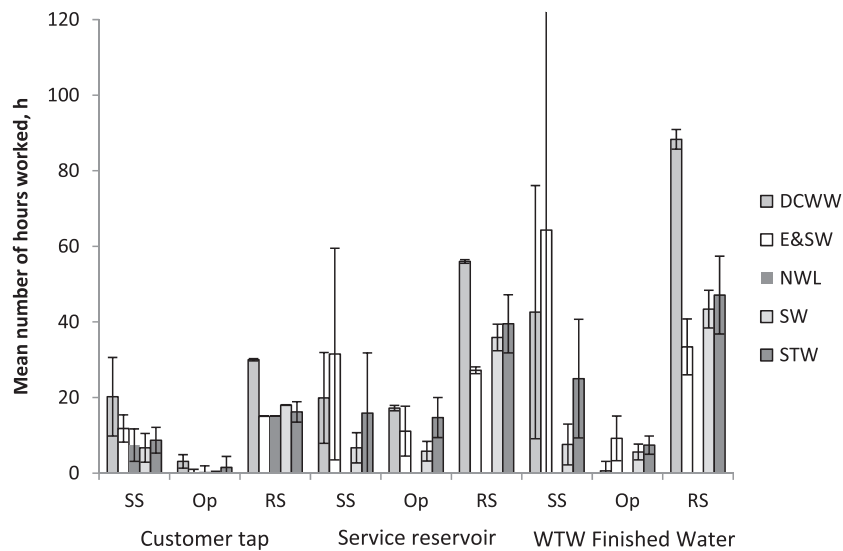


Figure 2. Mean numbers of hours worked for the different teams/investigation stages during the investigation of failures at Customers' taps, Service reservoirs and WTW finished waters for DCWW (2010–2014), ESW (2009–2014), NW (2011), SW (2013–2014) and STW (2008–2011). Standard deviation shown. SS = Samplers and Scientists; Op = Operations/Regulations Inspections; RS = Report Generation and Sharing.

ESW and NW who had fewest failures per year required 0.37 and 0.20 FTEs respectively to investigate bacteriological non-compliances. NW's results only relate to customer tap failures, so this does not represent their total time investment in bacteriological failure investigations. DCWW and STW required 1.05 and 1.15 FTEs correspondingly and SW needed 3.58 FTEs to complete their investigations per year.

3.3.2. Sampler visits

The number of sampler visits needed to collect re-samples is an important factor in the overall cost of the investigation, as it impacts hours worked and distance travelled. SW showed the least variation in sampler visits across the three sample points and made a maximum of 5.0 visits (Figure 3a). DCWW, ESW and STW made significantly more visits (within 1.0 standard deviation) during WTW finished water investigations than those at

customers' taps; for ESW this was also true for their service reservoir failures. Multiple sampler re-visits were needed for between 21.8% (SW) and 58.9% (DCWW) of investigations.

3.3.3. Re-samples

The number of re-samples collected has an impact upon the number of hours worked by samplers and scientists. SW collected significantly fewer samples (within 1.0 standard deviation) from all sample points than any of the other water companies (Figure 3b). This difference cannot be fully explained by the small number of failures where no re-samples were collected because of problems that were identified before the regulatory results came in or because of the laboratory incident. The number of samples collected from WTW finished waters was significantly greater than for customer tap failures at DCWW, ESW and STW; ESW and STW also collected significantly more samples from service reservoirs.

