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Assessing service reservoir performance for preventative asset maintenance

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"Where I was born, water fell from the sky and ran over the land in wide rivers," she said. "There were oceans of it so broad you could not see the other shore. I've not been trained to your water discipline. I never before had to think of it this way."

- Frank Herbert, *Dune*

Declaration

I declare that no portion of the work contained in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute. The work presented is my own except where indicated.

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Abstract

Service reservoirs are critical assets of drinking water distribution systems, providing storage and balancing demand and supply. A variety of operational and integrity issues, such as water age and ingress or leakage, are known to impact chemical and microbiological water quality, with the risk of deteriorated water reaching end users. To ensure that service reservoirs are functioning effectively water companies conduct inspections every 3-5 years. However, due to the lack of a precise assessment method, maintenance interventions are currently scheduled according to predetermined time intervals rather than specific performance indicators. This research presents findings from newly developed metrics derived from routinely monitored hydraulic and water quality parameters at service reservoirs, designed to assess their performance and maintenance requirements. Data from 11 service reservoir sites within operating drinking water distribution networks was analysed over a span of 5 years. Data-driven multi-parameter metrics based on level and flow time series were developed to calculate mass balances and daily residence times. To rank service reservoir water quality performance, data from regulatory sampling and flow cytometry testing was investigated. Results showed that the mass balances were able to identify integrity issues up to 3 months prior to scheduled inspections. Furthermore, sites with residence times greater than 48 hours were found to have higher average values of 3-day colony counts and intact cell counts. This research showcases the inherent value of hydraulic and water quality parameters already monitored at service reservoirs to provide insights on asset performance. This contribution carries significant implications for water infrastructure management, as the use of data-driven metrics can effectively guide water companies in prioritising site inspections. Consequently, this advancement marks a departure from a purely reactive approach, fostering a more proactive mindset in infrastructure maintenance and management practices.

Contents

List of Acronyms

CFD Computational Fluid Dynamics

CFU Colony Forming Units

DBP Disinfection By-Products

DMA District Metered Area

DWDS Drinking Water Distribution System

DWI Drinking Water Inspectorate

FC Flow Cytometry

GRP Glass Reinforced Plastic

HPC Heterotrophic Plate Counts

ICC Intact Cell Counts

MAD Median Absolute Deviation

NTU Nephelometric Turbidity Unit

NOM Natural Organic Matter

PODDS Prediction of Discolouration in Distribution Systems

SOM Self Organising Map

SR Service Reservoir

TCC Total Cell Counts

WHO World Health Organisation

WTW Water Treatment Works

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Chapter 1

Introduction

Safe drinking water is an essential resource to sustain life, and its quality has important implications on public health. During its journey from treatment to tap, water can experience a wide range of problems that compromise its integrity, such as contamination events or degradation of the distribution network's assets; these can lead to consumer complaints for aesthetic issues like poor taste and odour or discolouration, and in the worst scenarios might provoke outbreaks of waterborne diseases. It is therefore necessary to implement regulations to guarantee a high quality and accessible water supply in order to preserve human health (*Discover Water* 2020; *Drinking Water* 2019; The National Archives, 2016).

One of the most critical assets of Drinking Water Distribution System (DWDS) are finished water storage facilities, also known as Service Reservoirs (SRs). Drinking water storage is located strategically either in correspondence of Water Treatment Works (WTW) or further downstream the trunk main network, and consists in ground level reservoirs or elevated tanks. These infrastructures have traditionally been designed to respond to the hydraulic demands of the distribution network: to balance the constant output from WTW with the variable and less predictable consumer demands, covering both daily and seasonal variations; to maintain the distribution system's pressure; to provide storage for peak demands and contingency storage to supply water during failure of a source works or a trunk main, as well as providing volumes needed for fire suppression (Brandt *et al.*, 2017).

Even though the condition and performance of these assets is critical in protecting drinking water safety, currently there is a knowledge gap in thoroughly understanding the root causes of failures at Service Reservoir (SR)s. A service reservoir is a complex infrastructure comprising both an engineering and an ecological system, and many of the issues which can arise within SRs are interrelated as different types of problems can share the same origins (National Research Council, 2006); therefore, considering only one of these problems in absence of the others, greatly oversimplifies the global issues associated with SRs.

There is an increasing demand from the water industry to efficiently assess the performance of storage tanks to ensure the safety of drinking water. In this scenario, the overarching needs of water companies are to monitor the conditions of these critical infrastructures without causing disruptions or interruptions in the supply service, and to effectively plan and carry out both ordinary and extraordinary maintenance activities. The current custom of water companies is that of performing time-based interventions on SRs; however, this approach implies that eventual failures can run for long periods of time prior to intervention, or that operations could be carried out when unnecessary, often resulting in an increase of maintenance costs (Ellis *et al.*, 2018; Carpitella *et al.*, 2020).

The main challenge is to define a new and proactive approach to service reservoir monitoring, in order to move from a purely time-based to a preventative maintenance system. A deeper understanding of the underlying mechanisms which impact SR integrity and their water quality, including a broader knowledge of the parameters involved in assessing service reservoir performance and how these are interrelated, can ultimately contribute to identify the root causes of failures of these infrastructures and enable water companies to determine if maintenance periods can be extended at certain sites or, else ways, whether they should be shortened.

Chapter 2

Literature Review

2.1 Introduction

Water is an essential part of life and the availability of water sources has been a salient point for the development of the first human settlements. The first records of engineering systems developed to store and convey water for human use date back several thousands of years, with complex distribution networks developed by several ancient civilisations, most notably in Ancient Greece and the Roman Empire (Angelakis *et al.*, 2012). Although DWDS have become increasingly advanced, with many developments and improvements brought forth in the last three centuries, their principal hydraulic components have remained unchanged through the ages: intake works collect water at surface or ground sources, the water is then treated to make it wholesome, it is consequently transported via trunk mains to storage facilities and finally distributed to customer taps by means of piping systems (Letterman, 1951; Brandt *et al.*, 2017). The majority of these systems comprises a combination of pipes ranging in length, diameter and material (AWWA, 2011). For example, in the UK most of the networks are made of cast iron pipes, which was the most commonly used material in the 19^{th} Century; however, these are now being replaced with contemporary materials such as plastic (National Research Council, 2005).

Currently, the resilience of these complex systems is subject to several threats of various nature; in particular, the rapidly increasing populations and the negative effects of climate changes on both large and small hydrological processes which are causing extreme events such as droughts and floods, are placing a strong strain on modern DWDS (Arnold *et al.*, 2020). As a result, many networks have deteriorated during use, and there is an increase in problems such as leaks and bursts (IPCC, 2014).

Drinking water quality can deteriorate in its journey through DWDS, primarily as a consequence of its interactions with the components of the network, which can trigger physical, chemical and biological changes in the water (Mounce *et al.*, 2016; Blokker *et al.*, 2016). A wide breadth of factors can negatively impact water quality within DWDS, causing a variety of customer complaints. Consequently, in order to keep providing safe drinking water, it is of fundamental importance for water utilities to monitor the factors which can affect water quality and to efficiently manage the water supply infrastructures; however, there is still a lack of efficient maintenance for these critical assets (Husband *et al.*, 2010).

This review aims to outline and classify the variety of issues that can arise at SRs in particular and, with the intent of defining the most appropriate methods to assess their performance, investigate the relations between the root causes of failure under different conditions. An overview will hence be given of the water quality parameters which are traditionally monitored by water utilities, how this data can be supported by other information such as hydraulic measurements, and exploring the links between different parameters.

2.2 Service reservoirs

Drinking water storage facilities are commonly known as SRs, and are used mainly to balance water demand and supply, to manage pressures in the distribution network, to meet consumer demands and to provide extra water volumes for emergencies such as fire demands. These are a critical asset within DWDS, and have a known, albeit little explored, impact on drinking water quality. The need to protect drinking water supplies during storage, preventing deterioration problems such as contamination, became increasingly important in the last century (Speight *et al.*, 2010). SRs come in many different shapes and sizes, and in a wide variety of materials, such as masonry, concrete and steel, with construction choices usually depending on the geology and topography of the area. These tanks can comprise more than one compartment, and their shape can be square, rectangular or circular. The inspection and maintenance of SRs is recommended every 3-5 years in order to mitigate and prevent the main issues which impact their integrity and the quality of drinking water (Brandt *et al.*, 2017). The effects that these infrastructures can have on drinking water quality, are overlooked, and most studies relating to SRs investigate in particular their hydraulic performance and the impact of shape on water mixing; however, efficiently managing SRs is a critical aspect of managing DWDS.

2.2.1 Location

The chosen location for treated water storage infrastructures mainly depends on the characteristics of the DWDS, and can be provided either in correspondence of WTW or further downstream. The elevation of SRs is calculated as the height necessary to maintain the pressure required by the network during peak flow demand, considering that where possible it is preferable to place SRs in order to feed the water distribution by gravity.

There are two main types of SRs according to their location: cross-over type and endmost type. In the first case the SR is located between the water source and the start of the distribution network, and is fed by a trunk main directly from the WTW, which is is the preferred configuration for small towns and centres. However, particular topographic and geographic conditions may suggest to locate the SR after the distribution network; in this second case the SR is fed by the network itself and water is supplied both directly from the WTW and from the SR (Brandt *et al.*, 2017).

According to their position there are three main types of SRs:

- underground;
- ground-level;
  - with surge tank,
  - with pumping station;
- water towers.

Currently most SRs in the UK are underground infrastructures, not only for geographical reasons but also because pumping costs and efficiency make elevated SRs less economically convenient (**UKWIR2017**).

2.2.2 Shape and pipeworks

The shape and design of a SR largely depend on the area of land available for construction. There are three main SR designs:

- circular;
- square;
- rectangular.

SRs are usually built with at least two compartments so that one can be drained during maintenance operations. To provide efficient water mixing and achieve plug-flow through the SR, baffle walls or curtains are often included (Brandt *et al.*, 2017). The shape of SRs has a documented effect on water mixing and age distributions (Hannoun *et al.*, 1997; Yeung, 2001; Tian *et al.*, 2008). Zhang *et al.* (2014) has shown, by means of Computational Fluid Dynamics (CFD) modelling water age for different shapes, that square tank design contributes to the formation of dead zones and increased water age in the corners of SRs, while the circular and rectangular design with higher length to width ratio are better at promoting water mixing.

A storage tank also comprises a complex pipework system which has to include different fundamental components: inlets, outlets, overflow, drainage system. All pipes are provided with valves in order to regulate flows, with exception of the overflow or drainage systems. Often a reservoir by-pass system is put into place in case for single-compartment SRs in the case that it has to be temporarily taken out of service (Brandt *et al.*, 2017). The inlet and outlet piping arrangements also have a particular impact on water mixing, and O'Neill *et al.* (2018) have shown that one of the most used and efficient configurations is to place inlet and outlet at opposite ends of the tank.

2.2.3 Material

Building materials and shape of a SR are chosen in order to provide storage resistant in time, to guarantee high water quality, to prevent water leakage and generally to create resilient infrastructures. The choice of materials largely depend on costs and availability, but also on the topography and geology of the area. Column and arch infrastructures in masonry were very common till the last Century; however, as bricks are more frequently subject to differential displacements, this material is now in disuse due to the possible formation of cracks leading to water quality degradation. Masonry is leaving place to reinforced concrete, often prestressed, as the most popular choice of material, with flat rather than vaulted ceilings. Reinforced concrete SRs are the most common and can be either jointed or monolithic. The latter are generally more economic where the ground is able to support the load without the risk of differential settlements. All SR joints and air vents should also be correctly protected by using waterproof membranes, sealants and coatings, and by using meshes to prevent ingress of small animals and insects which constitute a source of bacteriological contamination. Other materials include precast concrete panels, which are mostly used for industrial tanks and containers, Glass Reinforced Plastic (GRP) and welded steel plates, which are more common for oil storage (Brandt *et al.*, 2017). However, these materials are not usually employed in the water industry, as GRP is subject to problems such as absorption and delamination and steel heats easily when exposed to sunlight (**UKWIR2017**). To maintain an ideal water temperature, underground SRs are often built with grass covered roofs, both for thermal insulation and for aesthetic purposes (Fig.2.1) (Forth *et al.*, 2005).

2.3 Service reservoir integrity

There has recently been an increased awareness of the importance of drinking water storage assets, in particular regarding the impact that SRs can have on drinking water deterioration (Brandt *et al.*, 2017). A complete understanding of all the mechanisms which play a role in drinking water deterioration within SRs is problematic due to the

Figure 2.1: Example of a grass covered underground service reservoir in the UK.

many interactions between parameters which make it difficult to isolate specific individual processes (Husband *et al.*, 2010). For this purpose, it is important to underline the need of monitoring water quality at both the inlet and the outlet of SRs. Generally water quality is controlled at the outlet of storage facilities; however, measuring relevant parameters (*e.g.* bacteria concentration) also at the inlet, allows to understand the responses of the system to eventual changes in water quality as it transitions through the tanks. This approach to water quality control can help to determine if a failure is due to a contamination event upstream or whether the SR is responsible for low water quality, consequently defining when to intervene to inspect and clean the infrastructure (Fig.2.2a). Doronina *et al.* (2020) highlights that understanding the response mechanism of water to contaminant ingress in SRs can also be useful to predict the time lag between inlet and outlet bacteria concentration peaks, suggesting how much time is available for interventions to prevent failures downstream in the DWDS. This section aims to describe the main factors and root causes of failures at SRs, and a summary of the main findings is reported in Table 2.1.

2.3.1 Design and operation

The impact that design and operation characteristics such as age, shape and materials, can have on the formation of dead zones, circulation and water age is well known and documented in different studies (Kennedy *et al.*, 1993; Hope, 2016; O'Neill *et al.*, 2018). Long retention times can cause water stagnation which is often associated with microbial proliferation (Angeloudis *et al.*, 2016); other studies have also found that rectangular shaped SRs have the most effective water mixing and limit stratification problems (Zhang *et al.*, 2014). Furthermore, hydraulic models of contamination entry in storage facilities, and the resulting contaminant transport in the distribution system, have shown that the amount of population exposed to the contaminant strongly depends on the location of the reservoir within the DWDS, rather than the concentration of the contaminant and the duration of the contamination event (Speight *et al.*, 2010).

2.3.2 Physical

Excessive water age and insufficient turnover are considered critical factors impacting microbiological, chemical and physical degradation of drinking water in SRs (AWWA, 2002; National Research Council, 2006). These problems are exacerbated by long retention times and improper mixing of the stored volumes, as inadequate regulation of inlet and outlet flow rates can contribute to the formation of stagnant regions within the SRs, which promote microbial growth. Integrity issues such as improperly sealed openings, vents and overflows, can also contribute to both biological and chemical contaminant ingress in the infrastructures (AWWA, 2011). Biological contamination often occurs within SRs when their structural integrity is compromised by physical breeches, such as cracks in the external structure, which create potential pathways for contaminant ingress, such as animal and bird wastes or insects (Fig.2.2b) (Brandt *et al.*, 2017).

2.3.3 Chemical

Chemical contamination can occur from both external and internal sources (Gauthier *et al.*, 2001; Vreeburg *et al.*, 2007). Corrosion in particular is an issue which often occurs due to the leaching of substances from internal tank components, such as the coatings of the infrastructure or certain solvents used during maintenance operations, and is linked to material accumulation within storage tanks (Fig.2.2c). Most chemical contaminants, however, are not directly monitored and they are usually detected when consumer complaints regarding aesthetic water quality issues (e.g. taste and odour) arise (AWWA, 2002; National Research Council, 2005; Brandt *et al.*, 2017).

2.3.4 Microbial

Water storage tanks can provide favorable conditions for microbial growth and regrowth due to factors like stagnation, water age, and the presence of nutrients (AWWA, 2002). The accumulation of sediments, organic matter, and biofilms can serve as reservoirs for microorganisms, potentially leading to microbial proliferation and the formation of Disinfection By-Products (DBP) (Fish *et al.*, 2016). Another biological issue related to

DWDS and SRs in particular is nitrification, which has negative impacts on drinking water quality as the increase in nitrite and nitrate levels reduces water alkalinity, dissolved oxygen, and chloramine residuals, thus promoting bacterial regrowth (Fig.2.2d). Microbial water quality investigations at SRs and WTW usually require longer times and greater investments respect to monitoring water quality at the consumers' taps; however, due to their potential impact on great areas in case of contamination events, it is of great importance to monitor the performance of these assets. Storage facilities are particularly critical, and recent studies have shown that bacteriological faliures at SRs are almost twice as frequent as in WTW (Ellis *et al.*, 2018); however, without inlet monitoring of SRs it is impossible to ascertain if these assets were the source of contamination or if it occurred upstream (Doronina *et al.*, 2020).

(a) *Inside of an underground SR.*

(b) *SR top wall leak.*

(c) *Corrosion problem on a SR wall.*

(d) *Biofilm deposits on a SR inlet.*

Figure 2.2: Examples of service reservoir cleaning and the encountered integrity issues.

Typology	Problems	Causes	Assessment
Design and operation	– physical degradation – poor water mixing – long residence times – external contamination	– infrastructure design – construction flaws – ineffective maintenance – loss of information	Review of original designs and as built information. Evaluation of inspection records.
Physical	– formation of breeches – leakages and loss of volume – dead zones – sediment accumulation	– age of the infrastructure – poor water mixing – climatic conditions – ineffective maintenance	Monitoring flow and levels, turbidity, conductivity. Carrying out routine inspections. Early detection of joint failures.
Chemical	– depletion of disinfectant – external contamination – corrosion – leaching of components – DBP formation	– long residence times – improperly sealed openings – use of solvents for reparations – water temperature	Monitoring disinfectant and coagulant residuals, DBP concentrations.
Microbiological	– pathogen contamination – biofilm formation – nitrification	– long residence times – external contamination – water temperature – poor water mixing – low disinfectant residuals	Microbial water quality monitoring.

