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Service reservoir performance assessment: a data driven approach for smart water infrastructure management

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ABSTRACT

Service reservoirs (SRs) are critical assets within drinking water distribution systems, yet water service providers (WSPs) lack methods for in-service performance assessment. Using data from 17 SRs and 2 WSP, a novel framework assessing SR integrity and mixing characteristics is developed and validated. While single-parameter analysis yields limited insights, combining level and flow data enabled mass balance calculations to detect integrity issues such as leaks and ingress up to 3 months before the scheduled inspections. Hydraulic residence time calculations, based on flow and level data, identified SRs operating beyond their recommended range with water age, sedimentation, and disinfectant residual consequences. By comparing hydraulic to cross-correlation residence times, calculated using inlet and outlet conductivity data, SRs exhibiting short-circuiting were identified. These were linked to poor mixing behaviour, creating zones of reduced disinfectant residual and higher bacteriological risk. An operational trial was subsequently conducted that demonstrated that by enhancing the SR level cycling, an approach highlighted by self-organising map analysis of data from 329 SRs, a 33% improvement in mixing was obtained. This new framework, using standard network data, facilitates WSPs to transition from reactive and periodic assessment of SRs to proactive and effective real-time smart water infrastructure management.

Key words: asset management, drinking water quality, mixing, residence time, service reservoir

INTRODUCTION

The delivery of safe drinking water is essential to public health (WHO 2019). Deterioration of water quality can occur during storage and distribution through physical, chemical, and biological processes (Blokker *et al.* 2016; Mounce *et al.* 2016a, b). Service reservoirs (SRs) or water storage tanks are critical assets within drinking water distribution systems, providing storage to balance supply and demand, maintain pressure, and ensure resilience during supply interruptions (Brandt *et al.* 2017). However, recent studies show that bacteriological failures at SRs are twice as frequent as in water treatment works (WTWs) (Ellis *et al.* 2018). Despite their importance, there is a lack of data-driven approaches for assessing SR performance. Water service providers (WSPs) typically rely on scheduled structural inspections and reactive maintenance, with limited ability to detect emerging issues between visits. While flow and level data are regularly collected at SRs, they are primarily used for operational demand management purposes rather than performance assessment. Similarly, mixing performance, known to influence disinfection residuals and the development of dead zones, is difficult to evaluate without tracer studies or computational fluid dynamic (CFD) modelling (Zhang *et al.* 2014), neither of which is practical for routine asset management.

Discussions with water providers consistently returned two primary mechanisms of SR failure considered the greatest risk to distributed water quality. The first was structural integrity, such as leaking hatches or failure of wall roof joints, with breaches permitting ingress of potentially contaminated water (Clark *et al.* 1996). The second was poor internal mixing leading to dead zones with little, or no, turnover and consequences including ageing water, negligible disinfectant, and microbial proliferation (Gauthier *et al.* 2000). With SR maintenance typically complex and costly, approaches to assess these failure pathways, which could also inform and justify timely interventions, would be a powerful tool to help safeguard water quality exiting SR's and being supplied to downstream consumers.

The aim of this work was to develop a data-driven framework for SR performance assessment. The objectives were to (1) determine whether integrity issues such as leaks and ingress can be detected using routinely collected flow and level data; (2) evaluate hydraulic residence time as an indicator of SRs at risk of water quality deterioration; and (3) assess whether mixing performance can be inferred from inlet and outlet water quality monitoring, and validated against water quality outcomes.

Background

In SRs, bulk water microbiology is considered the dominant factor affecting water quality due to the high volume-to-surface-area ratio compared with pipes (Wingender & Flemming 2011). Traditional monitoring using heterotrophic plate counts can underestimate microbial contamination, capturing less than 1% of the microbial population (van der Kooij 2003; Berry *et al.* 2006). While not standard, continuous monitoring at both SR inlets and outlets can enable WSPs to distinguish whether water quality issues originate upstream or within the SR itself (Doronina *et al.* 2020) and can help predict the time lag between contamination events and their arrival at the outlet. While Machell & Boxall (2014) found that water age does not correlate strongly with individual water quality parameters, it remains a useful proxy indicator (Blokker *et al.* 2016). The hydraulic performance of SRs influences water quality outcomes, yet there is limited literature on how to assess this in practice. Zhang *et al.* (2011) introduced mean water age as a quantitative indicator within SRs, though this was applied only to chlorine residence time modelling. Mass balance approaches have proved valuable for large-scale reservoir systems (Chawanda *et al.* 2020; Song *et al.* 2022), but have not been applied to detect integrity issues at SRs.

Mixing performance is particularly challenging to assess. Poor mixing is often due to short-circuiting between inlet and outlet, reducing effective residence time and enabling the development of dead zones where water quality can deteriorate (Grayman *et al.* 2004). CFD modelling can characterise mixing but is computationally expensive and difficult to confirm outcomes, hence impractical for routine application. Mixing models such as tanks-in-series dispersion models offer an alternative approach, though their applicability to routinely monitored inlet water quality signals has not been established. A comparative method using hydraulic and cross-correlation residence times has been proposed as a practical alternative for assessing SR mixing (Gleeson *et al.* 2024), though validation against water quality outcomes has not previously been reported.

While the importance of SR performance is recognised, WSPs lack practical tools for continual assessment of performance and hence identification of assets that pose a risk to water quality. Flow and level data could support mass balance and residence time calculations, yet are not routinely used for this purpose. Where continuous water quality monitoring is deployed at SR inlets and outlets, these data could enable mixing assessment without tracer studies, but the relationship between such metrics and actual water quality outcomes has not been established.