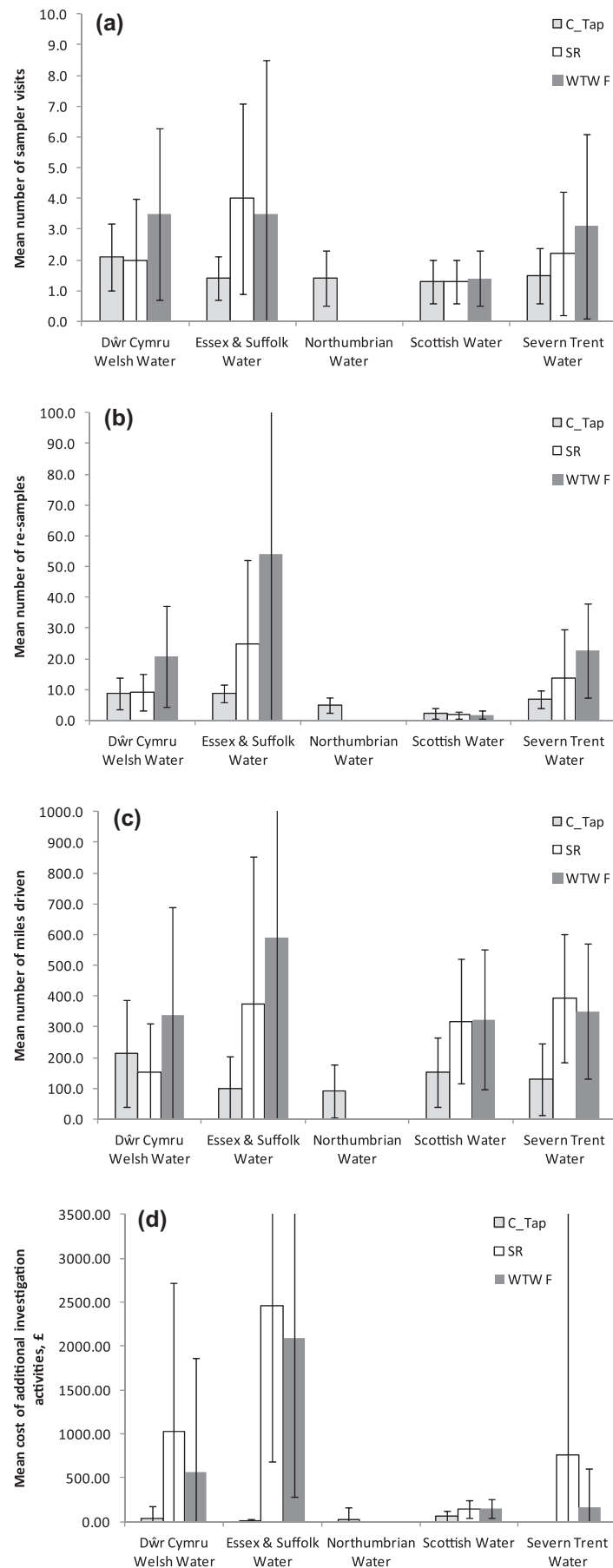


Figure 3. Mean numbers of sampler visits (a), re-samples (b), miles driven (c) and expenditure on additional activities (d) during the investigation of failures at Customers' taps, Service reservoirs and WTW finished waters for DCWW (2010–2014), ESW (2009–2014), NW (2011), SW (2013–2014) and STW (2008–2011). Standard deviation shown. C_Tap = Customers' taps; SR = Service Reservoirs; WTW F = WTW Finished Waters.

3.3.4. Road transportation

The number of miles driven is a function not just of the distance between laboratories or offices and sample points but also of the number of visits required by personnel. Despite the varying geographical ranges of the five companies, the number of miles driven did not vary significantly among water companies for each of the sample points. The largest maximum number of miles driven for service reservoirs (2,038.2 miles) and WTW finished waters (3,545.6 miles) were both recorded at ESW (Figure 3c) even though it is the water company which occupies the smallest geographical area (Table 1). This may be partly explained by its having one laboratory to cover two counties that are not adjoining.

3.3.5. Additional investigation costs

All transportation at DCWW, ESW, NW and STW was conducted by road. SW, which supplies water to properties on the Scottish islands and to remote locations, required some samples to be transported by aeroplane and/or ferry. Eighteen investigations required ferry transportation at a total cost (including staff time for samplers and operators) of £4,188. The minimum and maximum total journey costs were estimated at £143 and £377 respectively. Thirteen investigations needed aeroplane transportation at a total cost (including staff time) of £4,584 and the minimum and maximum total journey prices were estimated at £171 and £504 correspondingly. Three investigations required both air and sea transportation and all journeys also had mileage associated with them.

For all five water companies, the majority of investigations were closed following re-sampling and analysis, operations team site visits, and report generation. Sometimes, however, the investigations required additional activities in order to reach a conclusion about the root cause of the failure. The costs for these activities have been included where the report indicated that their purpose was to aid the investigation and develop recommendations for preventing future failures, rather than to remediate the failure at the given site. For example, service reservoirs may be drained and cleaned to facilitate an internal structural inspection; this was common across the water companies. The costs for some of the activities were calculated based on values previously detailed in this paper and other costs were provided by the companies (Figure 3d).