Table 2.1: Summary of the main issues related to service reservoir performance (Letterman, 1951; AWWA, 2002; AWWA, 2011; National Research Council, 2005; National Research Council, 2006; Speight *et al.*, 2010; Hope, 2016; Brandt *et al.*, 2017).

2.4 Drinking water quality

Drinking water quality can deteriorate in its journey through DWDS, primarily as a consequence of its interactions with the components of the network, which can trigger physical, chemical and biological changes in the water (Mounce *et al.*, 2016; Blokker *et al.*, 2016). A wide breadth of factors can negatively impact water quality within DWDS, causing a variety of customer complaints. Consequently, in order to keep providing safe drinking water, it is of fundamental importance for water utilities to monitor the factors which can affect water quality and to efficiently manage the water supply infrastructures (Husband *et al.*, 2010).

2.4.1 Regulatory framework

There are different legal instruments that regulate the quality of drinking water supplies at an international and national level; these monitor and control a variety of parameters such as the presence of micro-organisms, chemical substances such as pesticides and metals, and the general aesthetic appearance of drinking water. The most important documents in use by the Drinking Water Inspectorate (DWI), the independent regulator formed in 1990 to ensure that water companies in England and Wales provide safe drinking water, are the following (DWI, 2019):

- Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption (European Drinking Water Directive);
- The Water Industry Act (1991);
- The Water Act (2003);
- The Water Supply (Water Quality) Regulations (2016);
- World Health Organisation Guidelines for Drinking-Water Quality (2017).

The World Health Organisation (WHO) suggests limits for a variety of chemical and biological parameters, as well as providing guidelines for monitoring water supplies by introducing *Water Safety Plans*; these plans provide system assessments, define effective operational monitoring strategies to identify and control risks, and describe the management and communication actions to be taken during both normal operation and failures. Many countries worldwide have adopted the *WHO Guidelines for Drinking Water Quality* as ground rules for setting their national legal standards (*Drinking Water* 2019).

Current practice in the UK is to follow the *EC Drinking Water Directive*, who's requirements have been consequently implemented in the *Water Supply (Water Quality) Regulations 2016*. The latter defines water supply zones and the wholesomeness of drinking water, details the provisions for the monitoring of water supplies and water treatment, introduces drinking water protected areas and defines the role of the authorities in relation to drinking water quality (The National Archives, 2016). These regulations apply to water suppliers which are based in England, whilst the *Water Supply (Water Quality) Regulations 2018* apply in Wales (DWI, 2017). With regards in particular to SRs, the regulations define these infrastructures as:

> (...) any structure, other than a structure at a treatment works, in which a reserve of water that has been treated with a view to complying with the requirements of regulation 4 is contained and stored for the purpose of meeting a variable demand for the supply of water;

where the referred regulation describes the details of the hydraulic connections of the compartments comprising the structure in order to be treated as a SR.

2.4.2 Physical parameters

There is a wide range of parameters which can be used to describe drinking water quality; these include both direct and indirect parameters. Whilst the first provide direct measurements of water properties, the latter do not directly describe a specific aspect of water quality, but are often useful to generate understanding of how water changes and deteriorates travelling through DWDS (Brandt *et al.*, 2017). Due to the complexity of these systems, there is a lack of understanding regarding which parameters should be monitored to generate the most functional information to manage DWDS. This is true in particular for SRs, where a number of physical parameters, such as levels and flow rates, are monitored. Furthermore, physical parameters are generally easier and less expensive to monitor respect to chemical and microbial parameters, which indicate the presence and concentration of pathogens in water (Banna *et al.*, 2014).

Flow rates

Flow rates within a DWDS are particularly important to regulating and optimising the network, and time and space varying flow rates are one of the many characteristics which contribute to the complexity of these systems. The increasing world population is posing a strain on the availability of natural resources, hence reducing leakage has become a priority for most water companies (Cheung *et al.*, 2010). Flow rates are measured to perform mass balances in District Metered Areas (DMAs), which play a crucial role in understanding and managing water distribution systems (Alvisi *et al.*, 2014). By quantifying the inflows and outflows within a DMA, mass balances provide insights into water losses, identify areas of leakage, and help optimize water management strategies . Night line analysis, a method that involves monitoring water flow and pressure patterns during low-demand periods, can complement mass balances by pinpointing potential leaks or anomalies in specific sections of the distribution network, enabling targeted intervention and improved water efficiency (Cheung *et al.*, 2010). Several applications estimate real losses in DWDS by implementing minimum night flow analysis on DMAs, that is the lowest inflow rate usually reported at night time when most consumers are inactive; however, this approach is limited to the distribution network and is not yet applied to SRs. In intermittent supply networks this analysis is complicated by the fact that water will keep flowing into the storage tanks of the system even if customers are inactive, therefore the minimum night flow can occur at any time (Al-Washali *et al.*, 2018). Furthermore, flow rates and fluctuating hydraulic conditions, have consequences on both chemical and microbial water quality. For example, Prest *et al.* (2021) have shown that flow dynamics impact both turbidity and particle counts.

Flow rates in pipes are also related to the occurrence of pressure transients, which in presence of leaks can result in pollutant contaminated groundwater entering the pipes (Fox *et al.*, 2016). Montoya-Pachongo *et al.* (2016) have shown by means of CFD modelling, that flow rates and water levels in SRs also have an effect on mixing conditions and the formation of stagnant zones. While understanding how water flows through the tanks and impacts water age and water quality is one of the challenges identified by Dix *et al.* (2019) to improve water storage management, there is scarce literature regarding how to assess SR hydraulic performance. Describing system performance in terms of mass balances has proved to be valuable when studying larger scale hydrological models of reservoirs (Arnold *et al.*, 2020; Song *et al.*, 2022), but this approach has not yet been applied to DWDS infrastructures such as SRs.

Water age

Increased water age is a known factor which leads to the degradation of drinking water quality, and has a variety of impacts ranging from aesthetic issues such as poor taste and odour, to more serious consequences such as increasing the formation of DBP and higher microbial loads (USEPA, 2002; National Research Council, 2005). While longer residence times indicate insufficient mixing in storage tanks, leading to stagnation and the formation of dead zones, Zlatanović *et al.* (2017) have shown that water can stagnate also within pipework for several weeks before consumption, in particular during the warmer seasons. The health impacts of water age are mostly related to the formation of DBP, which is more likely to occur in stagnant waters where the disinfection residuals have already been depleted (Speight *et al.*, 2010).

Water age in distribution systems can lead to stratification, resulting in distinct layers with variations in temperature, disinfectant concentration, and microbial activity. This stratification poses challenges to water quality, including depleted disinfection residuals, biofilm growth, microbial regrowth, and increased risks of waterborne pathogens (LeChevallier *et al.*, 1991; Fisher *et al.*, 2009). While Machell *et al.* (2014) have found that water age does not have strong correlations with other water quality parameters, as water has more chances to deteriorate and be contaminated the longer it remains in DWDS, it is a useful indirect indicator of water quality (Blokker *et al.*, 2016). Zhang *et al.* (2011) have introduced the concept of mean water age within SRs as a quantitative indicator for water quality; however, this application was limited to modelling chlorine residence times, and has not been used to gain further insight on SR hydraulic performance.

Temperature

Water temperature has a widely recognised impact on water chemistry and microbiology (LeChevallier *et al.*, 1996; AWWA, 2002). Elevated water temperatures can effect health and sanitation; in particular, World Health Organization (2017) recommend that water be maintained below $20°C$ to reduce the risks associated to Legionella contamination. Water quality deterioration is known to correlate with higher temperatures (Agudelo-Vera *et al.*, 2020); for example, Blokker *et al.* (2016) have shown that water with an higher temperature has more potential to dissolve material, contributing to increased conductivity and turbidity. On the other hand, the concentration of disinfection residuals is inversely proportional to water temperature, resulting in an increased likelihood of DBP formation (AWWA, 2002; Blokker *et al.*, 2016). Within SRs, the impact of water temperature is particularly relevant during the warmer seasons, as higher temperatures can produce density gradients, leading to stratification problems (Mahmood *et al.*, 2005). This is especially important in water towers compared to buried storage tanks, due to the inherent characteristics of water towers, which are more exposed to environmental conditions such as direct sunlight and varying weather patterns (DWI, 2022).

Conductivity

Conductivity is a measure of the ability of water to conduct electricity, it indicates the amount of ionic salts and changes with the concentration of inorganic dissolved solids. For these reasons it is known to be a reliable indicator for real-time monitoring of changes in drinking water quality, with different sensors available on the market measuring this parameter (Banna *et al.*, 2014). Besmer *et al.* (2016) have suggested that measuring proxy variables such as conductivity, turbidity or pH is easier and economically more convenient than conducting microbiological analysis of discrete samples, to which these parameters have a good correlation.

2.4.3 Chemical parameters

Chlorine

There are several types of disinfectants which are used in the water industry either singularly or in combination; however, due to its availability and low cost, chlorine is the most vastly used disinfectant in DWDS across the world (*Drinking Water* 2019; Thompson *et al.*, 2007). Chlorine can be dosed into DWDS in different forms, with the most commonly used being calcium hypochlorites (*i.e.* solid state) as the liquid and gas states have a higher risk of leakage from storage facilities. Furthermore, chlorine is one of the least reactive oxidants, therefore problems such as the formation of DBP and corrosion of metallic components are limited with respect to other disinfectants (AWWA, 2011).

While water companies need to maintain a disinfectant residual throughout the whole system, for health reasons and to avoid customer complaints of poor taste and odour, it is important to keep the levels of chlorine concentration under $0.6\,mg/l$ (Thompson *et al.*, 2007). Banna *et al.* (2014) have shown that excessively elevated concentrations of chlorine in DWDS are highly dangerous for humans, causing skin irritations and lung damage; therefore, in order to inform how much disinfectant is necessary to maintain the correct protection from organic content and microbes, it is essential to understand how chlorine decays differently in different parts of the distribution network (Fisher *et al.*, 2009; Speight *et al.*, 2019). Many studies in literature have demonstrated that the rate of chlorine decay is directly proportional to higher temperatures, almost doubling for an increase of $5°C$ (Speight *et al.*, 2015). Chlorine decay models describe the pipe wall reactions, and are usually based on pipe characteristics such as diameters, lengths, age and materials. Natural Organic Matter (NOM) is one of the principal components which deplete chlorine concentrations in water, therefore, understanding NOM levels can inform operation and maintenance of DWDS (Fish *et al.*, 2018). Higher chlorine concentrations are also known to impact biofilm composition and structure, and contribute to its mobilisation, causing greater discolouration (Fish *et al.*, 2020). Most studies on chlorine decay in SRs are focused on CFD simulations of chlorine concentrations (Dix *et al.*, 2019), and there is little evidence of collecting real-world chlorine data at SRs to understand how storage impacts disinfectant depletion. Doronina *et al.* (2020) has shown that to determine the exact location of chlorine decay within DWDS, whether within the trunk mains or the storage tanks, it is necessary to carry out inlet monitoring of SRs; however, there are currently no requirements for water companies to perfom this type of monitoring.

Turbidity

Turbidity is a parameter indicating how clear drinking water is, and it is most commonly used as an indicator of discolouration. Drinking water quality guidelines suggest that potable water should measure less than 1 Nephelometric Turbidity Unit (NTU); however, under the current regulations, water companies are allowed up to 4 NTU if there is evidence that turbidity is not interfering with the standard operational regimes (DWI, 2019). A high turbidity measurement is a common measure of particle mobilisation within the network (Prest *et al.*, 2021). Discoloured water is mainly caused by the presence of suspended or colloidal particles in water and it is known to be associated with taste and odour complaints from consumers, as well as posing health risks due to the transport of nutrients for microbial growth in DWDS. Coliforms can be embedded in suspended solid particles (LeChevallier *et al.*, 1981; Husband *et al.*, 2016). Discolouration events occur when materials accumulated at the pipe walls during periods of lower hydraulic flow rates, such as iron and manganese deposits or biofilm, are mobilised following an increase in flow rates (Fish *et al.*, 2016). The knowledge of the relationship between hydraulic conditions and turbidity has contributed to a better understanding of discolouration events and improved the management of DWDS; in particular, Boxall *et al.* (2005) have demonstrated the value of controlled flushing of pipes to remove accumulated material.

pH

Water alkalinity is one of the most important factors determining drinking water quality, as most chemical processes are largely dependent on pH levels. It is involved in drinking water treatment as part of the coagulation processes to remove suspended particles and organic matter, and measuring pH in DWDS ensures that the treated water is safe for consumers and non-corrosive or aggressive for the network system (Brandt *et al.*, 2017). For example, Knowles *et al.* (2015) have shown that in water with low alkalinity there are greater concentrations of residuals of iron and aluminium from coagulation processes, which are known to contribute to lead release in the network. This parameter is particularly useful for lead corrosion control, and measuring pH has proven to be a useful surrogate to monitor water alkalinity, hence contributing to mitigate water quality degradation and controlling the corrosive potential of drinking water (Zraick *et al.*, 2019). On the other hand, higher pH levels are often linked to low disinfection efficiency,

2.4.4 Microbiological parameters

Biological contamination is one of the major health risks related to drinking water quality, and in order to guarantee that water complies with regulatory standards, water utilities need to perform effective monitoring of microbial loads. The presence of hazardous pathogens that can be found in drinking water include both faecal and non-faecal bacteria (e.g. *E. coli* and *Legionella* respectively), fungi, viruses and protozoa; exposure to these pathogens can provoke serious waterborne infections in humans (*Drinking Water* 2019; Brandt *et al.*, 2017). The microbiological body within DWDS consists of both planktonic state cells, microorganisms suspended in the bulk water, and consortia of microbes and pathogens which attach to pipe walls and other surfaces in biofilm consortia (Lechevallier *et al.*, 1988; Flemming *et al.*, 2010; Fish *et al.*, 2015). Biofilm formation and accumulation in DWDS cause different issues such as bio-fouling or enhancing pipe corrosion, and their activity impacts the quality of drinking water; consequently, managing biofilm regrowth is a crucial activity for water companies (Flemming *et al.*, 2016; Douterelo *et al.*, 2016). However, in SRs, bulk water water microbiology is the dominant factor in water quality as compared to pipes there is a much larger volume to service area (Wingender *et al.*, 2011).

Traditional microbial monitoring consists in laboratory analysis of discrete samples; however, there are often delays between sampling and the results obtained from the analyses, meaning that process operators are not able to immediately respond to variations of bacteria concentrations. Furthermore, culture dependent methods such as Heterotrophic Plate Counts (HPC) represent less than 1% of the microbial population in water and consequently real levels of contamination might be underestimated (Kooij, 2003; Berry *et al.*, 2006). Coliform bacteria such as E.coli, which are associated with both human and animal faeces, are a useful indicator for faecal contamination of drinking water; however, these can become part of the biofilm communities, hence making difficult their detection and increasing the risk that these be mobilised and transported downstream (Camper *et al.*, 1998). Flow Cytometry (FC) is a powerful analytical technique used in drinking water monitoring to rapidly and accurately assess microbial populations (Safford *et al.*, 2019). It provides real-time information on cell counts, viability, and size distribution of microorganisms, aiding in the detection of potentially harmful pathogens and the monitoring of overall water quality. FC enables a more comprehensive understanding of microbial dynamics, helping water utilities make informed decisions regarding disinfection strategies and the effectiveness of water treatment processes (Gillespie *et al.*, 2014; Besmer *et al.*, 2016).

While an increased awareness of microbial pathogens in drinking water can reduce outbreaks and transmission of waterborne diseases, these parameters are often difficult to monitor and require expensive laboratory testing; however, the past decades have seen an increase in the development of real-time bacterial instruments, allowing a better management of microbial risks in DWDS.

2.5 Summary and research gaps

SRs are a critical component of DWDS, as they have not only the essential function of balancing water demand and supply in the system, but also significantly impact drinking water quality. In the same manner that DWDS as a whole are characterised by a large variety of processes, storage tanks are equally complex infrastructures where many interactions occur between the hydraulics and the physical, chemical and microbiological processes that have a relevant impact on SR integrity (Tab. 2.1).

A limited understanding of how the hydraulic processes within SRs impact their functioning and water quality is currently preventing water companies from carrying out an effective preventative maintenance of these infrastructures. The consequence of this is that numerous SR issues are frequently addressed in a reactive manner, an approach that often leads to prolonged water quality issues before any remedial action is taken, as well as increased maintenance costs. The literature review hereby presented has highlighted that despite the knowledge that SRs are vulnerable to a wide breadth of issues, the problems related to these specific infrastructures are very often overlooked in favour of studies regarding other parts of DWDS, in particular WTW and pipe networks. Most recent research focused specifically on SRs investigates the hydraulic aspects regarding water mixing and stratification within the tanks, with a numerical approach using CFD modelling, that is not always representative of real systems. Moreover, the interrelationships between the hydraulic behaviour of SRs and water quality remain unexplored. Despite the importance of the role SRs play in DWDS, it is clear from these considerations that there exists a notable lack of information on SRs, and that research opportunities which could improve efficient SR performance assessment are being missed. Due to these gaps in knowledge in assessing SR overall performance, water companies face increasing challenges in identifying efficient methods for maintaining these infrastructures, as there is a lack of information to identify integrity issues and their impacts on water quality.