METHODS

Linking SR operation and water quality

Self-organising maps (SOMs) were used to identify relationships between SR operational parameters (including level data) and water quality outcomes at SR outlets. SOMs are unsupervised neural networks that project high-dimensional data onto a two-dimensional grid, enabling visualisation of inter-parameter relationships, and have previously been applied to drinking water distribution systems data analysis (Mounce *et al.* 2016a, b). Using such rare events as the target presents a challenge for analytical approaches. To overcome this, we used free chlorine residual at SR outlets as a proxy indicator for water quality, although it should be noted that this is particularly sensitive to residence time and hence more likely indicative of mixing issues than ingress. A historical dataset of regulatory sampling and operational data from 329 SRs, spanning 2019 to 2023, was used for the SOM analysis, which was performed using the SOM Toolbox 2.1 for MATLAB (Technology 2015).

Developing metrics for understanding SR performance

Four analytical methods were applied to explore and understand SR performance. They are combined in this research to form a data-driven framework for SR performance assessment. These are captured in Figure 1. First, a single-parameter analysis evaluating the impact of the rate of level changes was done. This was followed by multi-parameter approaches combining level with flow data (mass balance and hydraulic residence time), and finally integration of inlet and outlet water

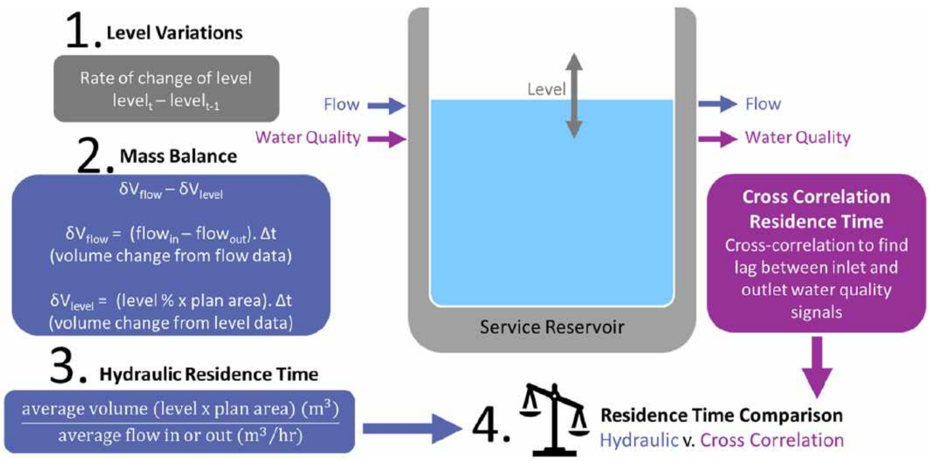

Figure 1 | Four analytical components underpinning a data-driven framework for SR performance assessment.

quality data to assess mixing performance, based on comparing two approaches for calculating the residence times. Each component was validated against operational records, regulatory sampling data, or controlled operational trials.

Level variations

The first analytical stage examined whether variations in SR level time series data alone could yield insights into SR behaviour, beyond some understanding of daily demand patterns. To isolate variations from underlying trends, time series level data were subjected to linear de-trending using backward differencing. This rate of change of level was then examined to identify periods of unusual behaviour that might indicate operational or integrity issues. This single-parameter approach requires only level data that are routinely collected at most SRs.

Mass balance

For the second stage, mass balance calculations were developed to try and detect integrity issues such as leaks and ingress. In a structurally integral SR, the change in volume calculated from inlet and outlet flow measurements (δV_{flow}) should equal the change in volume derived from level sensor data (δV_{level}). The residual volume, ΔV (δV_{flow}-δV_{level}), should provide information on SR integrity: positive values indicate ingress, negative values indicate leakage, and values near zero indicate a balanced system. However, ingress volumes are potentially small in comparison to the accuracy of level data, SR plan area, flow meter accuracy, and/or resolution. Daily residual volumes were calculated and monitored for anomalies that might indicate emerging integrity issues. Unlike the single-parameter level analysis, this approach requires both level and inlet/outlet flow data.

Hydraulic residence time

Hydraulic residence time was calculated as a metric for identifying SRs at risk of water quality deterioration due to insufficient turnover. Under the assumption of complete mixing, the residence time was calculated by dividing the average tank volume by the average flow rate (inlet or outlet). Daily residence times were calculated and compared with the recommended ranges specified in the WSP's operating manual, which were between 24 and 48 h.

Mixing performance

The applicability of tanks-in-series dispersion models was investigated as an approach for characterising mixing. These models represent an SR as a series of completely mixed compartments, with the number of compartments reflecting the degree of dispersion.

Mixing performance was also assessed by comparing the hydraulic residence time to a residence time derived from cross-correlation of inlet and outlet water quality signals. The hydraulic residence time, calculated from flow and volume data, represents the expected transit time assuming complete mixing. The cross-correlation residence time represents the time lag at which the inlet and outlet water quality signals are most strongly correlated, reflecting the actual transit time of water through the SR. For a well-mixed SR, these two residence times should be similar. Increased divergence indicates short circuiting and the potential to develop dead zones where aged water with reduced/negligible disinfectant residual and increased regrowth and other water quality degradation can occur.