DCWW conducted additional investigation activities for 42 of its 124 failures; 26 of these were at service reservoirs (sum = £52,550), with nine at customers' taps (sum = £1,940) and seven at WTW finished waters (sum = £9,050). Of all the water companies, DCWW employed the greatest variety of activities in their attempts to resolve the cause of bacteriological failures. These actions ranged from reviewing company practices, to laboratory audits and enhanced monitoring, to drain down and inspect operations for service reservoirs and clean water tanks at WTWs.

Of the 80 investigations undertaken by ESW, 22 at service reservoirs (sum = £63,930), eight at WTW finished waters (sum = £22,950) and four at customers' taps (sum = £240) had additional actions associated with them. For each of the four customer tap failures that warranted additional action, ESW issued a letter advising customers to boil water before drinking and made bottled water available. This response was made by all the water

companies, except NW, to a small number of complex customer tap failures.

NW had only one customer tap investigation that required additional action and this was to flush the main before collecting more re-samples (sum = £500).

STW instigated additional investigation activities for 25 of its 190 failures, all of which were at WTWs (sum = £2,620) or service reservoirs (sum = £49,660). The costs of individual actions ranged from £200 for sample line flushing to £14,780 for an extended drain down, clean and inspect operation at a service reservoir.

SW required additional activities for 16 of its 326 failures: one at a customer's tap (sum = £80); two at WTW finished waters (sum = £560) and 13 at service reservoirs (sum = £6,870). The costs ranged from £130 to investigate telemetry signals to £1,500 for a new sample line.

3.4. Overview of the RTCR

Under US Environmental Protection Agency's (USEPA's) RTCR, US utilities are required to conduct investigations, called assessments, for coliform detections within the distribution system when 5 % of monthly samples for a utility test positive for these bacteria and if any sample fails for *E. coli* (US Environmental Protection Agency 2013). Whilst many utilities conducted informal investigations under the Total Coliform Rule, the RTCR requires failures to be formally investigated and remedial actions identified and executed with full reporting to the regulator. The RTCR documentation includes a detailed economic assessment, which provides background information and cost calculations on investigations (US Environmental Protection Agency 2010). The RTCR categorises all costs based on the size of the water utility. For comparison to the UK water companies, only data for US utilities serving more than 96,000 people were utilised.

The hourly rate (labour rate) employed by the USEPA was US\$41.01, including overheads, at 2007 costs; since this project spanned 2008–2013, these costs have been inflated to 2010 prices: US\$43.13 (Bureau of Labor Statistics 2014) and is equivalent to £25.73 (currency conversion US dollars to pounds Sterling of 1:0.5972, used throughout; The Money Converter 2014). The total numbers of hours worked during an investigation were estimated to be between 159 h for a non-repeating coliform failure and 252 h for an *E. coli* failure or a repeating coliform detection. The cost estimates for staff time only were between US\$6,520 and US\$10,340 (US Environmental Protection Agency 2010). At 2010 values this gives a range of US\$6,860–10,880 (Bureau of Labor Statistics 2014), which equates to £4,100–6,500. If the number of hours required for a US investigation were multiplied by the hourly rate used for the UK assessments, the cost for a non-repeating coliform failure would be £3,180 and for an *E. coli* or repeating coliform failure, £5,040.

Under USEPA's RTCR, the number of re-samples required during an investigation is three in the first instance (original location and at two other locations to help understand the source of contamination); should one of these samples fail, there is a requirement to collect another set of re-samples to assess the bacteriological quality of drinking water. The distance travelled is estimated at a 30-mile round trip per re-sample visit (US Environmental Protection Agency 2010).

Ferry and aeroplane transportation as well as additional investigation activities are not expressly considered as part of the RTCR. The RTCR sampling is most comparable to UK customer tap sampling, as WTW sampling is regulated under separate requirements depending on source water type (US Environmental Protection Agency 1989, 2013). Service reservoir sampling is not commonly performed for routine monitoring under the RTCR but may be done as part of an investigation (US Environmental Protection Agency 2010).

