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DISINFECTION RESIDUAL BEHAVIOUR WITHIN DRINKING WATER DISTRIBUTION SYSTEMS

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Abstract

Understanding the persistence of different disinfection residuals in drinking water distribution systems (DWDS) is critical to water quality safety and public health. Chloramines are expected to persist, due to their chemical composition, further into the extremities of DWDS providing reduced risks to water quality, however there is limited evidence of this from operational systems. Total chlorine data from regulatory sampling at WTW outlets and customer taps from multiple DWDS was collected and analysed. The first data set compares long term performance from equivalent systems at the same time. Results showed the decay of residuals was similar across all seasons in the DWDS analysed, showing little correlation with residual type. The second data set compares six systems that experienced a disinfection switch from chlorine to chloramine. Decay of total chlorine residuals was clearly reduced for three and marginally reduced for a fourth following the switch, suggesting these DWDS experienced increased persistence. However, two sites showed little change. This analysis highlights the uncertainties around residual persistence under different disinfection types, indicating the assumption that chloramine persists for longer than chlorine in every distribution system is not a given.

Keywords
Drinking Water Quality, Disinfection Residuals, Drinking Water Distribution System.

1 BACKGROUND

Disinfectant residuals (although not legally mandatory) are common practice across the majority of developed nations, implemented to control against DWDS microbial growth and/or regrowth, particularly in old or degrading networks. DWDS are complex interlinked systems composed of long connecting pipe sections, storage facilities and hydraulic components of which vary in terms of age and condition. These characteristics, alongside pipe-wall interactions and the biological (biofilm and planktonic), chemical and physical properties of the DWDS, drive water quality deterioration. Importantly, these complex interactions can impede disinfection residual maintenance, particularly at the network extremities – increasing the likelihood of microbial failures.

The most well-known and widely used disinfection residual by water utilities is free chlorine. Yet, in response to the regulation of chlorine-formed disinfection by-products (DBP), the use of chloramines, specifically monochloramine for secondary disinfection is increasing [1], [2]. This is particularly common in DWDS experiencing high organic loads. Additionally, the properties of chloramine mean it is less reactive in solution, showing decay rates two times slower than that of free chlorine [3]. For this reason, chloramine is sometimes used in DWDS with high water ages, where residual maintenance at the network extremities may present a challenge. However, the biological, chemical and physical characteristics of DWDS effect residual decay, predominantly

pipe-wall interactions (with corrosion deposits and biofilms), reactions with naturally occurring compounds, such as total organic carbon (TOC) and elevated water temperatures [1], [4]–[8]. As a result, residuals can become depleted and drinking water quality may deteriorate during transit from the water treatment works (WTW) to customer taps [4]. TOC is of particular interest, as multiple studies show bulk water TOC to correlate with chlorine decay [9]–[12].

Previous research into chloramine and chlorine DWDS residual maintenance is heavily focused on reaction kinetics and decay models [13], [14], either computational or alongside bench top scale reactors [7], [8]. There seems to be limited studies considering the impact of both pipe wall and bulk water conditions on residual decay out in the field, whereby disinfection residuals are examined between two points within a DWDS [15]. Furthermore, there is limited direct comparisons of chloramine and chlorine residual maintenance in DWDS, likely due to DWDS complexity and variability. Despite this and the knowledge that residual decay is greatly influenced by network conditions and parameters, there still remains this idea that chloramine will persist for longer than chlorine in DWDS [16], [17]. Academic evidence in support of this statement is lacking - a concern when 90.6 % of U.S. utilities using chloramines stated that improved residual persistence was the main reason behind switching [2].

Improved understanding of disinfection residual persistence in both chlorine and chloramine systems is needed to protect against adverse water quality impacts and general water quality degradation. This is increasingly important as more and more water companies switch from chlorine to chloramine disinfection in response to DBP regulations and residual maintenance concerns. This paper compares the persistence of residuals in both long-term and newly switched chlorinated and chloraminated drinking water distribution systems (DWDS), to better understand residual behaviour. TOC (as a measure of organic load) is also considered, providing insight into potential reactions and bacterial food source availability.

2 METHODS

2.1 Case study introduction

In order to assess disinfection residual maintenance historic data was analysed. Two datasets were created from drinking water treatment works (WTW) outlet and tap water quality sample results. One data set allowed direct comparison, comparing different systems at the same time; while similar systems where compared there were differences. The second was for DWDS that experienced a switch in residual (from chlorine to chloramine), hence system characteristics were exactly the same but comparison is for sequential years. In combination the two datasets enable a more robust comparison.