Cross-correlation was calculated following the method presented by Gleeson *et al.* (2021) using week-long windows of inlet and outlet water quality data. For this work, conductivity was selected as a robust parameter, with less calibration and more stable overall performance than previously used chlorine sensor data, with windows advancing in 24-h increments. The mixing performance of each SR was characterised by plotting the hydraulic residence time (x) against the cross-correlation residence time (y). The line of unity ($x = y$) on this plot represents perfect agreement between the two metrics, indicating idealised mixing characteristics. The perpendicular distance from this line was used to quantify mixing performance: the greater the distance, the worse the agreement between the metrics and the poorer the mixing. Perpendicular distance was chosen as it does not favour either residence time determination as would a vertical or horizontal distance measure. SRs with both high hydraulic residence times and low relative cross-correlation residence times, represented by large distances from the line of unity, were identified as those with higher levels of water quality risk due to poor mixing performance.

Datasets and validation

Two datasets from UK WSPs were used for validation of the different metrics proposed for the framework, reflecting the different data requirements of each analytical component.

Dataset 1 comprised 11 SRs from a single WSP, with continuous 15-min interval monitoring of level and, at 5 sites, both inlet and outlet flows. This dataset was used to validate the level variation, mass balance, and hydraulic residence time components. Site inspection records were available to corroborate analytical findings.

Dataset 2 comprised six SRs (A-F) from a different WSP, with continuous water quality monitoring (conductivity, turbidity, and chlorine) at both inlets and outlets at 15-min intervals, a level of instrumentation not yet routine in the industry. Flow data were available at either the inlet or outlet. This dataset was used to validate the mixing performance metric. Regulatory sampling records, including free chlorine and log water quality risk score (WQRS; a proprietary flow cytometry–derived bacteriological risk scores, calculated and provided by the WSP), were available for comparison with the mixing metric outputs.

An operational trial was conducted at one SR (SR E) in Dataset 2, where the WSP implemented an enhanced level cycling regime, using the Aquadapt automatic cycler, over a period of 3 months starting in January 2025. This enabled a controlled comparison of the mixing metric under normal and enhanced cycling conditions, providing direct testing of both the metric and the potential for operational intervention to improve mixing performance.

RESULTS

Self-organising maps

Analysis of the data from 329 SRs revealed relationships between SR operational parameters and water quality parameters at the SR outlets. The SOMs presented in Figure 2 compare water quality parameters at SR outlets to parameters from upstream WTWs and SR level data. The strongest relationship identified through visual inspection was between free chlorine residual and the daily standard deviation of the SR level. This correlation between increased level cycling and higher disinfection residual suggests that enhanced level cycling promotes better mixing performance within SRs and informed the subsequent focus on developing metrics that incorporate level data.

Level variations and mass balance

Figure 3 presents three case studies from Dataset 1 where the level variation and mass balances approaches were applied. To facilitate interpretation and validation through inspection records, results were displayed for 6-month intervals centred around inspection dates. The mass balance results are presented alongside the level rate of change to demonstrate the value of the multi-parameter approach compared with single-parameter analysis. The first case study (Figure 3(a)) shows a peak in residual volume in April 2015. The change is readily apparent in the time series, significantly greater than the other variations that occur from instrument accuracy and resolution effects. There is confidence that this is a real ingress event as it occurs 3 months after an inspection that identified a leak that had been scheduled for but not yet repaired. Comparison of the top two plots in Figure 3(a) highlights that the mass balance approach can identify volume variation events that are not evident in the analysis of the level rate of change alone. The second case study (Figure 3(b)) shows significant

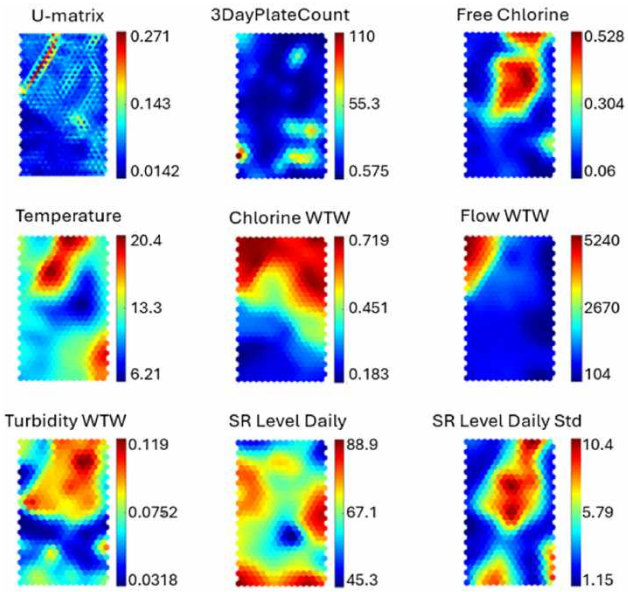

Figure 2 | Self-organising maps (SOMs) comparing water quality at treatment works outlet with downstream service reservoir level and water quality data. Enhanced daily cycling of service reservoir level (bottom RHS SOM output) is associated with improved chlorine residual (top RHS SOM output).

fluctuations in residual volume up to 3 months prior to inspection, which identified leaking outlet valves. The early detection of this issue demonstrates that the mass balance metric can identify SR integrity problems, preventing issues from going undetected for extended periods. The third case study (Figure 3(c)) shows a substantial increase in water entering the SR approximately 6 weeks before scheduled inspection, evidenced by abrupt changes in residual volume. The inspection found roof leaks, wall roof leaks, and floor joint splits, which were repaired within 8 days. Following the maintenance interventions, a new level of stability was achieved, demonstrating the potential of mass balance calculations both to identify issues before inspection and to evaluate the effectiveness of corrective actions.