4. Discussion

4.1. Costs of bacteriological failures

The UK investigation costs were dominated by staffing costs, but the US costs are anticipated to be even more so. The analysis of UK bacteriological failures showed that *E. coli* detections were rare and thus it was more practicable to model costs according to sample point. The US investigations are separated based on utility size, the organism(s) detected and whether the re-samples fail (US Environmental Protection Agency 2010). The UK results highlighted that there was a bias towards more failures in distribution than at WTWs and thus the average costs for a failure in the US will be an over-estimate of investigations where customers' taps are affected and an under-estimate of those where WTWs are affected.

The Water Services Regulation Authority for England and Wales (Ofwat) state that the privatisation of water companies in these two countries has improved the quality of drinking water supplied to customers. This improvement has been brought about through increased investment in infrastructure and better processes for managing water quality (Ofwat 2010). Equally, since the formation of SW, there has been significant investment in infrastructure and marked improvements in performance (Scottish Water 2013). The implementation of the RTCR should have the same beneficial impact upon drinking water quality compliance in the US.

4.2. Contributory factors

The RTCR anticipates that US utilities will need between two and eight times more hours on average than a UK company to successfully investigate a bacteriological non-compliance. The labour estimates account for 'water system technical staff', 'water system management staff', 'State field engineering staff' and 'State program office staff' and exclude the time worked by sampling and laboratory staff which are accounted for separately (US Environmental Protection Agency 2010). The numbers of hours calculated for the UK covered the work of samplers and scientists (SS), operators (Ops) (equivalent to water system technical staff) and staff involved in report generation and sharing with the regulator (RS) (equivalent to water system management staff). Broadly speaking, the numbers of hours worked per team per investigation increased from SS < Ops < RS. The State teams that will be involved with the US investigations are analogous to the DWI and DWQRS in the UK. USEPA has accounted for the hours dedicated to training on the RTCR requirements, annual administration of the Rule, reviewing the investigation reports, reviewing and approving planned remedial actions and for record-keeping (US Environmental Protection Agency 2010).

In this research project, the work of the regulators has not been accounted for, which explains some of the difference between estimated staff time. Nevertheless, water companies in the UK are able to take remedial actions without referring to the regulator first and that confers the benefit of more timely intervention following a failure.

The principal reason for bacteriological water quality samples failing at a UK water company was contamination of the tap itself (Ellis et al. 2013). The RTCR specifically allows for distribution system sampling to be conducted at dedicated sampling stations in the field (US Environmental Protection Agency 2012). Furthermore, routine sampling locations may be in public buildings in contrast to the random locations (usually residential properties) required in the UK (Standing Committee of Analysts 2010). In the US, dedicated sampling stations may reduce the likelihood of sample tap contamination and therefore the likelihood of repeat samples failing. This project has demonstrated that customer tap sampling can require up to seven re-sampling visits, whilst for WTWs and service reservoirs this increases to 18. Therefore, US water companies may find that they need to make more than one visit and collect more than the three re-samples identified as the required minimum by USEPA.

The average number of visits made by samplers in the UK was 2.2, which would result in an anticipated mileage of 66.0 miles per investigation under the RTCR. It is probable that US utilities could under-estimate the mileage that will be required in enacting the new regulations and will face significant additional costs in terms of both fuel and staffing. The need for some samples to be transported by aeroplane and/or ferry may also present unaccounted for travel costs to US water utilities (US Environmental Protection Agency 2010).

The RTCR outlines the need for water companies to develop standard operating procedures (SOPs) for operating and maintaining water system treatment and storage. They may serve as corrective actions if ineffective or out-of-date procedures were found to be the cause of the bacteriological failures. These SOPs should cover routine sampling, site inspections and emergency procedures (US Environmental Protection Agency 2010). The time required for the development of SOPs is estimated as part of the RTCR and not assumed to be part of day-to-day operations. This gives scope for properly funded development of better systems of work for proactive prevention of bacteriological water quality failures. Whilst the development of improved SOPs for US utilities will make decision-making following a failure easier, without investigations after every failure there is the risk of problems not being resolved in a timely fashion, putting consumers at risk.