Chapter 3

Aims and objectives

Aims

The scope of this study is to investigate how to move beyond time-based interventions at SRs and towards preventative maintenance of these critical infrastructures, with particular focus on the development of a metric to assess SR hydraulic performance and determining its impacts on water quality. To achieve this aim, this study seeks to meet the following objectives.

Research objectives

1. To identify how routinely monitored parameters at SRs can be utilised to enhance understanding of asset performance.

2. To develop a metric that assesses SR hydraulic performance and its relationship with water quality.

3. To evaluate the potential of the developed metric to support proactive maintenance of SRs.

Chapter 4

Methodology

4.1 Overview

While there are significant knowledge gaps regarding the assessment of SR performance and their management, the currently available literature (see Chapter 2) provides some suggestions on where to direct and focus new research to address these issues. There is potentially great scientific value in investigating the hydraulic performance of SRs by means of analysing flow rates and mass balances within storage tanks, as is, for example, already being applied to DMA assessment. Linking these results to eventual variations in drinking water quality will ultimately contribute to a deeper understanding of the processes involved in SR operation.

The overarching goal of this research is to develop new metrics to assess SR performance and their impact on water quality building upon historic data and using parameters already monitored at SRs. To achieve the research objectives explained in Chapter 3, a novel methodology has been developed to explore if SR hydraulics, residence times and water quality are inter-related and whether combining data sources such as hydraulic and water quality information to perform data analysis can reveal more information regarding SR performance. This Chapter presents a detailed account of the methodology employed in this study, outlining the data acquisition methods, the data analysis processes and the criteria used to select field sites and the corresponding network details. By adopting this methodology, the final goal is to provide a comprehensive understanding of the inter-relationships between these factors, thus contributing to inform more effective strategies for water management and control.

4.2 Data analysis

4.2.1 Single-parameter analysis

The initial concept to be investigated is that examining level variations could yield additional insights beyond solely observing daily patterns, which only reflect demand fluctuations. Therefore, the focus was primarily on detecting notable fluctuations in levels and flow rather than their absolute values, as level and flow variations are a measure of the rate at which changes occur within SRs. To comprehend the potential value that can be derived from the most basic, and readily available, hydraulic data collected at SRs, the initial phase involves a separate analysis of the level and flow measurements.

To ascertain with greater precision the potential seasonal impact on level variations, this study employed three-month windows selected to align with UK seasonal changes, rather than the more commonly used six-month time frames in existing literature on water parameter time series. In accordance with the aim of uncovering any potential trends in the data, to effectively reveal any variability in SR behaviour, the level and flow time series were subsequently subjected to linear de-trending by backward differencing (4.1):

$$\delta h = h|_t - h|_{t-1} \tag{4.1a}$$

$$\delta Q = Q|_t - Q|_{t-1} \tag{4.1b}$$

where t is time, h is the level and Q is the flow.

4.2.2 Multi-parameter analysis

The introduction of a multi-parameter analysis represents an advancement from the previous single-parameter approach. By integrating level and flow data, an opportunity emerges to reveal deeper insight on SR hydraulic performance and how this is linked to water quality issues.

Storage tanks are typically assessed by calculating the volumes based on SR volume per metre depth and level data, while the flow rates measured at the inlet and outlet of the tanks are used to verify standard SR operation. The proposed analysis method suggests using both data sources to compute mass balances and daily retention times. Mass balance models and daily residence times calculations both use level and flow data, however the outputs are different: the first provides information on leakage or ingress of water, the second on water age and water quality deterioration.

Mass balances

The continuity equation (4.2a) in differential form is derived from the conservation of mass and states that all flow rates into a control volume are equal to all flow rates out of the control volume plus the rate of change of the mass within. For a SR with constant plan area, this translates into the equivalence between the difference of inlet and outlet flow rates and the rate of change of the levels multiplied by the area (4.2b):

$$Q_{in} = Q_{out} + \frac{dV}{dt} \tag{4.2a}$$

$$Q_{in} - Q_{out} = A \cdot \frac{dh}{dt} \tag{4.2b}$$

where V is the volume and A is the plan area.

In finite terms (4.3):

$$\delta V(Q)|_t = (Q_{in} - Q_{out})\,|_t \cdot \delta t \tag{4.3a}$$

$$\delta V(h)|_t = A \cdot \delta h \tag{4.3b}$$

where δt is the fixed time step. This hydraulic metric is calculated over a time interval of 15 minutes, in accordance with the temporal resolution of the collected data.

In an ideal and perfectly sealed control volume the rate of change in volume calculated using the levels and the rate of change in volume calculated using the flows should be equal, hence their difference should be null; in reality a residual volume ΔV is always present and has been defined in (4.4). The sign and magnitude of the residual volume provide information on how the SR is performing:

$$\Delta V|_t = \delta V(Q)|_t - \delta V(h)|_t = \begin{cases} > 0 & ingress \\ = 0 & balanced \\ < 0 & leakage \end{cases} \tag{4.4}$$

Residence times

The theory explored herein is that by calculating daily retention times, it is possible to gain insights into the performance of a SR and determine whether it is operating within the recommended ranges specified in its operating manual, according to which recommended retention times typically range between $24 - 48$ hours. To determine daily residence times, the method proposes to calculate the average volume of water within the SR (4.5a) and the total average outlet flow (4.5b) using level and flow data, respectively. As this project focuses on exploiting standard data that water companies collect (*i.e.* levels, flow, regulatory sampling data), there was insufficient information to model more complex situations; therefore, these calculations were performed under the assumption that the SR is well-mixed, that is, the water is uniformly blended throughout the tank. The average daily retention time R is consequently defined as follows (4.5c):

$$\overline{V} = 1/n \sum_{i=1}^{n} V_n \tag{4.5a}$$

$$\overline{Q}out = 1/n \sum_{i=1}^{n} Q_{out} \tag{4.5b}$$

$$R = \frac{\overline{V}}{\overline{Q}_{out}} \tag{4.5c}$$

where n is the number of timesteps, and $\overline{V}$ and $\overline{Q}_{out}$ represent the average volume and outflow in a period of 24 hours.

To understand when water age might become an issue, a value was chosen to find the retention times R above a fixed threshold. Considering that SRs are usually designed to provide water for at least two days in case of interruption of supply from the WTW, a value of 48 hours was chosen as an upper bound limit. These calculations are crucial in detecting problematic retention times, which may necessitate further investigation into other water quality parameters such as chlorine, HPCs and FCs.

4.2.3 Water quality analysis

The scope of the final stage of the project was to use discrete sampling information and chlorine time series to draw conclusions on SR water quality.

Firstly, to perform SR water quality site ranking based on different sources of information, 3-day HPC and FC from sites belonging to the same distribution network were employed. This included analysing the samples from the upstream WTW to verify if the water quality changes throughout the DWDS. One of the limitations of discrete data analysis is that the samples collected at SR outlets are mostly non-homogeneously distributed in time, which can result in the inability of the data to represent all phenomena happening within the SR, as long periods of time can elapse between sample collection. To overcome this problem, the data points sampled over at least a 2-year period for all sites where both regulatory HPC and bench-top FC testing of discrete samples were available, have been averaged. Comparisons between SR water quality were made with the caveat that the number of samples taken across the different sites were of the same size. To allow immediate visual interpretation and ranking of SR water quality, the results were consequently displayed as bar plots.

To verify if low water quality is related to eventual chlorine depletion, the second step involved looking into chlorine regulatory samples and available chlorine time series for the sites with lower SR ranking. This process allowed to track eventual chlorine decay within the storage tanks and throughout the network by calculating the difference of chlorine time series traditionally measured at SR outlet sites with disinfection boosters (4.6):

$$\delta Cl = Cl_{up}|_t - Cl_{down}|_{t+\Delta t} \tag{4.6}$$

where Cl_{up} and Cl_{down} are the chlorine measurements at the outlets of the upstream and downstream SRs along the network, and Δt is the total time lag considering the residence time in both the storage tank and the upstream trunk main. While the first was calculated using the retention time metric (4.5c), when lacking information on the surrounding network the latter was estimated considering the airline distance between the two sites and a velocity of $0.5\,m/s$ in the pipes.

Finally, to understand how the multi-parameter approach (4.2.2) contributes to identifying sites at risk of water quality deterioration, a cross-interpretation of the outcomes from the water quality analysis with the outputs of the daily residence times analysis was performed.

4.3 Required data

The objective of this methodology is to conduct both single and multiple parameter analyses with the aim of improving the maintenance of SR. To accurately reflect SR performance, the key requirement of this combined approach is the use of authentic data obtained from functioning operational systems, which is representative of real-world phenomena related to SRs. To evaluate the efficacy of the proposed metrics, data was gathered from multiple sources in sufficient quantity to facilitate cross-site comparisons. The inclusion of data from diverse sources is necessary to gain a comprehensive understanding of the system, and the analysis of large data volumes can unveil patterns and trends that may not be discernible in smaller datasets. A particularly important role is played by site inspection records, which are used to confirm and validate the results obtained from the data analysis. A variety of data sources were obtained from the project sponsor, creating complex datasets to perform the analyses explained in section4.2. This section describes the details of the different data sources, the parameters which have been chosen for analysis and how these are typically monitored at the SR project sites.

4.3.1 Operation manuals

To develop the proposed mass balance and retention time models, it was necessary to consult operation manuals to obtain and extract all the relevant geometric information, including network details, pipework positioning, capacity and plan area. In addition, operation manuals provided crucial operational information, such as site location, supply area schematics, inlet and outlet control, telemetry and sample point information, and general operating instructions which are crucial for the correct daily functioning of the SR (*e.g.* commissioning procedures, by-pass arrangements, emergency shut downs). This information was collated across multiple sites to produce a digital repository with all the SR information needed for the project.

4.3.2 Historical data

To carry out the single-parameter and multiple-parameter data analysis processes (4.2), both historical time series and discrete sampling of various parameters were obtained for this project. It was deemed particularly important to guarantee that this data was collected over periods of time long enough to appreciate eventual impacts from external factors such as seasonality, maintenance interventions and operational changes. For these reasons, at least 2-year long time series have been requested and were processed for historical data analysis. This paragraph explains the details of how these parameters are monitored at the project sites.

Levels

Water levels are commonly measured using either mechanical or electronic sensors. Mechanical level sensors employ a float mechanism that moves with the water level and is connected to a gauge to indicate the level. In contrast, electronic level sensors use pressure, ultrasonic, or radar, to measure the distance between the sensor and the water surface. Reservoir alarm levels are set for the percentage water levels with respect to the overflow level, fixing four different thresholds of alert which are usually the same across the different sites (tab.4.1).

Table 4.1: Service reservoir level alerts according to site operating manuals.

Very high	98%
High	95%
Low	50%
Very low	30%

Flow rates

SR inlets and outlets are typically equipped with flowmeters, that can be electromagnetic, ultrasonic or turbine flowmeters, that continuously monitor the flow rates in and out of the tanks, allowing operators to adjust the inflow and outflow rates as necessary to maintain a stable and reliable water supply. When a SR has more than one outlet, which is often the case for larger storage tanks which serve separate portions of the DWDS, the flow rates are usually measured on each outlet pipe. The flow meters are monitored by leakage and network technicians and any faults are notified to maintenance staff.

Chlorine continuous monitoring

The level of chlorine in service reservoirs is continuously monitored using chlorine sensors, usually amperometric or colorimetric sensors, to ensure that the required concentration is maintained. Free and total chlorine is usually measured at the outlet of those SRs which include secondary chlorination as part of the network treatment processes. As for the levels, a reservoir alarm level is also fixed for high and low chlorine concentrations, however the thresholds vary between different sites. Frequently used alert limits are $0.75\,mg/l$ and $0.3\,mg/l$ for high and low chlorine residuals respectively.

Discrete sampling data

Regulatory sampling is routinely carried out by water utilities in order to verify that drinking water entering the network is compliant to regulatory standards (section 2.4.1). The samples are collected at outlet sampling lines and analysed in laboratory for the following parameters:

- temperature [$°C$];
- free and total chlorine [$mg\,l^{-1}$];
- 3-day colony counts [ml^{-1}];
- total and confirmed coliforms [$100\,ml^{-1}$].

In addition to the parameters traditionally monitored by regulatory sampling, the historical data which was collected for this project has included discrete samples analysed by means of bench-top FC.

4.3.3 Inspection records

To understand whether changes in hydraulic performance of SRs serve as a useful metric for identifying potential issues with SRs, it was essential to investigate the timing of problem discovery and subsequent remediation efforts. Inspections are typically carried out every $3-5$ years to assess SR overall condition, including roofs, walls, floors, columns, as well as any equipment, pipework, and metallic components. This is information is reported in detailed records which summarise and classify the problems, and include schematic diagrams highlighting the encountered defects. Inspection records were obtained and thoroughly studied for all project sites, and the main information was collated in the created database. This information was crucial in validating the results generated from the data analysis processes, confirming whether the issues could have been identified prior to scheduled maintenance, and if the interventions have been resolutive.

4.3.4 Accuracy and reliability

The telemetry data time series collected for this research have a temporal resolution of one measurement every 15 minutes, while the discrete samples exhibit some temporal irregularities, occasionally featuring extended intervals of up to 4 weeks between sampling events. For the scope of this project, a prima facie approach has been adopted, where the collected data is considered without an in-depth examination of potential sources of error, such as bias, noise, or incomplete data. This approach is deemed appropriate in this context, as the main aim of the project is to work with standard water company data.

4.4 Project field sites

In order to be able to draw conclusions from the analysis results and make comparisons between different situations and conditions, at least $3-4$ sites to investigate were deemed necessary for this project. To this end, criteria for site selection were pre-defined before requesting data.

4.4.1 Site selection criteria

The selection of project sites was based on a set of specific criteria:

1. the inclusion of solely post-treatment storage tanks,
2. the availability of complete level and flow time series,
3. the presence of supplementary water quality data such as chlorine, Colony Forming Units (CFU), and FC,
4. the inclusion of both well-performing and problematic sites,
5. the relevance of the selected sites to the water utility sponsor's interests.

4.4.2 Site details

For this project, a selection of eleven SR sites has been made. Table 4.4.2 provides a comprehensive overview of each SR site, including the SR number, primary geometric characteristics, inspection dates, significant issues detected, a summary of all available data and eventual operational details.

Table 4.2: Summary of the SR project sites main characteristics.

Site	Main physical characteristics	Reported issues	Data summary	Additional notes
1	– Construction yr.: 1976 – No. of compartments: 3 – Total capacity: 31297 m^3 – Overflow level: 4 m	– Leaking roof expansion joints – Minor floor degradation – Broken balance valve – Light corrosion	01/2015 – 05/2020: – Levels – Inlet/outlet flow – Outlet chlorine – HPC – FC	Date of inspection 31/10/2019.
2	– Construction yr.: 1985 – No. of compartments: 2 – Total capacity: 3400 m^3 – Overflow level: 3.8 m	– Heavy corrosion – Thick sediment layer – Leaking balance and outlet valves	01/2015 – 05/2020 – Levels – Inlet/outlet flow – CFU – FC	Date of inspection 03/06/2020.
3	– Construction yr.: 1979 – No. of compartments: 2 – Total capacity: 5098 m^3 – Overflow level 3.3 m	– Minor pipe tuberculation – Roof and side wall leaks – Light sealant degradation	01/2015 – 05/2020 – Levels – Inlet/outlet flow – Outlet chlorine – CFU – FC	Date of inspection 07/10/2015. Likely flowmeter sensor failure (5−year long data flatline).
4	– Construction yr. Tank 2-3: 1950 – Construction yr. Tank 1: 1970 – No. of compartments: 3 – Total capacity: 2405 m^3 – Overflow level Tank 1: 2.85 m – Overflow level Tank 2: 3.8 m	– Medium corrosion – Roof and side wall leaks – Leaking joint – Small floor holes	01/2015 – 05/2020 – Levels – Inlet/outlet flow – CFU – FC	Date of inspection Tank 1: 08/07/2015. Date of inspection Tank 2: 15/01/2015. Tank 3 currently disused.

Site	Main physical characteristics	Reported issues	Data summary	Additional notes
5	– Construction yr.: 1950 – No. of compartments: 1 – Total capacity: 4926.5 m^3 – Overflow level: 5.9 m	– Roof and wall joint leaks – Floor joint degradation – Damaged hand rails and ladders	04/2022 – 04/2022 – Levels – Inlet/outlet flow – CFU – FC	Date of inspection 21/12/2021.
6	– Construction yr.: 1994 – No. of compartments: 2 – Total capacity: 3958.2 m^3 – Overflow level: 4 m	– Side wall and joint leak – Minor sediment layer – Heavy corrosion – Passing valves	04/2020 – 04/2022 – Levels – Inlet/outlet flow – Volume	Date of inspection 07/04/2021. Compartment 1 mothballed.
7	– Construction yr.: n/a – No. of compartments: 2 – Total capacity: 1004 m^3 – Overflow level: 3.1 m	– Roof wall joint leaks – Passing valves – Light corrosion	04/2020 – 04/2022 – Levels – Volume	Date of inspection 16/06/2021..
8	– Construction yr.: 1950 – No. of compartments: 2 – Total capacity: 4375 m^3 – Overflow level: 3.5 m	– Light corrosion	04/2022 – 04/2022 – Inlet flow – Levels	Date of inspection 29/01/2019.
9	– Construction yr.: 1943 – No. of compartments: 1 – Total capacity: 645 m^3 – Overflow level: 2.9 m	– Wall cracks with ingress – Pipework surface rust	04/2022 – 04/2022 – Inlet flow – Levels	Date of inspection 16/01/2018. Booster chlorination carried out on site.