2.2 Datasets

Dataset 1: TOC, total and free chlorine results from WTW outlets and distribution taps between 01.01.18 and 31.07.21, across 9 DWDS were selected. Drinking water travel distance impacts disinfection residual decay, for this reason systems within a 10% population size of 37,000 and 10,000 respectively were chosen.

To consider the effect of temperature, (shown to impact microbial activity and residual decay) dataset 1 was segregated by season. Due to the delayed response of water temperatures to air temperatures, seasons were as follows; “Winter” - January, February and March, “Spring” - April, May and June, “Summer” -July, August and September and “Autumn” - October, November and December. The specification for this dataset can be seen in Table 1.

TOC was analysed due to it being a nutrient used by planktonic and attached phase (biofilm) microorganisms. In addition, TOC indicates organic load within the bulk water, this threatens residual persistence due to direct reactions between organics and disinfection residuals. As a

result TOC was also considered in this analysis. Annual average TOC from chloramine WTW outlets and taps for the period analysed was 1.59 mg/L and 1.57 mg/L, respectively. Annual average TOC from chlorine WTW outlets and taps was 1.08 mg/L and 1.07 mg/L, respectively.

Table 1 : Specifications of drinking water distribution systems used in dataset 1 and sample counts for total chlorine across each season. WTW data reported first followed by taps (n = "WTW", n ="Taps").

Disinfection Residual	No. of DWDS	DWDS Population Range	Data Points (WTW, Taps)
Chloramine	4	10% range of 37,000 people	Spring (n=729, n=395) Summer (n=537, n=312) Autumn (n=444, n=287) Winter (n=669, n=452)
Chlorine	5	10% range of 10,100 people	Spring (n=551, n=160) Summer (n=452, n=179) Autumn (n=431, n=178) Winter (n=545, n=192)

Dataset 2: TOC and Total chlorine results from WTW outlet and distribution taps of six DWDS (A-F), all which experienced a disinfection switch (chlorine to chloramine) between 2016 and 2021. Data from 1 year pre and 1 year post disinfection switch was included.

Table 2: Number of total chlorine data points per group in dataset 2, WTW data reported first followed by taps (n = "WTW", n ="Taps").

DWDS	Data points pre-switch (WTW, Taps)	Data points post-switch (WTW, Taps)
A	n=231, n=6	n=239, n=12
B	n=376, n=48	n=406, n=53
C	n=437, n=321	n=387, n=299
D	n=223, n=73	n=199, n=57
E	n=72, n=17	n=51, n=16
F	n=55, n=13	n=57, n=12

2.3 Analysis

Both datasets were analysed using the programming language and statistical software 'R'. In order to test the normality of the data Shapiro-Wilks was performed. As data was not normally

distributed, box and whisker plots were used, with medians being used for % change calculations. Box plot thick horizontal bars specifies the median, the box itself represents the interquartile range (IQR) and the whiskers the maximum ($Q_3 + 1.5 \times IQR$) and minimum ($Q_1 - 1.5 \times IQR$) values, with dots indicating outliers beyond this range.

3 RESULTS

Figure 1 and Figure 2 show a greater decrease in total chlorine concentration (mg/L) between WTW outlet and taps, across all seasons in chloramine DWDS compared to chlorine DWDS. In contrast, the % difference in medians shown in Table 3 indicates a similar proportional decrease in total chlorine residual across both chloraminated and chlorinated DWDS. This is likely due to the higher chloramine concentrations at the WTW outlet than chlorine systems, which contributes to exponential decay. Figure 1 displays more visible outliers of <0.2 mg1/L than Figure 2 suggesting that in specific areas of the chloramine DWDS greater decay of total chlorine.

