Assessing Service Reservoir Performance and its Effect on Drinking Water Quality

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Thesis submitted for the degree of Doctor of Philosophy

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Submitted: January 2022

I dedicate this thesis to myself.

"I don't think we can do this, but we have to."

Dr Grigorios Kyritsakas

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.

Abstract

Service reservoirs (SRs) are crucial components in drinking water distribution systems (DWDSs). These assets are often associated with water quality issues, including significant waterborne disease outbreaks, therefore understanding water quality at this stage of the DWDS is imperative to maintaining safety of supply. In the UK, monitoring is conducted infrequently at SR outlets and for disinfectant residual and bacteriological indicators only, which provides limited information on SR performance and effect on water quality, and origin of water quality deterioration. In this project, extensive monitoring conducted at SRs from four UK water utilities for various water quality parameters at the inlet and outlet of SRs, and analysis of SR accumulated material, provided valuable information on how SRs affect water quality. A concept that describes system performance in terms of 'sink or source' behaviour was developed and applied to the process of material loading in SRs. An innovative metric was created to quantify such sink or source behaviour using continuous turbidity data, providing a practical way to assess and quantify SR performance with changes over time. Applying the metric in combination with comprehensive water quality monitoring enabled, for the first time, the ability to evidence effectiveness of asset maintenance in improving SR performance and demonstrated that SRs can act as beneficial treatment stages, depending on how they are managed. Incorporating inlet monitoring made it possible to assess and differentiate between SR and upstream network performance, revealing the true location of water quality deterioration. With the ability to assess SR performance over time and identify sources of deterioration, water utilities can now make proactive, justifiable, and targeted decisions on the location and frequency of network maintenance and management, ensuring that interventions address water quality issues at their origin, preventing future reactive investigations and maintaining safety of supply.

Acknowledgements

I would like to extend my thanks to…

My better half and my best friend, Andrew Kennedy, for loving me when I was rain and holding me when I was fire.

David Michael Osborne, for being the main reason I have been fighting to improve my life and become the best version of myself since we met in 2007.

'Everyone thinks a soulmate is a perfect fit. But a true soulmate is a mirror, the person that shows you everything that is holding you back, a person that brings you to your own attention, so that you can change your life. Soulmates come into your life just to reveal another layer of yourself and then they leave, and thank God for it, it is too painful otherwise.' - E. Gilbert

My incredible friends, without whom I would struggle to be here, let alone do a PhD. You are my pillars, my kindred spirits. I am so damn lucky to have you, thank you.

My family, for always being brutally honest and for providing me with relentless and unwavering support, even when I had not asked for it.

Cecilia Costello, my dear foster mum, who took me in with open hands and heart when I was at my most damaged and hopeless. You changed the trajectory of my life and I wish you were here for me to tell you that in person. Have a cheeky glass of wine for me wherever you are.

Dr Steven Le Comber, for being my guide, my inspiration, and friend. Thank you for teaching me how to think independently and turn an idea into a wonderful creation. Most importantly, thank you for showing me the magic of science and the beauty of Scotland. This world is a darker place without you in it.

Professor Rob Knell and Dr David Hone for teaching me most of what I know today and somehow making statistics interesting.

Professor Vanessa Speight, Dr Stewart Husband, and Professor Joby Boxall for giving me this incredible opportunity and for your support, guidance, and friendship throughout the last 4 years. I am eternally grateful.

My sponsor water utilities, Anglian Water, Northumbrian Water, Scottish Water, and Dŵr Cymru Welsh Water, for making this work possible.

All the staff and students at STREAM-IDC for the development, support, and fun throughout this degree, especially at Challenge Weeks.

The staff at the University of Colorado, Boulder, especially Professor Fernando Rosario-Ortiz, for their accommodation, assistance, and knowledge exchange.

Jim Panton, for the opportunities you have given me, your humour, like-mindedness, and crazy ideas. I look forward to working with you.

Snail and Rabbit, my favourite independent teashop in Nottingham, whose tea have gotten me through the majority of the toughest moments in this PhD.

Last, but not least, my little cat, Buttons, for being my closest companion, always snoozing nearby whilst I work, and for being my biggest source of comfort, joy, and love.

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Abbreviations and Nomenclature Used Throughout the Thesis

- Autosamplers – Automatic samplers
- Al – Aluminium
- As - Arsenic
- CFD – Computational fluid dynamics
- CI – Cast iron
- Cu - Copper
- DBP – Disinfection by-product
- DI – Ductile iron
- DICL - Ductile iron cement lined
- DMA – District metered area
- DOC – Dissolved organic carbon
- DWDS – Drinking water distribution system
- DWI – Drinking Water Inspectorate
- DWQR – Drinking water regulator for Scotland
- EEM – Excitation and emission matrix
- EPS – Extracellular polymeric substance
- FCM – Flow cytometry
- Fe - Iron
- GRP – Glass reinforced plastic
- HDPE - High-density polyethylene
- HPC – Heterotrophic plate count
- ML - Mega litres
- Mn – Manganese
- NOM – Natural organic matter
- NTU – Nephelometric turbidity unit
- Ofwat - The water services regulation authority
- Pb - Lead
- PVC - Polyvinyl chloride

- ROV – Remotely operated vehicle
- SEEL – Sustainability, energy, and environment laboratory
- SI - Spun iron
- SR – Service reservoir
- SUVA - Specific UV absorbance
- TOC – Total organic carbon
- U - Uranium
- UV – Ultraviolet light
- WHO – World health organisation
- WTW – Water treatment works
- WQZ – Water quality zone
- Zn – Zinc

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Chapter 1: Introduction

Drinking water is the most vital human resource on the planet. As a race, humans have engineered sophisticated drinking water distribution systems (DWDSs) that allow the collection, treatment, storage, and delivery of drinking water at the turn of a tap. It is the responsibility of drinking water utilities to implement appropriate management strategies to sustain the production of a sufficient supply of safe and clean drinking water to consumers (DWI, 2020). If this is not done properly, water quality related aesthetic and public health risks can emerge. These risks tend to emerge from the eventual fouling of all DWDSs due to the accumulation of organic and inorganic materials within, which, if not managed properly, can lead to asset deterioration and issues like discolouration and bacteriological contamination (Husband and Boxall, 2011; DWI, 2020). Outbreaks of infectious water-related diseases are responsible for millions of hospitalisations and deaths worldwide each year (Hunter, 1997), and although contamination rates in the UK and Ireland are lower than in more economically deprived countries, outbreaks do still occasionally occur. For example, tens of thousands of consumers in Wales were exposed to water contaminated with *Cryptosporidium* in 2005 and again in 2008 (Carnicer-Pont et al., 2005; Mason et al., 2010), and in 2007, over 120,000 people were affected by a waterborne outbreak of *Cryptosporidium* in Ireland (Chyzheuskaya et al., 2017).

The primary management of water quality risks and system performance involves the removal of contaminants during treatment and treating the water with a combination of technologies. Post treatment, water quality can change and deteriorate as it travels through the DWDS and so water utilities carry out regular water quality monitoring at various stages of the DWDS to track any emerging water quality issues and identify which assets require maintenance. Although the current UK monitoring and maintenance programme is considered good practice in comparison to some other parts of the world, fundamental limitations remain. A key limitation is that the number of monitoring locations across the DWDS is sparse, making it difficult to link the performance of one stage of the system to another (Speight et al., 2019).

Service reservoirs (SRs) store treated water and balance supply, maintaining demands in the DWDS; they are crucial and integral components of the system. Yet, when it comes to the understanding of their performance, assessment, and maintenance, they have not been afforded the same attention as other stages of the DWDS, such as water treatment works (WTW) and pipes (NRC, 2006). For instance, key indicator water quality parameters (e.g., metals, turbidity, pH, conductivity, disinfectant residual, and bacteriological indicators) are regulated at WTW and customer taps. Whereas disinfectant residual and bacteriological indicators are the only regulated parameters at SR outlets (DWQR 2018;

DWI 2020). There is also no regulatory requirement to monitor water quality at SR inlets, making it impossible to track water quality changes with travel through these assets, or to attribute any observed changes in water quality directly to the SR (Grayman et al. 1999; Kirmeyer et al. 1999). The lack of inlet sampling and monitoring for a greater range of water quality parameters substantially limits the amount of information that could be obtained on SR performance and on water chemistry, microbiology, and parameter interactions within SRs (Grayman et al., 1999; Brandt et al., 2016). The ability to assess SR performance and its effect on water quality is imperative to maintaining high-quality drinking water at this stage of the network, especially as SRs are often associated with water quality deterioration linked to problematic processes like long retention times, ineffective mixing, and accumulation of material being prevalent in these assets. The range of drinking water quality problems associated with SRs range from nitrification, stagnation, and degradation of disinfectant residual to significant waterborne disease outbreaks (Clark et al. 1996; Craun and Calderon 2001; NRC 2006). SRs have been identified as a source of pathogen contamination that has resulted in serious illness and even death. For example, a 1993 *Salmonella typhimurium* outbreak in Gideon, Missouri, which stemmed from a SR, resulted in 15 hospitalisations, and 7 deaths (Clark et al., 1996a).

Drinking water is a vital but also perishable resource and its deterioration remains an important issue for water utilities, regulators, and most importantly, consumers. Despite the knowledge that SRs can cause both minor and major water quality deterioration, these assets are often overlooked, and, at present, there is no effective way to assess or quantify their performance, leaving them as a black box of the system. This lack of understanding is dangerous in that it prevents utilities from identifying potential water quality issues and means that most SR related issues are dealt with in a reactive manner, usually once the damage has already been done. Therefore, research on developing a way to assess SR performance and better understand their effect on water quality is essential in order to move towards effective and proactive operational management of these assets and the surrounding network, which will sustain both the distribution infrastructure and a high-quality water supply into the future. Throughout the literature review, key gaps in knowledge will be highlighted and future research needs suggested.

Chapter 2: Literature Review

2.1. Introduction

Service reservoirs (SRs) have been documented to impact water quality, yet these assets are often overlooked and not studied as often as other stages of the drinking water distribution system (DWDS), like pipes and water treatment works (WTW). The few studies that have looked at SRs tend to investigate hydraulic processes such as mixing conditions, not water quality. Furthermore, SR related research has typically been conducted in laboratory settings (non-representative of a real system), and therefore does not provide the perspective needed to understand SR performance in relation to the rest of the system. This literature review highlights that a huge opportunity is being missed to obtain great value from SRs through the assessment of their performance, the optimisation of which could enable these assets to not only function as vessels for water storage, but as beneficial stages in the delivery of high-quality drinking water.

2.2. Drinking Water Distribution Systems

A DWDS is a network of engineered hydraulic components that delivers water to consumers at an appropriate quantity and quality. In basic terms, these systems carry raw water from a water source (surface or ground), via WTW, storage facilities, and pipes, and out to customer taps as potable drinking water (Figure 2.1). They also provide water for irrigation, fire suppression, and other non-potable uses (AWWA, 1998). DWDSs vary in size and can range from ones that provide water to remote villages to those that serve millions. The majority of the system is made up of pipes of varying length, diameter, age, and material (plastic, iron, cement) which are buried underground (Vreeburg and Boxall, 2007; AWWA, 2012). In the UK, most of the pipework is cast iron, as this was the popular choice of material at the point of installation during the late 19th century (NRC, 2006). However, most systems are now coming close to the end of their life spans, and are being replaced with plastic (NRC, 2006).

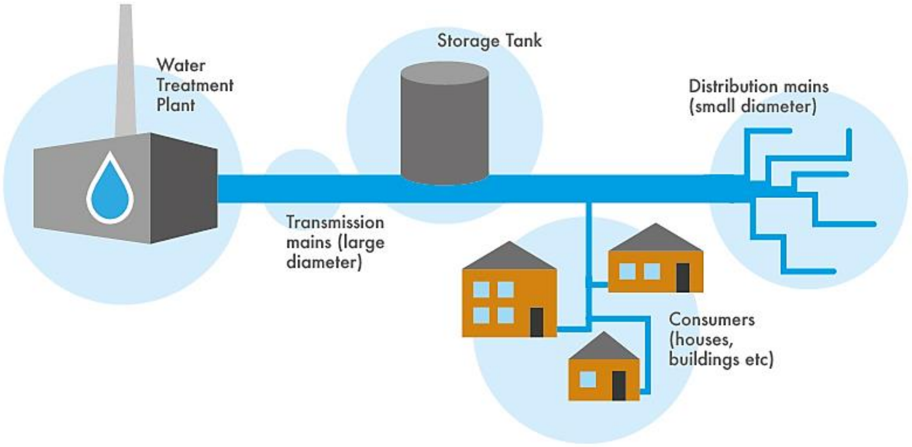

Figure 2.1 – **A basic layout of a standard drinking water distribution system. Image adapted from Linden et al. (2019).**

2.3. Water Quality, Customers, and Regulations

It is recognised that monitoring water quality immediately after it leaves the WTW cannot provide a representative analysis of water quality at customer taps (NRC, 2006; Jjemba et al., 2014). DWDSs are large-scale biological and chemical reactors, which means water quality can change as it makes its way through the DWDS, primarily through interactions with pipe and tank walls, and due to any hydraulic disturbances, planned or unplanned, along the way (LeChevallier et al., 1996; Vreeburg and Boxall, 2007; Blokker et al., 2016). The characteristics of every DWDS are unique, influenced by source water type, WTW processes, construction material, age, and the system's operational management and maintenance (Blokker et al., 2016). Although water quality deterioration is often associated with older and more stressed systems, problems also arise in new or recently improved ones (Larson, 1966; Brandt et al., 2016).

Numerous factors can affect water quality on its journey from source to tap, and in order to maintain high water quality and remain compliant with regulations set by drinking water regulators, it is of high importance that water utilities understand how to manage their systems comprehensively (Husband and Boxall, 2010). In the UK, regulators are either the Drinking Water Inspectorate (DWI) (for England and Wales) or the Drinking Water Quality Regulator for Scotland (DWQR), and The Water Services Regulation Authority (Ofwat). Their role is to ensure water utilities monitor and report the quality of water in the interest of public health and that water utilities carry out their statutory functions properly (Husband and Boxall, 2011; Ofwat, 2021). In Europe and the UK, water utilities have a set of drinking water standards under the Drinking Water Directive legislative act that they need to abide by (Council Directive, 1998). These standards come under two general categories, primary standards that are based on health considerations and secondary standards that involve aesthetic water quality issues. Water utilities are expected to implement appropriate management strategies to mitigate any potential standard breaches, which would be considered as water quality failures (Husband and Boxall, 2010). Failures can be classified into three categories: physical (aesthetic), microbiological, and chemical (Mounce et al., 2016).

Water utilities primarily manage water quality related issues and system performance by removing contaminants during treatment and treating water with a combination of technologies (Moel et al., 2006; Liu et al., 2013). The way this is done varies across different countries. For example, to manage bacterial regrowth some countries rely on disinfection residual in the system, whereas others rely on nutrient control (AWWA, 2011). Source water type also plays a role; surface water (reservoirs, lakes, and rivers) can vary in its composition throughout the seasons and requires extensive treatment before it is safe to supply, whereas groundwater (aquifers and boreholes) tends to be more stable (Hydes, 1999). However, irrespective of these differences, the overall goal is always the same, to provide safe, wholesome drinking water (WHO, 2011).

To monitor system performance, water utilities carry out routine water quality monitoring at various stages of the DWDS, primarily at the WTW, SR outlets, and customer taps (Blokker et al., 2016). Numerous samples are collected each year, for instance, water utilities across England tested 3,502,637 water quality samples in 2019 (DWI, 2020). Although taken for compliance purposes, most data is archived without being utilised and analysed for a deeper understanding of system performance. Such archives traditionally include historic asset records, customer contacts, and discrete and continuous water quality sample data. Despite the volume of data collected and stored, the number of monitoring locations across the DWDS is sparse, making it difficult to link the performance of one stage of the system to another (Speight et al., 2019). For instance, there are approximately 23 million households supplied in England, yet only 1,767,048 samples were collected at customer taps in 2019, which means that water quality monitoring was not conducted at over 21 million households that year (DWI, 2020). Additionally, other parts of the network do not have any regulatory requirements for water quality monitoring at all, such as at the inlets of SRs.

When reported, customer perception of water quality is a direct indicator for potential issues in the network (Vreeburg et al., 2004). For instance, aesthetic complaints are not only indicators of changes in water quality but are also signs of potential contamination in supply (AWWA, 2011). For example, during the 1993 *Cryptosporidium* outbreak in Milwaukee USA, there were significantly more water quality complaints prior to the issue being identified (Proctor et al., 1998). Customer complaints are also a major driver for UK water utilities as they may be fined large sums for each customer complaint, and these costs can rapidly escalate if standards are not maintained (Mounce et al., 2015). Relying on customer complaints to improve system management means that issues are often dealt with in a reactive manner (Blokker and Schaap, 2015). A proactive approach is considered more desirable as an effective and reliable control of water quality and system performance (Husband and Boxall, 2016).

2.4. Service Reservoirs: An Overview

Service reservoirs (SRs) are treated water storage tanks, used to balance water supply and maintain diurnal demand in the DWDS (Brandt et al., 2016). They can be either underground, ground level, or elevated (water towers) structures (Figure 2.2), of which there are approximately 6,500 public ones across the UK (DWI, 2014). At present, there are more underground SRs than there are water towers, mainly because the construction of new water towers is considered less economically viable than underground SRs due to the efficacy of new pumping technologies, which require less energy and expense to force water into the network, thus the reliance on hydrostatic pressure from elevated SRs has decreased (UKWIR, 2019). Additionally, underground SRs can store more water and have better temperature regulation than water towers.

Figure 2.2 – An example of an underground service reservoir (A) and an overground water tower (B).

The storage of treated water gained its importance in the 19th century with the increasing need to meet the demands of the growing population and to protect water supplies from deteriorating or becoming contaminated in the interest of public health (Brandt et al., 2016). SRs also help to manage system pressure and are used to store a supply of water in case of emergencies, such as network failures (e.g., bursts) and fire demands, and are placed strategically within the DWDS to meet those demands (Brandt et al., 2016). SRs are therefore crucial and integral components of DWDSs.

SRs come in a variety of materials, shapes, and sizes. In the UK, the earliest SRs were masonry; usually brick on a concrete base. The roofs were traditionally built as an arch and were supported on masonry columns; some are still functional. Because masonry SRs are prone to movement, they are also prone to cracks, which can lead to operational and water quality issues. Therefore, they tend to be replaced or built with reinforced concrete, with flat instead of vaulted roofs, typically covered with earth and grass for aesthetics and insulation (Figure 2.3). Any air vents near the roof of the SR should be protected with a fine mesh as these gaps are prone to colonisation by flying insects, who prefer cold and damp surfaces to lay their eggs on (Brandt et al., 2016).

Figure 2.3 – An underground service reservoir with a grass covered roof.

SRs can also be constructed using steel, polypropylene, or glass reinforced plastic (GRP) (Brandt et al., 2016). However, concrete is by far the most popular construction material, with over 85% of all UK SRs built with some form of concrete (UKWIR, 2019). GRP is rarely used, as the material is prone to water absorption, delamination, blistering, and microbiological build up (Figure 2.4). Steel is also an undesirable choice as it easily heats to high temperatures if exposed to sunlight, which can result in numerous water quality issues (UKWIR, 2019).

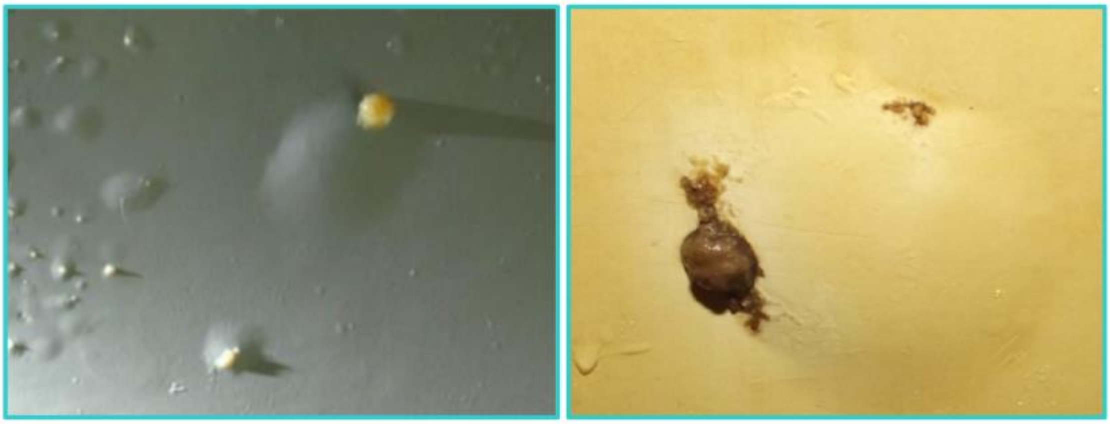

Figure 2.4 – An example of blistering and biofilm growth on glass reinforced plastic service reservoir walls. Image source: UKWIR (left) and Northumbrian Water (right).

Internal SR structures, such as ladders and pipes, can be made from a variety of materials, including plastic, metals (iron, steel, aluminium alloy), or reinforced concrete. In every SR, there is usually at least one inlet and outlet pipe, an overflow, withdrawal, and a SR bypass pipe. There is usually also a channel on the floor leading to a drainage sump and/or scour to drain away water and material during a SR inspection or clean. The floor and columns (if present) tend to be of the same material as the rest of the SR (Brand et al., 2016).

SRs vary in size, which depends on the demands of the DWDS. In the UK, SR capacity ranges from anywhere below 0.05 ML to over 270 ML (UKWIR, 2019). SRs can be comprised of more than one compartment and tend to be built with two so that when one is drained for maintenance, the other can remain in operation (Brandt et al., 2016). In regards to shape, SRs can be rectangular, circular, or square. For visual examples of various SR types, please refer to Chapter 5: Site Details, which contains photos and SR schematics of SRs studied in this research.

To ensure the safety of supply and to assess SR performance, water utilities in the UK are required to monitor water quality at the outlet of SRs on a weekly (discrete) basis (DWI, 2018). There is a set standard, ISO 5667-5, that all regulatory outlet sampling points must meet (DWI, 2018). As part of that standard, all sample lines should be located as close as possible to the SR to ensure that samples are representative of the water being supplied by the SR and to decrease contamination risk (UKWIR, 2019). The sample line should also be no more than 25 mm in diameter and should deliver a flow of 0.1-0.2 l/s to the sample tap. Where a SR has more than one compartment, and the two are not hydraulically connected, there should be a separate outlet sample tap at each compartment. If they are hydraulically connected, one common outlet sample tap is used (Figure 2.5). Where a SR has a single ebb flow main serving as both the inlet and outlet, samples should only be taken when the main is acting as an outlet (UKWIR, 2019).

Figure 2.5 – **An example of a regulatory service reservoir outlet sample tap.**

The current UK SR monitoring programme is considered good practice in comparison to other countries, like the US, where there is no specific regulatory requirement for routine sampling at SRs at all, although some utilities still carry out sampling at SRs (Kirmeyer et al., 1999). However, the lack of inlet monitoring at SRs in the UK makes it difficult to attribute any observed changes in water quality between the previous sampling point and the SR outlet, directly to the SR. For instance, over 66% of bacteriological failures in water quality samples collected at SR outlets in the UK have not been directly attributed to the SR (UKWIR, 2019), potentially because the source of failure was actually upstream of the asset. Kirmeyer et al. (1999) and UKWIR (2019) argue that to successfully assess SR performance, pinpoint the location of water quality problems, predict and prevent potential future issues, and avoid costly repeat errors, routine sampling at SRs should, at the least, include both inlet and outlet monitoring, and, ideally, at least one representative location within the facility. They state that monitoring and assessing water quality performance of SRs provides valuable information not only on that asset, but also on the operational management of the DWDS in general.

The water quality parameters stipulated by regulation to be monitored at SR outlets are disinfectant residual and bacteriological indicators (DWI, 2018). In practice, water utilities regularly report that these requirements are limited in providing information on SR performance and in identifying the root cause of water quality failures at SRs (UKWIR, 2019). This notion is also supported by the chief inspectorate of the DWI (DWI, 2018). Sampling for other parameters, such as turbidity, metals, nitrite, nitrate, temperature, and pH, which are monitored at other stages of the network, can provide additional information on asset performance, such as water age, seasonal impacts, and rate of water quality deterioration (Grayman and Kirmeyer, 2000; AWWA, 2012). Although, prior to developing an additional monitoring programme at SRs, it is important for water utilities to evaluate their needs as it is not necessary to always monitor for all additional parameters at all SRs (Grayman and Kirmeyer, 2000). For instance, measuring nitrate and nitrite in a chlorinated system may not be as informative as measuring these parameters in a chloraminated system where there is a higher risk of nitrification due to the addition of ammonia as part of the chloramination process.

The discrete once a week sampling at SR outlets is also limiting in that this data cannot capture real-time changes in water quality or rapidly determine developing trends, restricting operational insight into SR performance (ATi, 2021). The use of continuous online monitoring equipment for water quality parameters, commonly chlorine, pH, temperature, and turbidity, is becoming more popular in DWDSs (Douterelo et al., 2018; DWI, 2020). However, at present, online monitoring is rarely utilised at SRs (UKWIR, 2019). Kirmeyer et al. (1999) and ATi (2021) suggest that monitoring chlorine residual in real-time at SRs can help inform water utilities on how to proactively manage residual levels in the DWDS. In general, the combination of both discrete and continuous water quality monitoring at SRs would be a vast improvement on the current regulatory sampling at SRs, providing a much more comprehensive assessment of asset performance, especially if also coupled with SR flow and level data (Grayman and Kirmeyer, 2000; UKWIR, 2019; ATi, 2021). Improving monitoring programmes at SRs may also help alleviate some of the pressure water utilities experience with the low replacement rate of ageing assets by improving understanding of asset performance and therefore management, thus extending asset life (Hope, 2016).

2.5. Service Reservoirs: Effect on Water Quality

2.5.1. Introduction

Water is subjected to a variety of complex reactions and interactions as it travels through the DWDS (Kirmeyer et al., 2000). Some parameters and reactions considered to have the most impact on water quality across DWDSs include loss of disinfectant residual, disinfection by-product (DBP) formation, bacteriological growth, nitrification, material accumulation, corrosion, discolouration, pH, and temperature (USEPA, 2002; Machell et al., 2010; AWWA, 2011; Brandt et al., 2016). Figure 2.6 below demonstrates how these and other water quality parameters and related processes interact and influence one another in SRs.