Hydraulic residence time

Hydraulic residence times were calculated for all 11 SRs in Dataset 1, with one example shown in Figure 4. This SR exhibited consistently long residence times exceeding the 48-h threshold (from WSP Standard Operating Procedure), except for a brief period from May 2015 to October 2016, indicating that the SR was not operating at levels and flows that ensured adequate water turnover. Another SR in the same network displayed similar behaviour, with residence times persistently above the threshold. Inspection records, in this case, reported thick layers of deposits and corrosion, conditions known to correlate with extended water age and insufficient mixing. These results indicate that a daily residence time metric may prove effective in evaluating SR hydraulic performance and identifying assets potentially at risk of water quality deterioration.

Mixing performance

The applicability of tanks-in-series model for characterising mixing was investigated using inlet and outlet conductivity data from Dataset 2. Figure 5(a) shows how increasing the number of cells in a tanks-in-series model simulates different degrees of mixing, changing the downstream concentration profile assuming a stepped input function. Figure 5(b) shows the effect of applying this same range of assumed cells to typical inlet and outlet conductivity data from an SR in Dataset 2. While the models provide a good match for the outlet conductivity data, the improvement in fit for different numbers of tanks is marginal. This is due to the relatively slow and continual change in the input signal. Without distinct step changes in inlet water quality, the practical applicability of tanks-in-series models for operational SR assessment is limited. However, it may be applicable in systems that experience distinct step changes or via the intentional introduction of 'impulses', for example, a pulse of salt tracer that could be well below taste and odour levels and readily measured with conductivity monitoring. The mixing characteristics could also potentially be assessed by fitting other models such as advection diffusion or

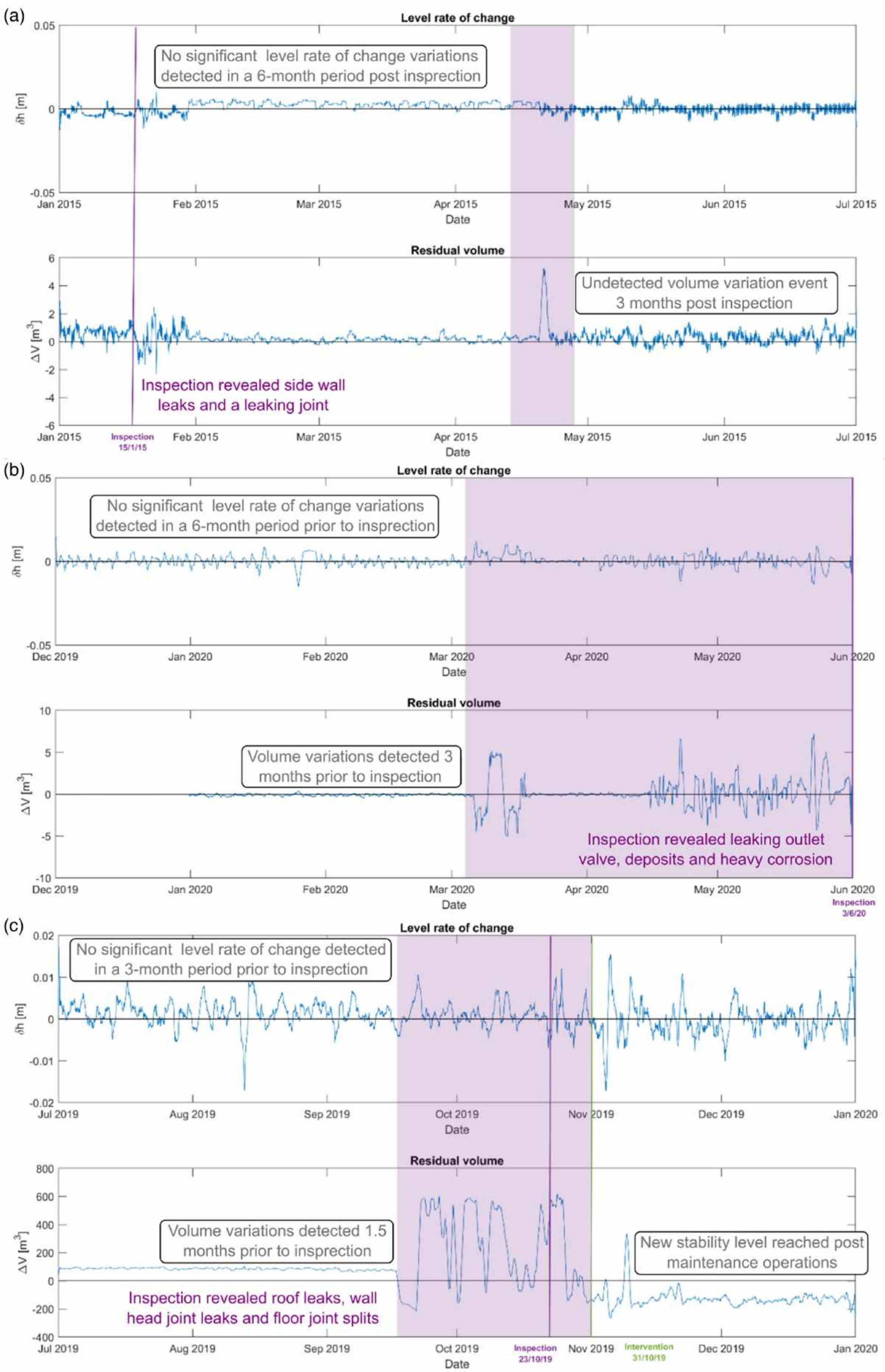

Figure 3 | 3 SR sites with the level rate of change and mass balance (residual volume) time series alongside site inspection records.