Site	Main physical characteristics	Reported issues	Data summary	Additional notes
10	– Construction yr.: 1915 – No. of SRs: 2 – Total capacity: $8043\,m^3$ – Overflow level SR 1 1: $4.2\,m$ – Overflow level SR 2 2: $3.6\,m$	– Roof leaks with ingress – Missing inner lining – Floor sealing decay	04/2022 – 04/2022 – Inlet flow – Inlet/outlet chlorine	Date of inspection 07/07/2011. Chlorine gas system removed February 2021 when commissioning new inlet main.
11	– Construction yr.: 1960 – No. of compartments: 2 – Total capacity: $3513\,m^3$ – Overflow level: $4.6\,m$	– Small areas of missing coating from walls and columns	04/2022 – 04/2022 – Levels	Date of inspection 24/04/2019. Compartment 1 mothballed.

4.5 Data processing

To overcome the difficulties and constraints of interpreting long time series of raw data measurements, which can present great variability and numerous extreme data points which are not representative of real SR performance, a metric was developed to post-process the results obtained from the single and multi-parameter computations. As moving average and moving standard deviations are influenced by the presence of outliers, the Hampel identifier method for outlier detection was chosen to post-process the data. This digital filter is frequently used in environmental time series analysis because of its robustness in detecting and excluding outliers, and is based on identifying outliers as elements more than three local scaled Median Absolute Deviation (MAD) from the local median of a sliding window of fixed length (Liu *et al.*, 2004; Pearson *et al.*, 2016; Berendrecht *et al.*, 2023). To obtain more realistic data, these outliers are consequently replaced using the centre value obtained from the method.

To establish the most apt sliding window upon which to calculate the MAD, three different lengths of 6, 12 and 24 hours were tested. Figure (4.1) shows examples of the results obtained from applying the Hampel filter with various windows to three months of level variations and residual volumes data from one of the project sites. The main purpose of this metric is to identify the general trends and eventual anomalies in SR performance over long periods of time, unaffected by signal variations which do not constitute significant events; therefore, a 12-hour moving window was chosen and applied to all results. This window proved to be efficient in eliminating most data outliers while capturing significant changes in SR behaviour, as it is the period which typically elapses between morning and evening demand peaks in water supply.

After removing the outliers and substituting them with values which are more representative of genuine SR performance, the results of the single and multiple-parameter analyses were still highly variable, making the visual interpretation of results difficult. To overcome this problem a 24-hour moving average was hence applied to level variations and residual volumes, in order to smooth the effect of short temporary changes related to supply and demand fluctuations.

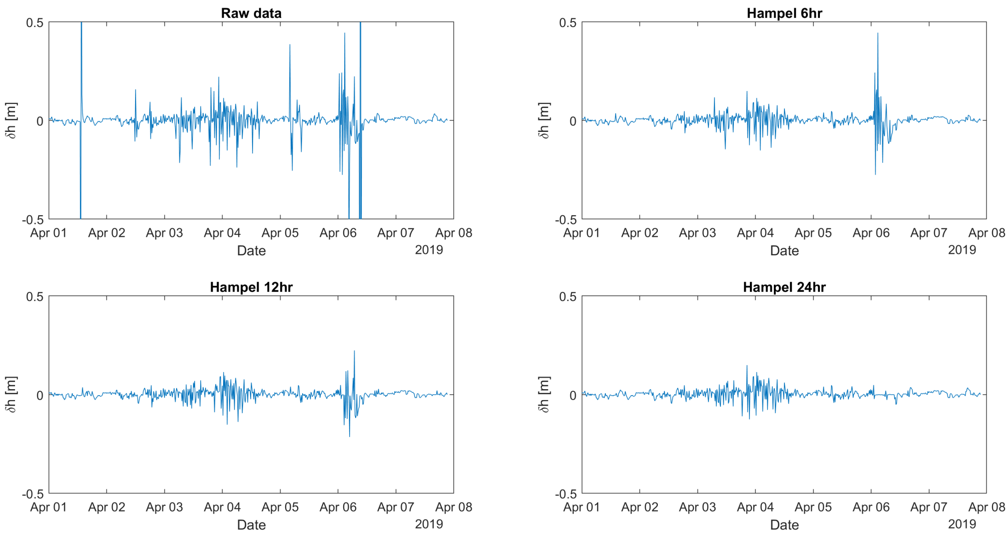


Figure 4.1: Examples of the Hampel outlier identifier using different window lengths on one week of level rate of change for Site 1.

4.6 Preventative maintenance metrics for service reservoirs

The aim of the methods described in this chapter is to fulfill the primary research objective, which is to comprehend the significance of historical data related to parameters conventionally monitored at SRs and how this can be used to achieve better asset maintenance. To achieve this goal, the project has utilized pre-existing datasets of hydraulic parameters such as levels and flow rates, as well as water quality parameters including free and total chlorine concentrations, HPC and FC from discrete sampling and continuous chlorine time series. The flowchart depicted in figure 4.2 delineates the manner in which disparate data sources are integrated to achieve the ultimate objective of advancing SR preventive maintenance. Commencing with levels, which represent the most easily accessible and readily interpretable source of data on network operation, the incorporation of inlet and outlet flow rates facilitates the computation of mass balances and residence times, as explained in section 4.2.2. These produce in turn information on hydraulic performance and water quality. Simultaneously, discrete sampling and chlorine time series analysis supplement the water quality data. The combination of all these components culminates in the guidance of SR preventive maintenance.

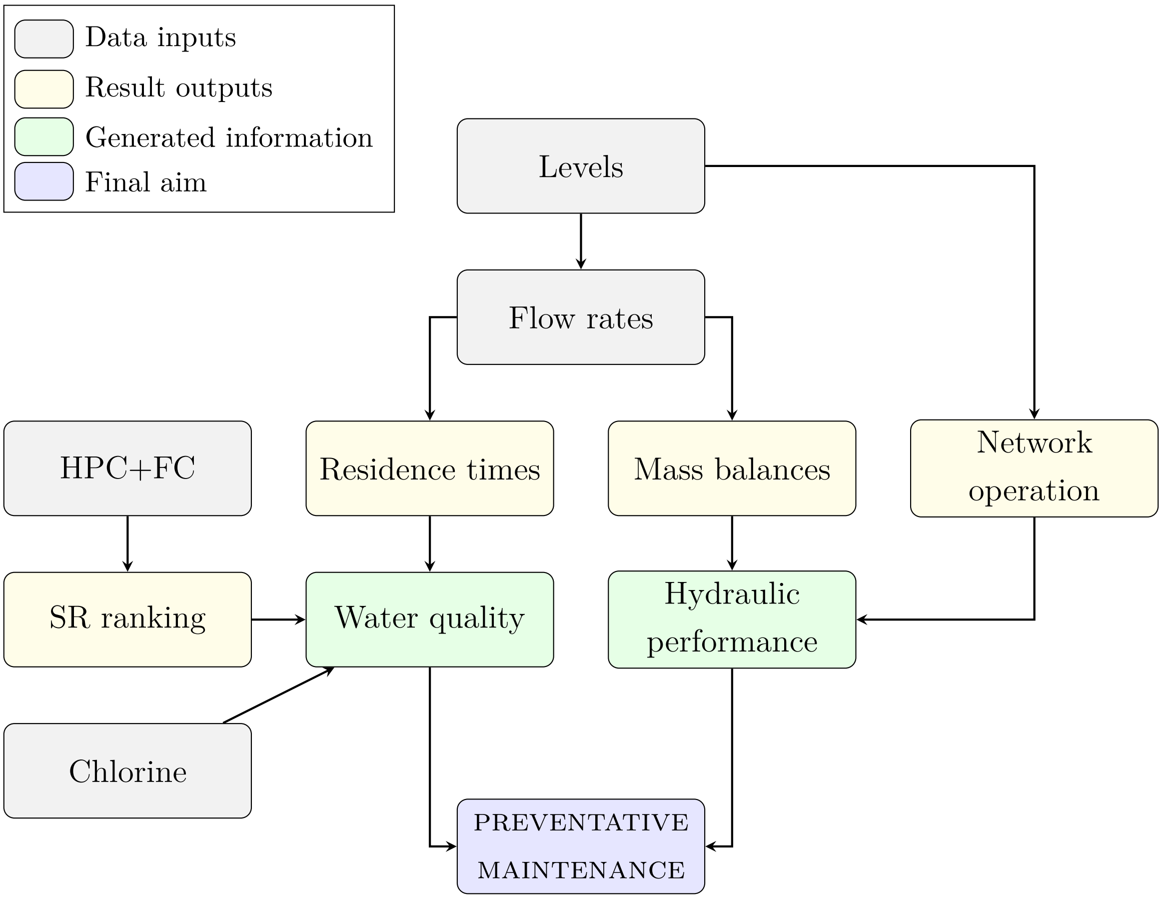


Figure 4.2: Service reservoir preventative maintenance schematic flowchart highlighting the different metrics and their integration.

Chapter 5

Results

This Chapter presents the results of the proposed research method, as described in Chapter 3, which were obtained from analysing the entire SR database consisting of eleven sites summarized in Tab. 4.4.2. The metrics were applied to all project sites and their respective time series datasets. To maintain conciseness, a subset of the results is here presented. This accurate selection focused on highlighting significant observations regarding SR behavior, discernible trends, alterations in temporal patterns, with specific attention to mass balance and retention time outcomes.

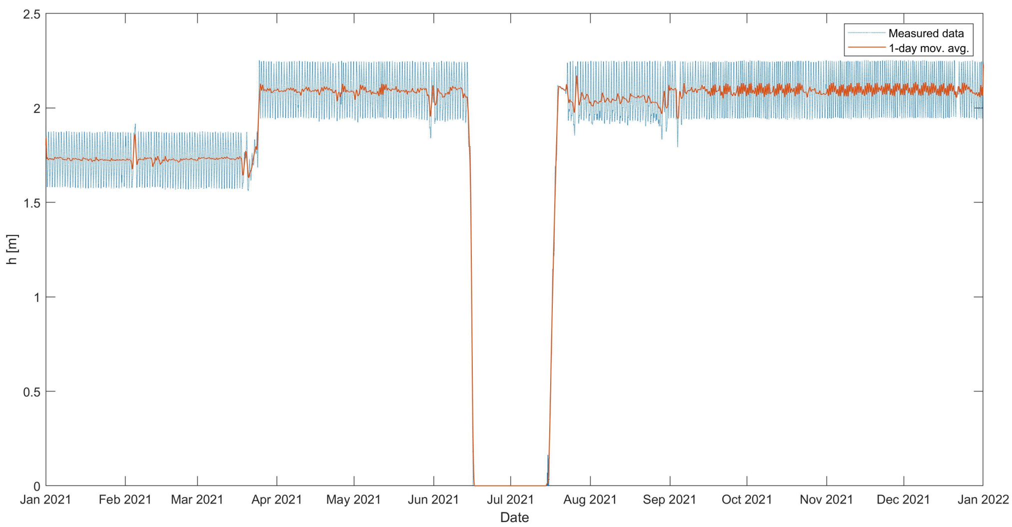
5.1 Service reservoir level and flow analysis

This section examines the results from the single parameter analysis approach (4.2.1). Yearly level plots were employed to show seasonal fluctuations in levels resulting from changes in demand and supply. For example, the plot in Fig. 5.1a shows changes in operational regime, most probably consequence of the decision to keep the tank filled to a higher level from April 2021. Furthermore, time series plots provided valuable information concerning the network's performance, such as Fig. 5.1b which shows a sudden level drop in Site 11 over a few days, followed by a sudden recovery. This event suggests that a burst occurred which was consequently repaired elsewhere on the system; however, to confirm this theory, it would be necessary to find further information on the works conducted in the downstream DWDS. Similarly, analysing the flow time series aided in identifying anomalies in the data, with a year-long flatline observed in the inlet flow data for Site 3, indicating a potential sensor failure (Fig.5.2). However, analysing flow variations did not yield any significant insights into SR behaviour, as demonstrated by Site 9 inlet flow changes (Fig. 5.3).

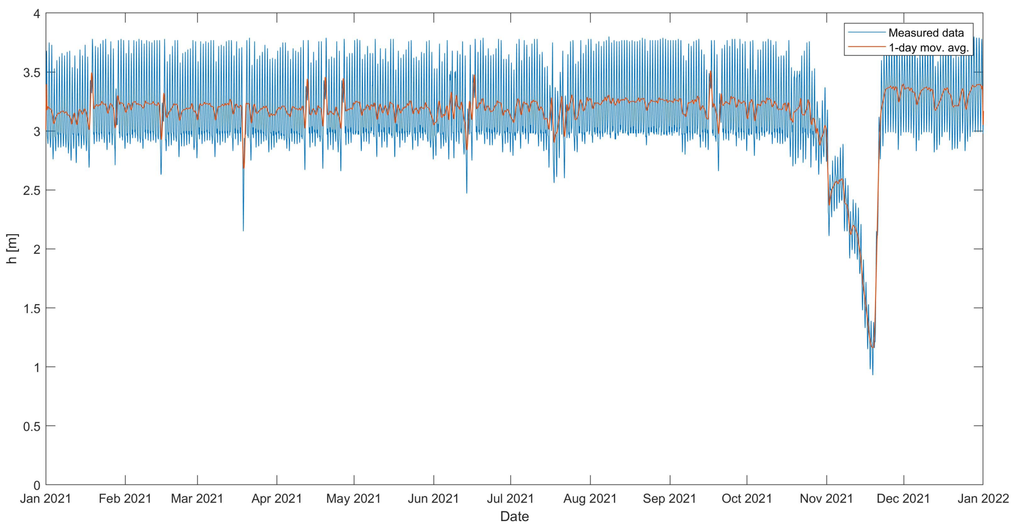
Studying the level rates of change uncovered patterns that were not apparent from simply examining the raw data. Although seasonal variations in Site 1 did not expose any underlying seasonal trends, as evidenced by the constancy of the 1-day moving average across the different seasons (Fig. 5.4), a sudden change was observed in the month of April

2019 and a bigger range of δh values was present from November 2019 onwards. Similar periods of unusual SR behaviour, characterised by more rapid changes in water levels, were found in other project sites, such as Site 8 (Fig. 5.5).

While the collected data was useful in understanding changes in SR operation and identifying operational trends, a deeper understanding of system performance is not achieved by simply looking at the raw data or single parameters, hence no insights into SR maintenance needs are generated.



(a) *Site 7.*



(b) *Site 11.*

Figure 5.1: Level time series examples for two different SR sites.

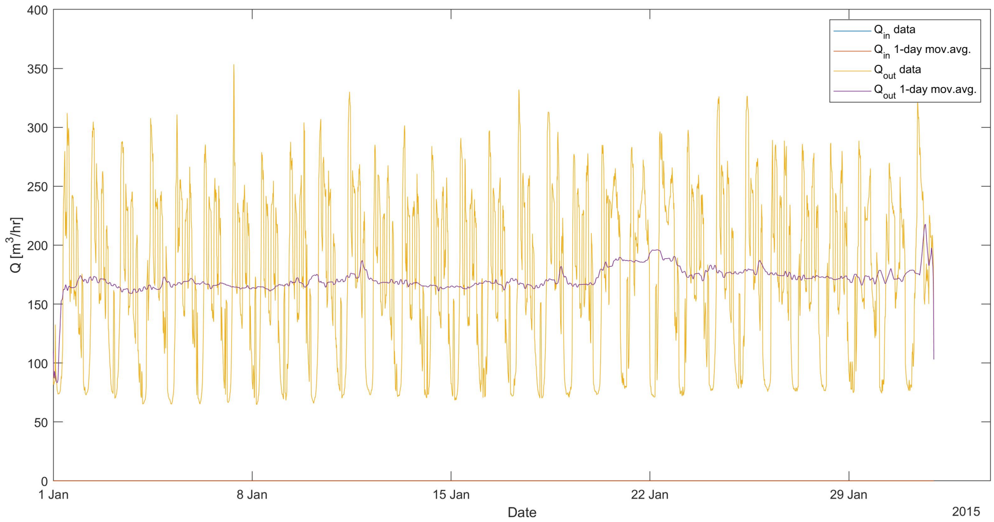


Figure 5.2: Site 3 flow time series.

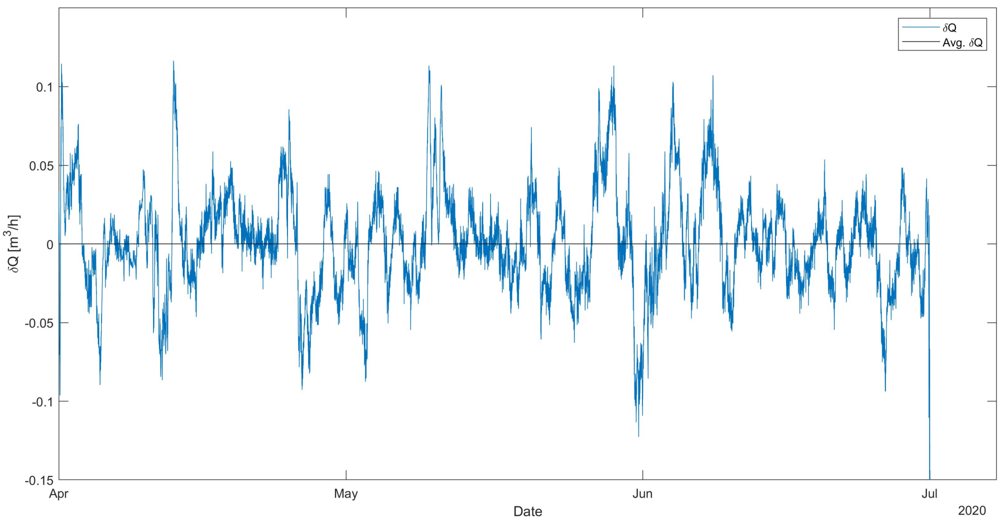


Figure 5.3: Site 9 inlet flow rate of change.