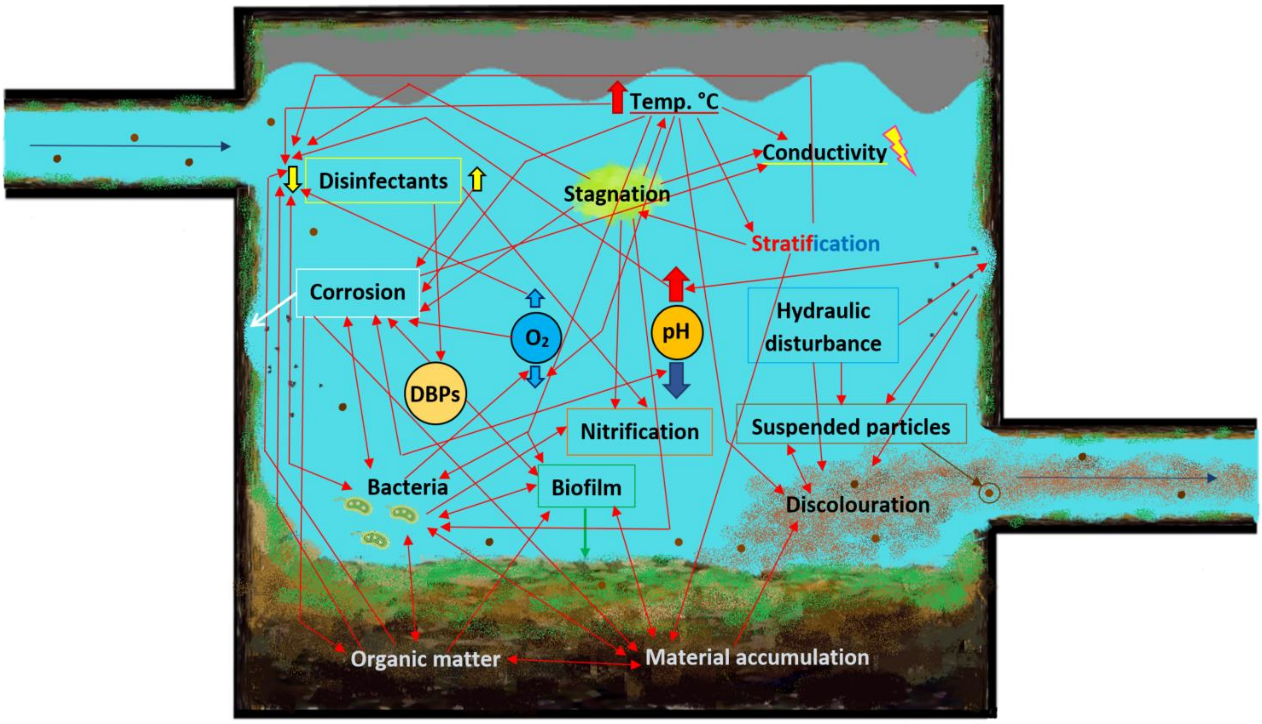

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Figure 2.6 – **A diagram demonstrating how different water quality parameters and processes related to DWDSs interact and influence one another in a service reservoir. The red arrows point in the direction of cause to effect, for instance, material accumulation can lead to discolouration events. Where arrows point in both directions the cause and effect is interchangeable, for instance, bacteria can contribute organic matter into the system, and organic matter can act as a food source for bacteria.**

As most of the parameters and reactions in Figure 2.6 are kinetic in nature, their effect on water quality positively correlates with residence time (or water age) of the system (USEPA, 2002). As water is frequently stored in SRs longer than at other stages of the DWDS, SRs are often associated with water quality deterioration (Mahmood et al., 2005). In general, SRs are often associated with having a negative effect on water quality (Grayman and Kirmeyer, 2000). However, issues seen in SRs are similar to those at other stages of the DWDS in that system design and maintenance, construction material, operational management, and environmental factors all influence asset performance (NRC, 2006). Nevertheless, perhaps because SRs are perceived to have a peripheral role in meeting storage and hydraulic requirements in the DWDS, they have not been afforded the same attention as pipes and WTW when it comes to the understanding of their performance, assessment, and maintenance (NRC, 2006). This was highlighted by the chief inspectorate of the DWI, who, in a recent report, stated that there is a lack of investment and priority afforded to this stage of the DWDS and that this needs to change (DWI, 2018). This section explores and describes a variety of changes water quality can undergo as it travels through the DWDS and the possible effect SRs can have on these changes.

2.5.2. Material accumulation

2.5.2.1. Suspended solids and material accumulation

Physical, chemical, or biological changes to water quality tend to come about from the fouling of all DWDSs, associated primarily with the accumulation of organic and inorganic materials (Larson, 1966; Kirmeyer et al., 2000; USEPA, 2002). Material can settle out in DWDSs, the gradual accumulation of which can come from external or internal sources (Vreeburg and Boxall, 2007). Externally, material can enter through ineffective treatment of source water, the addition of particles as part of treatment, or external contamination (e.g., through ingress) (Gauthier et al., 2001; Vreeburg et al., 2004; Douterelo et al., 2014). Internally, material can come from corrosion by-products, leaching of compounds from coatings of construction material, biological growth, and chemical reactions (Gauthier et al., 2001; Slaats et al., 2003; AWWA, 2011).

Typical locations for material settling are areas of low flow, such as dead ends and SRs (Brandt et al., 2016; Qin et al., 2017). Accumulation of material in SRs is an especially prevalent process, primarily associated with low velocities in these assets, which allow suspended material entering storage to settle on interior surfaces (Figure 2.7) (Grayman and Kirmeyer, 2000). The rate of material accumulation in SRs can also be exacerbated by poor mixing conditions (Kirmeyer et al., 1999; Speight et al., 2009).

Figure 2.7 – Examples of accumulated material from three different service reservoirs. Image source (from left to right): Severn Trent Water, Northumbrian Water, and Panton McLeod.

The most common constituents in DWDS accumulated material are carbon, iron, manganese, calcium, magnesium, phosphorous, aluminium, and zinc, which vary in concentration throughout the system (Gauthier et al., 1996; Gauthier et al., 1999; Friedman et al., 2010; Lytle et al., 2012). The accumulation of individual particles can shield bacteria and provide sanctuary from disinfectants (Smith et al., 2006; Brandt et al., 2016). Particles can also carry nutrients, such as organic carbon, that can support biofilm growth (Zacheus et al., 2001). Gauthier et al. (1996), who collected material from trunk mains and SRs, and Qin et al. (2017), who collected material from SRs, both found that samples were colonised by microorganisms. Liu et al. (2014) found that, in general, DWDS material harbours 60-90% of all microorganisms in DWDSs.

Resuspension of accumulated material can lead to the degradation of the safety of the water supply by decreasing disinfection efficacy and introducing viable microorganisms into the system (Twort et al., 2000, AWWA, 2011). For instance, *Salmonella typhimurium* that caused a deadly outbreak in Missouri in 1993 was isolated from material that had accumulated in a SR, which entered the downstream network upon remobilisation (Kramer et al., 1996). More recently, Qin et al. (2017) found that collected SR accumulated material contained viable opportunistic pathogens. Resuspended material can also alter the aesthetic quality of the water by discolouring it and changing its taste and odour (Frateur et al., 1999; Grayman and Kirmeyer, 2000).

Remobilisation of accumulated material can be triggered by changes to the normal operating flow regimes of water in DWDSs, including planned works, flushing activities, unplanned bursts, high demand, and filling and draining cycles of SRs (NRC, 2006; Vreeburg and Boxall, 2007; Husband et al., 2008). In SRs, water is often drawn from the bottom to maximise storage volume where material accumulation is prevalent, meaning that, aside from a hydraulic event, material can also remobilise and enter the downstream network if the accumulative capacity of material is exceeded in the asset (Kirmeyer et al., 1999; Speight et al., 2009; AWWA, 2011).

Under regular and stable operational conditions, DWDSs can be described to be functioning as sinks of material (Parsons and Jefferson, 2006; Vreeburg and Boxall, 2007). If material remobilises and enters the downstream network, the DWDS becomes a source of material (Vreeburg and Boxall, 2007). Describing the behaviour of a system, as a ‘sink or source’ is not a new concept in other disciplines. For example, the concept is applied to research on ecosystems and construction materials with respect to their sequestration and release of nutrients, elements, and compounds (Oechel et al., 1993; Kumar and Little, 2003; Chen et al., 2008; Ma et al., 2021). However, the concept has not been widely applied to the water industry as a way to assess DWDS performance. The only reference of the concept in drinking water research relates to corrosion scales in pipes serving as a source or sink of various organic and inorganic contaminants (Rushing et al., 2003; McFadden et al., 2011; Benson et al., 2012; Sun et al., 2017). The knowledge that material accumulates at all stages of the DWDS could serve as a potential introduction of the ‘sink or source’ concept as a way to measure system performance.

Controlling the accumulation of material in DWDSs is a challenge for water utilities (Ginige et al., 2011). Periodic cleaning of the DWDS and removal of material is considered a necessary control measure (NRC, 2006). For instance, material is regularly removed from SRs; details on how this is done can be found below in section 2.6.1. Improving coagulation, flocculation, clarification, and filtration processes that remove suspended particles at the stage of treatment is considered preferable (Vreeburg and Boxall, 2007; AWWA, 2011). Some argue that irrespective of the lengths water utilities take to remove material, DWDSs can never be fully free of particles or microorganisms (Carrière et al., 2005). Carefully and proactively managing the rate and location of material accumulation therefore needs to be considered.

Understanding the origin and composition of particulate matter is important in improving its management and overall system performance (AWWA, 2011). Unfortunately, material accumulation is a complicated process involving many factors, and is currently not well understood (Vreeburg and Boxall, 2007). Moreover, sampling material in DWDSs is difficult, which is why material accumulation processes are largely overlooked (Liu et al., 2013). To overcome this, a lot of research is now being applied to the improvement of water quality monitoring in the DWDS, although, most of the focus is on WTW, pipes, and customer taps, not SRs (Douterelo et al., 2018).

2.5.2.2. Turbidity

Turbidity is a measure of suspended material in water and can be used to indicate water quality issues or contamination events (Figure 2.8) (Blokker et al., 2015). Turbidity is strongly correlated with discolouration events, and iron and manganese deposits (Seth et al., 2004; Douterelo et al., 2014). It is also associated with unpleasant tastes and odours of the supply and a drop in disinfection efficacy (AWWA, 2011).

Figure 2.8 – A set of several water samples showing increasing turbidity (left to right), as well as changes in colour. Image source: Village of Chase, British Columbia.

A turbidity measure is obtained by detecting light scattered off particles; higher particle concentration results in greater light scattering (LeChevallier et al., 1981). This is typically measured in Nephelometric Turbidity Units (NTU), using a nephlometer. Treated potable water should have a measure of < 1 NTU

(Brandt et al., 2016). However, up to 4 NTU is allowed if the water utility can provide evidence that turbidity did not interfere with the normal operational regime, including disinfection (LeChevallier et al., 1981; DWI, 2014). Turbidity levels can vary throughout the diurnal cycle and with operational changes in the DWDS (Vreeburg and Boxall, 2007). For instance, Lehtola et al. (2004) found that turbidity was highest in the DWDS at 9 pm, when water consumption is also typically at its highest. To account for such fluctuations, turbidity is continuously monitored at WTW and frequently at customer taps, however it is seldom measured at night (outside of normal sampler hours) or at other stages of the DWDS, such as SRs (not required by regulation) (van den Hoven and Vreeburg, 1992; Vreeburg and Boxall, 2007). Although, the use of portable online turbidity monitors with advanced logging and communication features is becoming more popular at all stages of the DWDS (Vreeburg and Boxall, 2007). This equipment provides the means to record real-time changes in turbidity across the DWDS, helping to improve the assessment and understanding of system performance.

There are some drawbacks to using turbidity as a measure of suspended material in that the quantification of light scatter can be influenced by other factors, like air bubbles, which can cause an inaccurate measurement (Russell, 1994). Although, modern turbidity monitors are believed to provide more accurate turbidity measurements, with less chance of incorrect readings being caused by entrained air (DWI, 2018). Even with setbacks, at present, turbidity remains the primary indicator of suspended particles in supply (Boxall and Saul, 2005; Parsons and Jefferson, 2006).

2.5.2.3. Organics: Carbon

Natural organic matter (NOM) in drinking water originates externally from the breakdown of naturally occurring organic material in source water, ineffective removal of it at WTW, and from treatment additives and chemicals (Parsons and Jefferson, 2006, AWWA, 2011). Internally, NOM can originate from materials within the DWDS, such as pipes, internal coatings, and SR walls and floors (Szewzyk et al., 2000). The presence of NOM, usually in the form of accumulated particulate matter, is considered the main cause of microbiological growth, and general water quality deterioration (Gauthier et al., 1999, Liu et al., 2002).

The overall NOM in drinking water is quantified in terms of total organic carbon (TOC) (AWWA, 2011). This is because carbon is the most important organic nutrient in the DWDS as it is the limiting factor for heterotrophic bacterial growth (AWWA, 2011). TOC is composed of dissolved organic carbon (DOC) and particulate organic carbon (AWWA, 2011).

Significantly reducing concentrations of NOM (especially TOC), as well as using construction materials that do not leach organic compounds into the water supply (e.g., uncoated SR concrete surfaces) is likely to be an effective way to control biological stability and improve disinfection efficacy in DWDSs (van der Kooij et al., 1982; Volk and LeChevallier, 1999; Ginige et al., 2011). However, this is often difficult to achieve, as, at present, little is understood about the abundance, location, and role of NOM in DWDSs (Gauthier et al., 1999).

2.5.2.4. Inorganics: Metals

2.5.2.4.1. Iron and manganese

An inorganic compound is a chemical compound that does not contain carbon (Parsons and Jefferson, 2006). All inorganic compounds in the DWDS influence water quality, but the most prominent influence comes from metals, primarily iron and manganese. Water percolating through rock and soil dissolves minerals with iron and manganese, which means that both metals are found in every water source, but their concentrations vary based on the geology of the area and source water type (surface or ground) (Brandt et al., 2016). For instance, in comparison to iron, concentrations of manganese tend to be higher in groundwater (Brandt et al., 2016). However, overall, iron is the more predominant metal in the DWDS (Gauthier et al., 1996; Boxall et al., 2003). One of the reasons for grouping these two metals together is because oxidised manganese (MnO_2) is a very effective adhesive of ferrous iron (Fe^{2+}) and so they are often found in conjunction with one other (AWWA, 2011). In DWDSs, sources of iron and manganese can come from the corrosion of metallic structures and carry-over from ineffective removal at WTW (Vreeburg et al., 2008; Peng and Korshin, 2011). Upon contact with oxygen or disinfectant, both metals are oxidised, and are no longer soluble in solution, which can lead to water quality issues (Brandt et al., 2016). Although, there are no health-based guidelines for concentrations of iron and manganese in drinking water, there are aesthetic based ones (Sharma et al., 2005). In the UK, the limits are 0.2 mg/l for iron and 0.05 mg/l for manganese (DWI, 2014). With higher concentrations, the metals can precipitate out and discolour the water supply a reddish or brown-black colour (Slaats et al., 2003; Seth et al., 2004). Although the two metals are very similar, there are specific chemical and physical properties of each, which are discussed below.

Iron

Iron is considered the most problematic metal in the DWDS. In nature, iron is present in two main forms: (1) ferrous iron (Fe^{2+}), the most common form, which is soluble in water and can taint it a brown-black colour, and (2) ferric iron (Fe^{3+}), which is insoluble in water and tends to precipitate out as a red-black-brown particulate (Colter and Mahler, 2006; Li et al., 2016). In DWDSs, not only is iron present in bulk water, but most of the pipework and some internal SR structures are constructed out of iron-based material (AWWA, 1996; Swietlik et al., 2012). In fact, cast (CI) or ductile iron (DI) pipework accounts for three quarters of the DWDSs across the world (Veschetti et al., 2010). Soluble iron (Fe^{2+}) is often found in reducing areas (low or absent in oxygen, leading to the gaining of electrons by metals) of the network e.g., dead ends, stagnant waters, and within pipe scale (AWWA, 2011). It is oxidised to its insoluble form (Fe^{3+}) upon exposure to oxygen or disinfectant, which then collects as deposits in the system (AWWA, 2011; Benson et al., 2012). Some factors affecting the quantity of iron in supply include pH, temperature, microbiology, the amount of oxidant available, and phosphates and silicates, which are sometimes added to water to prevent the oxidation or precipitation of iron (Lytle et al., 2002; AWWA, 2011).

Iron is released into the network as a result of two main processes: physical force and dissolution (AWWA, 2011). Physical force is usually associated with hydraulic changes, such as the dislodgement of material from a surface due to a change in shear stress or flow velocity (AWWA, 2011). Dissolution results from chemical processes such as corrosion, which is one of the biggest contributors of iron to the system (Sarin et al., 2004; AWWA, 2011). At concentrations as low as 0.3 mg/l iron deposits can discolour the water and appear as suspended black pieces, which usually happens when the particulate form is dislodged somewhere along the network (Sarin et al., 2004). Seth et al. (2004) found that iron is the dominant material mobilised regardless of pipe type, which means that it is transported throughout the DWDS. The discolouration caused by oxidised iron (Fe^{3+}) not only makes the water appear unattractive but can also stain household fittings and laundry, which leads to customer complaints and penalties for water utilities (Seth et al., 2004; Colter and Mahler, 2006). The above problems can be reduced if iron is removed at the source, and there are ways to control the corrosion of iron pipes in the network (Lytle et al., 2002).

Manganese

Manganese, a naturally present metal in surface and groundwater sources, is less prominent in DWDSs than iron, but is just as much of a problem to water utilities (WHO, 2011). Like iron, manganese is easily oxidised to its insoluble form when in contact with oxygen or disinfectant. Manganese has eleven oxidative states, but its most stable form is soluble Mn^{2+}, which can enter the network when there is inadequate removal of manganese during treatment (Sly et al., 1990). It is then oxidised further by disinfectants to its insoluble state, Mn^{3+} or Mn^{4+}, which precipitates out as a dark black particulate substance or slime (Manceau et al., 1992; Gerke et al., 2016). Manganese can also be released from materials within the DWDS, such as iron or polyvinyl chloride (PVC) pipes (Cerrato et al., 2006; Peng et al., 2010). Precipitation of manganese can lead to discolouration and fouling of the DWDS, which can happen at concentrations as low as 0.02 mg/l (Booth and Brazos, 2004; Dietrich, 2006). At levels of 0.1 mg/l manganese imparts an unpleasant metallic taste to water and stains laundry and internal fixtures in customers' homes, leading to complaints (Griffin, 1960; Brandt et al., 2016). Finally, manganese oxides are capable of adsorbing metal ions and NOM, which can lead to contamination of the network with bacteria and other unwanted substances (Manceau et al., 1992). As with iron, the above problems can be lessened by the removal of manganese during treatment and through regular maintenance of the DWDS (Parsons and Jefferson, 2006).

Speciation of iron and manganese

The variation in different metal forms is referred to as 'speciation', which is defined as the oxidation state and the chemical form of the metal. The speciation and solubility of metals is highly dependent on pH. Figure 2.9 represents simplified versions of the Pourbaix diagram, which depicts the prevalence of the most stable species of Fe and Mn in aqueous solution as a function of electrode potential (on the y-axis) and pH (on the x-axis). Generally, an increase in the solubility of both metals (Fe^{2+} and Mn^{2+}) is observed in more acidic conditions, whereas a higher pH is required to oxidise iron and manganese to their insoluble forms (Fe^{3+}, Mn^{3+}, and Mn^{4+}) (Prasad and Danso-Amoako, 2014; Rumsby et al., 2014; Tan et al., 2015). However, lower pH can also lead to the oxidation of metals under higher electrode potential (Sarin et al., 2004).

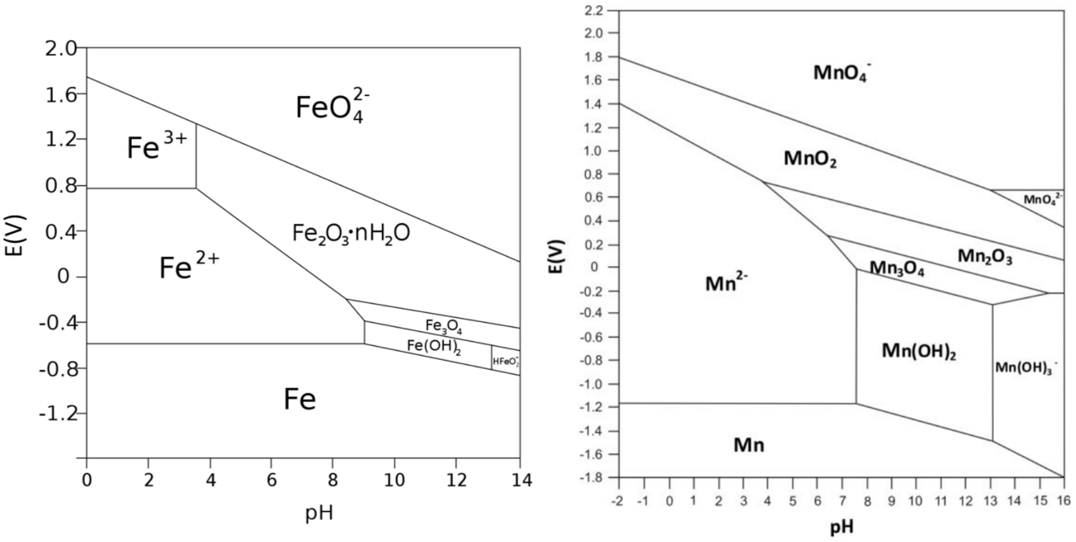

Figure 2.9 – EV-pH Pourbiax diagrams for iron (Fe) and manganese (Mn) oxides and hydroxides respectively (Pourbaix, 1974).

2.5.2.4.2. Aluminium

Although iron and manganese are the predominant metals of concern in the DWDS, other metals such as aluminium, lead, zinc, and copper are also common, and can influence the quality of the water supply (Seth et al., 2004). Aluminium is not a common structural material in DWDSs but is frequently used in water treatment. Aluminium and ferric salts are the most common chemical additives used in coagulation, which is a treatment process that facilitates agglomeration of suspended particles and dissolved organic and inorganic contaminants into larger particles (flocs) so that these can be physically removed during treatment (Parsons and Jefferson, 2006). If not properly controlled, excess aluminium residuals can enter the DWDS through the means of carry-over from the WTW (Parsons and Jefferson, 2006).

2.5.2.5. Metals: Associated system processes

Metals entering treatment in source waters are predominantly in their insoluble, particulate forms. After the process of their removal during treatment, any metals that are still carried over into the DWDS tend to be in their dissolved, soluble forms. As water travels through the network, soluble metals can precipitate out and accumulate in the system on internal surfaces as a result of chemical and microbiological influences on their chemical states (e.g., changes in pH, temperature, microbiological sequestration). Internally, metals can be released as corrosion by-products, both in their insoluble and soluble forms, the latter of which can later change state and precipitate out in the network. Accumulated material that contains metal particulates can cause discolouration events when remobilised (Husband and Boxall 2011).

2.5.2.5.1. Corrosion

Corrosion describes the degradation of materials that happens when they react with their environment (NRC, 2006). In DWDSs, it affects all kinds of materials, including cement-based structures (AWWA, 2011). However, it is mostly prevalent on metals; especially iron (Nawrocki et al., 2010). Corrosion is one of the biggest problems in the drinking water industry as it can influence public acceptance of water quality, and, most importantly, affect public health (Edwards, 2004). Corrosion also deteriorates assets and can incur huge costs in resources, maintenance, and repairs for the system (AWWA, 2011). The scales formed from corrosion reduce hydraulic capacity of the pipes and make it harder for water utilities to maintain desired flow rates in the system (Figure 2.10) (Larson and Sollo Jr 1967). If metals are released from these scales, they can increase turbidity and discolour the water (Sarin et al., 2004).

Figure 2.10 – A video still image of corroded scale on the inside of a pipe, which is visibly restricting its hydraulic capacity. Image source: Severn Trent Water.

Corrosion can be either an external (in contact with soil) or an internal (in contact with water) process (Sander et al., 1996; NRC, 2006). Many different types of corrosion exist; in DWDSs these tend to be electrochemical and microbiological (Jjemba et al., 2014). Electrochemical corrosion involves the transfer of ions to electrolytes and is usually associated with the corrosion of metals (Figure 2.11) (AWWA, 2011). The process is exacerbated by the presence of oxygen and acidic environments.

Figure 2.11 – Visible corrosion on an iron pipe in a service reservoir. Image source: Australian Broadcasting Corporation.

Microbiological corrosion results from the reaction of material and microorganisms, their metabolic by-products, or both (Bremer et al., 1991; Little and Wagner, 1997). Microbiological corrosion can be a self-promoting process as the by-products released from this type of corrosion can serve as nutrients for microorganisms, decrease disinfection efficacy, and thus further promote microbiological growth (LeChevallier et al., 1993; Nawrocki et al., 2010). The same by-products can accumulate in the DWDS and shield microorganisms from disinfectants, which can lead to several aesthetic issues, and potentially threaten the safety of the supply (Zhang et al., 2007; AWWA, 2011).

A vast number of factors affect corrosion rates and types; these can be chemical, biological, or physical (AWWA, 2011). Any dissolved chemical substance in water will have some sort of effect on both corrosion and its control (AWWA, 2011). In some waters, corrosion happens due to excess chlorine and dissolved oxygen, which react with the metals in water causing them to remain in a soluble state; this increases the conductivity of water, which further exacerbates corrosion rates (AWWA, 2011; Brandt et al., 2016). In chloraminated systems, free ammonia increases the solubility of metals, and can interfere with protective film formation, therefore increasing corrosion rates (AWWA, 2011).