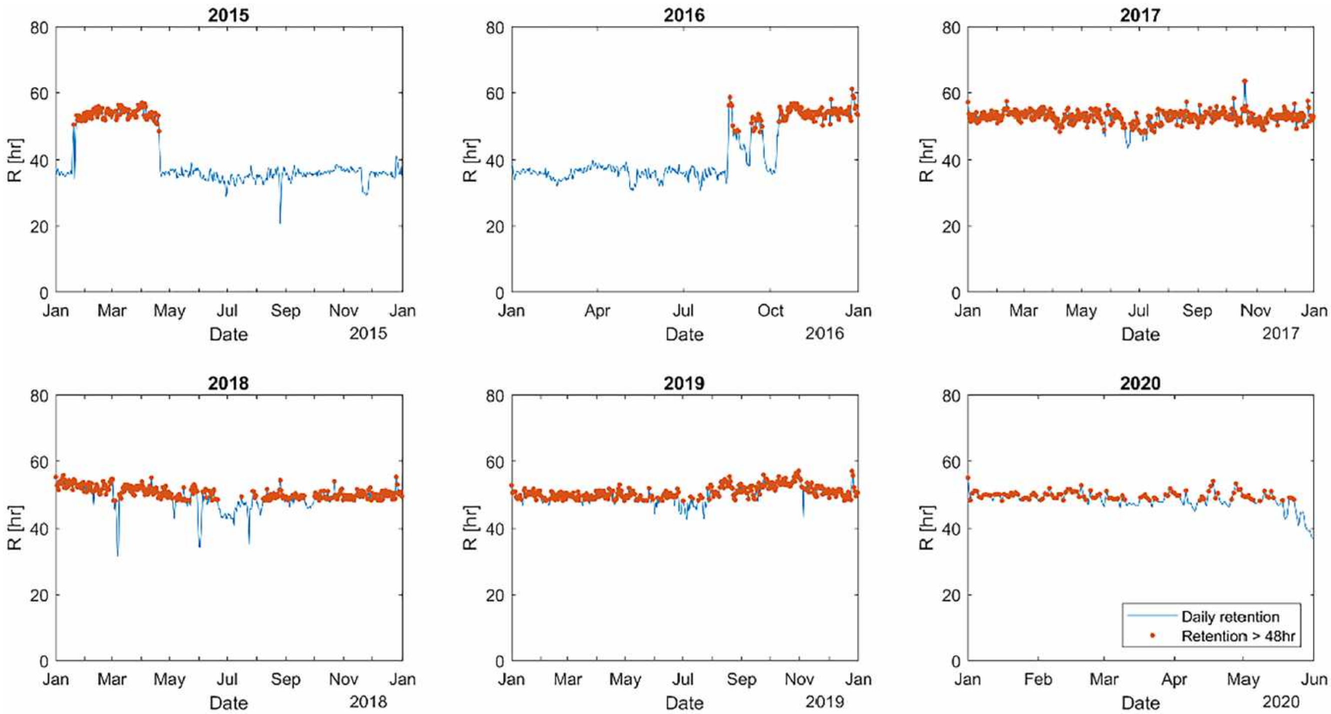

Figure 4 | Hydraulic residence times calculating from 2015 to 2020 with data above the 48 h threshold marked in red.

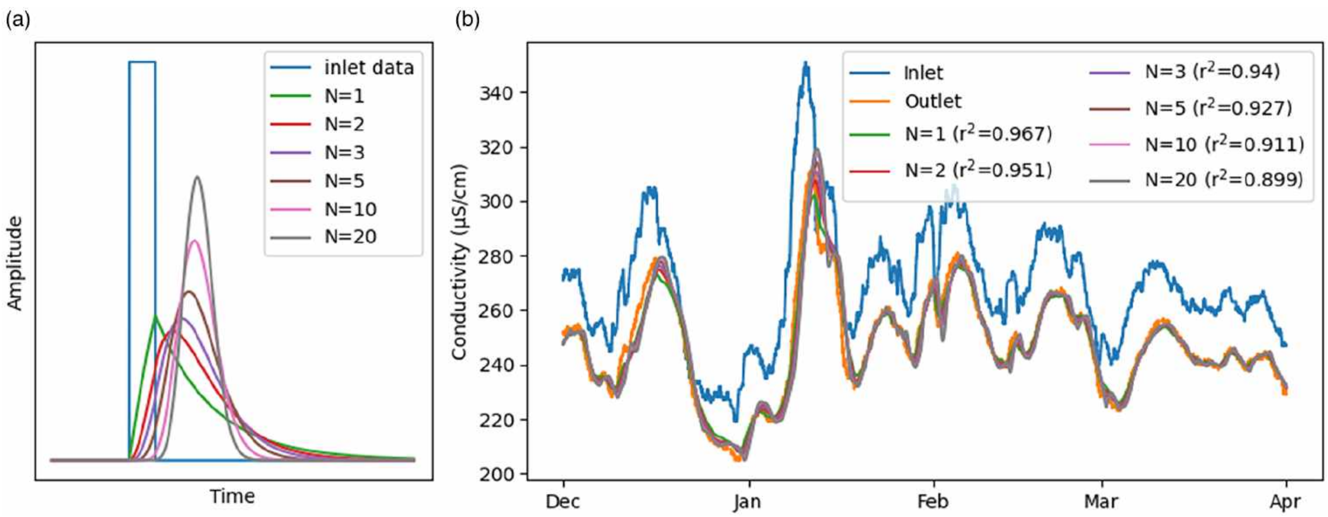

Figure 5 | Tanks-in-series dispersion model applied to simplified step function for different numbers of tanks in series (representing different dispersion coefficients) (a) and applied to SR inlet conductivity data (b).

aggregated dead zone models, rather than the cells-in-series model investigated here. However, these will also be limited by the relative smooth, slow change in the input signal.