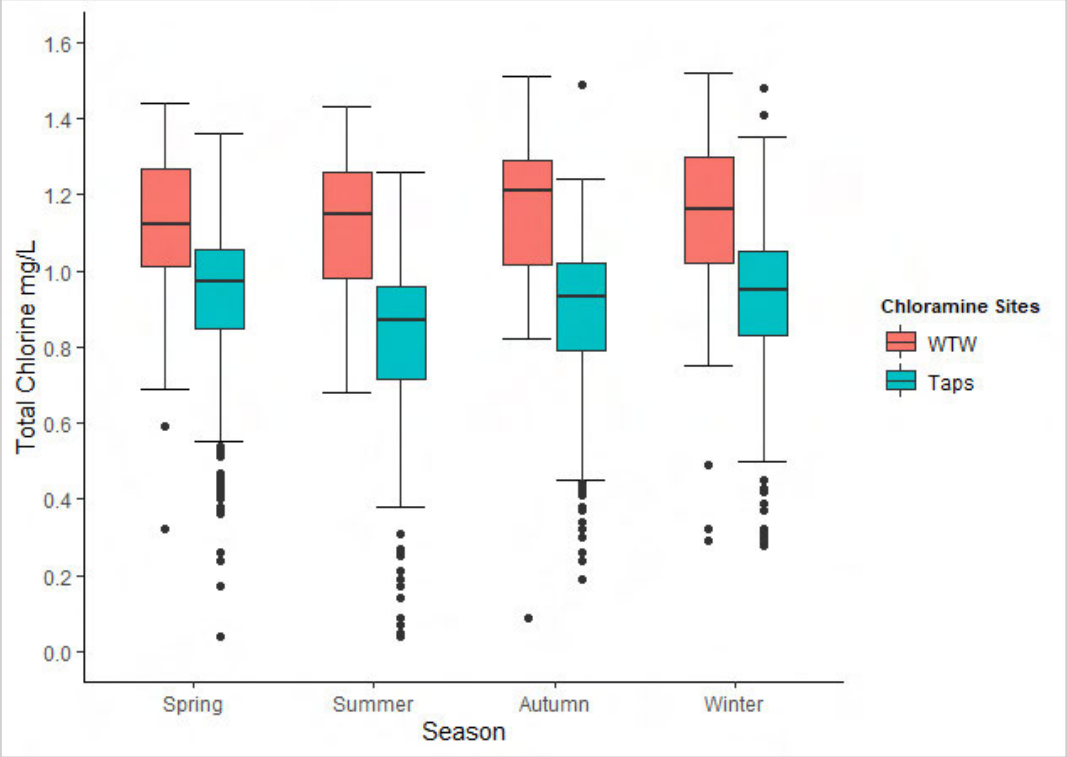

Figure 1: Impact of season on total chlorine concentrations at the water treatment works outlet and taps of four long-term chloraminated DWDS (Dataset 1)