As for biological factors, some NOM reacts with a metallic surface and forms a protective film, therefore decreasing corrosion rates (Campbell, 1971). Other NOM can react with corrosion by-products and further exacerbate the process (Korshin et al., 2005). Most commonly, NOM becomes food for microorganisms in the system and leads to enhanced corrosiveness due to their increased activity on the surface (AWWA, 2011). Biofilm, and microorganisms that compose it, can influence corrosion by changing pH, reducing dissolved oxygen levels, and altering other chemical reactions in the microenvironment around the surface (Bremer et al., 1991; Teng et al., 2008). However, biofilm can also form a protective layer and protect surfaces against corrosion (Zuo et al., 2005).

The main physical characteristics of water affecting corrosion are flow, velocity, and temperature (Snoeyink and Wagner, 1996; AWWA, 2011). If the velocity is high, it can mobilise weakly adhered material, such as metals and biofilm (AWWA, 2011). Regular changes in SR level can also strip material off the walls. This will expose the layers below to the risk of further corrosion (Snoyenik and Wagner 1996). Typically, corrosion is enhanced with higher temperatures due to increased reactivity and microbiological activity (Blokker et al., 2016). Stagnant conditions in SRs can enhance corrosion of internal SR structures and coatings through both electrochemical and microbiological pathways (Sarin et al., 2004; Speight et al., 2009).

It is impossible to eliminate corrosion completely, but there are ways to keep it under control (AWWA, 2011). The type of control method depends on specific water quality and material of the system, as a particular method may work in one section of the DWDS, but not the other (AWWA, 2011).

2.5.2.5.2. Discolouration

The accumulation of particulate material in DWDSs, which may contain high levels of insoluble iron and manganese, has been shown to be responsible for discolouration events when mobilised (Husband and Boxall 2011; Mounce et al., 2015a). When sudden remobilisation occurs, metals remain predominantly in their insoluble forms, although there is a potential for them to dissolve but this process tends to have a slow reaction time; both forms can discolour the water supply (AWWA, 2011). Water utilities attempt to reduce the risk of discolouration through regular flushing programmes to remove accumulated material, and by renewing, re-lining or invasively cleaning parts of the system (e.g., SRs) (WRc, 1989; Williams, 2000). However, this is not enough to eliminate the risk of discolouration and other control measures exist (Husband and Boxall, 2016). Husband and Boxall (2016) have shown that conditioning pipes by regularly increasing hydraulic flow is an effective, long-term mitigation strategy. Putting in place protective measures, such as lime or phosphate, which may form protective scales, is another way (AWWA, 1996). Although there are some existing proactive measures to manage discolouration, events are mostly dealt with in a reactive manner (Vreeburg and Boxall, 2007). This is because water utilities do not currently have a complete understanding of system processes leading to discolouration issues, such as the relationship between mobilisation of material and discolouration response, and are therefore unable to build durable and reliable operational regimes to manage discolouration effectively (Husband and Boxall, 2011).

Summary

Despite the common link between metals, discolouration, and corrosion, metals are not always present or prevalent (Gauthier et al., 2001). It is only from thorough understanding of entire system processes and mechanisms that lead to corrosion and discolouration events that water utilities will be able to foresee such incidents and act in a proactive, instead of a reactive manner (Vreeburg and Boxall, 2007).

2.5.3. Disinfection

2.5.3.1. Disinfectants

Disinfectants are routinely used in DWDSs to inactivate microbial contaminants of concern, such as pathogens. This is in the interest of public health, and in accordance with regulations. There are several different types of disinfectant used, most commonly chlorine, chloramines, and UV, although UV is only typically used at WTW (Brandt et al., 2016). Prior to the application of a disinfectant, water commonly undergoes a multi-barrier treatment process, which includes coagulation, flocculation, sedimentation, and filtration mechanisms (Shannon et al., 2010). The Netherlands are among a small number of countries that do not use disinfectant residual post-treatment. They instead try to achieve a biologically stable drinking water supply at the stage of the WTW (van Der Kooij, 1998). For the rest of the world, challenges can arise when choosing disinfectant type and dose (Mi et al., 2015). Disinfectant effectiveness heavily depends on the conditions within the DWDS, such as temperature, pH levels, and microbiology (Gopal et al., 2007; Brandt et al., 2016). Another challenge is maintaining disinfectant residual, which depletes with travel through the DWDS, usually due to its interaction with NOM, internal surfaces, biofilms, and accumulated material (Vasconcelos et al., 1996; Valentine et al., 1997; DiGiano et al., 2004; Al-Jasser, 2007). Disinfection decay rate often increases in SRs, where water residence times tend to be longer and temperatures higher than in other parts of the system (NRC, 2006). Furthermore, mixing conditions are often poor in SRs, especially in warmer months when there is a risk of thermal stratification (Fisher et al., 2009). This leads to even longer detention times and stagnation, which further exacerbates disinfection decay (Grayman and Kirmeyer, 2000).

The reaction of disinfectants with NOM can lead to the production of disinfection by-products (DBPs) (Deborde and von Gunten, 2008). DBPs are a concern as they have carcinogenic properties and are therefore a risk to public health (Gopal et al., 2007). Like disinfection efficacy, the formation of DBPs is temperature dependent and increases at warmer temperatures, irrespective of system type (Williams et al., 1997). Organic compounds that leach from system materials (e.g., concrete SR surfaces) can increase the NOM content of the water, which increases the reactivity of disinfectant and thus the formation of DBPs (Grayman and Kirmeyer, 2000).

2.5.3.1.1. Chlorine

Chlorine is the most widely used primary and residual disinfectant in DWDSs across the world (WHO, 2011). This is largely due to its vast availability and low cost (Deborde and von Gunten, 2008). Managing chlorine residual levels in supply requires careful consideration. Generally, water utilities strive to maintain a detectable chlorine residual of 0.2-0.3 mg/l throughout the entire DWDS as this concentration has been shown to control bacteriological regrowth (Rossman et al., 1994; Parsons and Jefferson, 2006). However, it is also important for water utilities to maintain residual levels below 0.6 mg/l to avoid acceptability problems from consumers as above this value chlorine can give off an unpleasant taste and odour (Thompson et al., 2007). Moreover, at higher concentrations, chlorine can oxidise metals, which precipitate out into the water supply and can lead to discolouration issues (Brand et al., 2016).

Chlorine reacts with both organic and inorganic compounds in the DWDS, which can quickly deplete it. As a result, it is important for water utilities to monitor chlorine concentrations at different stages of the system, and manage these as required (Hallam et al., 2003; Deborde and von Gunten, 2008).

2.5.3.1.2. Chloramine

Chloramine is a common residual disinfectant and is formed from a controlled reaction between chlorine and ammonia (Thompson et al., 2007). Chloramine is considered less effective than chlorine because higher concentrations of it are required to inactivate microorganisms (Gagnon et al., 2004). For instance, a typical guideline for chloramine residual in the DWDS is 0.5 mg/l, in comparison to 0.2 mg/l for chlorine (LeChevallier et al., 2010). The benefit of chloramine is that it is less reactive than chlorine and can therefore persist for longer in the network, also producing less of the regulated DBPs (Mitcham et al., 1983). This becomes useful in large DWDSs, in those with long residence times, and during warmer months (McVay, 2009). However, it has also been observed that sometimes chloramines decay as fast as chlorine, especially in the presence of corroded surfaces and NOM (Powell, 2004; Zhang et al., 2007). The use of chloramines can also lead to an increased risk of nitrification in the system (AWWA, 2013). This is due to the ammonia content of the disinfectant, which nitrifying bacteria in the DWDS can utilise as a food source by oxidising it to nitrite and nitrate (Regan et al., 2002). Nitrification is a concern as the process depletes disinfectant residual and promotes microbiological growth (Skadsen, 1993). Like most other reactions, nitrification is temperature dependent and longer detention times, like those in SRs, can increase the potential for nitrification episodes (AWWA, 2013).

2.5.4. Microbiology

2.5.4.1. Biological stability

Biological stability is a term used to describe the tendency of DWDSs to promote or prevent microbiological growth (van der Kooij, 2000). The lower the nutrient content of the water, the more biologically stable the system is considered to be as the availability of nutrients is a limiting factor for microbiological growth (Liu et al., 2013). It is considered important for water utilities to strive to achieve good biological stability as poor stability can negatively affect disinfection efficacy. For instance, chlorine concentrations as low as 0.05 mg/l have been shown to control bacteriological presence in the DWDS, however, in cases with poor biological stability, chlorine residuals as high as 4 mg/l had little impact on preventing biofilm and bacteriological development and regrowth (Norton and LeChevallier, 2000; Helbling and VanBriessen, 2008; LeChevallier et al., 2010). Maintaining disinfectant residual and removing growth-promoting compounds at the stage of treatment are some of the ways in which control can be implemented (Hammes et al., 2010). Maintaining biological stability, however, may be hard to achieve due to the complexity and large-scale infrastructure of DWDSs (NRC, 2006).

2.5.4.2. Biofilm

Microbiology within DWDSs consists of either planktonic microorganisms suspended in bulk water, or those attached to surfaces of pipes, walls, and materials within (AWWA, 2011). Any surface that encounters water can support biofilm growth and essentially all types of surfaces in DWDSs worldwide are covered in biofilm (Figure 2.12).

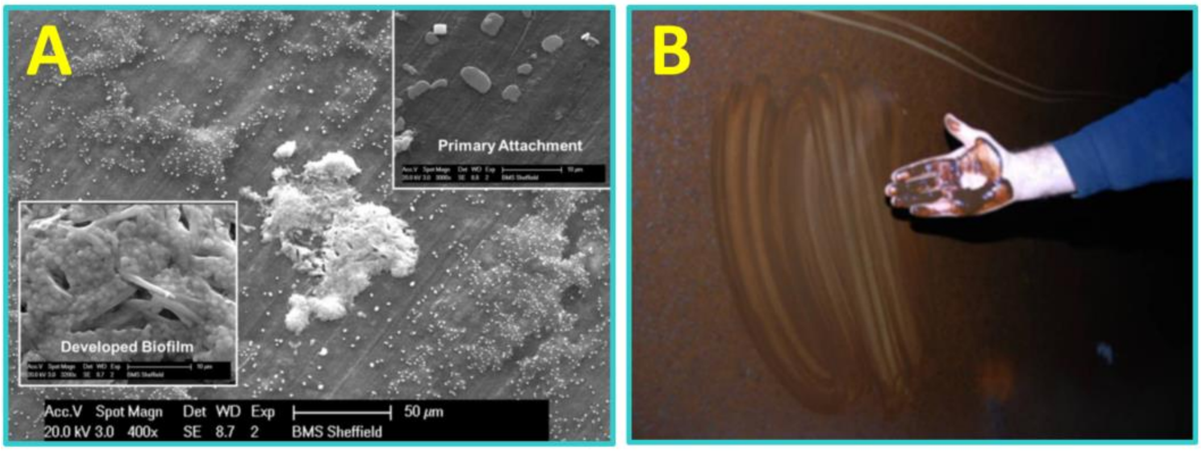

Figure 2.12 – (A) a scanning electron microscope image of a drinking water biofilm, and (B) a photo of biofilm/material coating on a wall of a trunk main. Image sources: (A) University of Sheffield, and, (B) PODDS, University of Sheffield (Husband et al., 2016).

DWDS biofilms are made up of heterogenic microorganisms that can survive in hostile and oligotrophic environments by assembling into a patchy film (Costerton et al., 1987; Zacheus et al., 2001; Douterelo et al., 2014a). Within the biofilm, organisms can be dead or living, and include bacteria, fungi, and other microscopic organisms (Characklis and Marshall, 1990). Biofilms either originate from organisms already present on materials when the system was installed, through external sources, or by attachment of microbes transported in the bulk water (AWWA, 2011). In the DWDS, a self-produced matrix of extracellular polymeric substances (EPS) supports the biofilm, composed of polymers, polysaccharides, proteins, and DNA, protecting them from the direct action of disinfectants and providing physical stability against various hydraulic influences (Flemming and Wingender, 2010). The way these microorganisms adhere to surfaces and establish is dependent on several factors, including water quality parameters (e.g., organic loading, pH, disinfectant residual, and temperature), surface type (material, size, and roughness), and hydraulics (e.g., shear stress, and flow) (Pedersen, 1990; Zacheus et al., 2001; Yu et al., 2010; Douterelo et al., 2014). Once established, the rate of biofilm growth is dependent on nutrient availability (LeChevallier et al., 1996; NRC, 2006). Microorganisms metabolise organic or inorganic substrates, such as carbon, iron, manganese, and nitrite (AWWA, 2011). The transport and accumulation of organic and inorganic molecules on surfaces can serve as nutrients for biofilm, giving them the ability to survive even if the water itself is nutrient poor (Marshall, 1988). Some organic or inorganic compounds come from internal materials, including pipes, linings, and fittings, which release these into the system (Colbourne, 1985; Schoenen, 1986). Concrete material, which is often used to construct SRs, or any coated SR surfaces, may accelerate biofilm growth as these materials can leach organic compounds, which act as a food source for bacteria (Woolschlager and Soucie, 2003; Chowdhury, 2012). If concrete surfaces or internal metal structures, like ladders and scours, experience any corrosion, they can become porous, which provides a greater surface area and shelter for microorganisms and biofilm growth, especially if these structures are permanently submerged in water, which they are in SRs (Grayman and Kirmeyer, 2000).

Biofilms can cause several cascading issues; they affect infrastructure, network management, and modify the quality of drinking water (Douterelo et al., 2014; Fish et al., 2016). Over time, biofilms can cause fouling of the DWDS (Douterelo et al., 2013). Biofilms trap particles such as iron and manganese and are therefore key contributors to discolouration issues (Ginge et al., 2011; Douterelo et al., 2013). If flow conditions change, biofilms can detach and shed into the aquatic matrix, contributing to the deterioration of water quality (van der Wende et al., 1989). Biofilms can also serve as shelter for pathogenic bacteria by shielding them from disinfectants (Chowdhury, 2012).

Controlling biofilm growth is a complicated process because, as they are endemic, they can find refuge in inaccessible areas, where neither disinfectants nor cleaning can be used to manage them (Szewzyk, et al., 2000; NRC, 2006). Biofilms are also highly resistant to disinfection, having adapted to certain levels of disinfectant over time and utilising the defensive properties of the EPS (Szewzyk, et al., 2000). Some studies have suggested boosting chlorination at key DWDS points, primarily at the inlet and outlet of SRs, as a means of controlling biofilms (Brandt et al., 2016), although latest research suggests that even elevated concentrations may not be effective and may even increase water quality issues (Fish et al, 2020).

The presence of biofilm is often perceived as undesirable; however, biofilms may also be safeguarding drinking water (Fish et al., 2016). For example, biofilms could be acting as filters and sinks of harmful materials, such as metals (Schwarts et al., 2003). If biofilm levels are maintained using techniques such as flow conditioning, they could be used as part of the treatment process (Husband et al., 2012). In the future, it is likely water utilities will need to find a way to utilise the presence of biofilms, rather than go to great lengths to try to eradicate them.

2.5.4.3. Bacteria

Out of the many microorganisms present in biofilm, bacteria are considered the highest concern due to their direct association with disease, and their stability, adaptability, and regrowth (Simoes and Simoes, 2013). Bacteria can enter the DWDS from numerous sources, like ineffective treatment of raw water, growth in treatment filters, or through ingress caused by structural issues, for instance, in SRs this can happen through broken access hatches, faulty vents, and cracks in the structure (NRC, 2006). Once inside the DWDS, bacteria can travel through the system or colonise biofilms and accumulated material as both offer protection from disinfectants and are therefore a much safer environment than bulk water (Parent et al., 1996; LeChevallier and Au, 2002; Speight et al., 2008). Many conditions, such as surface type, organic carbon concentration, stagnation, disinfectant residual, and nitrification can result in higher bacterial counts (NRC, 2006; Yu et al., 2010). Higher water ages and potential poor mixing conditions in SRs can also create stagnant areas of water, which can rapidly deplete disinfectant residual and encourage microbial growth (Kerneis et al., 1995; Kirmeyer et al., 1999).

A concern is that some bacteria harboured in DWDS biofilms and material may be pathogenic, which, when disturbed, can be released into the bulk supply, exposing consumers (Speight et al., 2009; Douterelo et al., 2014). Pathogens can be indigenous or opportunistic, which grow in the biofilm itself, or accidental ones, such as *Cryptosporidium,* which can be trapped in the biofilm after a contamination event (Lehtola et al., 2007). Conditions, like the air-water interface in SRs, can also create favourable conditions for opportunistic, airborne pathogens (Grayman and Kirmeyer, 2000).

Bacteriological contamination events are a serious concern for water utilities as they can lead to adverse health impacts and loss of public trust in their supplier (Besner et al., 2011). For instance, SRs have been associated with pathogen contamination that has resulted in serious illness and even death. In 1993, a *Salmonella typhimurium* outbreak in Gideon, Missouri, which stemmed from a bird-infested water tower, resulted in over 650 illnesses, 15 hospitalisations, and 7 deaths (Clark et al., 1996a). It was determined that birds got into the tank through inadequately protected entry hatches (Kramer et al., 1996). Similarly, a 2008 *Salmonella* outbreak in Alamosa, Colorado, which also resulted in hundreds of illnesses and a death, was linked to animal contamination of a SR (Ailes et al., 2013). In 2012, a Sapovirus and *Escherichia coli* outbreak in Vuorela, Finland, which affected 600 people, was associated with a faulty pipe repair, which led to the contamination of a nearby SR (Jalava et al., 2014). Aside from public health concerns, bacteria create process-related and aesthetic issues. Bacteriological presence is known to increase disinfection demand, corrosion, and turbidity (Douterelo et al., 2013; Brandt et al., 2016; Fish et al., 2016).

Despite a wide range of problematic bacteria in DWDSs, coliforms are the key regulated type. Although most coliforms are not themselves pathogenic, they can indicate the potential presence of faecal pathogens, and are therefore a measure of risk to public health (AWWA, 2011; Ellis et al., 2018). Coliforms originate from untreated source water, vegetation, biofilm, soils, and faecal matter (Characklis et al., 1986; AWWA, 2011). As drinking water is not their natural environment, their presence in supply is usually interpreted as an external contamination event, or poorly maintained assets (Geldreich et al., 1992; Rompré et al., 2002). In the UK, coliform failures are rare, but are still present enough to be a problem. For instance, in 2020, the highest DWI compliance risk index (CRI) scoring parameter was coliforms, with 55 failures at WTW and 108 at SR outlets (DWI, 2020).

2.5.4.4. Measuring microbiology

Water utilities routinely sample for microbiological parameters across the entire DWDS (Ellis et al., 2018). In the UK, monitoring is focused on indicator organisms, which are coliforms, *Escherichia coli*, *Enterococci*, and *Clostridium perfringens* (Ellis et al., 2018). All four parameters have prescribed values of 0 cells per 100 ml, where any positive results indicate a contamination event (Council of the European Communities, 1998). If, upon sampling, indicator bacteria are detected, water utilities must take immediate action to restore the safety of supply (Standing Committee of Analysis, 2002). This can be challenging, as the detection of indicator organisms at one stage of the DWDS does not necessarily mean that the source of contamination is localised there (Ellis, 2013).

Currently, the worldwide method for biomass quantification and bacterial identification is the heterotrophic plate count (HPC) (WHO, 2003). This involves concentrating bacteria using membrane filtration, staining with a fluorescent dye, and using a microscope to count cells (Boe-Hansen et al., 2002). Despite popular use, this method has many setbacks. Firstly, the method can only detect a small percentage of microorganisms in water (Hammes et al., 2008). Secondly, only fast-growing microorganisms are detected; slow ones do not culture in time to be registered (NRC, 2006). Other limitations include expense and the requirement for optimisation to suit specific conditions (NRC, 2006).

Presently, all current microbiological sampling methods are constrained. However, the use of molecular methods, such as polymerase chain reaction and flow cytometry (FCM) are becoming more popular as they can help achieve a more complete microbiological profile at a faster rate (AWWA, 2011; Prest et al., 2013). FCM is one of the most up-and-coming cultivation-independent methods for monitoring cell counts in flows of water and is now starting to be applied to DWDSs where it can determine whether disinfection was successful and identify problematic stages of the network (Elhadidy et al., 2016). FCM can detect both viable and non-viable cells (Veal et al., 2000), specific bacteria (Clarke et al., 1998), and their characteristics (Phe et al., 2005). FCM works by measuring particles of < 50 µm as they flow in a stream of liquid past a laser beam (Wang et al., 2010). All particles induce light scattering, therefore, to distinguish between abiotic particles and bacteriological cells, the target cells need to be labelled with a fluorescent tag (Wang et al., 2010). This is done using dyes, such as SYBR® Green I and Propidium Iodide (PI) (Gasol et al., 2000; Zipper et al., 2004). The lasers are then used to excite the dye and fluorescence is measured using photomultiplier tubes (Wang et al., 2010). The different dyes can characterise both intact (SYBR® Green I and PI) and total cell counts (SYBR® Green I only) (Hammes et al., 2008). A stringent protocol with fixed settings on staining and gating is used across the world to ensure reliable quantification of bacteriological cells (Prest et al., 2013).

FCM is gaining popularity for its simplicity and rapid analysis, whereby results can be available in 15-20 minutes, in comparison to at least two days for HPC (Berney et al., 2008). Furthermore, bacterial count detected by FCM is magnitudes higher than from HPC analysis (Hoefel et al., 2003). However, FCM use in drinking water systems is still relatively rare and HPC remains the primary method (Gillespie et al., 2014). Nevertheless, there is a clear awareness in the water industry for the need for more advanced methods of bacteriological monitoring, including online tools to enable real-time collection and analysis of bacteriological data, and the industry is slowly heading in that direction (Ellis, 2013; Gillespie et al., 2014).

2.5.5. Physicochemical properties of water

2.5.5.1. pH

One of the most important determinants of water chemistry is pH as almost all water based chemical processes are dependent on it (Brandt et al., 2016). pH itself is not generally a concern in terms of public health, however, pH has an impact on disinfection and corrosion, which in turn affects the microbiological composition and activity in DWDSs (Fish et al., 2016). For instance, lower pH has been associated with an increase in the oxidation of metals and dissolution of concrete, therefore enhancing the rates of corrosion (Sharma et al., 2005; WHO, 2014; UKWIR, 2019). Whereas higher pH has been shown to lower disinfection efficacy (Sadiq and Rodriguez, 2004). It is therefore important to get the pH balance right in the DWDS, which is a difficult process as pH is not uniform in all parts of the network. For example, pH at the surface of a pipe may be considerably different to the pH of bulk water (Snoeyink and Wagner, 1996). Additionally, pH levels can increase on surfaces of concrete SR structures due to the leaching of lime from concrete materials (AWWA, 1996; Grayman and Kirmeyer, 2000). Long detention times, like those in SRs, also mean that surfaces can be exposed to the same body of water for prolonged periods of time, which can enhance the rate at which pH increases (Grayman and Kirmeyer, 2000).

The easiest stage of the DWDS to control the pH is during treatment, which is also critical to do at this point as most water treatment processes require careful pH control to optimise their efficacy (Brandt et al., 2016). Water utilities tend to use lime, the principal component of which is calcium hydroxide, to elevate the pH of drinking water making it more alkaline (Abdullahi, et al., 2012). Lime is an odourless, soluble, and generally safe white powder (Brandt et al., 2016). However, if dosing is not managed properly, it can lead to an increase in turbidity of the treated water and excess levels can be carried over into distribution (Brandt et al., 2016).

2.5.5.2. Conductivity

Conductivity is a measure of water's capability to pass an electrical current, which is directly related to the concentration of ions in water. This makes conductivity a good indicator of the presence of dissolved solids and salts in water (Brandt et al., 2016). The higher the conductivity, the higher the concentration of dissolved solids (Brandt et al., 2016). Because conductivity is temperature dependent (higher temperatures equate to higher conductivity), in the UK there is a standard to measure it at a reference temperature of 20°C (Brandt et al., 2016). Conductivity is typically used to monitor the aesthetic quality of the water as a high concentration of dissolved solids or salts can lead to an unpleasant taste of the water supply. Due to its direct relationship with temperature, conductivity can also be a useful surrogate indicator for disinfection efficacy, which decreases with higher temperatures (Brandt et al., 2016).

2.5.5.3. Temperature

In the DWDS, temperature has an influence on water chemistry, microbiology, and its physical parameters (Boulay et al., 2001; LeChevallier et al., 1996a; Blokker et al., 2016). Many chemical and microbiological reactions are temperature dependent, and higher temperatures tend to correlate with increased water quality deterioration (Machell and Boxall, 2012; Blokker and Pieterse-Quirijns, 2013). For example, at higher temperatures, the rate of corrosion and discolouration increases, and disinfection residual decreases (Blokker et al., 2016; Cook et al., 2016; García-Ávila et al., 2020). Microorganisms flourish in higher temperatures as it increases their metabolic rates (Clarke et al., 2004; Blokker et al., 2016). Summer algal blooms and source water de-stratification events can lead to extra organic matter entering the DWDS and becoming available as nourishment for microorganisms (AWWA, 2011). Biological activity is therefore significantly higher within DWDSs during this time (Hallam et al., 2001). The inorganic composition of source water is also higher in warm weather, for instance, both iron and manganese levels are highest in surface waters in summer (AWWA, 2011). This increase in concentration puts a strain on treatment processes, often leading to ineffective removal of organic and inorganic compounds, which are then carried over into the DWDS.

In SRs, the temperature differential between the water flowing into the tank and the bulk water within, which is often warmer than incoming water, can create a density gradient if the water is not well mixed (Mahmood et al., 2005). This leads to issues of stagnation and thermal stratification, which can increase water temperatures further, exacerbate poor mixing conditions, and lead to the deterioration of surrounding water quality (Fisher et al., 2009; Jjemba et al., 2014; WHO, 2014). Even a small difference in temperature (0.4°C) between two layers of water can lead to thermal stratification in SRs (Fisher et al., 2009). During summer months, solar radiation can contribute to thermal stratification within SRs, especially in water towers, which are directly exposed to sunlight (Chuo et al., 2003). In colder months, SRs tend to be fully mixed, mainly because the air above or around the SR cools more overnight than the water within, which helps to de-stratify the temperature and chemical parameters of the water through convective plunging, and daytime solar radiation is too weak to re-establish stratification (Imberger and Patterson, 1979; Fisher et al., 2009).