5. Conclusions

This paper has shown that coliform and *E. coli* failures are rare in the UK. The average costs of UK investigations for failures at customers' taps were £575–1,250, at service reservoirs were £1,200–4,150 and at WTW finished waters were £1,350–4,775. The US RTCR treats all failures the same, but in reality the costs vary depending on the sample point.

The numbers of hours spent on investigations accounted for the greatest proportion of investment. Between 0.37 and 3.58 FTEs were required annually. Multiple sampler re-visits were needed for between 21.8% and 58.9% of investigations. On average, between

2 and 54 re-samples were collected per investigation. The average distance travelled in the UK ranged from 91.3 to 591.0 miles. This mileage differs from the estimated 30-mile round-trip anticipated in the RTCR but may reflect the compact municipally-based US utilities versus the regional nature of UK water companies. Some investigations required ferry or aeroplane transportation. All five UK companies needed to perform additional investigatory activities to complete some of their investigations.

Whilst customer tap investigations were relatively simple to complete, service reservoir and WTW finished water failures required more time and investment, and a wider range of investigatory tools. Improved understanding of the financial and staffing implications of investigating bacteriological failures can be used to budget operational expenditures, justify increased funding for preventive strategies, and as a basis for incorporating economic considerations into sampling plan design and optimisation.

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Disclosure statement

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References

- Berry, D., C. Xi, and L. Raskin. 2006. "Microbial Ecology of Drinking Water Distribution Systems." *Current Opinion in Biotechnology* 17: 297–302.
- Besner, M.-C., M. Prévost, and S. Regli. 2011. "Assessing the Public Health Risk of Microbial Intrusion Events in Distribution Systems: Conceptual Model, Available Data, and Challenges." *Water Research* 45: 961–979.
- Bureau of Labor Statistics. 2014, June 3. *CPI Inflation Calculator*. United States Department of Labor. Accessed June 3, 2014. http://www.bls.gov/data/inflation_calculator.htm
- Council of the European Communities. 1998. *Council Directive of 3 November 1998 on the Quality of Water Intended for Human Consumption*. 98/83/EC. European Commission.
- Cozzolino, L., R. D. Morte, A. Palumbo, and D. Pianese. 2011. "Stochastic Approaches for Sensors Placement against Intentional Contaminations in Water Distribution Systems." *Civil Engineering and Environmental Systems* 28 (1): 75–98.
- Curriero, F., J. A. Patz, J. B. Rose, and S. Lele. 2001, August. "The Association between Extreme Precipitation and Waterborne Disease Outbreaks in the United States, 1948–1994." *American Journal of Public Health* 91 (8): 1194–1199.
- Dŵr Cymru Welsh Water. 2015. *Welsh Water - Key Facts*. Dŵr Cymru Welsh Water. Accessed July 2015. www.dwrcymru.com/en/Company-Information/Dwr-Cymru-Welsh_water/Key-Facts.aspx
- Eboigbodin, K. E., A. Seth, and C. A. Biggs. 2008. "A Review of Biofilms in Domestic Plumbing." *Journal of the AWWA* 100 (10): 1–15.