The comparative method using hydraulic and cross-correlation residence times was applied and verified on the 6 SRs in Dataset 2, with results in Figure 6 showing a range of mixing characteristics. The values displayed in this figure are averages over the course of up to a year, with varying quantities of data utilised due to the variation in data availability and quality across the input parameters. SR F in Figure 6 exhibited the highest hydraulic residence time (96 h) but a cross-correlation residence time of only 3.5 h, suggesting extreme short-circuiting and resulting in a perpendicular distance of 65.4 from the

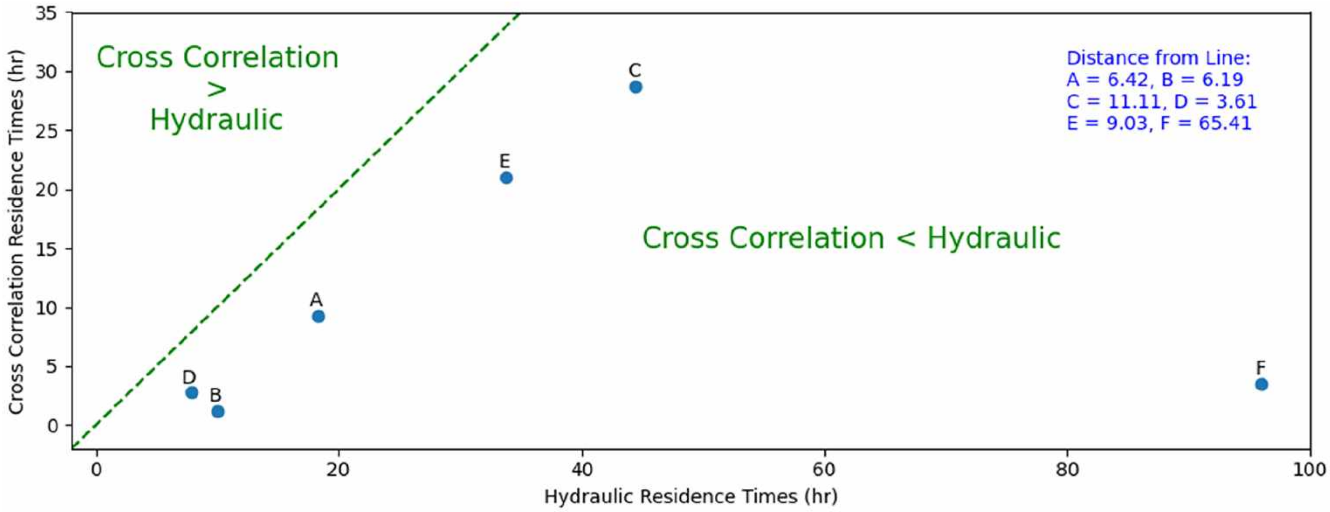

Figure 6 | Scatter plot showing hydraulic versus cross-correlation residence times for six service reservoirs.

line of unity. SRs C and E were also identified as having higher levels of water quality risk due to both their high residence times and their low relative cross-correlation residence times, suggesting poorer mixing performance.

Validation against regulatory samples and operation change

Regulatory samples taken at the outlets of the six SRs in Dataset 2 were examined, with box plots of free chlorine and log WQRS (a proprietary metric derived from flow cytometry data indicating bacteriological risk, with scores above 9 most likely to result in failures) shown in Figure 7. SR F was a clear outlier for both parameters, with consistently low disinfection residual and high bacteriological risk. SR E also exhibited a high median log WQRS, indicating increased biological activity. These results provide initial validation of the mixing performance metric with SRs with poorer regulatory sampling water quality outcomes identified as having poorer mixing characteristics.

Enhanced cycling validation

An operational trial was conducted at SR E to validate the mixing performance metric and assess whether enhanced level cycling could improve mixing. Figure 8 shows the level time series data under normal (blue) and enhanced (green) cycling regimes, alongside both residence time calculations using overlapping week-long windows advancing every 24 h. As shown in the level data, achieving consistent enhanced cycling proved challenging due to operational constraints balancing work output and consumer demands. The enhanced cycling period also coincided with lower average tank levels.