Understanding the impacts of temperature can be useful in improving operational efficiency of the DWDS (Husband et al., 2016). For example, carrying out maintenance works to remove biofilm growth would be most beneficial in the summer, when biofilm growth rates are at their highest (Lehtola et al., 2004; Husband et al., 2016). However, the effects of temperature are complex and difficult to assign to specific processes in the DWDS. The DWDS is a dynamic system, where temperature fluctuations can be quite high (e.g., 0 to 30°C) and can influence numerous processes and parameters all at the same time (Niquette et al., 2001; AWWA, 2012). Because of this, temperature effects are often misapplied and over generalised (AWWA, 2011).

2.6. Service Reservoirs: Current operational management and maintenance

2.6.1. Cleaning and removal of accumulated of material

In the UK, cleaning of SRs is currently recommended on average every three to ten years to mitigate issues related to the accumulation of material (Lambertini et al., 2011; Brandt et al., 2016). Traditionally, the SR is drained, accumulated material is removed, after which the SR is jet washed with clean water, disinfected (with a chlorine solution of at least 20 mg/l), half-filled with a minimum 0.5 mg/l chlorine residual for ~24 hours, tested for coliforms, and, if the sample is negative, put back into service (Brandt et al., 2016). Sometimes, the SR interior is sprayed with a biocide solution for several minutes before being hosed down with a gentle stream of water. Biocide solutions made for this purpose are considered to be highly effective at removing iron and manganese fouling and are used in place of jet washing to decrease risk of structural damage to concrete from the high pressure exerted by the jet wash stream (Figure 2.13) (Stainsby, 2014). Regular cleaning can be difficult to manage as the whole cleaning procedure can cost water utilities between £50,000-100,000 (Hope, 2016; UKWIR, 2019). Furthermore, the SR may need to be taken out of service for anywhere between 8-72 hours, sometimes longer, which causes a disruption to supply (Brandt et al., 2016).

Figure 2.13 **– An example of the biocide solution used to clean service reservoirs in practice. Source: USEPA.**

Despite common knowledge that material accumulates in SRs and that there are regular cleaning programmes to remove it, material is rarely collected or analysed for its composition. Kirmeyer et al. (1999) argue that water utilities should consider sampling and analysing SR material as this could provide information on material accumulation rate and help to inform site-specific cleaning frequencies. Analysing material for its constituents can also help to inform the location of water quality issues in the DWDS, for instance, if material contains high quantities of aluminium, this could be an indication of excess aluminium coagulant carry-over into the system from treatment (Grayman and Kirmeyer, 2000).

The collection of material samples using a remotely operated vehicle (ROV), whilst the SR is still in service, could be a very useful and accurate way of mapping out different areas of accumulation in the SR, avoiding the dispersal of material during a drain down of the tank (Figure 2.14). ROVs are also able to remove the material without the need to take the SR out of service and without creating a turbidity response, which is why it is becoming a recognised method for carrying out more complicated SR cleans (UKWIR, 2019). Although ROV cleaning is currently slow and not always as effective as a manual clean, improvements in technology could see a wider uptake (UKWIR, 2019).

Figure 2.14 – A remotely operated vehicle removing accumulated material in a service reservoir. Image source: Panton McLeod.

2.6.2. Improving hydraulic conditions within service reservoirs

A critical component of hydraulic integrity of DWDSs is to have sufficient mixing of the water supply to prevent zones of high water age (USEPA, 2005; NRC, 2006). This can be a problem in SRs, as much of the volume of water is unused and is typically held in SRs longer than it is ever held in pipes (Grayman and Clark, 1993; USEPA, 2005; Fisher et al., 2009). If water utilities fail to achieve effective mixing in SRs, age-related water quality degradation can arise from stratification, stagnation, and material accumulation (Grayman et al., 2004; Mahmood et al., 2005). There is also the potential for poor disinfectant dispersal and contact in inadequately mixed tanks (AWWA, 2011).

One of the ways mixing conditions can be improved is by adjusting SR operating levels by changing pumping schedules in fill/drain cycles to allow levels to drop lower than the normal operating regime before re-filling (Brandt et al., 2004; AWWA, 2012). The difficulty in doing this is that SRs are usually operated at full capacity (80-90%) for maximum system resilience in case of emergencies, and water utilities are reluctant to change that mode of operation (AWWA, 2012).

SR shape can also play a role in mixing conditions. For instance, Zhang et al. (2014) found that the rectangular shape was best in terms of maintaining sufficient mixing. They also found that the worst shape was square due its impact on water age, which was high in these types of tanks (Zhang et al., 2014). However, the results of this study are limited to SRs with inlet and outlet pipes at opposing ends of the tank, as this was the only configuration studied. Due to the variations in SR configuration in the field, computational fluid dynamic (CFD) modelling has been shown to be the most popular method in optimising flow based on individual SR characteristics (Brandt et al., 2016; Fard et al., 2021).

One of the biggest problems with achieving good mixing is tank size, with large tanks making it difficult to achieve complete mixing due to limited inflow energy, which also depends on inlet pipe diameter and positioning (Mahmood et al., 2005, Zhang et al., 2014). Of particular concern are SRs with the same pipe for the inlet and the outlet, as demand is met directly from one side of the tank, resulting in typically low turnover of water in tanks of this configuration (Figure 2.15) (Brandt et al., 2016). It is becoming more common to use CFD to optimise the arrangement of inlet and outlet pipes where there are regular water quality problems (Brandt et al., 2016). CFD is also useful in positioning baffle walls, although Grayman et al. (2004) argue that under most circumstances baffle walls can actually inhibit good mixing, rather than promote it. More recently, CFD modelling is being used for the installation of mixers in SRs (Figure 2.16). Mixers help to create homogenous mixing conditions in SRs, and their use is becoming more popular as they can be more effective than passive mixing or baffle walls. Mixers can also be used to dose and disperse additional disinfectant when required.

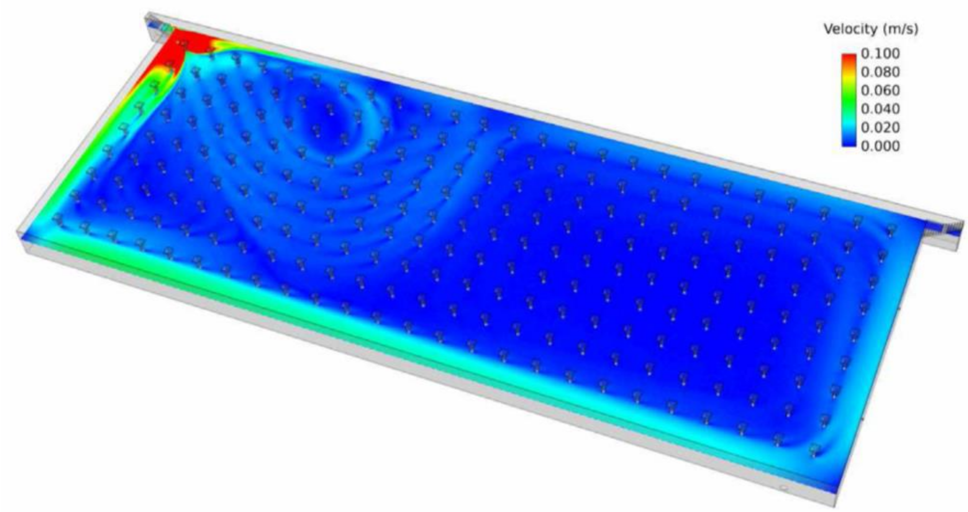

Figure 2.15 – An example of poor mixing conditions using CFD modelling in a service reservoir with the same inlet and outlet pipe configuration. Image source: Fluid Group.

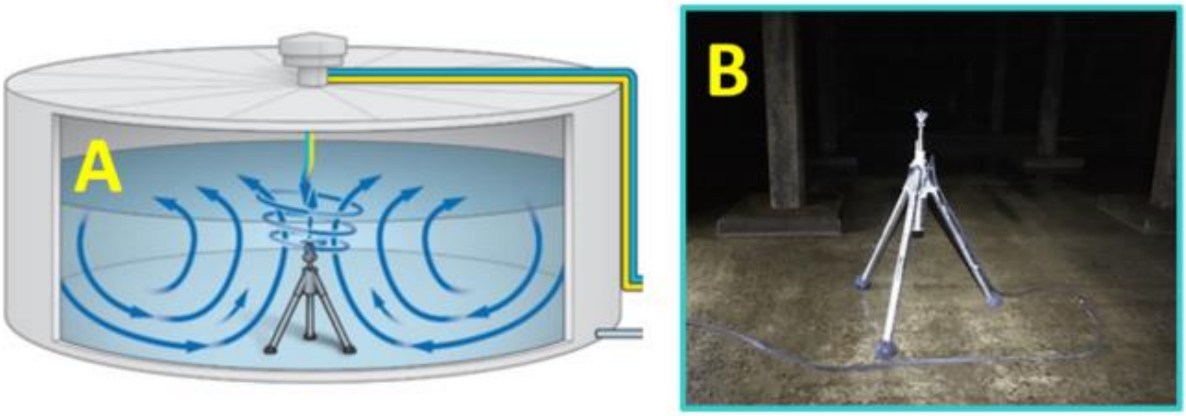

Figure 2.16 – A schematic drawing of a mixer installation in a service reservoir (A) and a real-life photo of a PAX impeller mixer in a service reservoir (B). Image source: PAX Water (A) and Panton McLeod (B).

2.6.3. Addressing contamination risk related to structural issues

Old or poorly constructed SRs can be prone to structural issues, which can lead to ingress and contamination of the stored water with pollutants and bacteria (Craun et al., 2001; Brandt et al., 2016). For example, a *Salmonella* outbreak in Alamosa, Colorado, which resulted in 434 cases, 20 hospitalisations, and 1 death, was linked to animal contamination of a SR that had numerous cracks and inadequately protected entry points (Ailes et al., 2013). Insects, worms, and fly larvae are also often found in SR material, suggesting external entry (Grayman and Kirmeyer, 2000). Washouts, drainage, overflows, and access hatches in particular present a high contamination risk as they are exposed to the outside environment (DWI, 2018). Protective entry mesh and sealants can become damaged through excessive hydrostatic pressure, corrosion, poor workmanship, age related deterioration, and vermin (Figure 2.17) (UKWIR, 2019). Ensuring water tightness of the SR is difficult to achieve and SR components such as roof membranes and wall and floor joints are often the sources of internal ingress (Hope, 2016). Cracks can form in the walls, roof, and floor of concrete SRs as a result of structural and operational defects like corrosion, thermal contraction, overloading, and poor construction (Figure 2.17) (UKWIR, 2019).

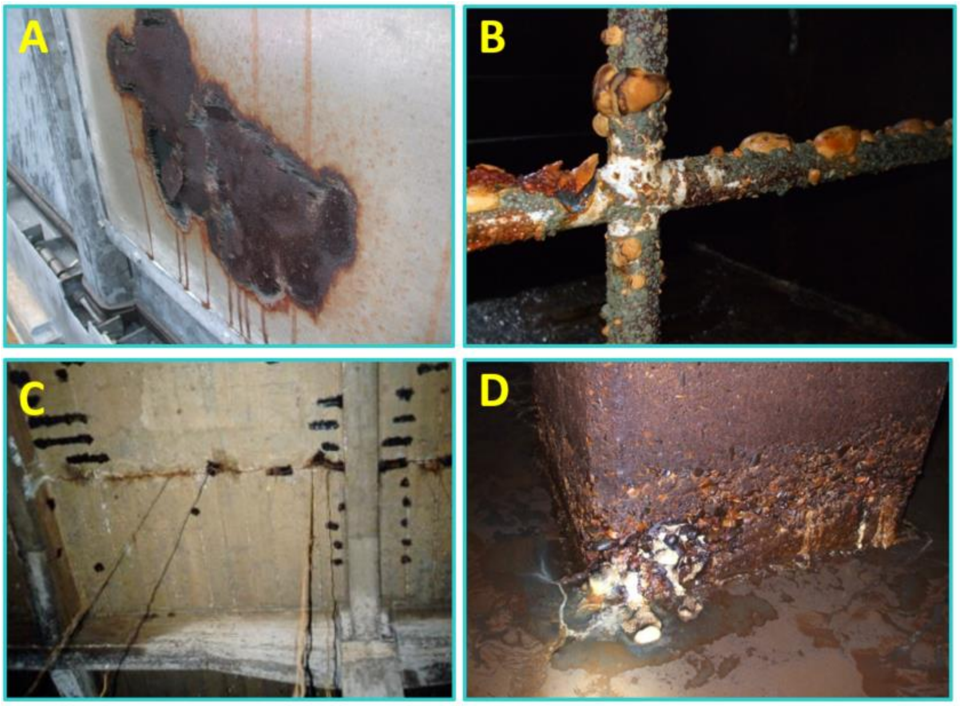

Figure 2.17 – A collection of photos showing some common issues seen in service reservoirs: (A) A broken and corroded access hatch; (B and D) Corrosion of internal structures, and (C) Ingress through cracks in a service reservoir roof. Image source: Northumbrian Water (A, B, and D) and UKWIR (C).

Age does not always correlate with structural issues, which is evidenced by a significant number of SRs built in the 19th century that are still fully functional to this day (UKWIR, 2019). If regularly inspected and well maintained, many SRs will remain operational long after their original design life expiration date (UKWIR, 2019). Cleaning and inspecting a SR often happen concurrently, however, inspections are often carried out on a more regular basis than cleaning (Lambertini et al., 2011). The purpose of physically inspecting a SR is to obtain information on asset performance by evaluating the structural integrity of the SR and identifying any water quality risks, such as structural issues that need repair (Kirmeyer et al., 1999; Hope, 2016; DWI, 2018). Any remedial SR work is often determined using a cost-benefit analysis (Lindhe et al., 2011). For instance, SRs reaching the end of their lives need to be replaced, but to do so would incur major costs and a disruption to the vital, around-the-clock, water supply (Brandt et al., 2016). Because it is difficult and often impossible to foresee and quantify long-term benefits from carrying out costly capital works, the costs often outweigh the recognised benefits when it comes to taking on major projects (UKWIR, 2019). This makes it difficult to manage any water quality issues related to the structural integrity of the SR itself. In such instances, the DWI states that inspections should be carried out more frequently at older and more high-risk sites (DWI, 2018). These additional inspections would incur more costs; an average SR inspection in the UK costs £4200 (Ellis et al., 2018). It may, therefore, be more proactive and financially beneficial for water utilities to invest in bigger, "costly", projects in terms of future financial gain and avoidance of fines related to water quality failures.

Many water utilities cite the inability to isolate a SR for inspection as a reason for inspection delay (DWI, 2018). However, there are many advances in the use of unmanned ROVs and drones to overcome this difficulty (UKWIR, 2019). This technology can be used to inspect the asset without needing to take it out of service, all while reducing health and safety risks (e.g., by removing the need for manned entry into a confined space) and reducing cost (UKWIR, 2019). The use of ROVs and drones can also improve the quality of inspection records, as these devices are able to store a huge amount of digital information about the SR (e.g., HD video and images), which can be easily accessed at any point via a digital platform (UKWIR, 2019). This technology can also accurately capture specific details about the asset, such as its measurements, which can help to eliminate some human error. Other benefits include the ability to carry out a check for ingress under full loading conditions, rather than having to take the asset out of service to carry out a flood test, which can save a lot of time (UKWIR, 2019). ROVs are also able to collect water samples, which could prove particularly useful in mapping out stagnant areas of the SR (UKWIR, 2019).

2.7. Summary and gaps in knowledge

It is clear from the literature that SRs play a critical role in DWDSs, not only in terms of managing system pressure and demand, but also in affecting water quality (Brandt et al., 2016). Just like in the rest of the DWDS, there are many complex interactions between water quality parameters and related processes (hydraulic, physical, chemical, and biological) that occur, interact, and influence one another in SRs (Figure 2.6). Some processes and water quality changes are associated with SRs more than other stages of the network, which include ineffective mixing, stagnation, stratification, and the accumulation of material (Grayman et al., 2004).

Despite the knowledge that SRs can alter water quality, paucity of research highlights how these assets are often overlooked and not afforded the same attention given to other stages of the DWDS, like pipes and WTW (NRC, 2006). The few studies that have looked at SRs (e.g., Grayman et al., 2004; Zhang et al., 2014) tend to investigate hydraulic processes such as mixing conditions and not water quality. Furthermore, existing research on SRs has typically been conducted in a laboratory setting (non-representative of a real DWDS), and therefore does not paint the bigger picture that is needed to understand SR performance in relation to the rest of the system. In general, literature, and relevant documents on storage facilities are “rare” (NRC, 2006).

It is evident from this review that a huge opportunity is being missed to obtain a lot more value from SRs through the assessment of their performance, the optimisation of which could enable them to not only function as vessels for water storage, but as beneficial stages in the delivery of high-quality drinking water. Presently, the lack of understanding on SR performance has prevented effective operational management and maintenance scheduling to sustain high water quality in SRs (Clark et al., 1996). This means that most SR related issues are dealt with in a reactive manner, which would not be the case if there were a method to assess changes in SR performance in real time (Speight et al., 2019).

One of the main reasons why SR performance is difficult to assess is due to the common lack of inlet monitoring, without which water quality changes cannot be tracked with transport through these assets, nor can any observed changes in water quality at SR outlets be attributed directly to the SR (Grayman et al. 1999; Kirmeyer et al. 1999). Additionally, the lack of regulatory monitoring for parameters other than disinfectant residual and bacteriological indicators at SR outlets means that a substantial amount of information is not gathered on water chemistry, microbiology, and parameter interactions within SRs (Grayman et al., 1999; Brandt et al., 2016). Throughout the course of this literature review, only one paper was identified to have conducted monitoring for non-regulatory parameters at both the inlet and outlet of SRs (Sathasivan et al., 2010). However, hydraulic conditions (flow and level data) are monitored at SRs, and, alongside additional water quality parameters, could support a comprehensive view of asset and system performance with changes in physical conditions.

It is known that material accumulates in SRs and can negatively impact water quality if it resuspends, yet the ‘sink or source’ concept, which is actively and effectively used in other disciplines to quantify system performance, has not been applied to the process of material accumulation and resuspension in SRs. The application of this concept could provide information on changes in SR performance over time, helping to manage these assets proactively. For instance, conceptually, if a SR is acting as a sink of material, it is effectively removing undesirable compounds out of supply and thus improving outgoing water quality. If the accumulative capacity of material is exceeded in the SR, it may gradually become a source of material (Kirmeyer et al., 1999). This means that the SR is now contributing those same undesirable compounds into the downstream network, thus performing badly. A proactive measure could therefore be instigated, such as further investigation in the form of an inspection and/or clean, which could then prevent the occurrence of an incident (e.g., microbiological failure). Material is also rarely collected or analysed, and, even if the latter has been done (e.g., Qin et al., 2017), findings are almost never correlated with the SR’s physical or operational characteristics. By taking advantage of a scheduled SR clean, material could be collected and analysed, helping locate the original source of material, which could help direct water utilities to identify or investigate unexplored network issues, leading to a better understanding and management of the system.

The ability to detect and measure changes in SR condition and performance over time, and locate sources of deterioration, can inform appropriate maintenance, inspection, and cleaning frequencies (UKWIR, 2019). This would be of value to water utilities in saving effort, time, and expense that goes into unnecessary, unhelpful, and often reactive investigations (Ellis et al., 2018; Speight et al., 2019).

Although there are evident gaps in knowledge, there are also several suggestions on how these can be addressed. This nationally coordinated project sets out to use all of the listed recommendations in an effort to, for the first time, assess and quantify SR performance and its effect on water quality. These recommendations include the collection and assessment of SR accumulated material, monitoring a variety of water quality parameters at both the inlet and outlet of SRs, and applying the concept of ‘sink or source’ to the process of material loading in SRs.

Chapter 3: Aim and Objectives

Aim:

Investigate how SRs affect drinking water quality as water travels through these essential assets and how to determine this effect, with a focus on developing a metric for assessing and quantifying SR performance in terms of a sink or source of material, and identifying factors that influence this performance.

Objectives:

Objective 1: Understand what material accumulates in SRs by determining its composition, primarily with respect to its organic/inorganic content, and assess its effect on water quality.

Objective 2: Characterise the value of existing historical data in revealing changes in water quality during transport through the DWDS, and specifically whether any of the observed behaviours can be attributed to SRs.

Objective 3: Investigate how monitoring at the inlet and outlet of SRs for water quality parameters other than just those currently required by regulation, and the frequency of sampling, can improve understanding of asset performance.

Objective 4: Define a material sink or source behaviour model to develop a practical metric for quantifying SR performance.

Objective 5: Identify factors influencing SR performance, including operational practices and maintenance, seasonality (temperature changes), and site differences (e.g., source water type, network configuration, material, and treatment, and SR geometry).

Objective 6: Use research findings to make recommendations for future operational management of SRs.

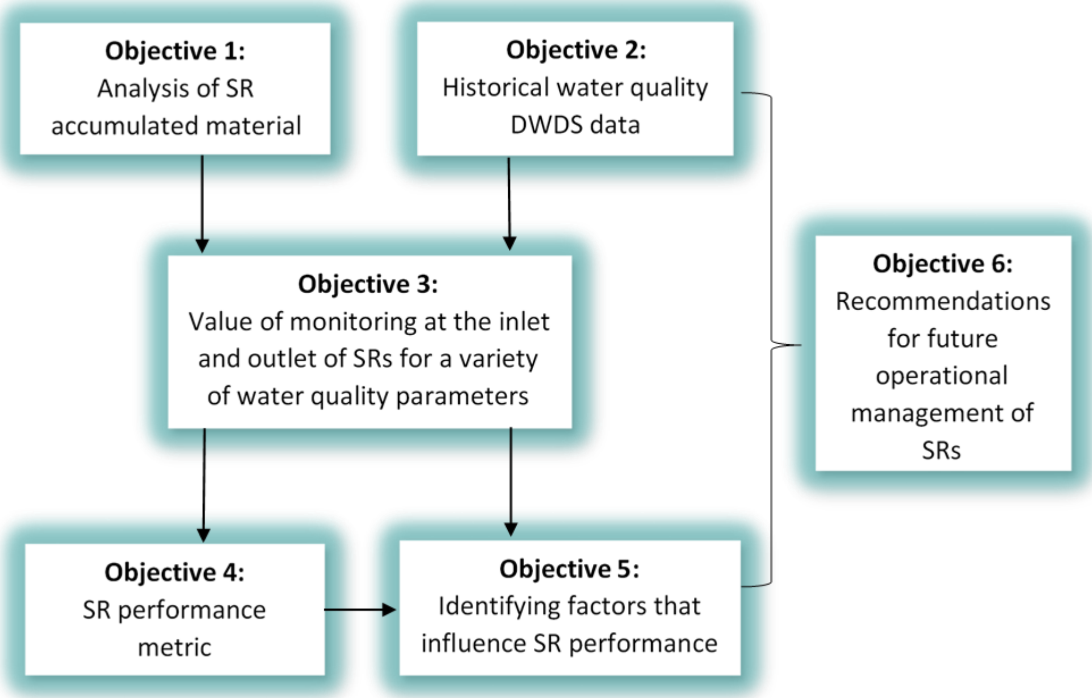

Figure 3.1 – A flow diagram demonstrating how objectives 1-6 interlink with and build on one another.

Chapter 4: Methodology and Methods

4.1. Introduction

This chapter presents the methodology and methods implemented to achieve the research aim and objectives outlined in Chapter 3. The chapter is divided into five main sections:

1. The collection and analysis of SR accumulated material.
2. Project field site selection.
3. Data collection.
4. Data analysis.
5. Number and colour reference system for project sites and parameters.

4.2. Analysis of accumulated material in service reservoirs

The purpose behind the methodology and methods described in this section was to achieve **Objective 1** of the project.

In this research, advantage was taken of scheduled cleans for selected SRs, during which accumulated material was collected and analysed for its organic and inorganic composition in a set of two experiments, one investigating the effect of material resuspension on surrounding water quality and the other the influence of sampling location within SRs on material composition.

The criteria for site selection was to collect material from a variety of different SRs with respect to geometry, retention time, distance from WTW, and secondary disinfectant type, with the intention to increase the representability of experimental results to wider distribution system application. Following communication with project water utilities, six SRs were selected (B5, B6, C7, C8, C9, and D4). Summary information about each site can be found in Chapter 5 (Table 5.1). For detailed network layouts and SR schematics, please also refer to Chapter 5.

For the first experiment, material was collected from selected SRs scheduled to be cleaned in March/May 2019, and subsequently analysed in June 2019. For the second experiment, material was collected from selected SRs scheduled to be cleaned in September/October 2019, and subsequently analysed in November 2019.

Material was collected by either water utility operatives or me using a SR material sampling protocol (Appendix 1), which was created for the purposes of the project, as there is currently no standardised protocol for the collection of accumulated material from SRs either across project water utilities or in existing literature. The protocol was developed upon an existing confined space entry protocol for SRs, which was modified to incorporate material sampling into the process. Method for the physical collection and transportation of material was developed based on work by Gauthier et al. (1999), Lu et al. (2015), and Qin et al. (2017), who collected accumulated material from SRs, and Kneebone et al. (2002) and Peck et al. (2004) who had collected loose deposits from rivers and reservoirs.

Sampling guidelines in the protocol stipulate that material needs to be collected in a way that covers the entire floor area of the SR. This includes, where feasible, collection from every corner, middle of the tank, and from around any other features such as inlet and outlet pipes. All samples were collected after SRs were drained, but before cleaning, which was the most straightforward and cost-efficient approach. All material samples were collected using sterile plastic spatulas, kept in sterile plastic sample bottles, and refrigerated as soon as possible using cooler boxes and fridges.

The limitation of sampling material after the SR has already been drained is that there is a risk that accumulated material had moved from its original location due to hydraulic disturbance during drain down. For instance, water is drained via a discharge point, which could cause the pulling of material by water flow in the same direction. Additionally, upon draining, material is likely to be disturbed, resuspend, and re-settle in a different location within the SR. The exposure of accumulated material to air may also influence microbiological contaminants, potentially causing them to dry out, or result in further reactions of inorganic compounds in the material upon exposure to oxygen. In consideration of these potential limitations, it is important to highlight that all aforementioned studies that had collected SR accumulated material had done so after the SR was drained. Lu et al. (2015) and Qin et al. (2017) both went on to measure microbiology in the collected samples and Gauthier et al. (1999) analysed material for inorganic compounds. The alternative option for collecting material was to use an ROV, but as this is not common practice in the water industry, there was no guarantee that extending the time and cost of the project by hiring an external contractor to try to carry out this type of sampling would be more beneficial to the outcomes of this work.