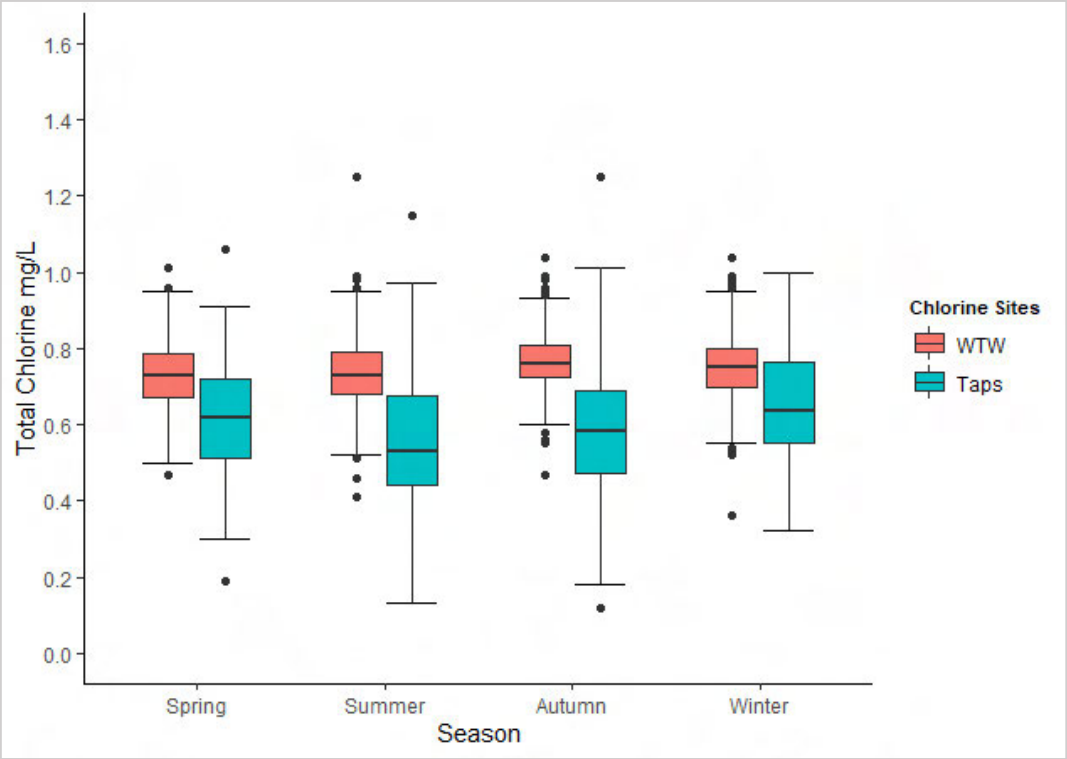

Figure 2: Impact of season on total chlorine concentrations at water treatment works outlet and taps of five long-term chlorinated DWDS (Dataset 1).

Table 3: Difference between the total chlorine median of WTW outlet and tap total chlorine as a percentage (%) across chlorine and chloramine DWDS, segregated by season, from dataset 1.

Chloramine DWDS	Chlorine DWDS	Season
18.1	15.13	Winter
13.39	14.47	Spring
24.35	26.32	Summer
23.14	23.03	Autumn

The largest % difference in total chlorine medians and thus decay is shown in summer of both chloraminated and chlorinated sites, 24.4% and 26.3% respectively. Indicating the importance of temperature in network residual persistence.

In order to consider the impact of water age on chloramine residual persistence, total chlorine data in dataset 2 was analysed (Figure 3). This dataset compares chlorine and chloramine persistence within the same DWDS (pre and post disinfection change), therefore network characteristics including water age remain the same. This is advantageous over Dataset 1 as this compares different DWDS experiencing different residuals and water ages. Dataset 2 analysis shows contrasting results to those presented in previous Figures 1 and 2, as higher total chlorine is seen at taps post-switch than pre-switch at DWDS A, C, D, E (Table 3).This suggests networks are experiencing less decay the year following the switch than the year before. However, low total

chlorine concentrations are still recorded in some tap samples as shown by outliers, this is particularly true for DWDS A and C (Figure 3). DWDS B shows limited change between WTW and tap total chlorine concentration pre- and post-switch. Similarly, DWDS F shows a 12.5% reduction in residual through the network prior to the switch and a small increase 1.03% increase after (Table 3), indicating little change in residual persistence pre- and post- switch at these two sites.

The TOC concentration the year pre- and post-disinfection change from chlorine to chloramine is presented in Figure 4. DWDS A has been omitted due to a lack of data. TOC decreased between WTW and tap results prior to the switch in DWDS C, D and E. Post switch the opposite occurred, with TOC increasing from WTW to taps. Suggesting the switch to chloramine is contributing to increased TOC generation within the network. This trend is not seen in DWDS B and F, with TOC concentrations at DWDS B remaining low at both WTW and taps regardless of the disinfection switch and DWDS showing a similar reduction in TOC between WTW and taps pre and post switch, 18.75% and 22.73% respectively.