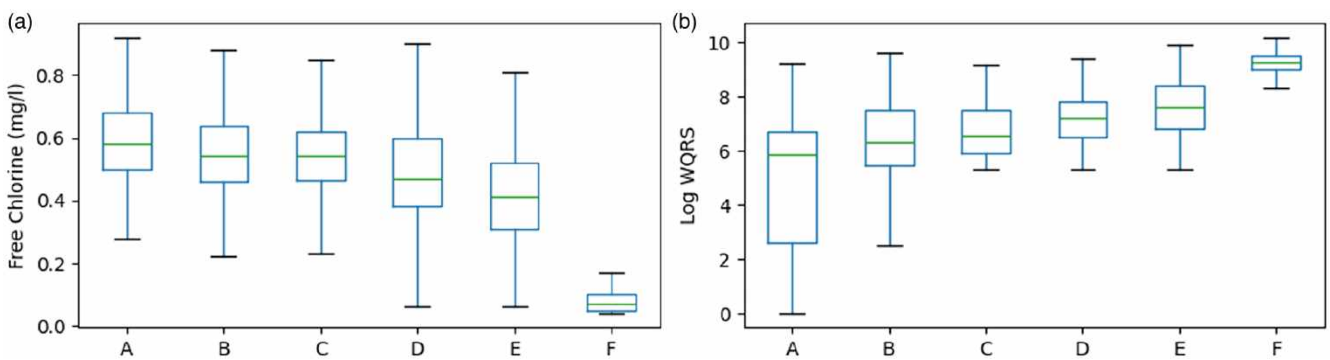

Figure 7 | Boxplots showing the spot sample results for (a) free chlorine and (b) log WQRS across the six service reservoirs between 2019 and 2025.

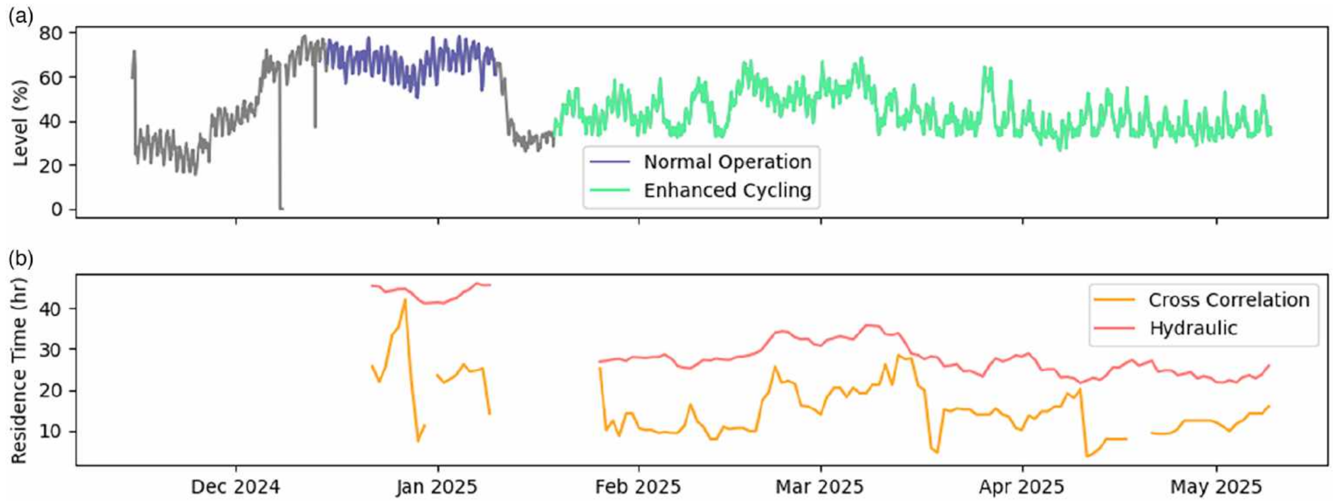

Figure 8 | SR E level time series with normal and enhanced cycling periods marked (a) both residence time methods calculated on week-long overlapping windows every 24 h (b).

Despite these constraints, the cross-correlation residence time was observed to move closer to the hydraulic residence time during the enhanced cycling period, indicating improved mixing characteristics. Figure 9 presents these results as a scatter plot, with each point representing a weekly calculation and the star marker representing the centroid. This figure shows that the cross-correlation residence times during enhanced cycling (green points) were on average 33% closer to the hydraulic residence times than during normal operation (purple points), demonstrated by proximity to the line of unity. This provides initial validation that the comparative residence time method can detect changes in mixing performance, and that enhanced level cycling represents a practical operational intervention for improving SR mixing.

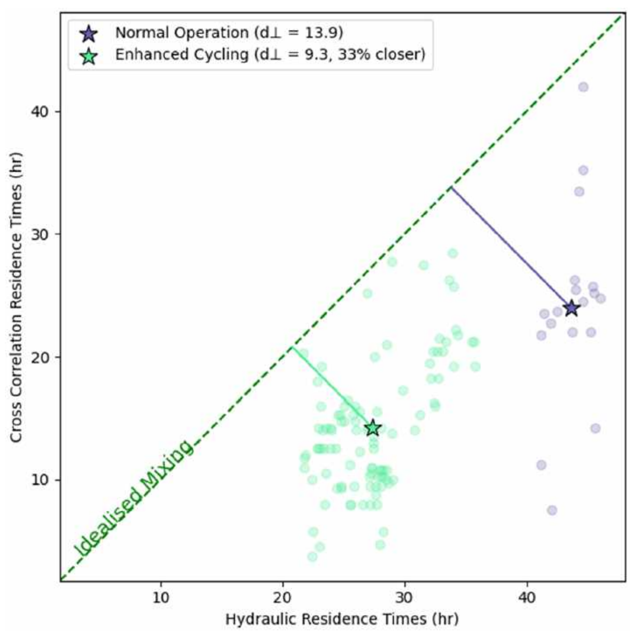

Figure 9 | Scatter plot showing the hydraulic and cross-correlation residence times for SR E during the normal operation (purple) and enhanced cycling (green) where the enhanced cycling results are on average 33% closer to the line.