- Ellis, K. 2013. *Improving Root Cause Analysis of Bacteriological Water Quality Failures*. EngD thesis, University of Sheffield.
- Ellis, K., B. Ryan, M. R. Templeton, and C. A. Biggs. 2013. "Bacteriological Water Quality Compliance and Root Cause Analysis: An Industry Case Study." *Water Science and Technology: Water Supply* 13 (4): 1034–1045.
- Fricker, C. R. 2003. "The Presence of Bacteria in Water after Regrowth." In *Heterotrophic Plate Counts and Drinking-Water Safety*, edited by J. Bartram, J. Cotruvo, M. Exner, C. Fricker, and A. Glasmacher, 52. London: IWA Publishing/World Health Organization.
- GOV.UK. 2014, June 2. *Holiday Entitlement*. GOV.UK. Accessed June 4, 2014. www.gov.uk/holiday-entitlement-rights/entitlement
- Hart, W. E., and R. Murray. 2010. "Review of Sensor Placement Strategies for Contamination Warning Systems in Drinking Water Distribution Systems." *Journal of Water Resources Planning and Management* 136 (6): 611–619.
- HM Revenue & Customs. 2012, June. *Travel - Mileage and Fuel Allowances*. HM Revenue & Customs. www.hmrc.gov.uk/rates/travel.htm
- Kistemann, T., F. Dangendorf, and M. Exner. 2001. "A Geographical Information System (GIS) as a Tool for Microbial Risk Assessment in Catchment Areas of Drinking Water Reservoirs." *International Journal of Hygiene and Environmental Health* 203: 225–233.
- Lindhe, A., L. Rosén, T. Norberg, O. Bergstedt, and T. J. Pettersson. 2011. "Cost-Effectiveness Analysis of Risk-Reduction Measures to Reach Water Safety Targets." *Water Research* 45: 241–253.
- Northumbrian Water Ltd. 2015. *Northumbrian Water - At a Glance*. Northumbrian Water Ltd.. Accessed July 2015. <https://www.nwl.co.uk/your-home/at-a-glance.aspx>
- Office for National Statistics. 2011. *Statistical Bulletin: 2011 Annual Survey of Hours and Earnings (SOC 2000)*. Office for National Statistics. Accessed May 1, 2014. <http://www.ons.gov.uk/ons/rel/ashes/annual-survey-of-hours-and-earnings/ashes-results-2011/ashes-statistical-bulletin-2011.html#tab-Hourly-earnings-excluding-overtime>
- Ofwat. 2010. *Service and Delivery - Performance of the Water Companies in England and Wales 2009–10*. Birmingham, AL: Ofwat.
- Passerat, J., N. Ouattara, J.-M. Mouchel, V. Rocher, and P. Servais. 2011. "Impact of an Intense Combined Sewer Overflow Event on the Microbiological Water Quality of the Seine River." *Water Research* 45 (2): 893–903.
- Schets, F. M., M. During, R. Italiaander, L. Heijnen, S. A. Rutjes, W. K. van der Zwaluw, and A. M. de Roda Husman. 2005. "Escherichia Coli O157:H7 in Drinking Water from Private Water Supplies in the Netherlands." *Water Research* 39: 4485–4493.
- Scottish Water. 2013. *Performance Summary 2012/13*. Dunfermline: Scottish Water.
- Scottish Water. 2014. *Key Facts*. Scottish Water. Accessed May 21, 2014. www.scottishwater.co.uk/about-us/freedom-of-information/key-facts
- Severn Trent Water. 2014. *Our History*. Severn Trent Water. Accessed May 21, 2014. www.severntrent.com/about-us/our-history
- Speight, V. L., W. D. Kalsbeek, and F. A. DiGiano. 2004. "Randomized Stratified Sampling Methodology for Water Quality in Distribution Systems." *Journal of Water Resources Planning and Management* 130 (4): 330–338.
- Standing Committee of Analysts. 2002. *The Microbiology of Water 2002: Part 1 - Water Quality and Public Health*. London: Her Majesty's Stationery Office.
- Standing Committee of Analysts. 2010. *The Microbiology of Water 2010: Part 2 - Practices and Procedures for Sampling*. London: Her Majesty's Stationery Office.
- The Money Converter. 2014, June 2. *Currency Conversion and Latest Exchange Rates for 90 World Currencies*. The Money Converter. Accessed June 2, 2014. www.themoneyconverter.com
- US Environmental Protection Agency. 1989. *National Primary Drinking Water Regulations: Total Coliforms (Including Fecal Coliforms and E. coli)*, 40 CFR Parts 141 and 142, Federal Register 54:124, June 29 1989. Cincinnati, OH: USEPA Office of Water.
- US Environmental Protection Agency. 2010. *Technology and Cost Document for the Proposed Revised Total Coliform Rule*. Cincinnati: USEPA Office of Water.
- US Environmental Protection Agency. 2012. *Economic Analysis for the Final Revised Total Coliform Rule*. USEPA Office of Water. Accessed April 12, 2013. www.regulations.gov/#documentDetail;D=EPA-HQ-OW-2008-0878-0275
- US Environmental Protection Agency. 2013. *National Primary Drinking Water Regulations: Revisions to the Total Coliform Rule; Final Rule, 40 CFR Parts 141 and 142, Federal Register 78:30, February 13 2013*. Cincinnati, OH: USEPA Office of Water.