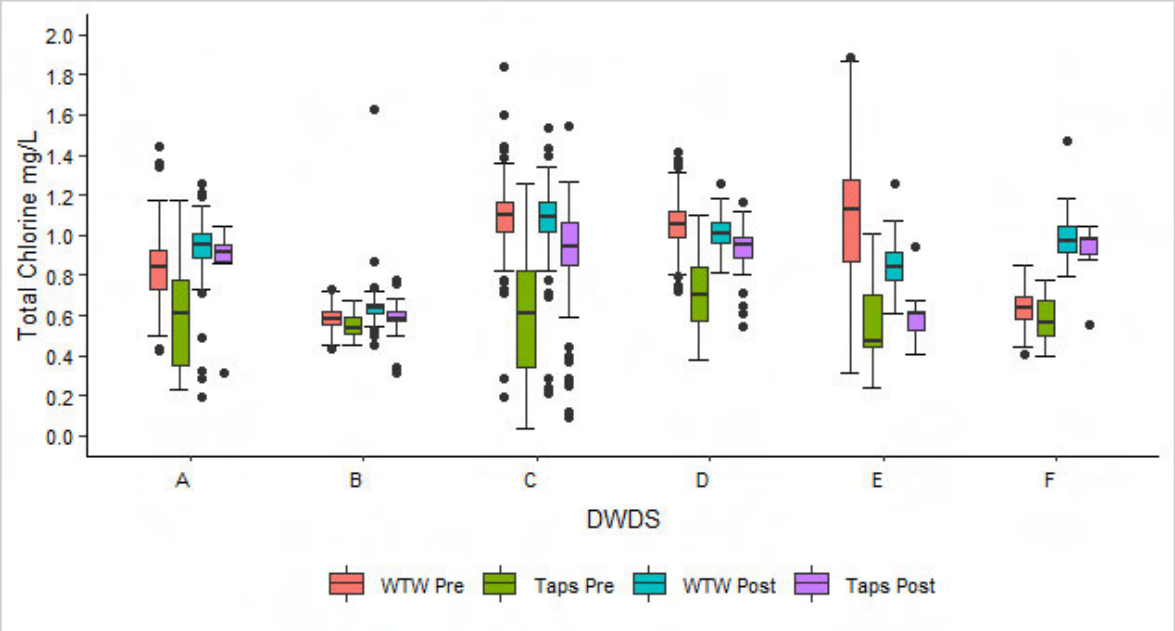

Figure 3: Total chlorine concentrations across six drinking water distribution systems (A-F), the year pre and post disinfection switch from chlorine to chloramine. Water treatment works concentrations before ("WTW Pre") and after ("WTW Post") and customer tap concentrations before ("Taps Pre") and after ("Taps Post") the disinfection switch are shown (Dataset 2).

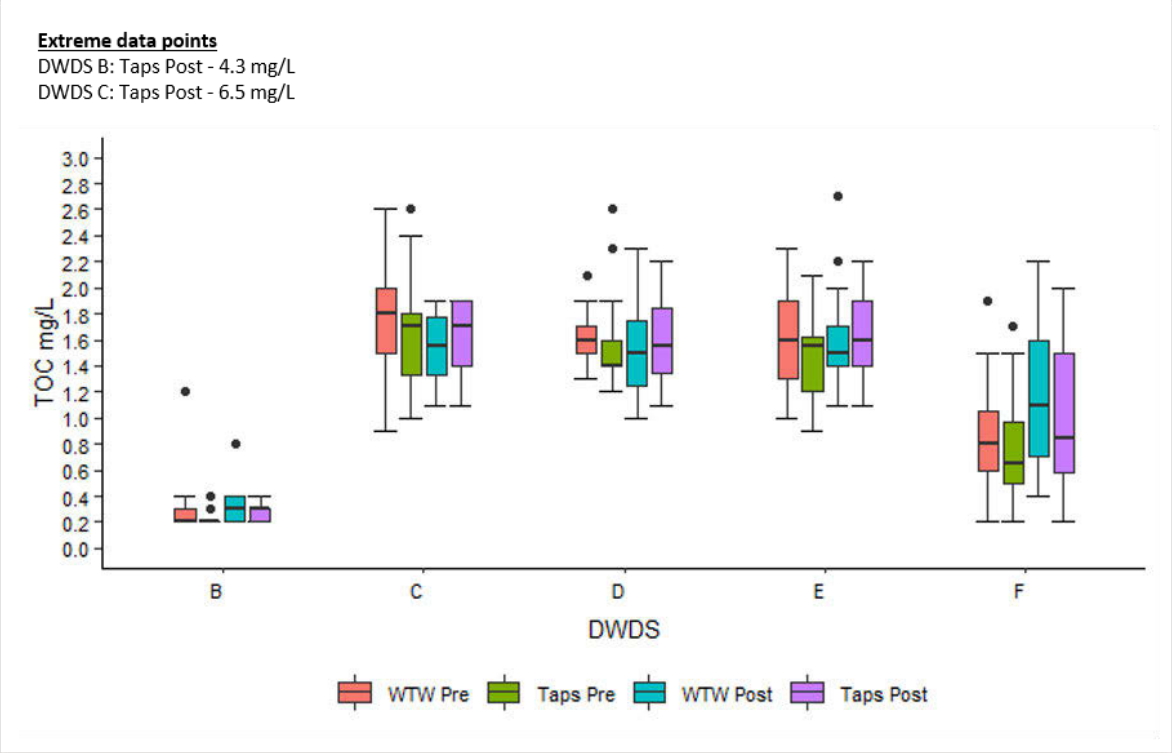

Figure 4: Total organic carbon (TOC) across five drinking water distribution systems (B-F), the year pre and post disinfection switch from chlorine to chloramine. Water treatment works concentrations before ("WTW Pre") and after ("WTW Post") and customer tap concentrations before ("Taps Pre") and after ("Taps Post") the disinfection switch are shown (Dataset 2).