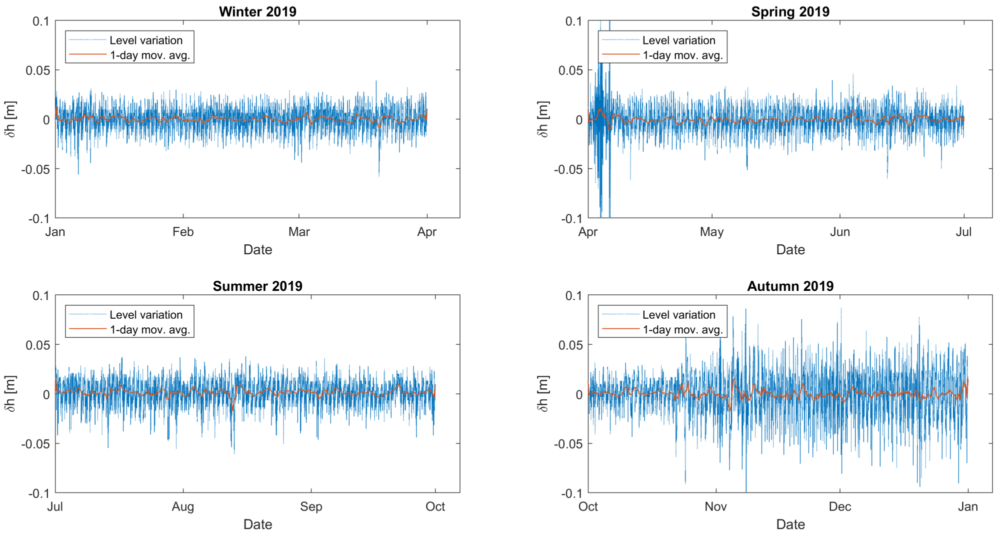


Figure 5.4: Site 1 seasonal levels rate of change.

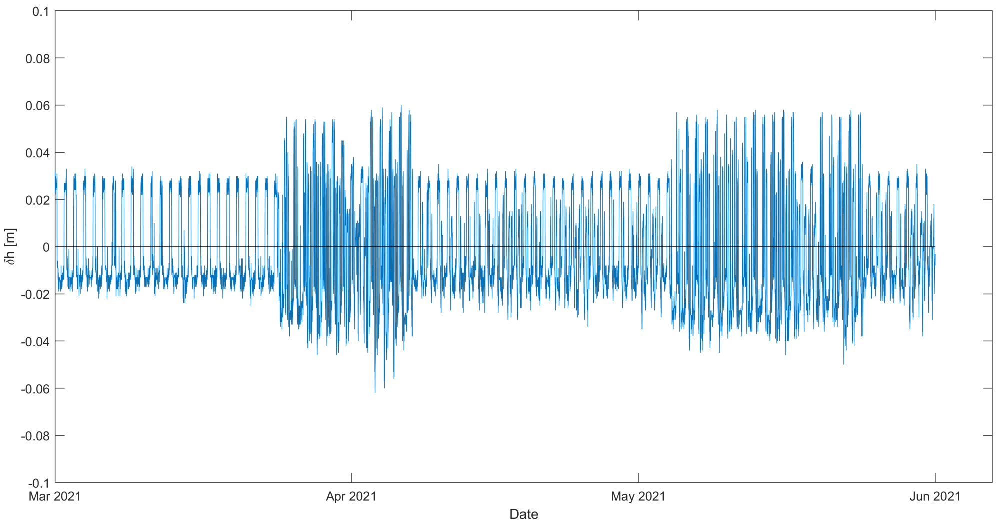


Figure 5.5: Site 8 level rate of change.

5.1.1 Level variations sensitivity analysis and distributions

The plots in Fig. 5.4 and Fig. 5.5 show some promise in revealing deeper insight on SR behaviour, but rely only on human visual interpretation. While this approach is sufficient when investigating a limited amount of sites, it is not feasible for analysing vast amounts of data. In this case a threshold would be needed to flag significant events.

To establish an appropriate threshold for detecting sudden changes in the rate of change of levels within the tanks, sensitivity and distribution analyses were conducted on δh time series, using Site 1 as a case study. The objective was to determine a threshold value that could identify significant changes in water levels while avoiding false alarms triggered by routine fluctuations due to demand and supply. Two distinct approaches were used to achieve this goal. Firstly, to identify a value that could be used across all SRs, a sensitivity analysis was conducted on the level variation time series by fixing three different thresholds of ± 0.05, 0.1, $0.2\,m$, chosen according to visual interpretation of the raw data. Secondly, to identify a site-specific critical level variation, distribution analysis was performed using compressed box plots to better represent eventual peaks in the distribution of level variations. To enable validation checks these analyses were conducted for the year 2019 when inspection and maintenance operations were carried out.

As shown in Fig. 5.6, a threshold of $0.05\,m$ appears to be too low as it highlights numerous data points that are not indicative of significant changes in the water level. Conversely, a threshold of $0.2\,m$ only highlights two data points, which are likely big outliers and not reflective of typical SR behaviour. Therefore, a threshold of $0.1\,m$ is the most effective option for this site and this year. This threshold captures most of the sudden changes also in other years of the time series for Site 1; however, periods of time were observed where a value of $0.1\,m$ resulted in a loss of detail, with more non-relevant δh values being highlighted.

A limitation of using a general fixed value is that it does not take into account eventual site-specific behaviour and characteristics. A distribution analysis was hence performed on the level variation data for each month in the selected year. Figure 5.7 demonstrates that the median water level variation remains constant throughout the year. However, there is a noticeable surge in the number and magnitude of outliers in April 2019, implying that an abrupt event may have occurred during that month. Furthermore, the dispersion of the data increases following the inspection in October 2019, indicating that the interventions have triggered more variable level variations. The majority of outliers fall within the range of $\pm 0.15\,m$, suggesting this is a more reliable threshold value for Site 1. Although this value demonstrates enhanced efficacy in attenuating the smaller δh values that lack relevance, the distribution calculations should be tailored to each SR site and periodically updated to align the threshold with dynamic SR demands.

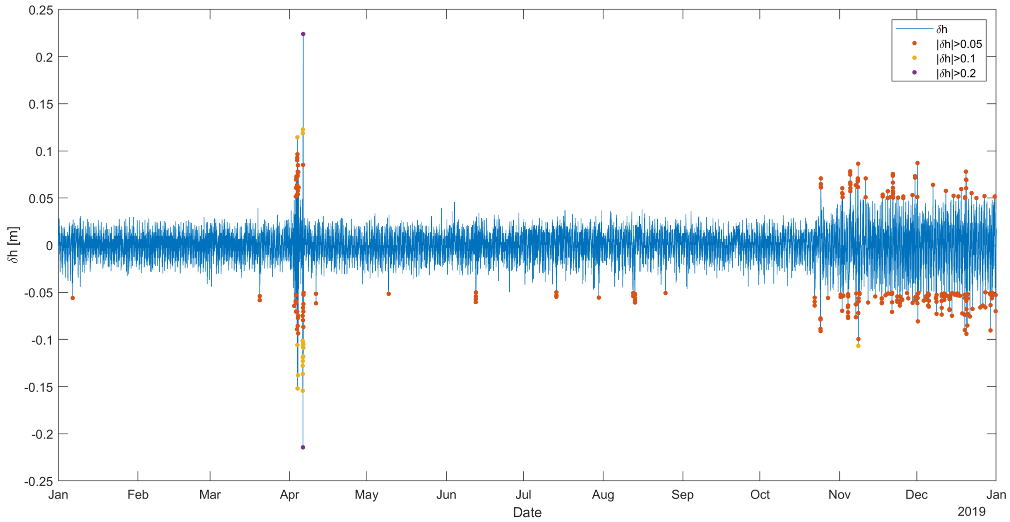


Figure 5.6: Level variations sensitivity analysis for Site 1 during year of inspection.

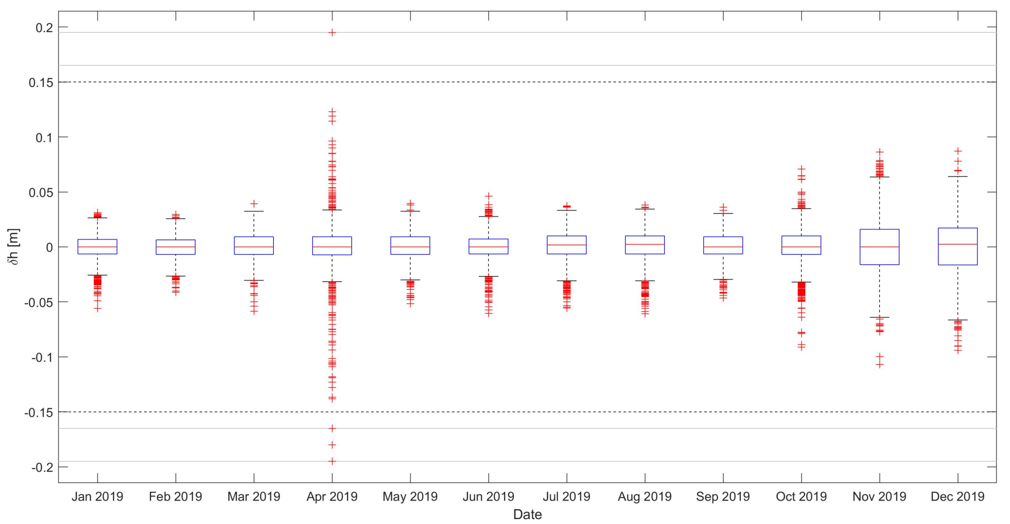


Figure 5.7: Level variations box plots for Site 1 during year of inspection.

5.2 Service reservoir mass balances and residence times

To allow immediate comparisons with the single-parameter stage, this section presents the results of mass balance and retention time calculations as time series. The calculations explained in 4.2.2 were applied to all sites with available level and flow data, resulting in five case studies. To facilitate interpretation and validation through inspection records, the results of mass balances were displayed for six-month intervals centred around the inspection date, and to highlight the value of the multi-parameter approach with respect to the single-parameter, these were also represented in combination with the levels rate of change plots. To evidence eventual prolonged periods of time with extended retention times, the findings from retention time calculations were exhibited for each year within the data time series, with a specific focus on three selected sites as examples.

5.2.1 Residual volumes

The first case study (Fig.5.8) demonstrates that residual volume variations can be employed to evaluate the normality of the system. In this particular case, it was observed that no significant volume changes occurred for six months after the inspection. Conversely, the second case study (Fig. 5.10) highlights a peak in ΔV in April 2015, which occurred three months after the inspection date. This finding suggests that the mass balance approach can identify volume variation events that are not captured by the level rate of change. The third case study (Fig. 5.9) shows that significant fluctuations in volume residuals were observed up to three months prior to the inspection, revealing leaking outlet valves. The wider oscillations in ΔV observed from March to June 2020 indicate the occurrence of such variations outside the period of scheduled intervention. The early detection of this issue shows that the mass balance metric can be used to identify SR issues, thereby preventing integrity problems from going undetected for long periods. The plot in Fig. 5.11 expands this concept, illustrating also the efficacy of mass balance calculations in assessing the effectiveness of interventions, where roof and wall leaks were found after the tank was taken out of service. The results for Site 1 (Fig. 5.12) indicate that there was a substantial increase in water entering the tank about six weeks before the scheduled inspection. This is evidenced by the abrupt changes in residual volume. After maintenance interventions were implemented, a new level of stability was achieved, demonstrating the ability of mass balance calculations to identify SR issues before inspection and to evaluate the effectiveness of corrective actions.

The results obtained from the mass balance calculations highlight their importance in assessing the hydraulic performance of SRs and demonstrate the effectiveness of this metric as a tool for assessing both the normality of the system and identifying volume variation events, which may be indicative of potential issues with the system.

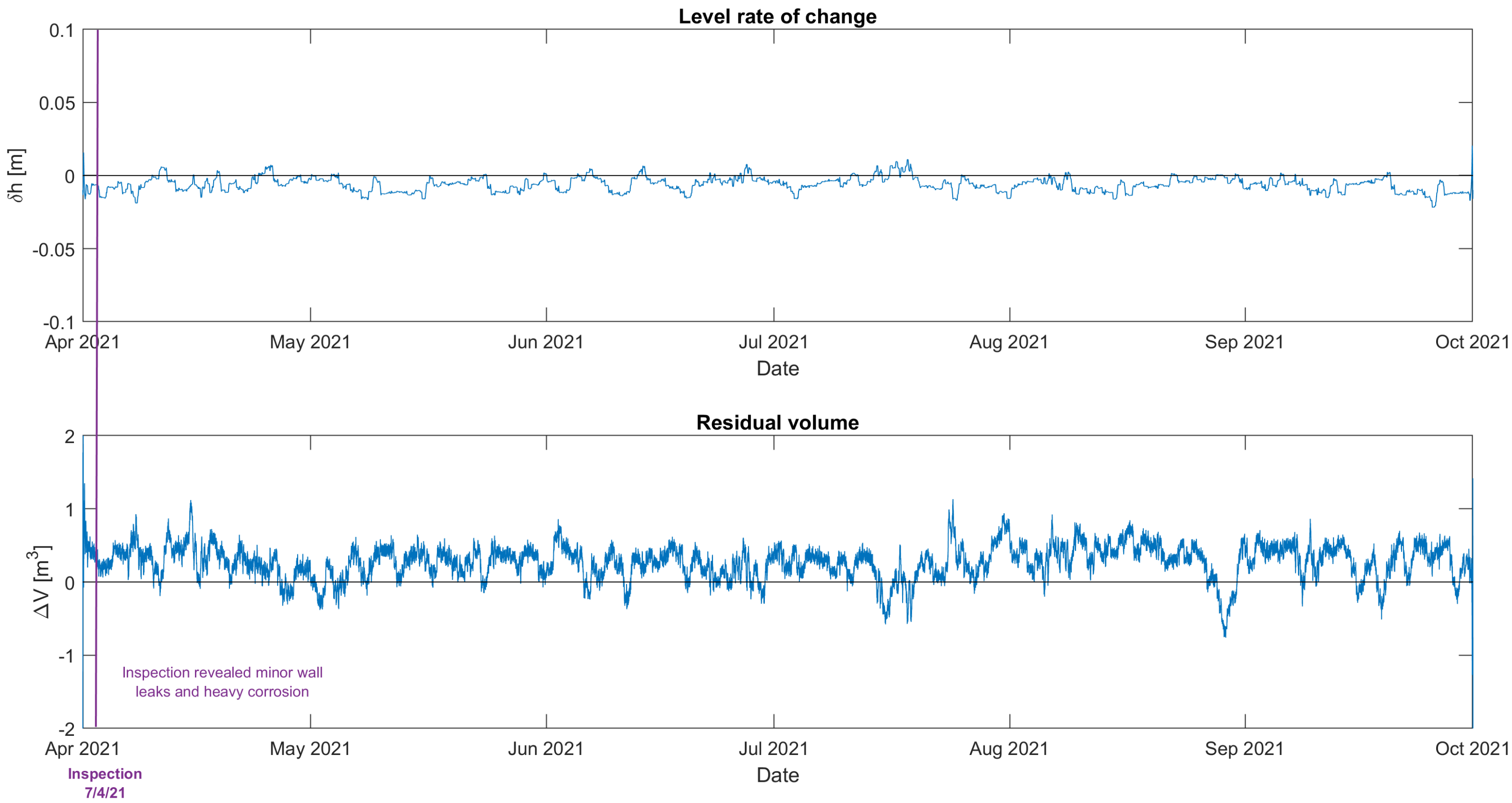


Figure 5.8: Site 6 mass balance.