In addition to collected material, regulatory water quality data was acquired across a period of several months prior and post the cleaning operation at the outlets of WTW and SRs. Inlet water quality sampling data was only available for one of the SRs (D4). This data was acquired as supporting site-specific network water quality data to be used in conjunction with experimental data analysis for a more comprehensive understanding and assessment of experimental results.

4.2.1. Investigating the effect of material resuspension on surrounding water quality

To investigate how resuspension of SR accumulated material may affect surrounding water quality, a controlled experimental programme was conducted. The aim was to recreate a resuspension event similar to that in a real DWDS, but on a smaller scale, using dry material samples collected from operational SRs and resuspending these at varying concentrations and lengths of time in deionised water, followed by analysis of the water for organic and inorganic properties.

4.2.1.1. Sample collection

For this study, material was collected from three SRs:

1. D4 SR (Company D)
2. B6 SR (Company B)
3. B5 SR (Company B)

These sites were chosen predominantly as their inspection and cleaning coincided with the allocated timeframe for material collection. The three SRs are also different in network configuration, secondary disinfectant residual type, and source water, which provided variability between them.

Material from D4 and B6 SRs was collected without any residual SR water (dry sample), whereas material from B5 SR was collected in combination with residual water that was sitting on top of the deposits (wet sample) (Figure 4.1). This was done to assess whether there is any difference between the organic and inorganic composition of water that has never been previously exposed to material upon contact with it, versus water that has been exposed to material for a longer duration of time. The latter is more representative of the conditions in a DWDS.

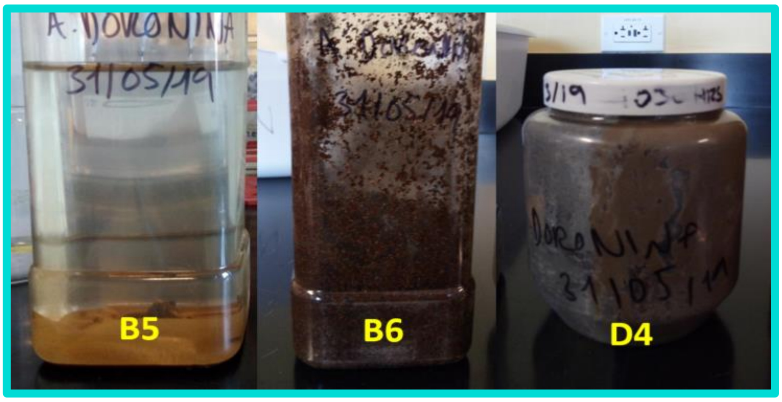

Figure 4.1 – Collected service reservoir material from B5, B6, and D4 SRs.

B5 SR

B5 SR was cleaned in May 2019, which allowed Company B operatives access to collect any accumulated material from different locations within the SR. The sample was composed of both material and residual SR water and kept in a sterile plastic 1-litre sample bottle (Figure 4.1).

B6 SR

Company B operatives collected SR material from the B6 SR during its clean in May 2019. The sample was composed of dry sediment only and kept in a 1-litre plastic sterile sample bottle (Figure 4.1). Based on the inspection report by the contractor, Stonbury (www.stonbury.com), the sample was collected mostly around the inlet of the SR, as this is where most of the accumulated material was.

D4 SR

Company D operatives collected accumulated material from different locations within one of the compartments of D4 SR, which had been taken out of service for structural investigation in November 2018 and recommissioned in March 2019. The material itself was collected during the second week of March 2019 and was composed of dry material only, kept in a 0.5 L sterile plastic jar (Figure 4.1).

Immediately after collection, all material samples were kept refrigerated in a cooler box and sent to the University of Sheffield where they were kept in a laboratory fridge until shipping in a cooler box with ice packs to the University of Colorado, Boulder.

4.2.1.2. Sample preparation

An experimental programme was created to prepare collected material samples for the analysis of metals and elements, total organic carbon (TOC), absorbance (UV), and turbidity. A range of concentrations for the collected B6 and D4 SR material were chosen based on the typical observed TOC levels in finished drinking water, which range from 0.05 to 12.2 mg/l (Symons et al., 1975). Originally, three different concentrations of material were decided on as follows: 1 mg/l (low), 5 mg/l (medium), and 10 mg/l (high). However, these low concentrations were at the limits of detection of the laboratory scales and several analytical instruments at the University of Colorado, Boulder SEEL laboratories. As a result, elevated concentrations were derived, which also allowed samples to be analysed for all of the desired components from a single batch: 60 mg/l (low), 120 mg/l (medium), and 240 mg/l (high). These were made by adding the required mass of dried material to deionised water. Sterile 250 ml – 500 ml high-density polyethylene (HDPE) bottles were used as reservoirs in which the final samples were prepared. Concentrations of material were adjusted for a 250 ml sample volume.

Material was scooped from the original B6 and D4 samples (Figure 4.2) using a metal spatula, which was cleaned between the two samples with deionised water. As these samples had air-dried over time, no residual water remained. The material was then weighed on laboratory scales (Table 4.1) and transported into the sterile 250-500 ml HDPE bottles, after which 250 ml of deionised water was added to each sample bottle.

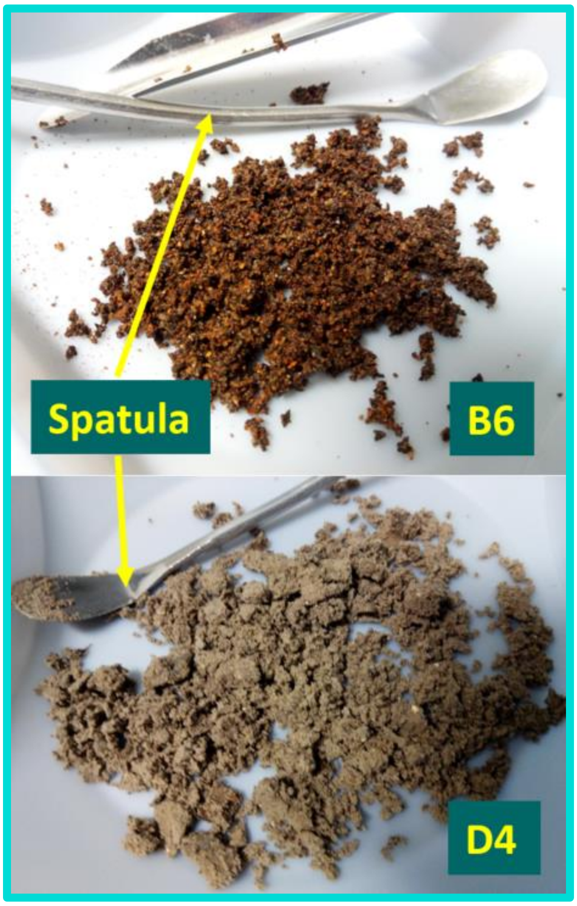

Figure 4.2 – Dry service reservoir material collected from B6 SR (top photo) and D4 SR (bottom photo).

Table 4.1 – **Service reservoir material concentrations (mg/l) used in the investigation of the effect of material resuspension on surrounding water quality.**

Sample name	Type of analysis sample prepared for	Measured material weight (mg/l)
D4 LOW	TOC[1] & UV	**60.0**
D4 MED	TOC & UV	**123.2**
D4 HIGH	TOC & UV	**240.0**
D4 LOW	METALS/ELEMENTS	**65.6**
D4 MED	METALS/ELEMENTS	**123.6**
D4 HIGH	METALS/ELEMENTS	**238.0**
D4 LOW SET (SETTLED SAMPLE)	TOC, UV, METALS/ELEMENTS	**59.2**
D4 MED SET (SETTLED SAMPLE)	TOC, UV, METALS/ELEMENTS	**121.6**
D4 HIGH SET (SETTLED SAMPLE)	TOC, UV, METALS/ELEMENTS	**237.6**
B6 LOW	TOC & UV	**62.8**
B6 MED	TOC & UV	**120.0**
B6 HIGH	TOC & UV	**243.2**
B6 LOW	METALS/ELEMENTS	**58**
B6 MED	METALS/ELEMENTS	**119.2**
B6 HIGH	METALS/ELEMENTS	**240.8**
B6 LOW SET (SETTLED SAMPLE)	TOC, UV, METALS/ELEMENTS	**65.6**
B6 MED SET (SETTLED SAMPLE)	TOC, UV, METALS/ELEMENTS	**124.8**
B6 HIGH SET (SETTLED SAMPLE)	TOC, UV, METALS/ELEMENTS	**242.4**

A blank, deionised water only, sample was also prepared as a control to account for any organic carbon or other contaminants that may leech from the HDPE plastic bottles. Once the samples were prepared, they were placed and secured on a VWR standard analog shaker table to simulate mixing of material into water in a SR (VWR, 2021) (Figure 4.3).

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[1] Total organic carbon

Figure 4.3 – **Prepared samples secured on a VWR standard analog shaker table.**

Samples were then shaken for a total period of 48 hours with the highest possible speed setting, whilst avoiding samples becoming unstable and coming off the shaker table. The table was temporarily stopped at 2, 4, 24, and 48 hours to pipette 40 ml per sample into glass vials for TOC and UV analysis and at 2, and 48 hours to pipette 50 ml per sample into plastic vials for metals and elements analysis. Varied shake times were chosen to reflect immediate resuspension of material (e.g., following a sudden event like a burst in the DWDS) and prolonged resuspension (e.g., from a change in hydraulic operation of a SR, like changing fill and drain cycles). Six of the eighteen samples were removed from the table entirely at the 24-hour mark and left to settle for an additional 24 hours, after which 40 ml per sample was pipetted into glass vials for TOC and UV analysis, and 50 ml per sample into plastic vials for metals and elements. The purpose of removing the samples from the shaker table was to see whether the re-settling of material begins to reverse any potential effects that resuspension might have on the surrounding water quality. Clean pipette tips were used between each sample. The described experimental method is summarised in Table 4.2 below.

Table 4.2 – A summary of the experimental set up and method used to investigate the effect of the resuspension of service reservoir accumulated material on the surrounding water quality.

Analysis type	Shake -->		Stop at 24 hours		SETTLED SAMPLE
	Shake time				
	DAY 1 (2h) 12:00 PM Take sample:	DAY 1 (4h) 2:00 PM Take sample:	DAY 2 (24h) 10:00 AM Take sample:	DAY 3 (48h) 10:00 AM Take sample:	DAY 3 (48h) 10:00 AM Take sample:
TOC	✓	✓	✓	✓	✓
UV	✓	✓	✓	✓	✓
Metals	✓			✓	✓

A wet sample, B5 SR, was also prepared for analysis by shaking the original sample (material combined with water from the SR) for 30 seconds by turning the bottle rapidly up and down to saturate the surrounding water with particulates and then leaving to settle for 72 hours (Figure 4.4). Following this, 40 ml of sample water was pipetted directly into glass vials for TOC and UV analysis, and 100 ml into a plastic vial for metals and elements.

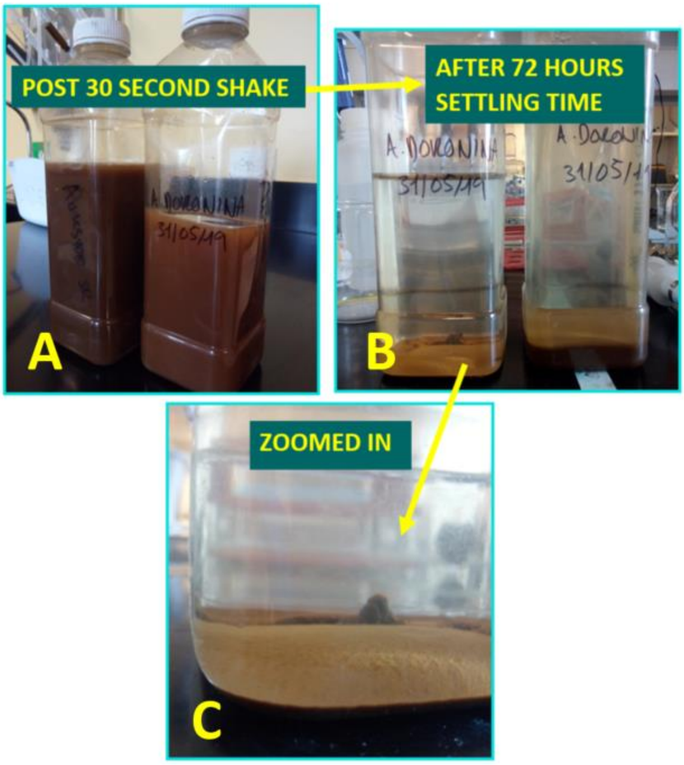

Figure 4.4 – Wet sample from B6 SR immediately post shake (A) and 72 hours after settling (B and C).

4.2.2. Investigating the influence of sampling location within service reservoirs on the composition of accumulated material and the effect of its resuspension on disinfectant demand

It is apparent that material accumulates at different rates in different locations within SRs, which is evidenced by photographs and videos collected during underwater inspections and based on the poor mixing conditions often associated with SRs. The aim of this study was to investigate whether the composition of accumulated material is heterogeneous at different locations within SRs.

Material collected from D4, B6, and B5 SRs was not used in this study as, despite the material being collected in a way that is representative of the entire SR (from the corners, middle, and around key internal structures), it was placed in one bottle per SR, making it impossible to investigate the influence of individual sampling location.

4.2.2.1. Sample collection

For this study, three Company C sites from were chosen, which are as follows:

1. C7 SR
2. C8 SR
3. C9 SR

The above SRs were selected, as they were the most variable sites in terms of network configuration, geometry, and secondary disinfectant type, scheduled to undergo an inspection and clean during this phase of material collection. The amount of material that had accumulated in selected SRs was no more than 0.5 cm in depth and the decision was made to collect wet material samples instead of dry ones, for ease of collection. This choice was also preferable as combining material with existing SR water is more representative of the conditions in a real-life DWDS. All samples were collected by me, following the protocol developed for this project (Appendix 1), which involved collection immediately after the SRs were drained and before any further work or cleaning had commenced, except in one case where cleaning was inadvertently started prior to collection of one sample (C7 SR - middle of compartment 2).

C7 SR

Four samples were collected from C7 SR (Figure 4.5) during its clean in September 2019:

- Bottle 1 – within a 1 metre radius around the inlet of compartment 1

- Bottle 2 – from the middle of compartment 1
- Bottle 3 – within a 1 metre radius around the outlet of compartment 2
- Bottle 4 – from the middle of compartment 2

It was not possible to sample around the inlet of compartment 2 and the outlet of compartment 1, as both were physically inaccessible.

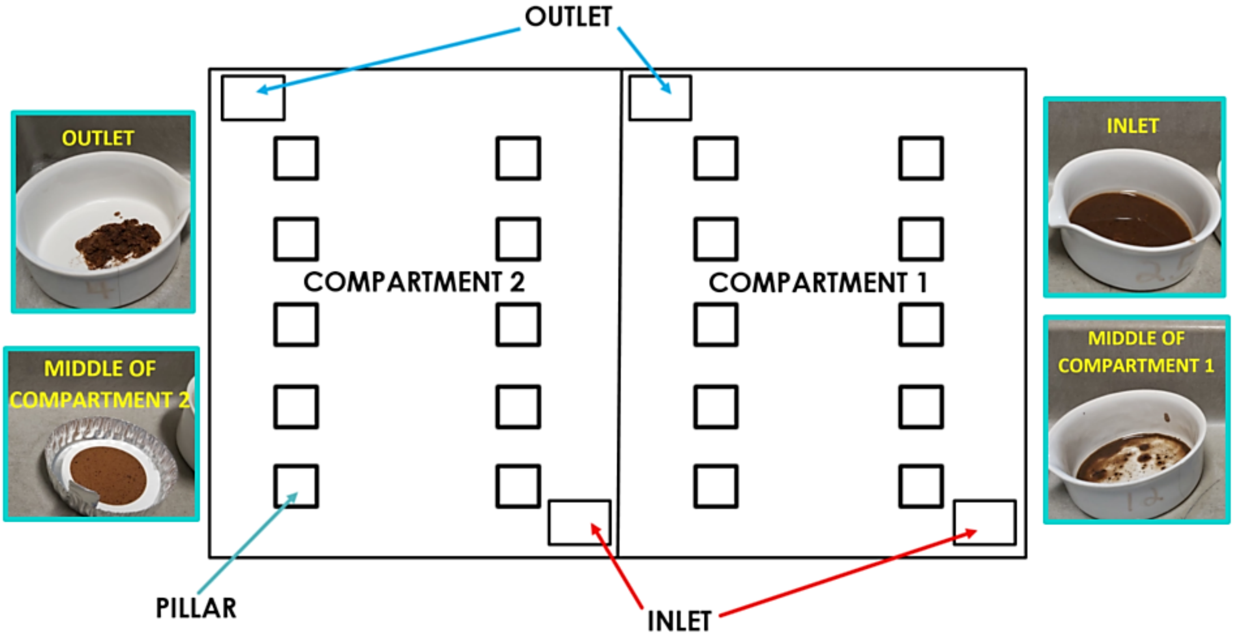

Figure 4.5 – **A basic schematic of C7 SR and photos of some of the material collected from the different locations within.**

C8 SR

Three samples were collected from C8 SR (Figure 4.6) during its clean in September 2019. Only one compartment was undergoing a cleaning operation that day, which is where the material was collected from:

- Bottle 1 – within a 1 metre radius around the inlet
- Bottle 2 – from the middle of the tank
- Bottle 3 – within a 1 metre radius around the outlet

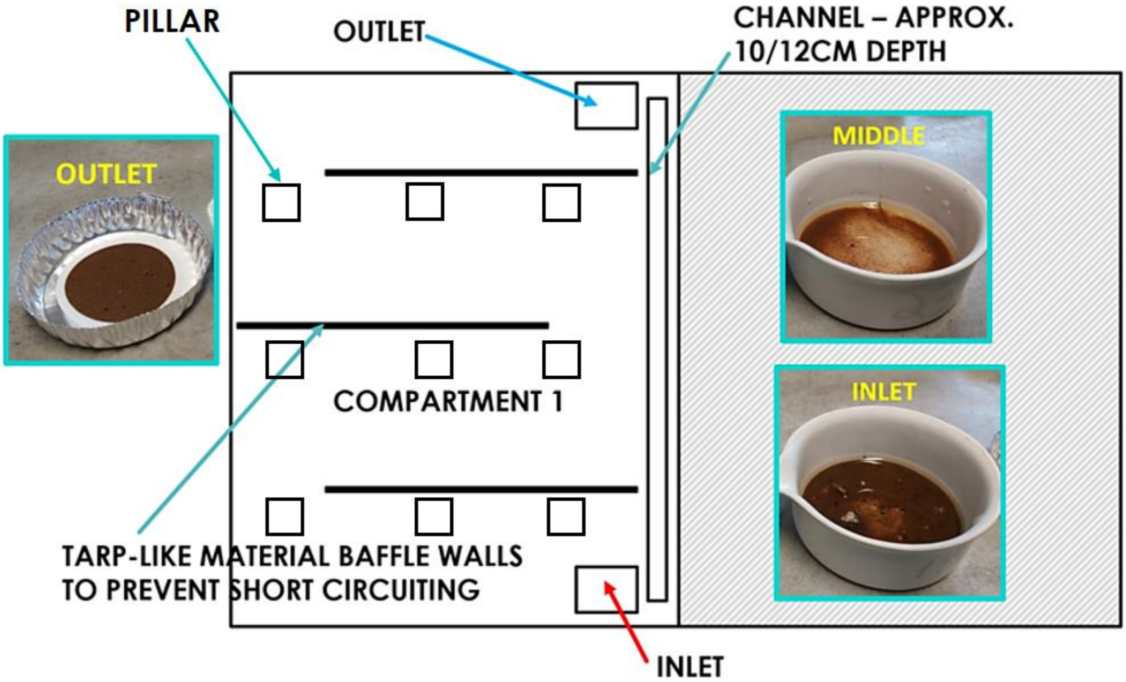

Figure 4.6 – A basic schematic of C8 SR and photos of some of the material collected from the different locations within.

C9 SR

Five samples were collected from C9 SR (Figure 4.7) during its clean in October 2019:

- Bottle 1 – within a 1 metre radius around the inlet
- Bottle 2 – within a 1 metre radius around the outlet
- Bottle 3 – directly under and around the access ladder as it was fairly corroded with evidence of some of the corroded material present in the accumulated material below
- Bottle 4 – directly under a telemetry probe as several zoological organisms were found underneath it (Figure 4.8), evidencing a potential ingress issue
- Bottle 5 – general collection from all over the tank

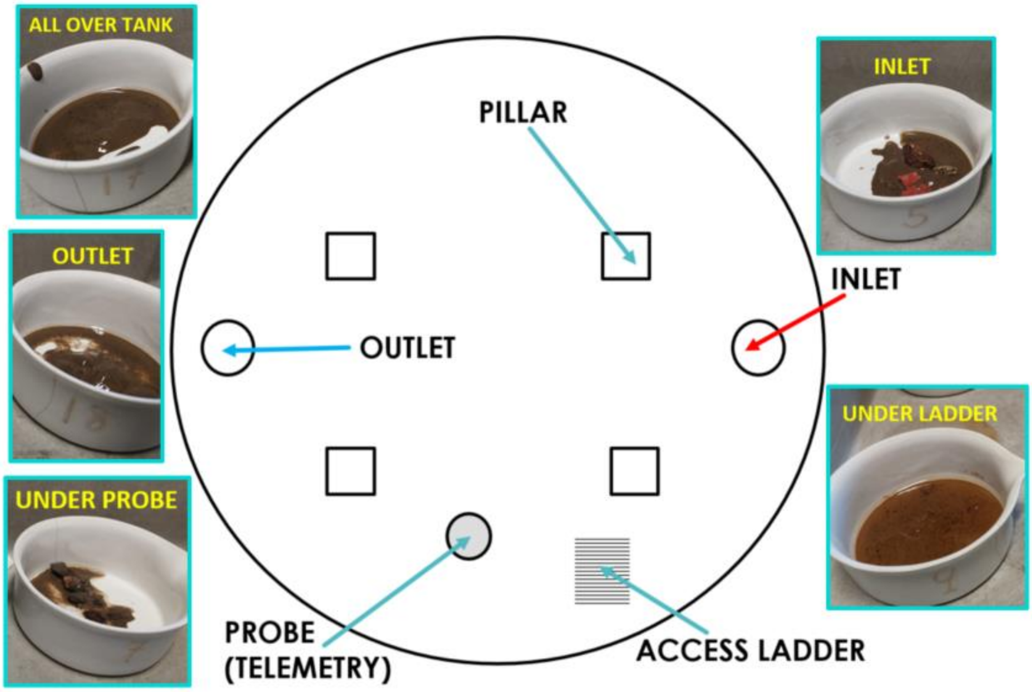

Figure 4.7 – A basic schematic of C9 SR and photos of some of the material collected from the different locations within.

Figure 4.8 – Some of the organisms and an egg sack found under the telemetry probe in C9 SR.

Cooler boxes were used to refrigerate samples during transit immediately post collection. Samples were first transported to the University of Sheffield, where they were kept in laboratory fridges and then shipped in a cooler box with freezer packs, using a 24-hour express service, to the University of Colorado, Boulder, where they were received the following day and promptly relocated into laboratory fridges prior to further analysis.

4.2.2.3. Sample preparation

An experimental programme was designed to analyse collected material for metals and elements, TOC, absorbance (UV), fluorescence, turbidity, and chlorine demand. Samples were prepared in different ways for different types of analysis. Samples in their original form (material combined with residual SR water) were used for turbidity analysis, filtered to carry out absorbance, fluorescence, TOC, and metals and elements analyses, and dried for the experiment on chlorine demand.

Drying of samples

A sterile metal spatula was used to scoop collected material into ceramic dishes (Figure 4.9), with the exception of ‘C7 OUTLET’ and ‘C8 OUTLET’ samples, which had to be collected onto filter paper using vacuum filtration because the material was too fine to collect with the spatula (Figure 4.10). Each filter was weighed and flushed with deionised water prior to use. Ceramic dishes and filtered samples (placed into foil trays) were then put in the oven to dry at 100°C for an hour and fifteen minutes. Once dry, 50 mg of each sample was weighed on a sterile plastic dish (Figure 4.11), except for the filtered samples, which were weighed at 38 mg for ‘C7 OUTLET’ and 32 mg for ‘C8 OUTLET’ (filter weight deducted) and returned to their respective foil trays.

Figure 4.9 – Some examples of what the collected service reservoir material looked like when initially scooped into ceramic dishes prior to oven drying.

Figure 4.10 – **On the left, is an example of one of the filtered service reservoir material samples, in comparison to the material on the right, scooped directly into a ceramic dish.**

Figure 4.11 – **Some of the prepared dry and filtered samples used in an experiment looking at chlorine decay rates exerted by service reservoir accumulated material.**

Filtering of samples

To filter samples, original sample bottles were first shaken for 30 seconds each, by turning the bottles rapidly up and down to saturate the surrounding water with particulates, and left to settle for 30 hours in the laboratory fridge. In the meantime, 12 (one per sample) 45 µm syringe filters were prepared by flushing 600 ml of deionised water through each filter. This method was devised by the University of Colorado, Boulder SEEL laboratories to flush out any residual carbon remaining on the filters from the manufacturing process. Once the settled samples were ready, a total of 110 ml was drawn using a syringe from the top of each sample and filtered into appropriate vials through the prepared filters (Figure 4.12). A new syringe and filter were used between each sample. For TOC, UV, and fluorescence analysis, 20 ml was syringed into individual glass vials, and for metals and elements analysis, 50 ml was syringed into plastic vials. Two 'filter blank' samples were also prepared by syringing deionised water through the flushed filters into a glass and a plastic vial. All samples were immediately refrigerated prior to analysis.