Table 3: The % change in total chlorine and total organic carbon (TOC) medians between the WTW and taps pre and post disinfection switch. Increase in change (+) and decrease in change (-). N/A refers to sites that did not have sufficient data available.

DWDS	WTW Pre - Taps Pre		WTW Post - Taps Post	
	Total Chlorine	TOC	Total Chlorine	TOC
A	-27.38	N/A	-4.21	N/A
B	-7.76	0	-9.38	0
C	-44.55	-5.56	-13.76	+9.68
D	-33.33	-12.5	-5.94	+3.33
E	-58.41	-3.13	-27.98	+6.67
F	-12.50	-18.75	+1.03	-22.73

4 DISCUSSION

The first stage of analysis shows chloramine DWDS to experience similar if not greater decay in total chlorine throughout the network than chlorine. This contradicts the perception that chloramine's lower reactivity enables it to persist for longer within the DWDS than chlorine [16],

[17]. However, this result should be treated with caution as dataset 1 doesn't consider all factors particularly that of water age – a result of chlorine and chloramine sites varying in size, which can influence residual decay. The construction of dataset 2, allowed for consideration of these factors and showed contradictory results, with four out of the six DWDS showing improved residual maintenance under chloramine disinfection than chlorine. Thus, supporting the belief that chloramine is less reactive and persists for longer within the network than chlorine. However, DWDS B and F indicate no benefit of chloramine residual persistence following the disinfection switch.

Post disinfection switch, DWDS F shows a 22.73% decrease in TOC, but maintains a comparable total chlorine residual throughout the network. In contrast, DWDS, C, D and E show TOC accumulation but also high residual decay the year post disinfection switch, suggesting that microbial activity may be contributing to the decay seen. However, this trend is tentative, due to the similarity of data ranges pre and post switch. The fact data sits well within the range of noise and the inability to perform statistical analysis to determine significance (due to unpaired data set) adds to this uncertainty. Additionally, it is difficult to infer biological activity based solely on TOC measurements. Assimilable organic carbon (AOC) would be a better parameter to determine microbial activity, particularly biofilm growth [18][18][18]. However, AOC is not routinely tested for and was not available for this historic data analysis.

It is important to note that the length of time that networks have been chloraminated differs between the two datasets. With dataset 1 being long-term chlorinated and chloraminated systems, and dataset 2, newly chloraminated systems. The length of time a network has been chloraminated is likely to influence the maintenance of residual. Thus, this could contribute to the contradictory results seen. Additionally, inferring residual loss from tap samples should be treated with caution due to the limited number of samples taken, which are unrepresentative of the vast complex DWDS that operate for 24 hours a day. The fact tap samples are collected randomly across various locations (unpaired data set), means statistical analysis to determine significance is not possible, this adds to the uncertainty of residual maintenance.

Dataset 1 shows the greatest decay in residual occurs in the summer of both chloraminated and chlorinated systems. Temperature is known to have a significant impact on chlorine decay rates, with decay approximately doubling for every 5 ˚C increase in water temperature [6] so this was expected. Whilst detailed water temperature data was not available for the datasets analysed, air temperature data was used to check summer months experienced higher temperatures range.

5 CONCLUSIONS

Analysis of data comparing long-term performance of chloramine and chlorine systems showed similar decay of residuals across all seasons, irrespective of residual type. The second dataset showed variable residual persistence across DWDS that underwent a disinfection switch from chlorine to chloramine. Specifically, three systems showed a clear reduction in residual decay and one a marginal reduction following the disinfection switch from chlorine to chloramine, indicative of improved residual persistence. Yet, two DWDS showed little change in residual persistence pre and post disinfection switch. This analysis highlighted the uncertainties around residual persistence under different disinfection residuals and suggests it would be wrong to assume that chloramine persists for longer than chlorine in every distribution system, meaning the common perception of this is not true.

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