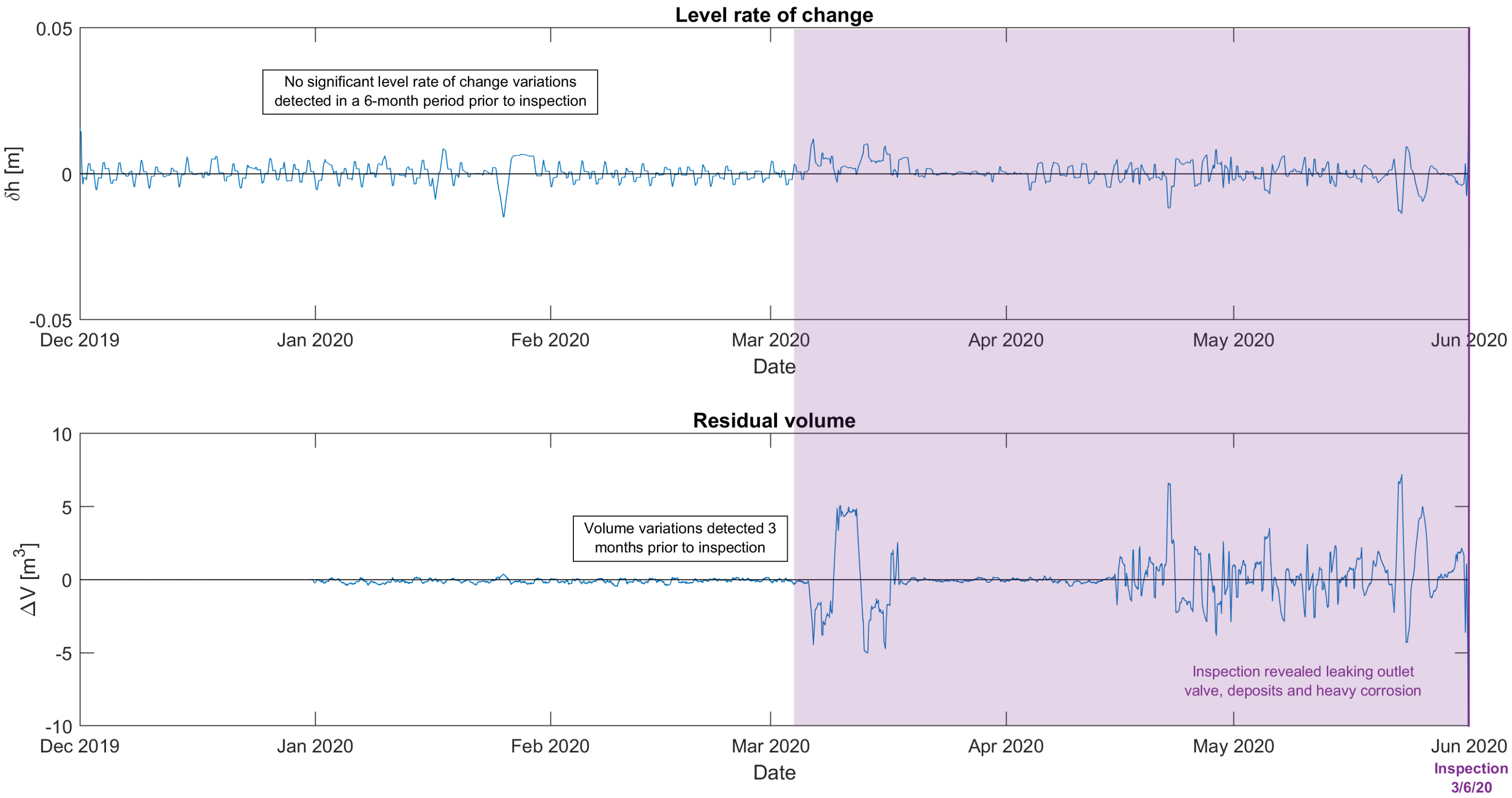


Figure 5.9: Site 2 mass balance.

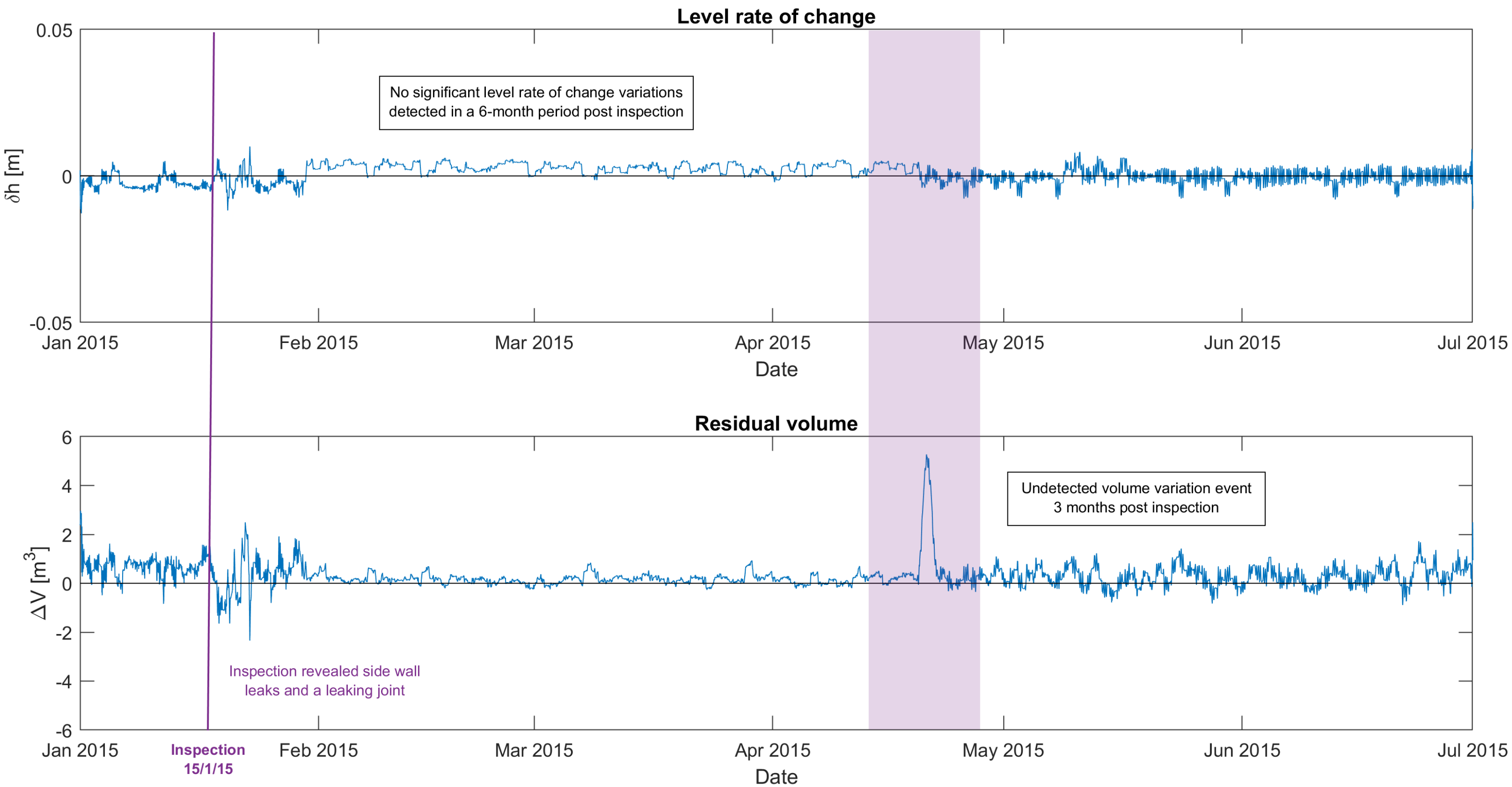


Figure 5.10: Site 4 mass balance.

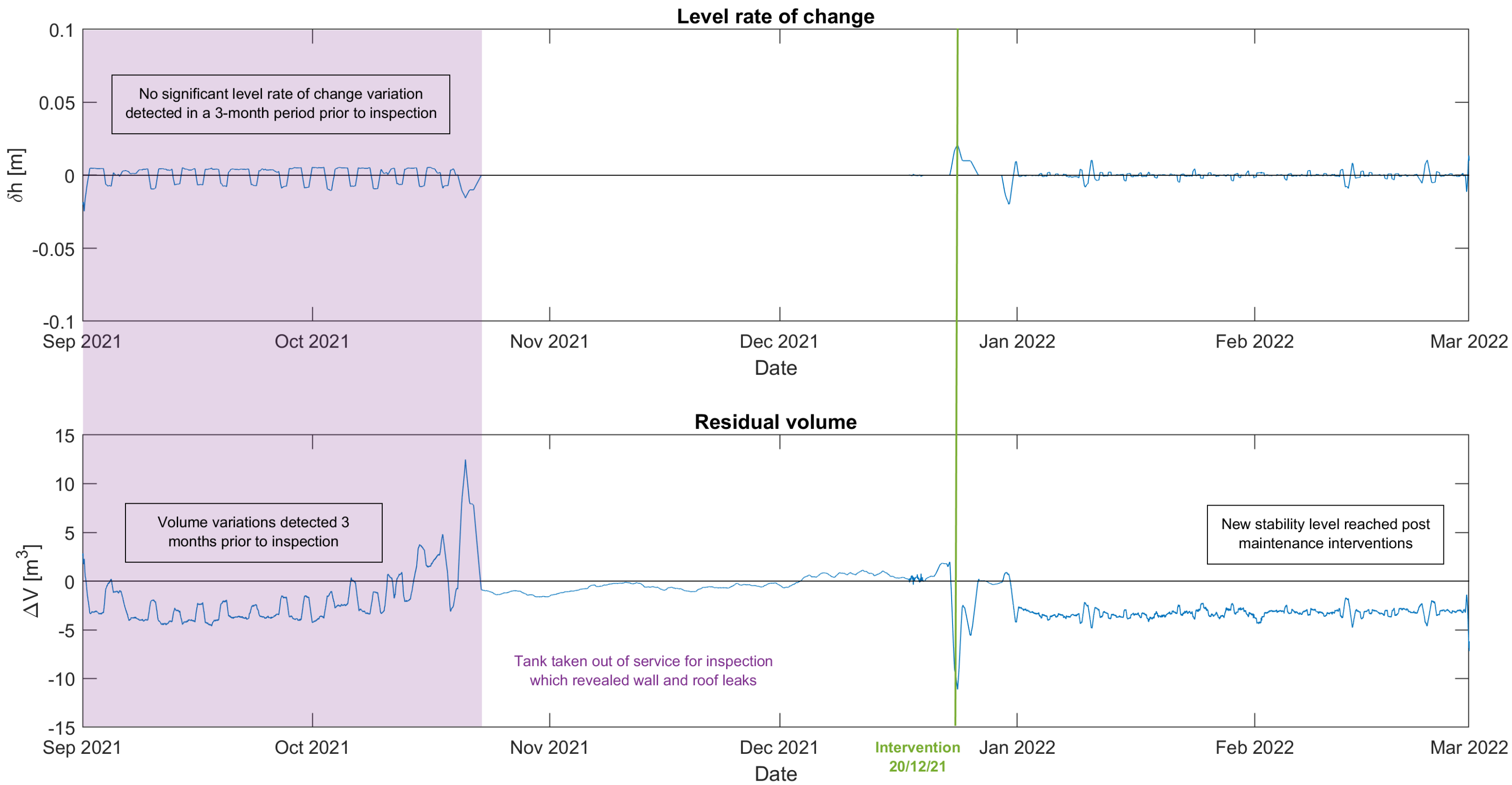


Figure 5.11: Site 5 mass balance.

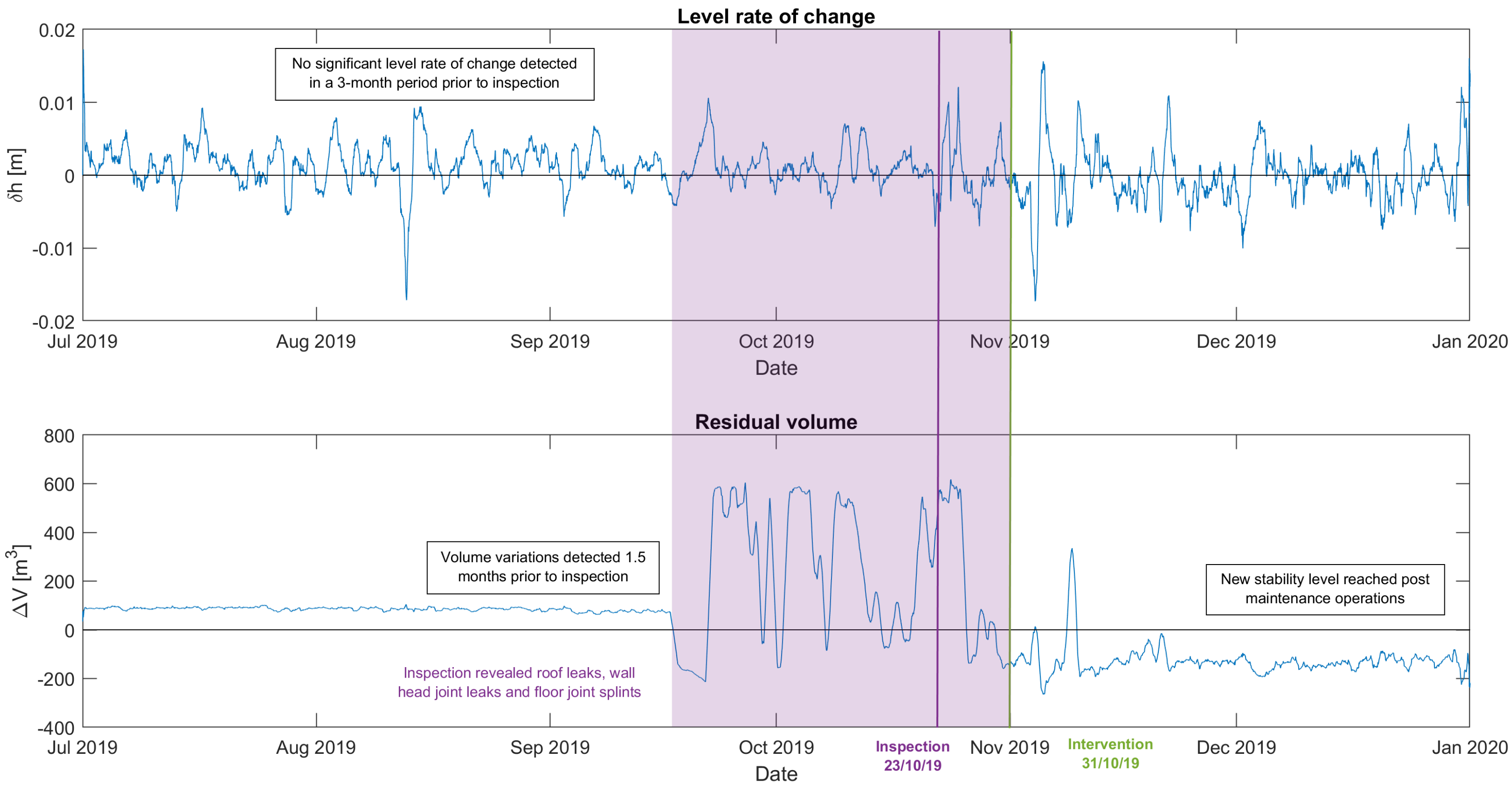


Figure 5.12: Site 1 mass balance.

5.2.2 Retention times

The hydraulic performance of SRs was further evaluated using the daily retention time metric under the assumption that the tanks are well mixed (see 4.2.2). The results showed that Site 1 (Fig. 5.13) performed well in terms of residence times, with few data points exceeding 48 hours. In contrast, Site 4 exhibited consistently long residence times (Fig. 5.14), except for a brief period from May 2015 to October 2016, indicating that the SR was not operating at levels and flows that ensured an adequate water turnover within the tank. Figure 5.15 shows that Site 2 displayed a similar behaviour to Site 4, with residence times persistently greater than the fixed 48-hour threshold. In this SR site the inspection form identified thick layers of deposits and corrosion problems, which are known to correlate with long water age and insufficient mixing. The daily retention time metric hence proved to be an effective tool for evaluating the hydraulic performance of SRs in terms of residence times.

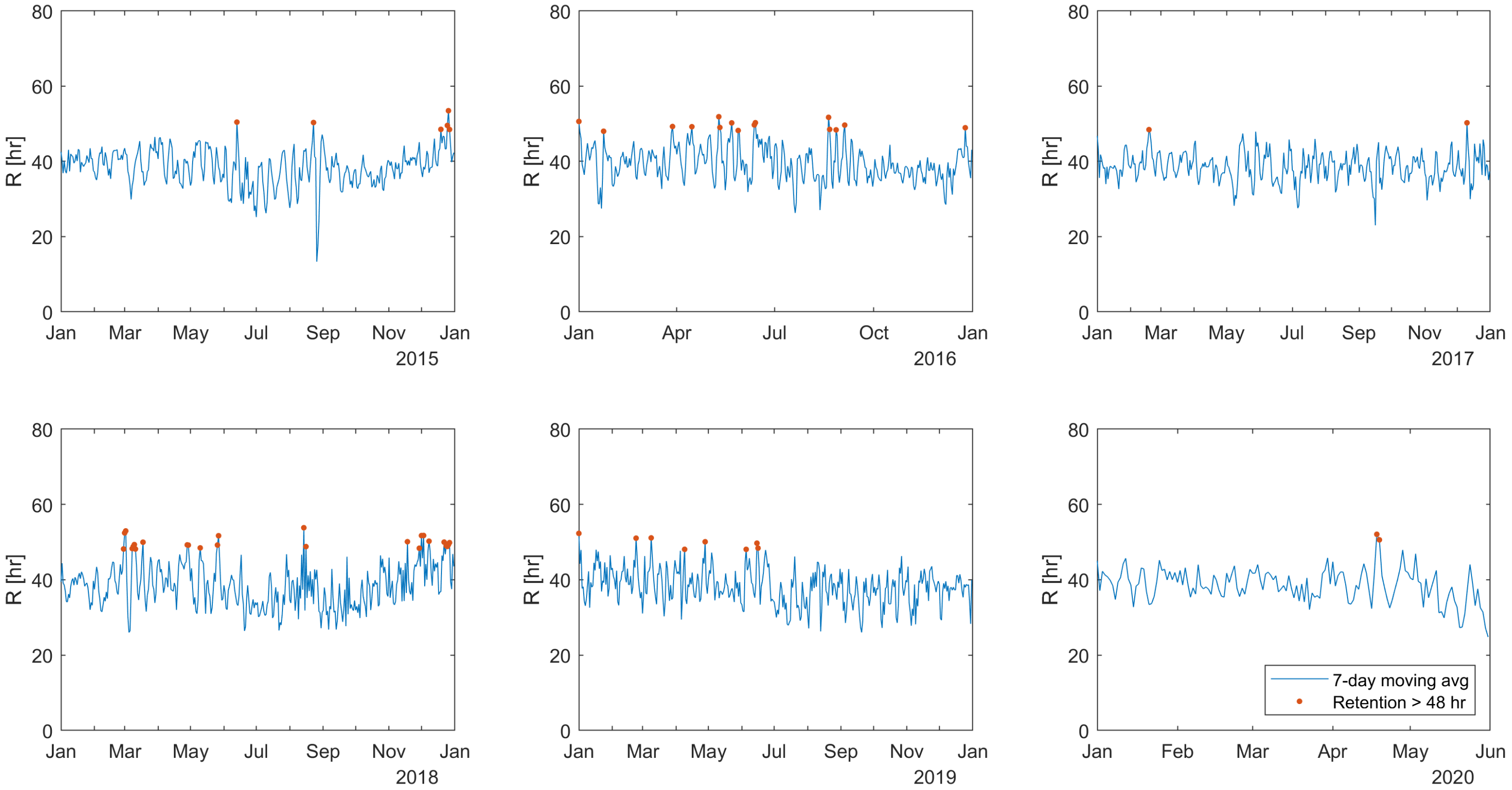


Figure 5.13: Site 1 residence time plots for 2015-2020.