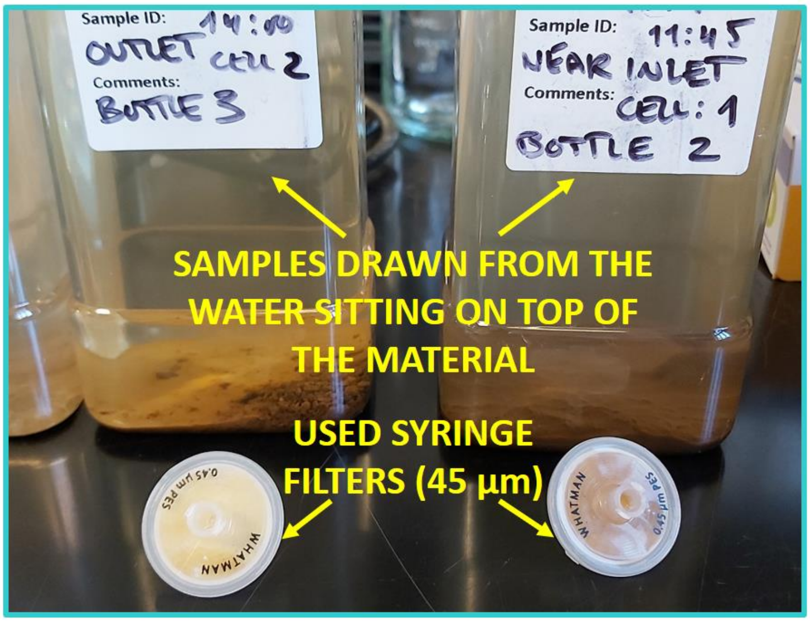

Figure 4.12 – Samples post 30 hours of settling time and the filters samples were flushed through prior to analysis.

4.2.3. Sample analysis

4.2.3.1. Metals and elements

All of the SR accumulated material samples collected in this project were analysed for a variety of metals and elements, predominantly those often found in DWDSs. These were as follows: aluminium (Al), arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), magnesium (Mg), manganese (Mn), nickel (Ni), potassium (K), uranium (U), and zinc (Zn). The analysis was done using an Agilent 7900 ICP-MS with Ultra High Matrix Introduction (UHMI) following manufacturer's guidelines (Agilent, 2021a).

One sample, C7 SR from the middle of compartment 2, required a five-factor dilution (using deionised water) as the TOC content of the sample was over 20 mg/l. According to operators notes this concentration is too high to run as it can create errors in the analysis of the sample by the ICP-MS. However, the original concentration was still analysed for comparison.

4.2.3.2. Total organic carbon

Understanding the composition of accumulated material in SRs in terms of its organic content is important in determining the effect it can have on the biological stability of the surrounding drinking water. The overall organic matter in drinking water is quantified in terms of TOC, which was measured in samples used to investigate the effect of SR material resuspension on surrounding water quality using Shimadzu TOC Analyser (functioning range 0 to 30,000 mg/l, accuracy ±1.5%) (Shimadzu, 2021) and in samples used to investigate the influence of sampling location within SRs on the composition of accumulated material using a Sievers TOC analyzer model M5310C (functioning range 0.004 mg/l to 50 mg/l, accuracy ±2%, sensitivity ±1%) (SUEZ, 2021), following existing protocols.

4.2.3.3. Absorbance (UV)

Organic compounds absorb light in the ultraviolet spectrum and thus UV absorbance is a great surrogate measure of dissolved NOM, such as humic substances (Edzwald et al., 1985). Absorbance scans are also necessary for completing the correction of inner filter effects for fluorescence analysis, which was carried out on samples used to investigate the influence of sampling location within SRs on the composition of accumulated material.

Absorbance was measured in samples used to investigate the effect of SR material resuspension on surrounding water quality using a Cary 100 Bio UV-Visible Spectrophotometer (functioning range 190-900 nm, accuracy ±0.2 nm, sensitivity ±0.1 nm) (Agilent, 2021b), following an existing protocol. Instrument baseline was set with deionised water. Each sample was run three times and a deionised water blank was run every seventh sample. The cuvette, in which samples were placed for analysis, was thoroughly cleaned with deionised water between each new sample.

Absorbance was measured in samples used to investigate the influence of sampling location within SRs on the composition of accumulated material using a Hach Benchtop Spectrophotometer DR6000 (functioning range 190-1120 nm, accuracy ±1 nm, sensitivity ±0.1 nm) following manufacturer's guidelines (Hach, 2021a). The spectrophotometer was blanked with deionised water at the beginning and then again between each sample. The cuvette in which samples were placed for analysis was thoroughly cleaned with deionised water between each new sample.

UV absorbance wavelength, 254 nm, is widely used as a form of measure for specific organic constituents in the water supply. It is used together with dissolved organic carbon (DOC) to calculate specific UV absorbance (SUVA). SUVA is useful when establishing the reactivity of DBP precursors and indicating the composition of NOM in the DWDS (Brandt et al., 2016). The higher the SUVA measure, the higher the DBP formation, NOM, and chlorine demand (AWWA, 2011). SUVA (L/mg-m) was calculated for all samples by dividing the UV254 absorbance value (in cm-1) by the DOC of the sample (in mg/L) and then multiplying by 100 cm/m.

4.2.3.4. Fluorescence

Fluorescence (excitation and emission wavelengths) is widely used to study changes in and composition of organic matter (Murphy et al., 2013), but is rarely applied to drinking water (Heibati et al., 2017), and especially to material accumulated in SRs. Fluorescence analysis was done on samples used to investigate the influence of sampling location within SRs on the composition of accumulated material using a HORIBA FluroMax 4 Spectrofluorometer (functional range 0-950 nm, accuracy ±0.5 nm, sensitivity ±0.3 nm) (HORIBA, 2021), following manufacturer's guidelines.

4.2.3.5. Turbidity

Turbidity was used as a measure of suspended material in collected samples using a Hach 2100N Turbidimeter (functioning range 0-4000 NTU, accuracy ±2%, sensitivity ±1%) which was calibrated before use following Hach protocol and standards (Hach, 2021b).

Samples for the investigation of the effect of material resuspension on surrounding water quality:

20 ml was pipetted from samples prepared for UV and TOC analysis into the Turbidimeter instrument vial and the first turbidity value recorded. The vial was rinsed with deionised water between each sample.

Samples for the investigation of influence of sampling location within SRs on the composition of accumulated material:

Original sample bottles containing collected material combined with SR water were shaken for 30 seconds by turning the bottles rapidly up and down to saturate the surrounding water with particulates and left to settle in the fridge for 30 hours (Figure 4.13). Once settled, 20 ml was pipetted from the top of each sample into the instrument vial, which was shaken ten times by turning the vial rapidly up and down before turbidity was measured. The first turbidity value was recorded and the vial rinsed with deionised water between each sample.

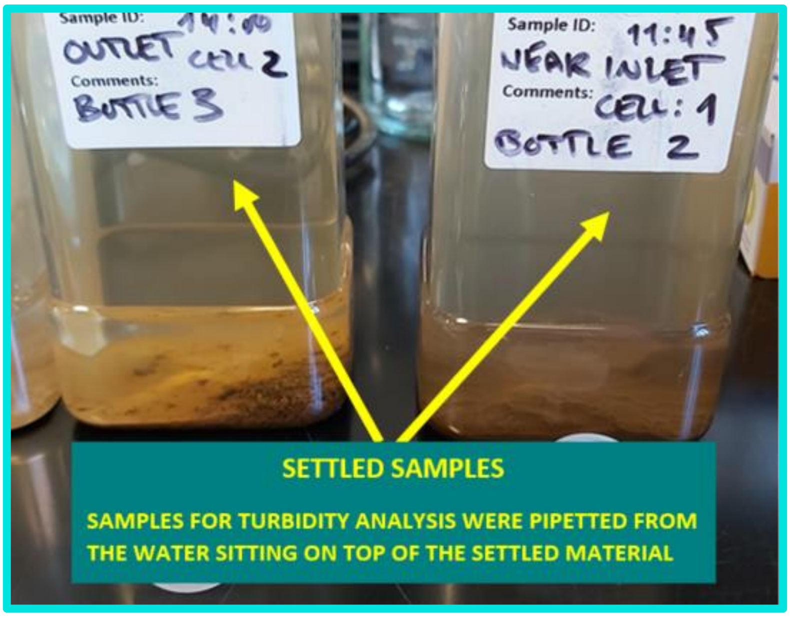

Figure 4.13 – An example of two of the original service reservoir accumulated material samples 30 hours post settling time.

4.2.3.6. Chlorine demand

Despite knowledge that resuspension of accumulated material can lead to water quality deterioration, including an increase in disinfection demand, the effect of resuspension of SR accumulated material on chlorine decay has not been previously measured.

The WHO guideline for residual chlorine in DWDS is 5 mg/l (WHO, 2017). However, as chlorine can give off an unpleasant taste and odour at residual levels as low as 0.6 mg/l, most UK water utilities do not tend to have chlorine residual levels surpassing 1 mg/l (DWI, 2010). Based on this understanding, an intermediate chlorine solution of 3 mg/l was used to measure rate of chlorine decay caused by the resuspension of material collected for the investigation of influence of sampling location within SRs (C7, C8, and C9). The aim was to quantify how much chlorine demand is exerted by accumulated SR material and whether the organic and inorganic composition of the material is a factor.

Prepared dry samples were added to individual sterile HDPE 1 L sample bottles, prefilled with 496.8 ml of deionised water. 1 L volume bottles were used as these could comfortably fit next to each other on the VWR standard analog shaker table and be filled with enough water required to measure chlorine levels. A blank deionised water only and a deionised water with a blank filter (pre-flushed with deionised water) control samples were also prepared. All samples were shaken for an hour and ten minutes on the maximum possible speed at which bottles remained stable on the table. This was done to allow material to mix with deionised water before adding 3.20 ml of the prepared chlorine solution (3 mg/l) to each sample. Following this, free chlorine concentration was measured at 0.5, 1.5, 2.5, 3.5, 16.5, 40.5, 49, and 89 hours shake time, using a Hach DR300 pocket colorimeter (functioning range 0.02-8.00 mg/l, accuracy ±5%) and Hach reagent (Hach, 2021c). It was important that long contact times were achieved to represent high water retention times often observed in SRs.

To measure chlorine, 5 ml of deionised water and 5 ml of prepared sample were pipetted into the instrument vial, after which the reagent was added and vial shaken exactly twenty times (standard procedure in SEEL laboratories) by rapidly turning vial up and down, after which a free chlorine measurement was taken. The instrument vial was rinsed three times with deionised water between each sample.

4.3. Project field site selection

Although, the term 'site' is mainly used in reference to project SRs, this also includes the surrounding network, i.e., the source water and WTW supplying that site, and the water quality zones (WQZs) and district-metered areas (DMAs) the SR feeds. In order to answer the aim and objectives of the research, it was established that at least three different sites were required with respect to background water quality, network performance, and physical geometry. Three or more varied sites would ensure reliability of results and increase the representability of project outcomes when it comes to their application to other DWDSs.

A field site was selected from each of the four UK water utilities sponsoring the project. The four sites provided experimental security should any issues occur and allowed contributions to be shared between project partners. Sites were selected based on the above and additional, more specific, requirements established using the objectives and scope of this work. These included the site:

1. **Having a consistent source water and treatment** - Mixing of water supplies and treatment styles can cause changes in water quality and can therefore complicate the cause-and-effect analysis of any downstream water quality changes.
2. **Being completely post treatment.**
3. **Either having a pre-existing accessible inlet and outlet sampling line and tap or having the scope for their installation** - Facilitates the tracking of water quality changes with transport through the SR, which is necessary to achieve **Objectives 3** and **4** of the project.
4. **Having separate inlet and outlet pipes** – It is impossible to track water quality changes through a SR with a combined inlet and outlet, plus changes in flow direction can lead to the detachment of biofilms and resuspension of material, which have undesirable effects on water quality.

5. **Having SR level and inlet and outlet flow data (or surrogate measures)** - to determine SR hydraulic behaviour, which is necessary to achieve **Objective 5** of the project.
6. **Having scope to carry out downstream/upstream sampling at the source water, trunk mains, WTW, and WQZs/DMAs** - To capture and distinguish water quality changes related to the SR from other parts of the DWDS – Necessary to achieve **Objectives 2** and **5** of the project.

Although not essential, it was desired that the selected sites should be of interest/value to the sponsor water utilities based on company metrics, such as risk assessments, high priority sites (those that experience regular water quality failures), and/or previously studied sites (tend to have more detailed existing historical data). Low priority/risk and more stable sites were also considered as a low-risk site could minimise chances that major remediation (that could delay the progression of the research) would be required within the timeframe of the project.

Following a thorough selection process and detailed discussions with host water utilities, a decision was made as a consortium on the chosen project sites, with each site significantly different from one another. These are as follows:

1. Company A – **A1**
2. Company B – **B2**
3. Company C – **C3**
4. Company D – **D4**

Although it would have been desirable to have multiple sites with each sponsor water utility, this was not deemed practical due to extra burdens placed on these utilities. Burdens included installation of new sample lines/taps, operator resources and additional costs for sampling directly for the purposes of the project, and time required to set up and maintain each site within the timeframe of the project.

Full description of site details can be found in Chapter 5: Site Details.

4.4. Data collection

4.4.1. Data acquisition for project field sites

It has been suggested in the literature that for effective assessment and management of SRs a combination of three types of data is required: (1) physical (geometry, network configuration); (2) water quality; and, (3) asset condition. Site-specific physical and asset condition data was obtained from host water utilities for all project sites. Full details can be found in Chapter 5: Site Details.

To obtain water quality data and have the ability to assess asset condition over time, a monitoring programme was devised. The programme included sampling for a variety of regulated and non-regulated water quality parameters at both SR inlets and outlets, and in the surrounding DWDS (**Objective 3** of the project). Table 4.3 below lists all the key parameters monitored in this research and the reasoning behind their selection.

Table 4.3 - A list of the parameters monitored and analysed in this research and the reasons behind their selection.

Parameter	Reason for monitoring
Absorbance and fluorescence	Organic/inorganic loading
Ammonium[2]	Inorganic content/water chemistry
Bacteriological indicators[3]	Bacteriological failures/contamination events
Conductivity	Water chemistry/inorganic loading/changes in total dissolved solids/disinfection efficacy/water age
Flow and water level	Hydraulic evaluation
Flow cytometry	Microbiological activity trends and loading
Metals: Aluminium, Iron, and Manganese	Water chemistry/network material characterisation and loading/discolouration and corrosion components/potential WTW coagulant carry-over
Nitrates/nitrites[2]	Inorganic content/water chemistry/possibility of nitrification
Organic carbon (total and dissolved)	Organic material loading
pH	Water chemistry
Residual disinfectant	Disinfection efficacy/microbiological activity/safety of the water supply
Temperature	Water chemistry/microbiological activity/seasonal impact/water age
Turbidity	Material loading/water aesthetics/water quality deterioration
SR accumulated material	All of the above

Aside from samples collected using continuous online monitoring equipment, all samples described in this section were collected and analysed by water utilities in accordance with their standard procedures for regulatory compliance monitoring. These are ISO 5667-5, EN ISO 19458, ISO/IEC 17025, ISO/IEC 17024, and the Drinking Water Testing Specification, accredited by the United Kingdom Accreditation Service (UK, 2018; DWI, 2020a).

4.4.1.1. Historical network data

At the start of the project, historical data was collected for each project site in order to begin to

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[2] Acquired for systems with chloramine as their secondary disinfectant only.

[3] (Colony counts, *Escherichia coli*, coliforms, and *Clostridium perfringens*)

characterise changes in water quality as water travels through DWDSs. This was done to achieve **Objective 2** of the project.

It is a regulatory requirement for water utilities to carry out routine water quality monitoring at various stages of the DWDS to manage and ensure good system performance. The majority of historical data encompasses such regulatory sample data collected at the inlets of WTW (raw source water), outlets of WTW (treated water), outlets of SRs, and from random sampling in WQZs and DMAs. Historical data does not include monitoring at SR inlets, as this is not a regulatory requirement. Any historical data that was collected by water utilities outside of regulatory requirements during any additional sampling campaigns was also acquired.

Historical data dates back to at least the start of 2017, a year prior to project start date, although some datasets extend back to 1997. This variability in timeframe is mainly due to utility records and reporting systems being incomplete or archived in a way that made the data inaccessible. It was important for data to date back at least a year prior to the project start date to warrant it being classed as historical, but no further back than twenty years to ensure its relatability to the current condition of project sites.

Literature review has highlighted that there is often an assumption in industry that because SRs are prone to structural issues, older assets are often associated with ingress and bacteriological contamination events. To test this assumption, historical data for bacteriological failures at SR outlets between 2012-2018, alongside company-wide data on the construction age of operational SRs, was collected from project water utilities and used to assess the potential relationship between the duration of time a SR has been in service against the likelihood of it experiencing a bacteriological failure.

Please refer to Tables a-d in Appendix 2 for a full list of historical data obtained for the four project sites.

4.4.1.2. Site-specific supporting background water quality data

To track source to tap changes in water quality, site-specific supporting background water quality data was collected at all stages of project networks for the duration of the project (January 2018 - October 2020). Data was predominantly composed of regulatory samples collected at the inlets of WTW (raw source water), outlets of WTW (treated water), and from random sampling in WQZs and DMAs. This data was used to help distinguish whether observed changes in water quality at project SRs were influenced by changes in upstream network water quality, which also helped to identify any operational and/or seasonal factors influencing SR performance (**Objective 5** of the project). Please refer to Tables a-d in Appendix 2 for a full list of supporting background water quality data collected for the four project sites.

4.4.1.3. Operational data

It was a suggestion in the literature that water quality data collected at SRs should be correlated to the hydraulic conditions within the asset for a more comprehensive assessment of SR performance. Therefore, in conjunction with site-specific supporting background water quality data, flow and level data was collected at the inlets and outlets of project SRs, which, in line with current standard sampling frequency, was recorded at fifteen-minute intervals. Collection of flow and level data also made it possible to capture and assess the influence of hydraulic changes outside of normal operation (e.g., changing the fill/drain cycle of a SR) and/or interventions (e.g., SR cleans) on water quality in SRs (**Objective 5** of the project). Because SRs are usually kept at full capacity, hydraulic operational changes are rare and the influence of these on water quality is not well understood.

4.4.2. Water quality monitoring at project service reservoirs

To enable the collection of water quality data required to achieve **Objectives 3, 4,** and **5** of the project, a sampling regime and data collection programme was established. The programme was comprised of three types of sampling:

- **Discrete sampling** – grab samples collected and analysed manually, typically once a week.
- **Continuous sampling** – conducted by means of online monitoring equipment.
- **Automatic sampling campaigns** – conducted using an automatic sampler.

4.4.2.1. Installation of sample lines and taps

As inlet monitoring at SRs is not a regulatory requirement for water utilities in the UK, there was no available inlet sampling location at most project SRs. Therefore, to enable the investigation of SR performance using incoming and outgoing water quality, inlet sample lines and taps were installed at all but one selected project site. The exception was B2 SR, where an existing inlet sample line was recommissioned for the project. Installation and recommissioning of inlet sample lines was carried out by water company personnel in accordance with UK Water Supply Regulation 8 and made from materials complying with BS 6920 (DWI, 2012; WRAS, 2021). For detailed site schematics, please refer to Chapter 5: Site Details.

4.4.2.2. Discrete sampling

To monitor water quality with transport through SRs, a discrete sampling regime was established at project SRs, following the installation of inlet sample lines and taps. Samples were collected weekly at the inlet and outlet of each SR for comparable periods of at least six months between January 2018 and October 2020, which provided enough data for the assessment of SR performance. It was also important to ensure a long sampling timeframe to capture the potential influence of external factors on water quality at SRs, such as seasonal variation in temperature, and any changes related to operational management in the DWDS.

Weekly sampling was the most effectual regime concerning sample collection and analysis, whereby water utilities mirrored the process at the inlet with the already existing weekly regulatory one at the outlet. The six-month timeframe allowed leeway within the project to manage issues that delayed sampling, such as planning approval for getting inlet sample lines and taps installed.

Please refer to Tables a-d in Appendix 2 for a full list of collected discrete data at all four project sites and to Chapter 5: Site Details for timeline of sampling and events at each project SR.

4.4.2.3. Continuous sampling

To capture real-time changes in water quality, a continuous sampling programme was established at SRs through the application of online monitors, which were either installed or recommissioned at all project sites. At present, online monitoring at SRs is rarely utilised and so conducting this type of monitoring in this project helped to contribute knowledge on the subject.

A1 SR

Because A1 SR has its own power supply and suitable space for connections, ATi MetriNet multi-parameter water quality monitors (Figure 4.14) were obtained for the project and installed on the inlet and outlet sample lines of the SR (ATi, 2021a). The monitors were set up to measure free and total chlorine (functioning range 0-4 mg/l), conductivity (functioning range 0-2000 µS), turbidity (functioning range 0-40.00 NTU), and temperature (functioning range 0 to 55°C) via a multitude of M-Nodes connected to the water supply. The data for these parameters was set to log at a 1-minute frequency, an accuracy of ±1% of reading and sensitivity of ± 0.1%, which is available to the user online depending on the upload frequency selected. Installation and regular maintenance of these project MetriNets was conducted by ATi.

Data was collected across a period of 18 months at the outlet of A1 SR and across two time periods of 5 and 4 months, with a time interval of 3 months in-between, at the inlet of A1 SR. The gap in monitoring at the inlet was related to the MetriNet monitor needing maintenance and recalibration of some of the M-Nodes, which required several site visits from ATi engineers that took some time to organise and carry out between ATi and the host water utility (Company A).

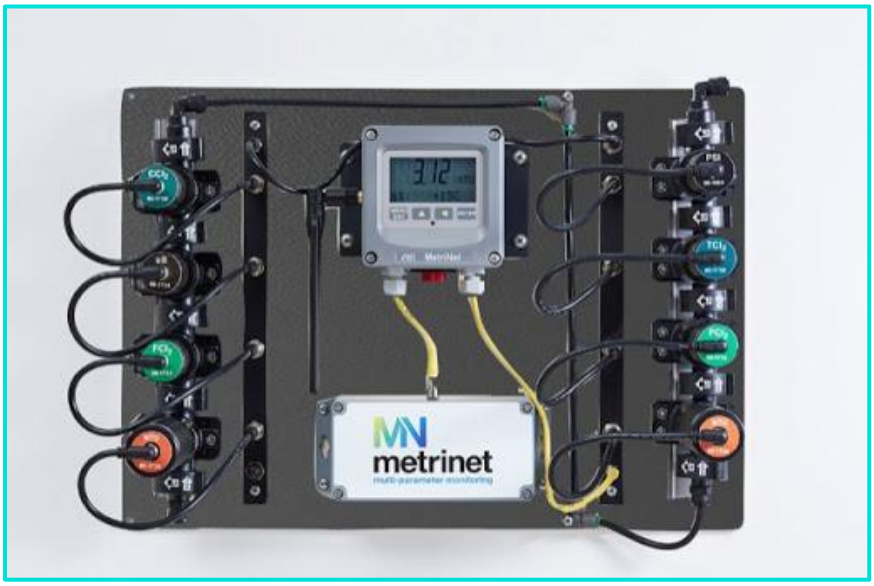


Figure 4.14 – **ATi MetriNet multiple water quality parameter monitor.**

<u>B2 SR</u>

B2 SR had existing but not commissioned SWAN AMI Turbiwell turbidity monitors (Figure 4.15) (SWAN, 2020) installed on the inlet sample line of B2 SR. These monitors were recommissioned upon putting the inlet sample line back into service. There was scope to install a turbidity monitor on the outlet sample line, but this had to be cancelled due to the covid-19 pandemic. The monitors were set to log at a 1-minute frequency, with logger functioning rate of 0-100.00 NTU, accuracy of ±5% of the reading and sensitivity of ±1%. The data collected by the SWAN monitors was sent to Company B's database, which was then forwarded by company staff in an Excel format to me.

Data was collected across two time periods, which equated to a total of 9 months of continuous turbidity data at the inlet of B2 SR. There was an 11-month interval between the two time periods because the water is pumped to the inlet sample line at this SR and one of the pumps experienced a technical fault and needed replacing, which was challenging and took time to plan in as the pump is located in a high-risk confined space chamber.

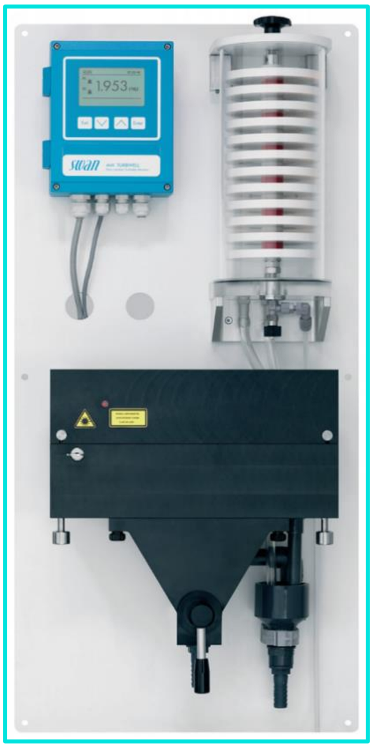


Figure 4.15 – **A SWAN AMI Turbiwell monitor.**

C3 and D4 SRs – turbidity

With no accessible power supply, battery run ATi NephNet turbidity response monitors (Figures 4.16 and 4.17) (ATi, 2021b) with infrared nephelometric measurement processing were ordered and installed at the inlet and outlet of D4 and C3 SRs by me and subject water utility project staff. The NephNets were set to log at a 1-minute frequency, with logger functioning range set to 0-20.00 NTU at an accuracy of ±5% of the reading and sensitivity of ±0.1%. The collected data was set to be available online within 6 hours, determined as the best balance between capturing effective real-time data and prolonging battery life.

Data was collected across five separate time periods, which equated to a total of 7 and a half months of continuous turbidity data at the inlet and outlet of the C3 SR. At the D4 SR, data was collected across two separate time periods, which equated to a total of 3 months of continuous turbidity data at the inlet and outlet. NephNet monitors needed manual maintenance (cleaning of the optics, re-charging batteries, and re-calibrating units) every 1 and a half months or so, which required them to be taken offline for the duration, hence the breaks in data collection.