DISCUSSION

This work reports on the development of a tiered framework for SR performance assessment, progressing from single-parameter analysis of level data through multi-parameter approaches combining level and flow, to integration of inlet and outlet water quality monitoring. The findings demonstrate that while analysis of level variations alone can identify changes in SR operation, combining data sources can provide improved understanding of SR performance and provide evidence-based actionable insights.

Mass balance calculations proved effective at identifying integrity issues such as ingress, in several cases, detecting problems later confirmed during scheduled inspections. The sudden changes in residual volumes observed (Figure 3) are likely attributable to issues such as wall cracks or joint degradation, as supported by inspection records. While the metrics alone cannot determine exact root causes, they provide early warning that enables targeted inspection of at-risk assets. This is a significant finding as this approach uses flow and level data that WSPs already collect but do not employ for this purpose. This represents a practical application of existing data streams, facilitating proactive asset management. It should be noted that representative inlet monitoring is not always available, hence the method cannot be universally applied. Where representative flow data are not available, investment should be made to obtain them and enable this analysis.

Hydraulic residence time calculations identified SRs operating outside recommended turnover ranges, with elevated residence times corresponding to inspection findings of sediment accumulation and corrosion. These results suggest that water quality and hydraulic performance are linked, consistent with the broader literature on water age as a proxy for water quality (Machell & Boxall 2014; Blokker *et al.* 2016). However, those studies focused on the distribution network rather than explicitly considering the effect of SRs. The findings here indicate that residence time calculations at SRs could play a key role in identifying assets at risk of water quality deterioration.

The comparative residence time method for assessing mixing performance was validated using multiple approaches. First, the SRs identified as having poor mixing characteristics, particularly SR F with its extreme divergence between hydraulic and cross-correlation residence times, corresponded to those with poorer water quality outcomes in regulatory sampling, exhibiting low disinfection residuals and high bacteriological risk. Next, the enhanced cycling trial showed that the mixing metric responded to operational changes, with cross-correlation residence times moving 33% closer to hydraulic residence times during enhanced cycling.

The enhanced cycling trial was challenging to implement, reflecting the operational constraints faced by WSPs whose priority is safeguarding network service, hence typically a desire to keep SRs nearly full to provide the greatest reserve volumes for resilience. Nevertheless, the improvement in mixing characteristics during enhanced cycling, consistent with the initial SOMs finding that increased level cycling is associated with improved chlorine residual, indicates that changing cycling regimes may represent a viable operational intervention for improving SR performance. This provides WSPs with both a method for identifying SRs with poor mixing and a practical means of addressing it.

Crucially, while previous characterisation of SR mixing has relied on tracer studies or CFD modelling (Grayman *et al.* 2004; Zhang *et al.* 2014), neither of which is practical at scale, this innovative work demonstrates that mixing performance can be inferred from continuous water quality sensor data, and this work is the first to validate such a metric against independent water quality outcomes and a controlled operational intervention. It is important to note that without inlet water quality monitoring, it is uncertain whether water quality deterioration occurs upstream or within the SR (Doronina *et al.* 2020). The value of inlet and outlet monitoring demonstrated here, enabling mixing assessment without tracer studies or CFD modelling, provides additional justification for WSPs considering investment in continuous water quality sensors at SRs.

This study provides a foundation for data-driven SR performance assessment with several directions for future research emerging. Applying the framework to a larger number of SRs across different WSPs, climates, and network configurations would help establish generalisability and enable more robust statistical validation. The datasets used here, particularly the six SRs with continuous inlet and outlet water quality monitoring at 15-min intervals, reflect the current scarcity of such instrumentation in operational settings. As WSPs increasingly adopt continuous water quality sensors, opportunities to expand this validation will grow. The enhanced cycling trial demonstrated promising improvements at a single SR. Extending this to additional sites with more controlled cycling regimes would strengthen the evidence base and help WSPs develop operational guidelines for optimising mixing through level management.

Overall, this research has shown that it is possible to move beyond time-based inspection intervals for SRs and that this can be achieved using a combination of existing level and flow time series data for stages 1 and 2 (where both inlet and outlet flows are available) and conductivity time series data for stage 3. It is notable that the analysis is possible with conductivity data, as this is a robust parameter that does not require the maintenance and calibration of (high accuracy) turbidity or chlorine data. It is also notable that these metrics assess the performance of the SR directly, not the resultant impact on the water quality. The framework can hence provide a true lead indicator, prior to impacts on water quality, and is not subject to either the complexities of water quality analysis or the poor temporal covering of discrete sampling that these parameters typically require.

CONCLUSIONS

This innovative work developed and validated a framework for assessing SR integrity and mixing performance. Mass balance calculations, using standard flow and level data, detected integrity issues that were later confirmed during scheduled inspections. Hydraulic residence time calculations allowed identification of SRs operating outside recommended turnover ranges, while mixing performance was assessed by comparing hydraulic residence times to cross-correlation residence times from inlet and outlet water quality (conductivity) sensors.

Validation against regulatory sampling confirmed that SRs with poor mixing characteristics exhibited lower disinfection residuals and higher bacteriological risk. An operational trial demonstrated that enhanced level cycling improved the mixing metric, consistent with findings from self-organising map analysis of historic data that increased level cycling is associated with improved chlorine residual.

This work provides WSPs with both a method for identifying SRs with poor mixing and a practical operational intervention for improving performance. While inlet and outlet water quality monitoring is not yet routine, these findings provide additional justification for such investment. More broadly, this framework supports a data-driven approach enabling proactive infrastructure management, improving on the current reactive or schedule-based maintenance.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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