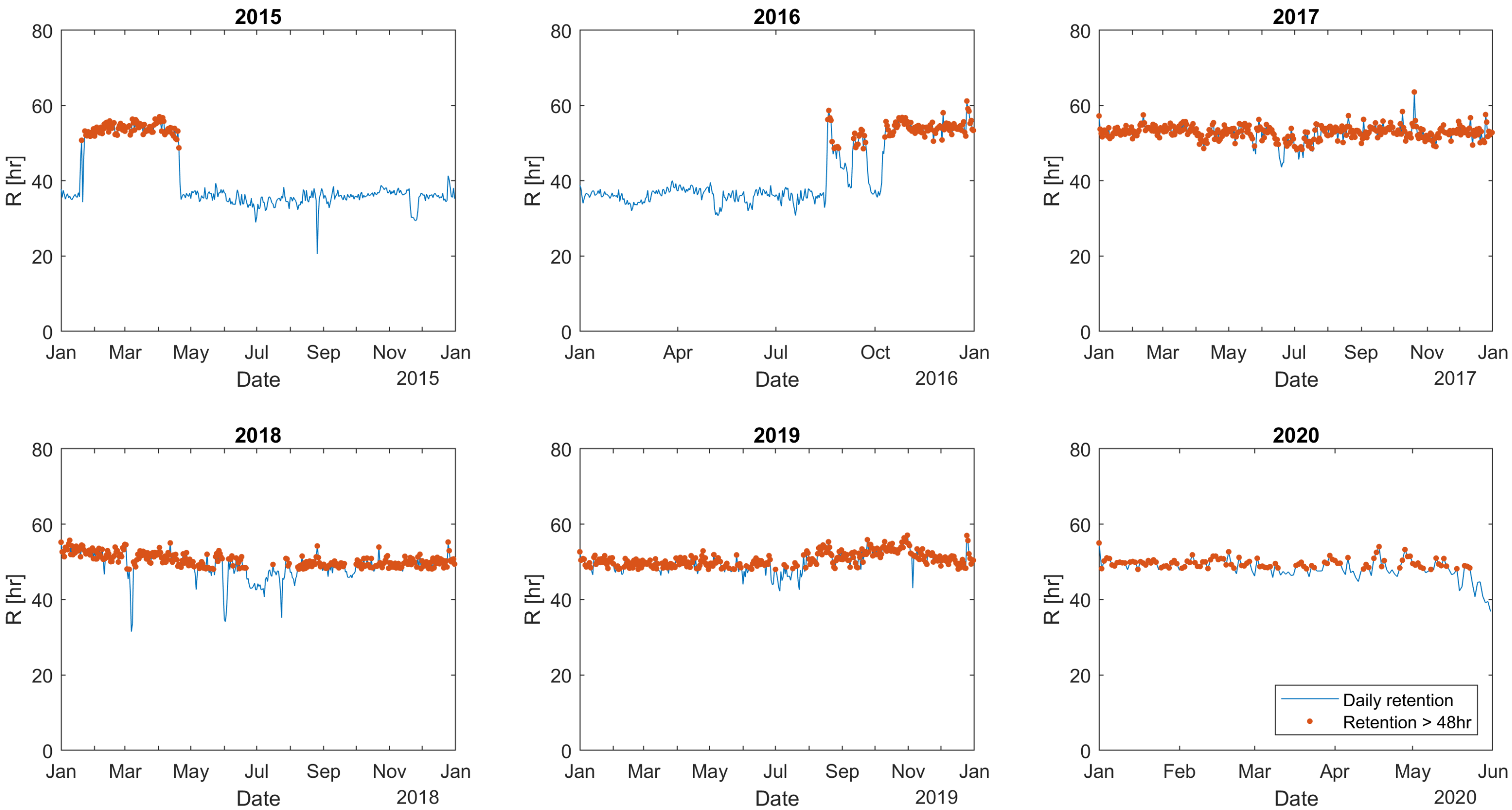


Figure 5.14: Site 4 residence time plots for 2015-2020.

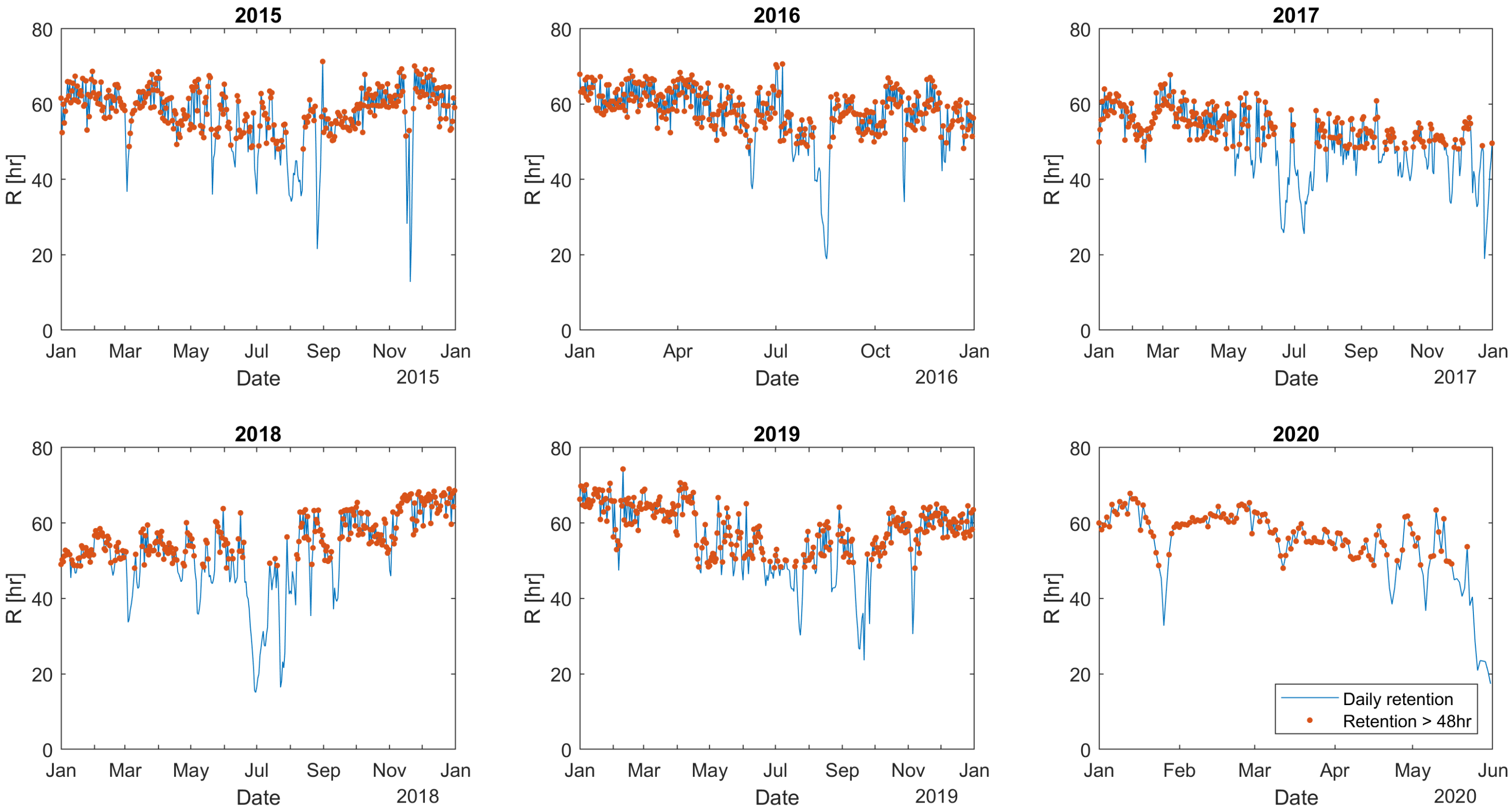


Figure 5.15: Site 2 residence time plots for 2015-2020.

5.3 Investigating the relation between service reservoir hydraulics and water quality

In this section the water quality of four interconnected sites is explored, together with the final water from the upstream WTW as shown in Fig. 5.16 (4.2.3). The results of the study indicate that Site 4 and Site 2 are the worst performing systems in terms of water quality. This is demonstrated by the higher average CFU from the 3-day HPC for these sites, as shown in the bar plot in Fig. 5.17. Furthermore, FC data adds value to regulatory sampling, as the average Intact Cell Counts (ICC) for both sites are also higher (Fig. 5.18), indicating the presence of bacteriological activity by the time the water reaches the SR outlet sampling points. Interestingly, this does not seem to be related to chlorine depletion problems, as the plot in Fig. 5.19 shows that the average free chlorine values in the same time period were above the recommended minimum concentration of $0,4\,mg/l$, albeit the two sites identified as having low water quality also had lower chlorine levels compared to the other sites in the same network.

Both Site 4 and Site 2 were problematic in terms of long residence times, as previously described in 5.2.2. This finding confirms the theory here explored that daily residence times act as an useful indicator of water quality issues in SRs. Although access to chlorine time series was limited in this project, it was possible to investigate Sites 1-3 which all have outlet continuous monitoring and belong to the same portion of a DWDS. Figure 5.20 displays the plots of the difference in the chlorine concentration between Sites 1-2 and Sites 1-3, and the positive values ranging between $0 - 0.45\,mg/l$ suggest that the chlorine depletion occurred between the sampling points. Chlorine decay is higher between Site 1 and Site 2, where the latter was also showing elevated residence times (Fig. 5.15). However, the lack of inlet monitoring prevents from drawing conclusions regarding the exact location of this issue and whether the disinfectant depletion occurred mainly along the pipe network or within the tanks.

The 1-year long chlorine time series available at the inlet and outlet of Site 10 (Fig. 5.21) shows that the outlet values are often greater than the inlet values, implying that either the continuous monitoring of chlorine may not be a reliable indicator of water quality in this case or that the monitoring of continuous chlorine data needs significant attention in the collection of data.

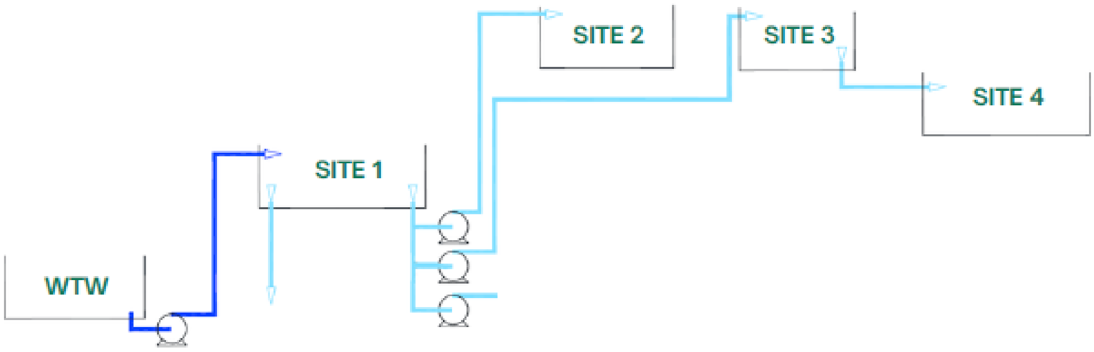


Figure 5.16: Network schematics of Sites 1-4 and the upstream WTW.

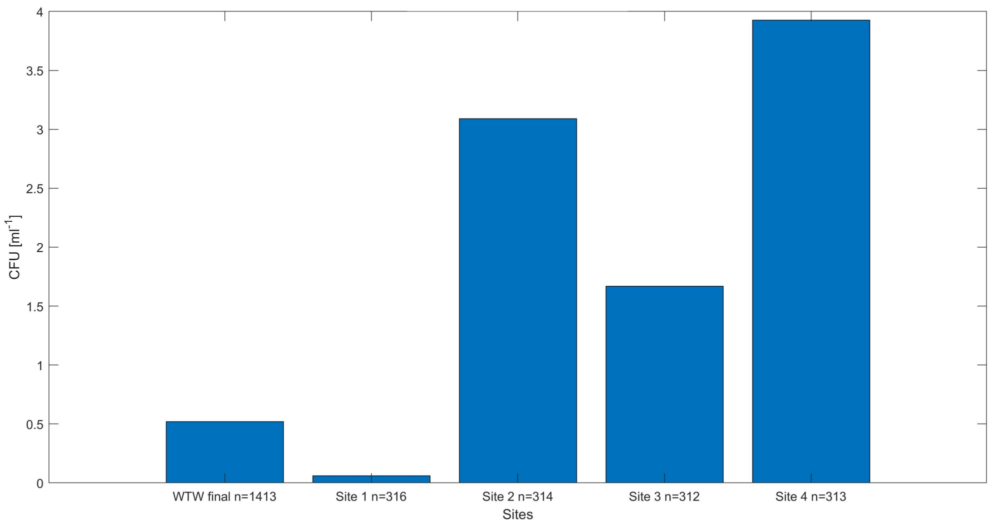


Figure 5.17: Average 3-day colony counts from 2015-2020 for five sites in the same DWDS.

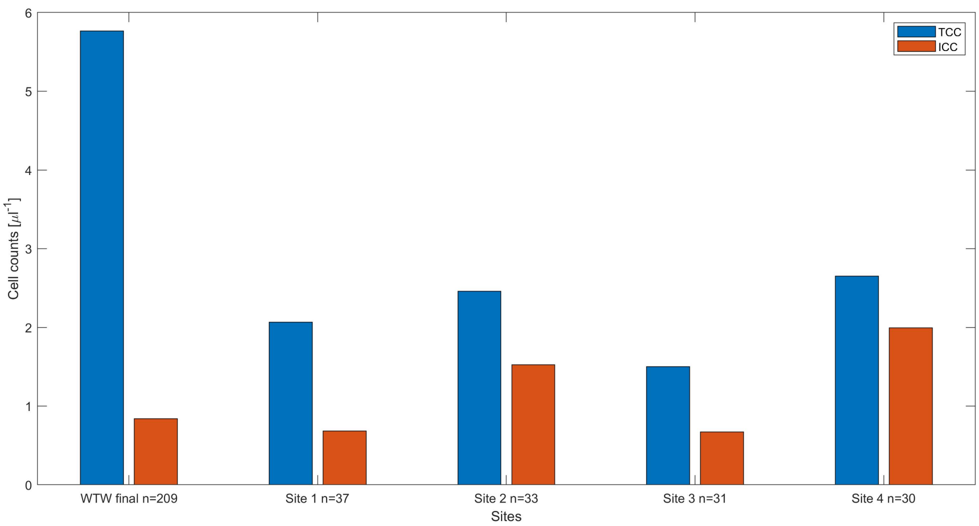


Figure 5.18: Average FC cell counts from 2015-2020 for five sites in the same DWDS.

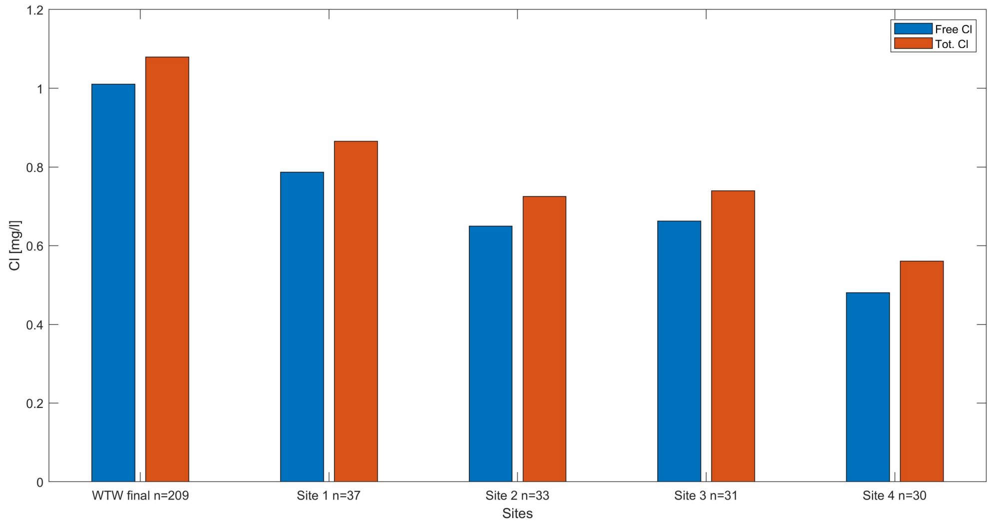


Figure 5.19: Average free and total chlorine from 2015-2020 for five sites in the same DWDS.

Figure 5.20: Chlorine decay between Sites 1-2 and Sites 1-3.

Figure 5.21: Continuous chlorine raw data from inlet and outlet monitoring at Ste 10.