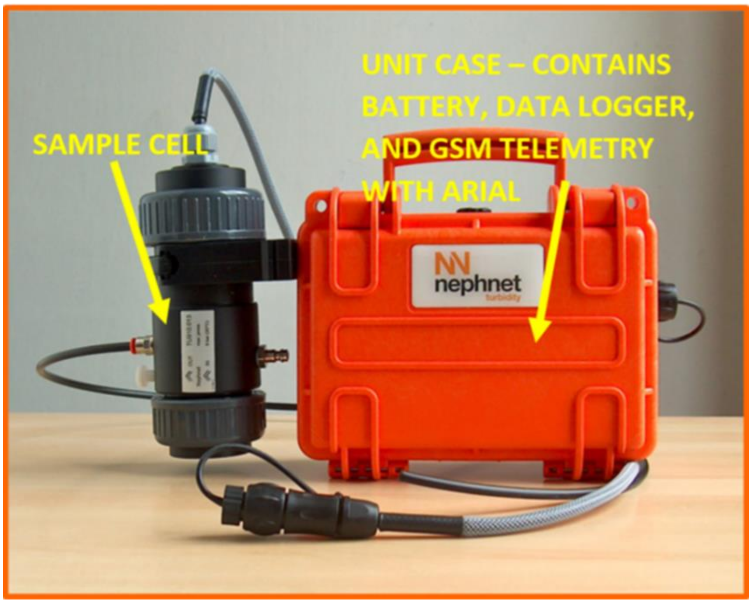


Figure 4.16 – **ATi NephNet turbidity response monitor.**

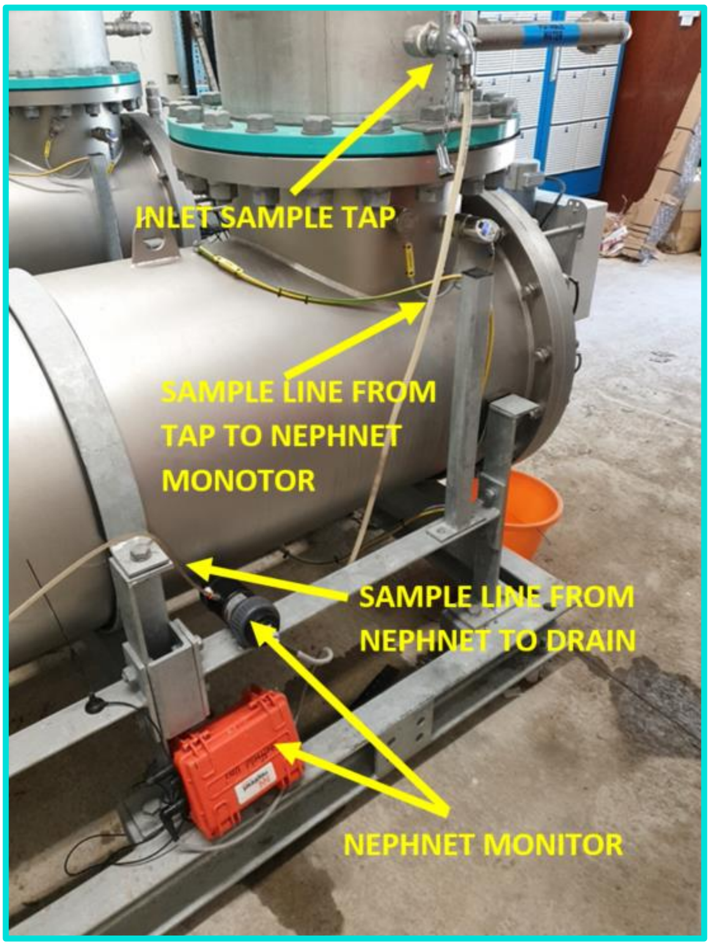
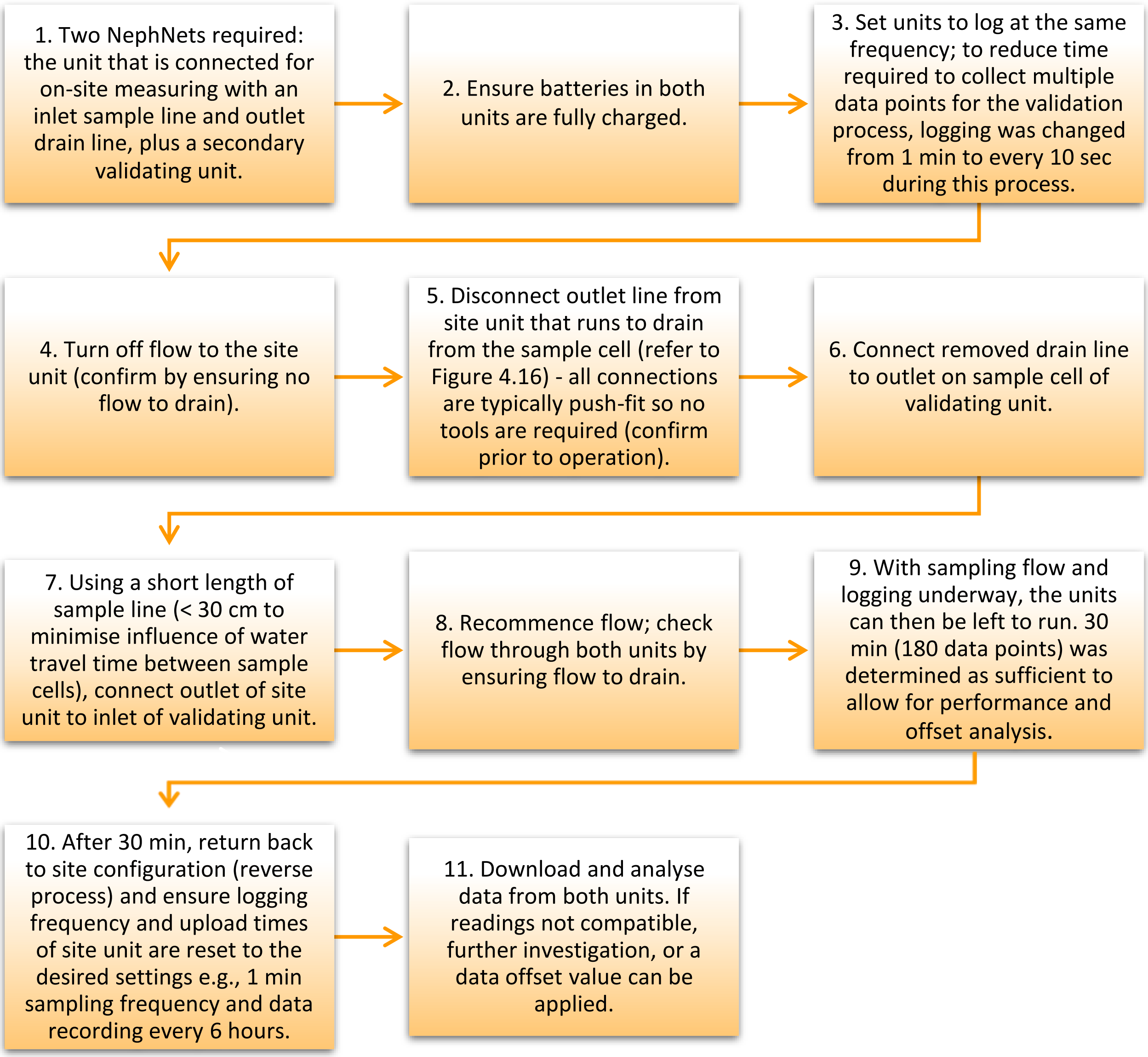


Figure 4.17 – **ATi NephNet turbidity response monitor installed on the inlet sample line at D4 SR.**

All NephNet monitors were dual validated prior to use to provide data confidence by ensuring that absolute inlet and outlet turbidity values recorded were comparable. This is required as turbidity sensors work on light reflected into the detector from particles in the fluid phase. Turbidity values are comprised of a complex combination of factors, with obscuration, reflection, refraction, diffraction, and scatter all contributing. This can result in minor differences in offset measurements during conversion of measured light to nephelometric units. To determine potential offsets, a testing unit was used to compare both inlet and outlet units using the following protocol developed specifically for this project (Figure 4.18).



1. Two NephNets required: the unit that is connected for on-site measuring with an inlet sample line and outlet drain line, plus a secondary validating unit.
2. Ensure batteries in both units are fully charged.
3. Set units to log at the same frequency; to reduce time required to collect multiple data points for the validation process, logging was changed from 1 min to every 10 sec during this process.
4. Turn off flow to the site unit (confirm by ensuring no flow to drain).
5. Disconnect outlet line from site unit that runs to drain from the sample cell (refer to Figure 4.16) - all connections are typically push-fit so no tools are required (confirm prior to operation).
6. Connect removed drain line to outlet on sample cell of validating unit.
7. Using a short length of sample line (< 30 cm to minimise influence of water travel time between sample cells), connect outlet of site unit to inlet of validating unit.
8. Recommence flow; check flow through both units by ensuring flow to drain.
9. With sampling flow and logging underway, the units can then be left to run. 30 min (180 data points) was determined as sufficient to allow for performance and offset analysis.
10. After 30 min, return back to site configuration (reverse process) and ensure logging frequency and upload times of site unit are reset to the desired settings e.g., 1 min sampling frequency and data recording every 6 hours.
11. Download and analyse data from both units. If readings not compatible, further investigation, or a data offset value can be applied.

Figure 4.18 – A flow diagram describing the systematic process for ATi NephNet turbidity unit validation.

C3 SR – flow cytometry

As well as the two ATi NephNet turbidity monitors, a BactoSense automated flow cytometer online monitor (Figure 4.19) was installed at the outlet of C3 SR by the manufacturer SIGRIST-PHOTOMETER and project water utility staff. The monitor was set to measure total cell counts at a 2-hour logging frequency, with logger functioning range set to 1000 - 2 million cells/ml at an accuracy of ±5% of the reading. The unit comes with a USB port and data was exported by water utility project staff in this way, after which data was sent to me in an Excel spreadsheet format. Data was collected across a single time period of 4 months at the outlet of the C3 SR.

Figure 4.19 – BactoSense automated flow cytometer online monitor.

The use of all the described monitors is established in the water industry. This meant standard risk assessments were acceptable and there were no issues with installation. With this equipment, it was possible to extract data directly into both water utility and university systems, allowing for the effective real-time assessment of water quality at sites. Please refer to Tables a-d in Appendix 2 for a breakdown of collected continuous data at all four project sites and to Chapter 5: Site Details for the timeline of continuous sampling at each project SR.

4.4.2.4. Automatic sampling campaigns

To collect non-regulated discrete water quality sample data on a more continuous basis, and to capture the potential influence of changes in diurnal demand on water quality, a 24-hour sampling programme was conducted with hourly collection from the inlet and outlet of C3 SR using Hach AS950 automatic samplers (autosamplers) (Hach, 2021d). Two autosamplers were used in conjunction with online turbidity sampling. One was connected to the NephNet turbidity monitor at the inlet and one to the monitor at the outlet. The NephNets have two low-flow sample lines; one that connects to the water source (tap off point on a main) and one from which water normally goes to drain. For automatic sampling, water from the NephNet drain line was captured in a 1.5 litre plastic reservoir, into which the peristaltic sampling pump line of the automatic sampler was inserted (Figures 4.20 and 4.21). This set up allowed up to 1-litre samples required by the autosamplers to be collected from this reservoir at defined intervals.

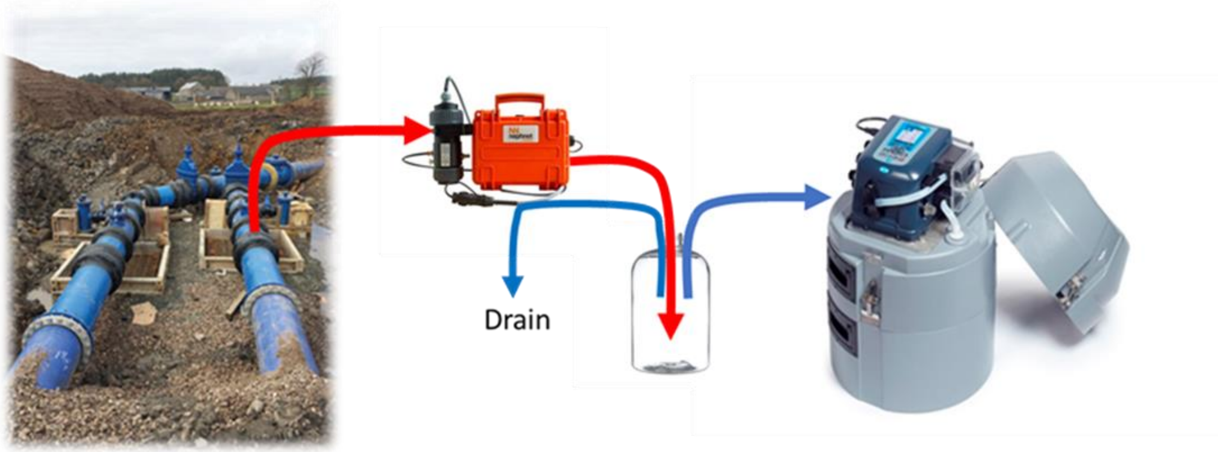


Figure 4.20 – **A basic layout of the experimental set up for automatic sampling on site.**

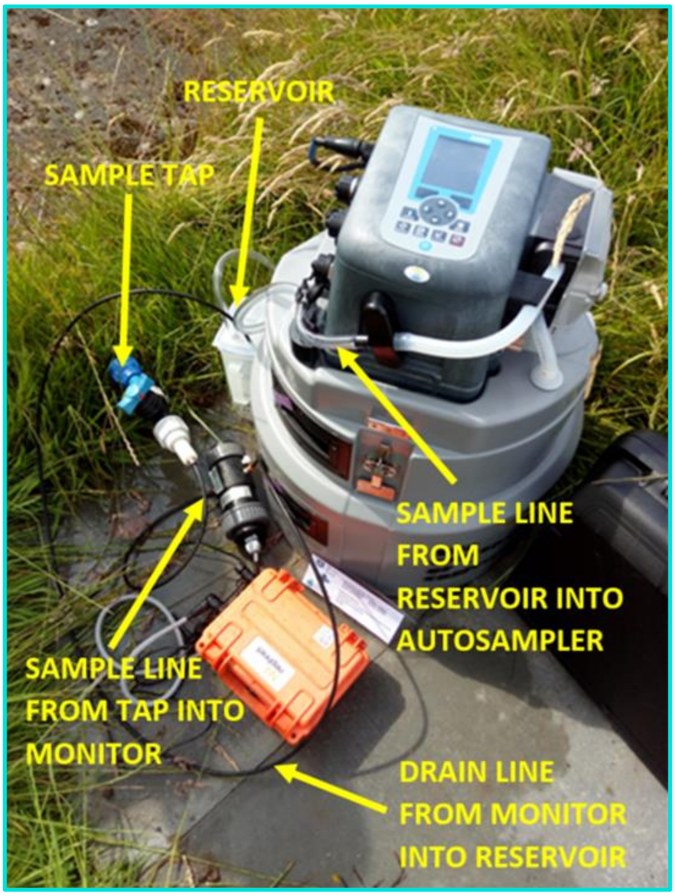


Figure 4.21 – **Diagram of on-site experimental set up at the inlet of C3 SR.**

Autosamplers are usually used to collect samples from a large body of water, such as a lake or a river, where the peristaltic intake tube is inserted directly into that water source. However, as this is not possible to do with a pressurised system, the plastic reservoir was incorporated. This was almost completely sealed to avoid any ingress, leaving only a small gap out of which excess water could overspill. However, this meant that automatic sampling could only be carried out at sites where the excess water had somewhere to overspill to without causing issues. As the sample points of D4 and A1 SRs are located in closed buildings with other equipment, having water overspill there would create a health and safety risk. Therefore, automatic sampling could only be conducted at the C3 and B2 SRs. Sampling was conducted at C3 SR in summer 2019 and winter 2020 to assess whether the observed behaviour changes with seasonal temperature variation. Table 4.4 outlines the programme settings used for these sampling campaigns. Automatic sampling was planned at B2 SR in spring 2020 but was cancelled because of the covid-19 pandemic.

Table 4.4 – Settings for the automatic sampling programme.

Setting	Selected option
Total bottles	24
Bottle volume	1000 ml
Tubing	100 cm, 9.5 mm (3/8”)
Pacing	1 hr
Sample volume	Fixed 800 ml
Distribution	1BPS (bottle per sample), 1SPB (sample per bottle)
Programme start	On Schedule (specific date and time were set)
Programme end	24 samples

Collected samples were analysed for metals (iron, aluminium, and manganese), conductivity, pH, and turbidity by water utility staff in accordance with standard procedures for regulatory compliance monitoring. It was not possible to analyse samples for disinfectant residual, as these would need to be tested in the first five minutes. Similarly, any bacteriological samples need to be tested within the first 24 hours of sample collection, which was not feasible with the type of sampling programme in place.

4.5. Data analysis

4.5.1. Graphical plots and statistical analysis

Quality checking

All data was quality checked prior to analysis. This included discarding any below minimum detection values that were recorded as the bottom limit of instrument detection, rather than the true value.

Where it was deemed necessary to present below minimum detection data, this was represented as the minimum detection limit value divided by 2 (Hornung and Reed, 1990). Any turbidity values that equalled zero were also discarded because even in a pure liquid light will scatter to a certain degree, meaning that it is impossible to have a solution with zero turbidity.

Graphical visualisation of the data

Data was visualised graphically either in the form of scatter, line, or box plots. Graphical plots were plotted either in Excel (Microsoft Corporation, 2020) or in 'R' version 3.6.3 (R Core Team, 2020). The only exception were fluorescence excitation/emission matrices, which were produced as an output of the analysis by the software used.

Box plots are the most common graphical plots used in this project and were exclusively plotted in 'R'. Whisker boundaries of box plots plotted in 'R' are calculated by multiplying 1.5 x the Inter-Quartile Range. A 'beeswarm' function was used to plot points on top of the box plots to give a clearer visualisation of the distribution of data. However, this function does not scale well to large numbers of observations (typically any sample number above 400), and so the function was omitted for data with sample numbers that were too high for it to run. Box plots require a sample size of at least $n = 5$, therefore, where sample size was ≤ 5, individual data points were plotted directly onto the graph, omitting the box and whiskers (Krzywinski and Altman, 2014).

Testing for normality and equal variances

Prior to carrying out any statistical analysis, continuous data was analysed for normality using a combination of descriptive statistics, box plots, and QQ-plots, and/or tested statistically using Shapiro-Wilks (sample size < 5000) or Kolomogorov-Smirnov (sample size > or = 1000) tests. Testing for normality is an important step in deciding measures of central tendency and statistical methods for data analysis. If data is normally distributed, means are taken as the representative value of the dataset and are compared using parametric tests, if data is not normally distributed, medians are used to compare the groups, using nonparametric methods. Various statistical methods used for data analysis make assumptions about normality, including correlation analyses and t-tests. Selecting the wrong representative value of a dataset and further significance tests based on this value might provide a false interpretation of the data.

Where there were two independent groups, data was also analysed for equal variances using an F-test. Determining variance is important in the selection of the appropriate statistical test for the dataset. Some statistical tests, like the two-sample t-test, assume equal variances and so if variances are not equal and the statistical test is used, the output of that test will likely produce an incorrect interpretation of the data.

Statistical analysis

Following any quality checks, descriptive statistics (mean, median, range, and standard deviation) were calculated for most sampled parameters to provide basic information about collected datasets and highlight any potential relationships between different variables.

To identify any statistical differences between datasets, parametric (t-test/Welch t-test) or non-parametric (Wilcoxon signed-rank test/Wilcoxon-Mann-Whitney U test) statistical tests were conducted, as appropriate. t-tests are significance tests for continuous variables, used to compare the means of two groups of data. The test calculates a test statistic called ‘t’, which is the difference between the two means, standardised by the standard deviation of the differences, and determines whether this difference is significant or due to random chance instead. A Welch t-test is a variant of the t-test, which takes unequal variances into account. Wilcoxon signed-rank and Wilcoxon-Mann-Whitney U tests are variants of the t-test that are used for nonparametric data; instead of comparing means of the groups, these tests report the difference between groups as medians or mean ranks, depending on the patterns of distribution of data of the two groups. Wilcoxon signed-rank test is used for paired samples and Wilcoxon-Mann-Whitney U test is used for unpaired samples.

Correlation analysis is a statistical technique used to show the extent by which variation in one variable is associated with variation in another variable. Although graphical illustrations of such data can provide a visual representation of a linear relationship between two variables, correlation tests make It possible to quantify the strength of that relationship, denoted by ‘r,’ and to determine whether the relationship is statistically significant. For any correlation analysis in this project, parametric (Pearson product-moment correlation coefficient) or non-parametric (Spearman's rank-order correlation) statistical analysis was conducted as appropriate.

For any parameter, at any location, sample number had to equal three or more for any comparison tests. All statistical analysis was carried out in ‘R’ version 3.6.3., with a significance level of <0.05.

4.5.2. Relationship between turbidity and other parameters at service reservoirs

Turbidity is a key parameter in this project as it is used as a surrogate measure for suspended material. Changes in turbidity are frequently associated with changes in other water quality parameters, such as disinfectant residual, cell count, and metals. To improve understanding on what additional information turbidity can provide about changes in water chemistry in SRs, aside from the ‘sink or source' behaviour of material, a correlation (non-parametric data) analysis was conducted between turbidity and other water quality parameters monitored at project SRs using 'R' version 3.6.3.:

- Discrete turbidity and iron at the inlet and outlet of A1, B2, C3, and D4 SRs.
- Discrete turbidity and manganese at the inlet and outlet of B2, C3, and D4 SRs.
- Discrete turbidity and total cell count at the inlet and outlet of B2 and C3 SRs.
- Continuous SR outlet turbidity and total cell count at the C3 SR.
- Discrete turbidity and intact cell count at the inlet and outlet of B2 and C3 SRs.
- Continuous SR outlet turbidity and intact cell count at the C3 SR.

4.5.3. Assessing and quantifying service reservoir performance in terms of sink or source of material

Introduction

In this project, the 'sink or source' concept, which is used in other disciplines to assess and quantify system performance, was defined as the process of material accumulation and resuspension in SRs. The concept was applied to discrete and continuous water quality sample data collected at project SRs to establish a way to assess and quantify SR performance. This was done to achieve **Objective 4** of the project.

SR performance with respect to sink or source behaviour of material can be described as follows. If more material enters than leaves a SR, it can be considered to be acting as a 'sink' of material, thus performing well as it is effectively removing undesirable compounds out of supply and therefore improving outgoing water quality. Contrarily, if more material leaves than enters a SR, it can be considered to be acting as a 'source' of material and thus performing badly as it is now contributing those same undesirable compounds into the downstream network (Figure 4.22).

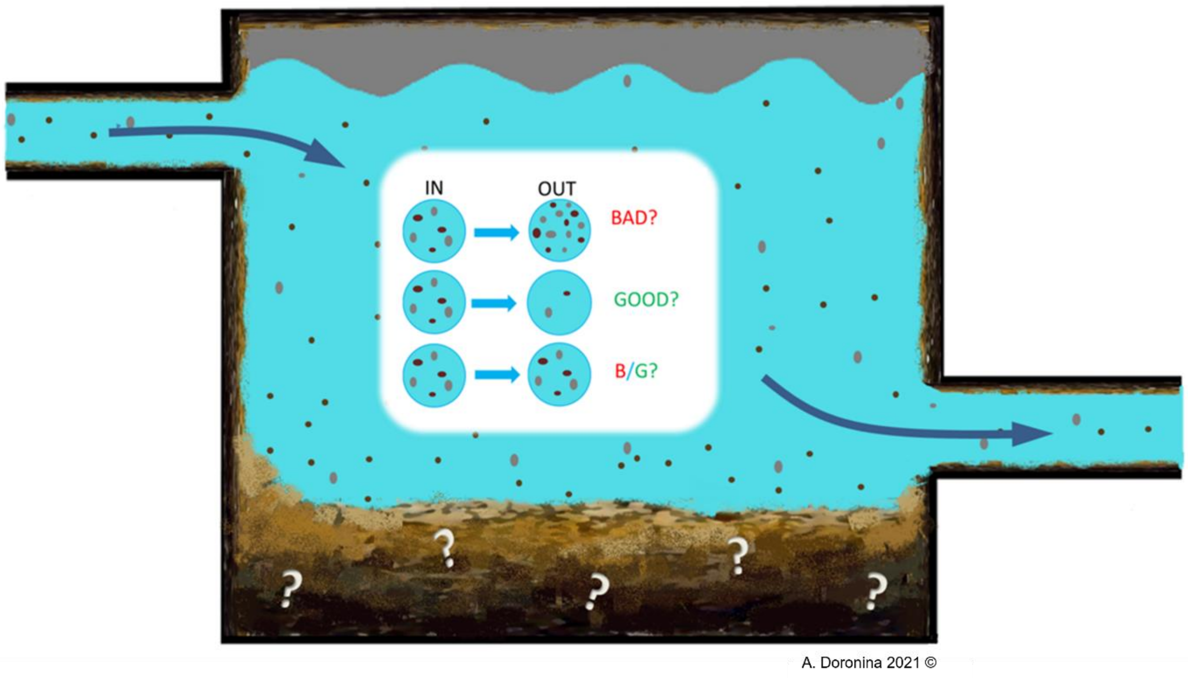


Figure 4.22 – **A graphical illustration of sink/source behaviour of material being applied to describe service reservoir performance. If more material leaves than enters, the SR can be considered to be performing badly, acting as a source of material. If less material leaves than enters, then it might be performing well by acting as a sink of material.**

Using discrete water quality sample data

SR performance was calculated as a mass balance in the form of percentage difference between paired chlorine, cell count (total and intact), iron, manganese, TOC, temperature, and turbidity discrete water quality sample data at the inlet and outlet of project SRs using the following equation:

(Outlet value – Inlet value)/Inlet Average * 100

A negative percentage could indicate that that the parameter in question is decreasing with travel through the SR, with a positive percentage indicating the opposite. A negative percentage could be seen as a positive indicator of SR performance as the asset is behaving as a 'sink' of that parameter, removing it out of supply. An exception to this is chlorine, where negative values indicate chlorine decay with travel through the SR and so the lower the percentage change in chlorine, the better.