5.4 Summary and applications

The present study emphasises the significance of utilising mass balance calculations to identify SR issues prior to scheduled inspections and improvement post maintenance operations; however, the root causes of these SR problems are uncertain. The findings indicate that this metric shows insights on SR hydraulic performance gained from data that is already collected, enabling early detection of possible integrity issues which may lead to costly repairs and potential contamination of stored water. Furthermore, the results suggest that the water quality and hydraulic performance of SRs are interlinked, with evidence of bacteriological activity in sites exhibiting longer daily residence times. The flowchart in Fig.5.22 represents the step by step process that water professionals can implement as an online application to assess SR hydraulic performance and ultimately alert process scientists regarding which sites might be problematic and needing further water quality investigations.

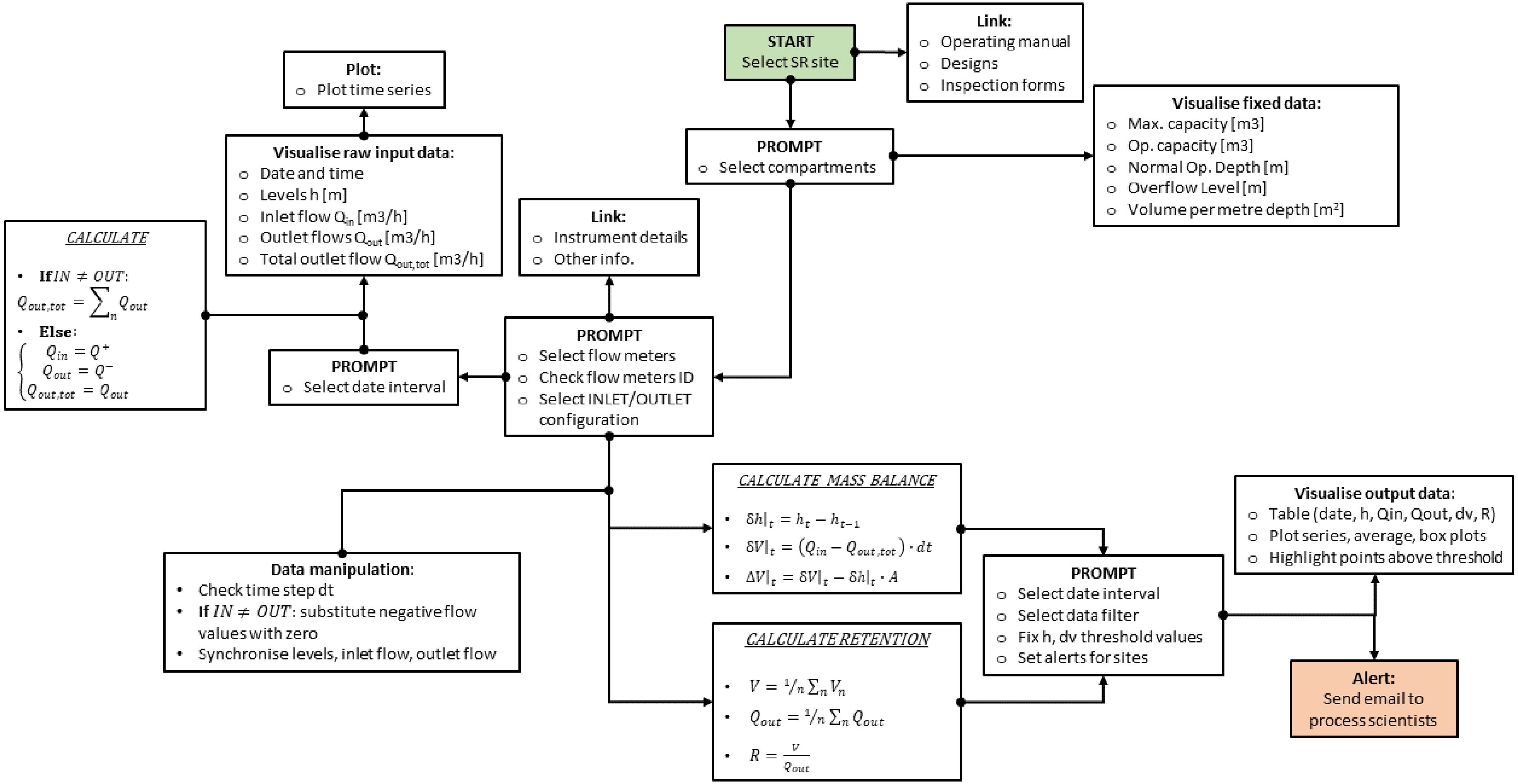


Figure 5.22: Hydraulic performance functional specification flowchart.

Chapter 6

Discussion

6.1 Data-driven metrics for service reservoirs

The multi-parameter approach consists of a data-driven metric to assess SR performance, based on combining level and flow data to perform real-time mass balances and daily retention times (4.2.2), which has demonstrated that valuable information can be generated from parameters which are already traditionally monitored at SRs. Analysis of the collected data revealed that single-parameter analysis of hydraulic parameters can only demonstrate changes in SR operation without being able to assess overall SR performance. However, by combining data sources to perform mass balance and retention time calculations, additional information can be generated, providing a more comprehensive understanding of SR performance. The findings illustrated in section 5.2.1 distinctly demonstrate antecedent information on hydraulic performance, and reveal improvement subsequent to maintenance interventions, a knowledge which was previously undisclosed. For example, the mass balances at Site 1 (Fig. 5.12) and Site 5 (Fig. 5.11) demonstrated that this metric can identify the effects of integrity issues, such as wall leaks, joint degradation, or passing valves, prior to scheduled inspections. The efficacy of remediation works at SRs can also be determined by observing how the residual volumes settle post-intervention, which is crucial in improving SR management.

The use of the multi-parameter metrics offers a significant advantage in providing valuable information for various functions. While the mass balances aid in identifying potential integrity issues prior to maintenance, the retention times not only flag sites at risk of water quality problems but also indicate when tank levels exceed standard SR operation. For instance, daily retention times for Site 4 (Fig. 5.14) consistently exceeded the 48-hour threshold except for the period between May 2015 and October 2016. If demand from the downstream DWDS is lower, tanks should operate at lower levels to optimise residence times and hence preserve water quality. The prolonged water residence in the SR indicates a decrease in the efficiency of water flow through the system, which is likely caused by a decrease in demand resulting from modifications in the downstream network configuration. One potential solution to this issue is to operate the SR at a lower water level, which would decrease the residence time while still maintaining an adequate level of water supply reliability if the serviced area downstream is reduced. However, this approach is rarely implemented in practice, due to the reluctance to reassess the continuity of water supply, despite the associated risks to water quality posed by elevated residence times. In this instance, the efficacy of the multi-parameter metric is demonstrated in its ability to provide valuable insights for both standard SR operation and proactive maintenance. This implies that in order to enhance effective management practices, a more comprehensive integration and equilibrium between water quantity and water quality considerations is needed.

Long residence times were observed at Site 2 (Fig. 5.15) and Site 4 (Fig. 5.14), which consistently showed elevated water age in their tanks. Consequently, water quality degradation was confirmed based from SR ranking based on water quality parameters, namely E. Coli and ICC (Fig. 5.17-5.18). This knowledge can be used to justify intensifying sample collection at problematic sites, which consequently enables a more proactive approach to managing water quality in SRs. It is of interest to note that the limit of 48 hours which was fixed as a threshold to alert when sites have long residence times was chosen on the basis that the tanks in the studied systems were designed to provide water for two days in the eventuality of interruption of supply from the WTW; however, there may be opportunities to explore how to adjust this value to site-specific characteristics and needs. Furthermore, these findings prompt the inquiry about the existence of a quantitative association between water age and water quality parameters. While previous studies, such as Machell *et al.* (2014) and Blokker *et al.* (2016), have modelled water age as a surrogate parameter for water quality, finding relationships between calculated water ages and different water quality parameters, these studies were focused on the DWDS and did not explicitly take into account the effect of SRs. Although this study confirmed a correlation between water age and microbial activity in SRs, the specific relationship between the duration of residence times beyond the 48-hour threshold and the values of colony forming units and total and intact cell counts was not examined, and could prove to be interesting for further investigation.

While looking at chlorine time series was needed to verify the presence of chlorine decay in between sites, as evidenced by Fig. 5.20, without inlet monitoring it is uncertain whether the water quality has deteriorated before or within the SRs (Doronina *et al.*, 2020). Moreover, Fig. 5.21 shows that continuous chlorine time series can be very irregular, and that there are several periods of time where the outlet chlorine is higher than the inlet chlorine. Gleeson *et al.* (2023a), have shown that cross-correlation of chlorine data can be used to improve understanding of networks connectivity, including estimating the transit times between sensors. This approach could be equally applicable to SRs as well as DWDS, and comparing transit times patterns to the residence times calculated with the multi-parameter metric could also provide insights on the accuracy of the assumption that the SR is well mixed. When this assumption fails, the tanks are likely to have stagnant areas and stratification problems, hence an elevated risk of water quality degradation. However, chlorine sensors need to be constantly and efficiently maintained to provide reliable data (Gleeson *et al.*, 2023b).

The water quality analysis revealed another finding, which emphasises the significance of using FC in support of regulatory sampling. The bar plots in Fig. 5.17-5.18 demonstrate that there is a higher level of bacteriological activity in the sites with elevated average CFU. This result suggests further investigation of water quality at SRs using advanced tools such as online water quality sensors might be a useful option.

In the context of this research, the examination of time series data related to level and flow measurements was conducted without incorporating considerations for biases, noise, and drift. While a more comprehensive analysis accounting for these factors would have resulted in heightened data accuracy, as the main purpose of the research was to explore the qualitative relationships between hydraulic behaviour and water quality at SRs, this approach was suitable for deriving meaningful results. Furthermore, while the project data included time series which did not always extend to cover a sufficient amount of time pre- and post- interventions, when inspection records are filed, the results of this study provide valuable insights into the use of real-time mass balances to assess SR hydraulic performance. For example, in the case of Site 6 (Fig. 5.8), only post-inspection data was accessible, while for Site 2 (Fig. 5.9), no data was available after the inspection. Nevertheless, the mass balance metric demonstrates its capability to assess normality and detect issues up to three months prior to the inspection. This newfound knowledge plays a significant role in providing valuable insights to water companies, enabling them to enhance their management and maintenance practices.

The adoption of a multi-parameter approach also provides valuable insights into pre-maintenance issues and post-maintenance performance improvements. It is likely that sudden changes in residual volumes, as illustrated in Fig. 5.9-5.12, can be attributed to integrity issues such as wall cracks or joint degradation, as supported by the analysis of inspection forms. Although these metrics alone cannot determine the exact root causes of SR failures, their results provide valuable prompts for inspecting assets at risk before the scheduled maintenance time. This is crucial as early warning is essential for effective preventative maintenance. By leveraging these metrics as early warning signals, proactive maintenance actions can be taken to mitigate potential risks and improve the overall resilience of SRs.

It is worth exploring the potential advantages of implementing a preventive maintenance strategy for SRs from a cost-benefit perspective. A comprehensive cost-benefit analysis would need to consider the expenses related to the planning and execution of preventive maintenance activities, as well as those arising from reactive interventions, such as unplanned maintenance or emergency repairs. By utilising available data, an online application incorporating mass balance and residence time metrics can effectively inform preventive maintenance needs at a low cost while providing substantial value.By balancing the costs and benefits of preventive maintenance against reactive interventions, a comprehensive understanding of the economic value of preventive maintenance can be achieved.

Overall this study shows for the first time that data-driven metrics based exclusively on data which is already collected by water utilities at SR sites can be used to anticipate integrity issues with the storage tanks and identify sites at risk of water quality deterioration. These metrics represents a significant novelty in the sector of water resources management, as it makes use of data already collected to generate different insights on SRs and has the potential to improve SR management significantly. The outcomes of this research challenge the current practice of purely time-based scheduled interventions every $3-5$ years, and suggest that planning inspections when anomalies in residual volumes are detected (*i.e.*, ingress or loss of water) would provide better quality control for future practice. Ultimately this research demonstrates that adopting a multi-parameter metric is an essential step for water utilities to transition from a reactive mode of operation.

6.2 Future research

Given the reliance on a limited dataset for this project, it would be recommended to pursue a broader validation of the proposed metrics. Additionally, the current approach of visually interpreting the results to identify anomalies in level rates of change and residual volumes presents challenges in extending the analyses to additional sites and longer time series due to the impracticality of manual analysis on large datasets. Developing algorithms to automatically define site-specific thresholds for the level rates of change δh and the residual volumes ΔV would be a vital step to improve the capacity of this approach to inform SR operation and maintenance needs. As the conducted sensitivity and distribution analyses (Fig. 5.6-5.7) have revealed that adjusting these thresholds can significantly influence the number of data points identified, it is important to better define site-specific values for these parameters, allowing for a more accurate assessment of SR performance and aiding in effective management and decision-making. Furthermore, a more thorough research of the root causes of failures would involve a more comprehensive analysis not only of the inspection records, but also of standard SR operation and eventual changes or works which are happening in DWDS both upstream and downstream the site in question.

A potential future research direction could involve exploring the possibility of defining appropriate alert systems for monitoring SR performance, with the utilisation of control theory as a means to effectively manage water supply infrastructures. While this approach is often used in other branches of engineering to analyse and regulate complex systems, for example in environmental monitoring or industrial control applications (Loehle, 2006; Ivanov *et al.*, 2018), it is still little used in the water industry, missing the potential of developing more comprehensive risk assessment tools. The few applications of data-driven metrics to DWDS operation are currently limited to local feedback control at WTWs. For example, Bakker *et al.* (2003) have shown that by applying a control algorithm based on adaptive demand prediction has improved optimisation of treatment processes, and Ellis *et al.* (2015) have used cross-correlation and Self Organising Map (SOM)s to identify water quality failures at WTWs. Control theory could be used to design systems that incorporate sensors to monitor key parameters and algorithms to analyse collected data and provide alerts when thresholds are exceeded or anomalies are detected. Furthermore, these algorithms could be designed to use feedback control to adjust the system's operation and prevent further deviations from the expected behaviour. In developing these alert systems, control theory could also be used to optimise the trade-off between sensitivity and specificity, so that alerts are only generated when there is an elevated likelihood of an issue or hazard occurring, while minimising false alarms. Control theory could also be used to incorporate fault detection and diagnosis algorithms to identify system failures, providing maintenance teams with valuable information for troubleshooting and repair.

In terms of water quality, future research should also prioritize the enhancement of SR assessment methods. Determining the best methods and sensors to collect valuable information to assess SR water quality is an important aspect of research that is still being explored. In order to get a more comprehensive understanding of the water quality in an SR, a combination of laboratory and field work would required. In the laboratory, chemical and biological analyses could be performed on water samples collected from the SR to determine parameters such as conductivity, pH, dissolved oxygen, turbidity, total organic carbon, and bacterial counts. These analyses could hence be used to identify potential sources of contamination or water quality issues. Once the most valuable parameters have been identified, sensors could be deployed in SR sites to continuously monitor water quality and detect changes in real-time, monitoring a variety of physical, chemical and microbial parameters. The data from these sensors would be analysed to identify trends and potential issues, ultimately allowing for timely corrective actions to be taken. However, the specific methods and sensors that are best suited to assessing water quality in SRs can vary depending on factors such as the water source and the surrounding environment, making it an area that requires continued research and exploration.

In conclusion, this thesis has provided valuable insights into the application of mass balance and residence time metrics for informing preventive maintenance needs. Further research is warranted to expand the validation of these metrics, improve assessment techniques for water quality, and explore additional avenues for enhancing the overall efficiency and effectiveness of maintenance strategies.

Chapter 7

Conclusions

The primary achievement of this study involved the creation of a novel measurement tool to evaluate the hydraulic performance of SRs, utilising easily accessible data on water levels and flow rates. This comprehensive approach demonstrated feasibility and practicality, enabling the real-time computation of mass balances and daily retention times through existing data sources, using only parameters which are already monitored at SR sites. Consequently, it facilitated the prompt detection of anomalies in the behaviour of SRs prior to planned maintenance activities and allowed for the evaluation of maintenance efforts effectiveness.

The mass balance calculations were crucial in detecting leakage or ingress issues within the tanks, while residence times provided valuable information on water age and standard operation of SRs. Additionally, residence times played a key role in identifying assets at risk of drinking water deterioration. This was further supported by a comprehensive assessment of SR water quality ranking, incorporating statutory sampling and FC analysis. By combining mass balances and residence times with water quality analysis, potential issues can be promptly identified, enabling proactive measures to address them and ensuring the consistent delivery of high-quality water to consumers.

The potential implications of the developed metrics are significant in that they allow water utilities to move beyond a reactive, time-based maintenance approach and towards a proactive maintenance approach. This shift in approach has several benefits, including increased efficiency and reduced costs associated with unscheduled maintenance. Specifically, the use of the mass balances and residence times metrics as an online application can provide real-time monitoring and alerts for anomalies in service reservoir performance, allowing for early detection of potential issues. This has practical applications in the field of water management, where timely maintenance can prevent contamination, ensure consistent water quality, and reduce the risk of service interruptions.

In the near future, climate change is anticipated to exert significant influences on water availability and quality, resulting in shifts in extreme weather events like floods and droughts; therefore, protecting drinking water storage is of vital importance. The challenges posed by a changing climate can have far-reaching implications for the operation and maintenance of crucial water infrastructures, including SRs. Thus, it becomes imperative to develop proactive approaches, such as the one presented in this research, to effectively manage and maintain these critical assets, ensuring the resilience of water systems in the face of impending climate change impacts. By promptly identifying anomalies in SR performance before they escalate into service disruptions, the methodology proposed in this study holds great potential in fostering the development of adaptive and sustainable water practices. The findings and insights from this research signify a significant stride towards achieving more environmentally conscious and efficient water resources management.

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