Using continuous turbidity monitoring data

In this research, turbidity was used as a surrogate measure for material loading as it is a primary indicator of suspended particles in water. Specifically, online turbidity monitoring at the inlet and outlet of project SRs, as in this continuous form turbidity provides information about real-time changes in SRs with respect to sink or source behaviour of material. Figure 4.23 below is an example of raw online turbidity data collected across a month at the inlet and outlet of one of the project SRs. Although informative, raw turbidity data collected in this way can also be highly variable, making it difficult to interpret visually.

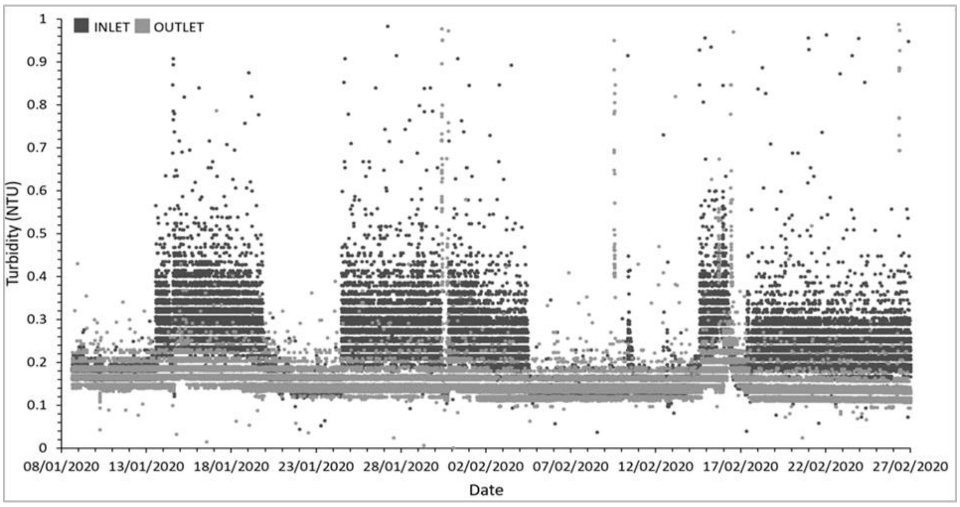


Figure 4.23 – An example of raw online turbidity data at the inlet and outlet of a project service reservoir.

To overcome the limitations of raw data, a practical metric was developed to quantify SR performance, which uses a moving average of SR net performance data (measured as NTU at SR outlet – NTU at SR inlet). The intended usage of the metric was to assess the general trend in SR performance over time, unaffected by changes in normal operating flow regimes (e.g., daily fluctuations related to diurnal demand patterns). To enable this, a moving average was required that would be long enough to smooth over changes in performance in response to normal operation, but not so long that it was no longer sensitive enough to capture fluctuations in performance related to other factors, such as operational events outside of normal operation. Additionally, the moving average needed to be at least of the order of the residence time of project SRs to account for retention time effects.

Several moving averages were tested to establish which would be the most appropriate, with a 96-hour moving average selected, applied ideally to a minimum of two weeks of monitoring. Figure 4.24 shows examples of the outputs of various moving averages applied to six weeks of online turbidity data collected under normal operating conditions at one of the project SRs. Below 24 hours (A), data is highly variable and the moving average windows are too short to smooth over the effect of changes in performance related to diurnal demand patterns, making it difficult to see genuine SR behaviour. A 36-hour moving average (B) is still too variable and does not account for the highest average retention time of project SRs, which is 41 hours at C3 SR (Chapter 5: Site Details – Table 5.1). Although a 48-hour moving average (B) is longer than the average retention time of C3 SR and is less variable than the 36-hour window, the 41-hour average retention time is an estimate and is calculated under the assumption that the SR is well-mixed, which is unlikely to be the case, meaning that the true retention time is likely to be much higher. Therefore, a longer moving average is required. Over a week-long moving average (D) is slow to respond, which means that subtle switches in SR behaviour are no longer picked up. Applying a moving average longer than a week also requires more data collection to obtain an understanding of asset performance. 72 and 96-moving averages (C) both meet the criteria for the intended usage of the metric, and both produce similar results. The 96-hour window was chosen over 72 to allow for a longer tail of retention time effects in poorly mixed SRs. Moving averages were also applied to a period of online turbidity data collected during a known operational event (Figure 4.25), with the same decision being made that a 96-hour moving average is the most appropriate for the purposes of the metric.

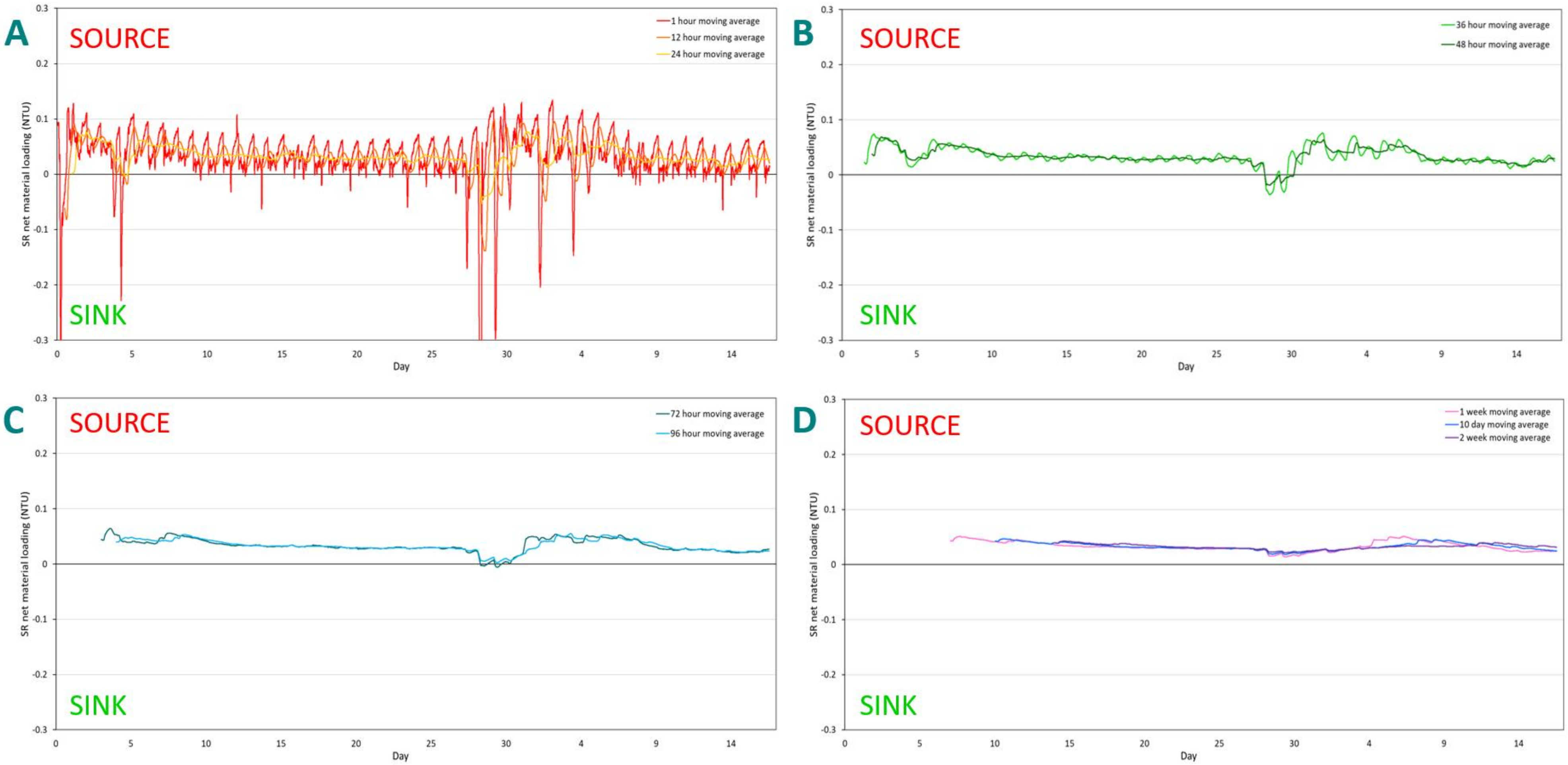


Figure 4.24 – **Examples of various moving averages ran on six weeks of online turbidity data, expressed as service reservoir net material loading (NTU). Moving averages: (A) 1, 12, and 24-hour, (B) 36 and 48-hour, (C) 72 and 96-hour, and (D) 1 week, 10 days, and 2 week.**

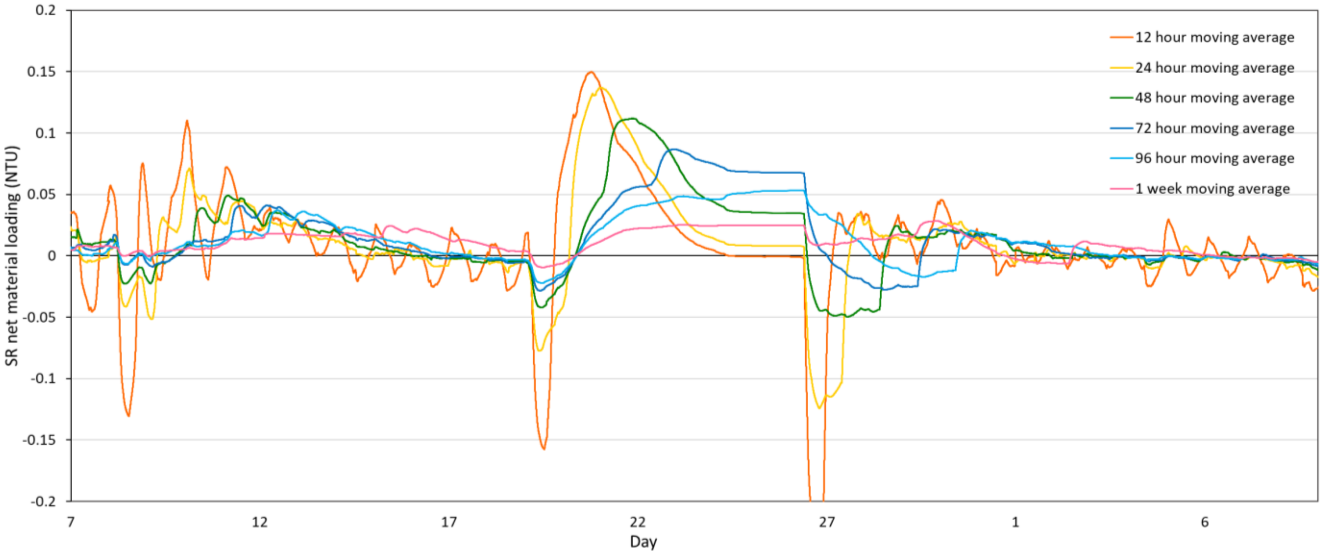


Figure 4.25 – Responses of various moving averages applied to four weeks of online turbidity data collected at one of the project SRs, during which time an unexpected operational event occurred (day 20-25).

The following is a systematic guide on how to implement the performance metric in practice:

1. Install online turbidity monitors at the inlet and outlet of desired SR site.
2. Ensure that the monitors are set to log data at consistent time intervals (ideally 1 min).
3. Collect data.
4. Quality check the data regularly.
5. Take inlet values away from the outlet (outlet-inlet) at each time step to work out SR net material loading:

$$P_{SR} = (M_{l,OUTLET} - M_{l,INLET})$$

Where M_l is material loading as NTU and P_{SR} is the SR performance such that;

$P_{SR} > 0$ – Source
$P_{SR} < 0$ – Sink
$P_{SR} = 0$ – Undetermined

6. Calculate P_{SR} that tracks sink or source behaviour determined by a 96-hour moving average of an unweighted mean of previous *n* outlet and inlet M_l data-points using the following equation:

$$\overline{P_{SR_n}} = \frac{1}{n}\sum_{i=1}^{n}(M_{l,\ OUTLET,\ t=i} - M_{l,\ INLET,\ t=i})$$

Where *t* is time and n = 96*f*, *f* = logging frequency per hour

7. Plot the values.

4.5.4. Influence of finished water type on service reservoir performance

Literature highlights that characteristics of each DWDS are unique and finished water quality is influenced by things like source water type, WTW processes, and construction material and age of the network. To investigate how different finished water types could influence the performance of project SRs, information on network configuration and water quality, alongside a metric value for SR performance, were collated for each of the four project sites. Finished water type was defined as source water + final treated water quality + supplying trunk main length and material. SR performance was taken as the average sink value in NTU using the performance metric described above in section 4.5.3., normalised against average incoming turbidity. This collated information is presented in Table 6.4.2 (section 6.4.3 of the 'Results' chapter). A traffic light inspired colour coding system was then applied to rank the different information in the table across sites from worst to best, where the worst performing sites are highlighted in red, then orange, then yellow, then green for the best. To do this ranking, the following assumptions were made based on existing literature and knowledge obtained throughout the course of this project:

- **Source water:** Groundwater is considered the most stable and best performing type of source water, followed by reservoir, and river source water respectively. If comparing all three types, groundwater would be ranked 'green', reservoir water 'yellow/orange', and river water 'red'.
- **Trunk main:**
    - **Length:** The longer the trunk main the more likely it is to contribute to water quality deterioration.
    - **Material:** Iron and steel trunk mains are more likely to cause water quality deterioration than plastic and lined mains.
- **WTW outgoing water quality:** Metals, turbidity, and TOC were chosen as indicators for outgoing WTW water quality because their presence is known to deteriorate water quality. The lower the outgoing value for observed parameters, the better the performance of the WTW.
- **SR inlet turbidity:** Higher turbidity values are indicative of poorer incoming water quality.
- **SR performance value:** Higher sink values indicate better performance.

Outputs from the ranking were then compared across different project sites.

4.5.5. Influence of seasonal temperature changes on water quality

Literature has shown that temperature has an influence on water chemistry, microbiology, and its physical parameters in the DWDS. Seasonal temperature changes tend to be broadly categorised into winter (cold) and summer (warm) months. To assess the potential effect of seasonal changes on water quality parameters in this research (**Objective 5**), the 'cold weather' and 'warm weather' window was narrowed to a time period of three months, rather than the six-month split that tends to be referred to in the literature, in order to produce more definitive results.

January, February, and March were selected as the cold weather months, and July, August, and September as the warm weather months. This decision was made based in part on coldest and warmest monthly average daily temperatures in the UK across 2017 to 2020. These years were chosen as they coincide with the duration of the project and most of the data collection. Data was obtained from the UK Department for Business, Energy, and Industrial Strategy; Met Office (Table 4.5). The decision was also based on communication with project water utilities, who stated that January to March tend to be the most problematic cold weather months for disruption issues in the network, such as pipe bursts, and July to September the most problematic months in terms of prevalence of bacteriological failures and demand issues due to hot weather. Therefore, despite December being on average colder than March and June being on average hotter than September, combining the data and utility advice, March was chosen over December, and September over June.

Table 4.5 – Monthly average daily temperatures (°C) across 2017 to 2020. Values highlighted in blue indicate coldest average temperatures across the years and values highlighted in yellow indicate the warmest average temperatures across the years.

Monthly average daily temperatures in the United Kingdom (UK) from 2017 to 2020 (°C)					
Month	2017	2018	2019	2020	Average across all years
Jan	4.3	5.3	4.2	6.7	5.13
Feb	6.2	3.1	6.9	6.4	5.65
Mar	8.5	4.9	7.9	6.8	7.03
Apr	9	9.5	9.1	10.3	9.48
May	13	12.9	11.2	12.6	12.43
Jun	15.9	15.9	14.3	15.1	15.3
Jul	16.5	18.7	17.6	15.7	17.13
Aug	15.6	16.7	17.1	17.2	16.65
Sep	13.5	13.8	14.3	14	13.9
Oct	12.3	10.7	10.1	10.5	10.9
Nov	7	8.2	6.5	8.7	7.6
Dec	5.1	6.8	6	5.3	5.8

Historical and project data for all sampled water quality parameters at all stages of the DWDS was split into these ‘cold weather’ and ‘warm weather’ time periods and any resulting differences in parameters were assessed.

4.6. Number and colour reference system for project sites and parameters

A summary number and colour reference system (Table 4.6) was created to simplify the interpretation of the multitude of data analysed in this project, especially concerning graphical plots and some tables. Each water utility, SR, and parameter assessed in this project has a specific, unique to it, number and/or colour assigned to it.

Table 4.6 – **Number and colour reference system for project water utilities, service reservoirs, and sampled parameters.**

Category name	Number	Symbols	Colour
Water utilities			
Company A		○	🟩
Company B		Δ	🟨
Company C		◊	🟦
Company D		☐	🟪
Service Reservoirs			
A	1		🟩
B	2		🟨
C	3		🟦
D	4		🟪
B	5		🟨
B	6		🟨
C	7		🟦
C	8		🟦
C	9		🟦
Parameters			
Absorbance			N/A
Aluminium			▨
Arsenic			🟥
Chlorine (free)			🟩
Chlorine (total)			🟩
Conductivity			🟪
Copper			🟫
Flow (inlet)			🟦
Flow (outlet)			🟩

Flow cytometry (ICC)			🟩
Flow cytometry (TCC)			🟩
Fluorescence			N/A
Iron			🟫
Level			🟧
Magnesium			🟦
Manganese			🟧
Organic carbon (dissolved)			⬛
Organic carbon (total)			⬛
pH			🟥
Potassium			🟨
Temperature			🟦
Turbidity			⬛
Zinc			⬜

Chapter 5: Site details

5.1. Introduction

This chapter contains detailed information on all project study sites including summary site details, network layouts, WTW process diagrams, site schematics, and timelines of sampling and key significant events. The purpose of the chapter is to be used as a reference tool to gain comprehensive understanding on how site details may influence research outcomes. This chapter also showcases differences between project sites, demonstrating the complexity of extrapolating findings from a specific site and highlighting the importance of a broad and inclusive study when looking at DWDSs.

Network layouts: These give a source-to-tap overview of the stages in project DWDSs, including distances between supplying WTW and project SRs (highlighted in yellow).

Water treatment works process diagrams: To achieve the best final water quality possible, WTW processes are specifically tailored to incoming source water. Different approaches to treatment result in varying outgoing water qualities, which are important to understand to make sense of further water quality changes in the DWDS. Thus, WTW process diagrams are provided for the four main project sites (A1, B2, C3, and D4), which had ongoing sampling campaigns.

Site schematics and photos: SR configuration has been shown to influence outgoing water quality. Therefore, to provide visual details of structural configuration and condition of project SRs, detailed SR schematics were drawn of each project site and photos showing asset condition collated to go alongside these.

Timeline of sampling and key significant events: These are provided for main project sites (A1, B2, C3, and D4) as this is where inlet and additional outlet water quality monitoring was conducted (Figures 5.4, 5.8, 5.16, and 5.25)

5.2. Summary site information

Table 5.1 is a collection of summary information about project sites, which was produced to give an overview of site characteristics and to allow for an easy comparison between sites.

Table 5.1 – **Summary information about project sites.**

Service reservoir name and year commissioned (if applicable)	Geometry and Material	Volume (ML)	Height (m)	Average retention time (hours)	Inlet pipe (direct upstream main) length, diameter (inches), and material	Source water	Secondary and on-site disinfectant (where applicable)	Last inspected	Past bacteriological failures at SR outlet	Water treatment works	Water quality zone(s) and/or district metered area(s) and approx. population served (individuals)
A1 1996	Overground Donut shape One compartment No columns Coated concrete	0.9	6	26.8	Length: ~ 10.1 km 11” PE (62.86%) 10" PVC (27.46%) 9.8” DI (9.64%) 7" CI (0.04%) Inlet sample line (15 mm diameter copper pipe) taps off of the inlet main, and is 7 m in length to the inlet MetriNet monitor and 11 m to the inlet sample tap	Ground: blended from 6 boreholes in a chalk aquifer Very hard water	Secondary: Chlorine	March 2018	NA	M_WTW	B_WQZ Population: 215
B2 1972	Underground Rectangular Twin compartment 384 columns (192 per compartment) Reinforced concrete	90	7	31.0	Supplied by a twin main Length: 7.2 km (1) 49” – ST (2) 35.4” – concrete lined DI	Surface (river) Slightly hard water	Secondary: Chlorine	July 2012: North compartment November 2012: South compartment	2007: 1 failure 2008: 6 failures 2009: 2 failures 2014: 1 failure 2015: 3 failures 2016: 3 failures	H_WTW	BH_WQZ Population: 570000
C3	Underground Rectangular Twin compartment 24 columns (12 per compartment) Reinforced concrete	4.8	5.3	41.3	Length: 50 km 44" ST for 22 km down to 18” unlined CI for 28 km	Surface (highland reservoir) Soft water	Secondary: Chlorine On site: Chlorine (dosed at the inlet)	June 2018: Compartment 1 (closest to outlet) July 2018: Compartment 2 (closest to inlet)	2012: 1 failure	D_WTW	G_WQZ: M_DMA WS_DMA P_DMA Population: 4695
D4	Underground Rectangular Twin compartment 24 columns (12 per compartment)	9.1	5.4	28.1	Length: 0.223 km 23.6” DI cement lined	Surface (reservoir) Soft water	Secondary: Chlorine On site: Ultraviolet irradiation (dosed at the inlet)	March 2019 (taken out of service in November): South compartment (B/2)	NA	CD_WTW	Feeds O_SR and Y_SR These feed CY_WQZ Gravity feeds N_WQZ and A_WQZ Population: 11874 (CY_WQZ)

	Reinforced concrete with a brick dividing wall							August 2019: North compartment (A/1)			25975 (N_WQZ and A_WQZ) Total: 37849
B5 1993	Underground Rectangular One compartment 6 columns Glass reinforced plastic and laminate	0.04	2.04	NA	Length 1.4 km 3.2” DI cement lined	Surface (reservoir) Slightly hard water	Secondary: Chloramine	May 2019	2007: 1 failure 2016: 3 failures	L_WTW	LBM_WQZ Population: 2283
B6 2011	Underground Rectangular Twin compartment 72 columns Reinforced concrete	9.4	4.8	NA	Length: ~52 km 22.1” HPPE down to 17.7” DI	Surface (river and surface) Slightly hard water	Secondary: Chlorine	May 2019	2007: 1 failure 2008: 12 failures 2010: 2 failures 2012: 2 failures 2017: 1 failure	W_WTW F_WTW H_WTW TS_WTW	HA_WQZ Population: 27873
C7	Underground Twin compartment Rectangular 20 columns (10 per compartment) Reinforced concrete	5.2	6.7	63.5	Length: 0.51 km 15.7” DI	Surface (reservoir) Soft water	Secondary: Chlorine	September 2019	NA	R_WTW	HH_WQZ: F_DMA S_DMA SD_DMA Population: 5766
C8	Underground Twin compartment Rectangular 18 columns (9 per compartment) Reinforced concrete	0.8	4.8	82.4	Length: 1.1 km 12” SI	Surface (reservoir) Soft water	Secondary: Chloramine	October 2019	2014: 1 failure 2016: 1 failure 2019: 1 failure	P_WTW	R_WQZ: R_DMA SO_DMA to G_DMA Population: 1000
C9	Underground (part exposed) One compartment Circular 4 columns Concrete	0.4	3.3	71.6	Length: primary main from WTW 11.5 km, but immediate main tapping off this is 0.02 km 9” primary main and 6” immediate main, both AC	Surface (reservoir) Soft water	Secondary: Chloramine	October 2019	NA	P_WTW	K_DMA Population: 685

5.3. Company A site: A1

A1 SR is an overground, donut-shaped, singular-compartment, 0.9 ML coated concrete SR with an average retention time of 27 hours, last inspected and cleaned in March 2018 (Figure 5.3). It is fed by a 10 km trunk main composed of various materials (Figure 5.1). The SR supplies a population of approximately 215 people. Treated water is groundwater abstracted from six boreholes with free chlorine as the secondary residual disinfectant (Figure 5.2).

5.3.1. Network layout

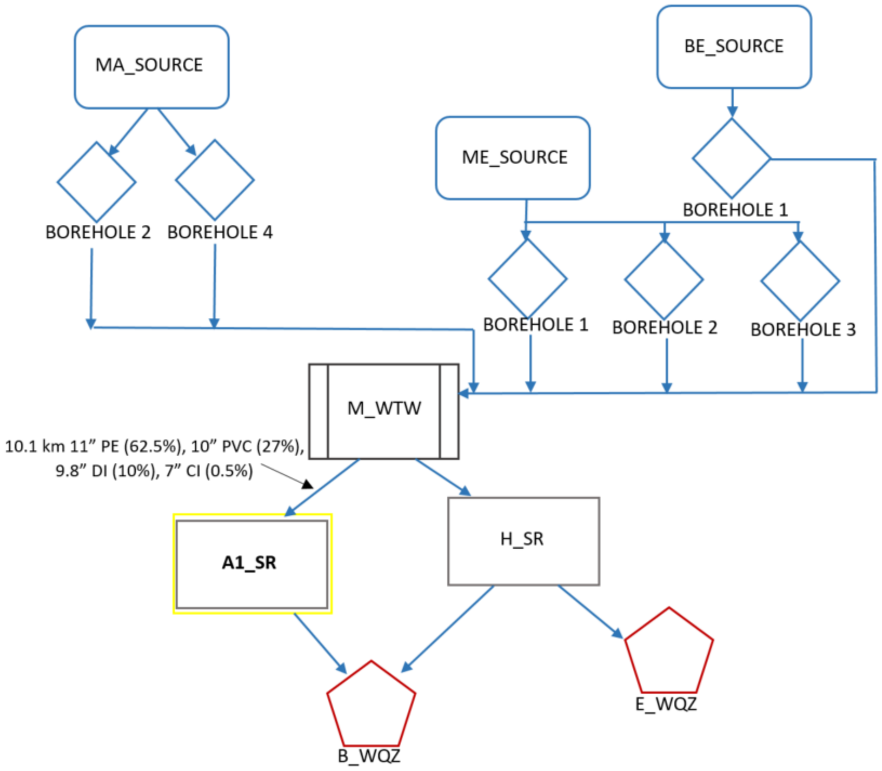


Figure 5.1 – Site A1 network layout.

5.3.2. Water treatment works process diagram

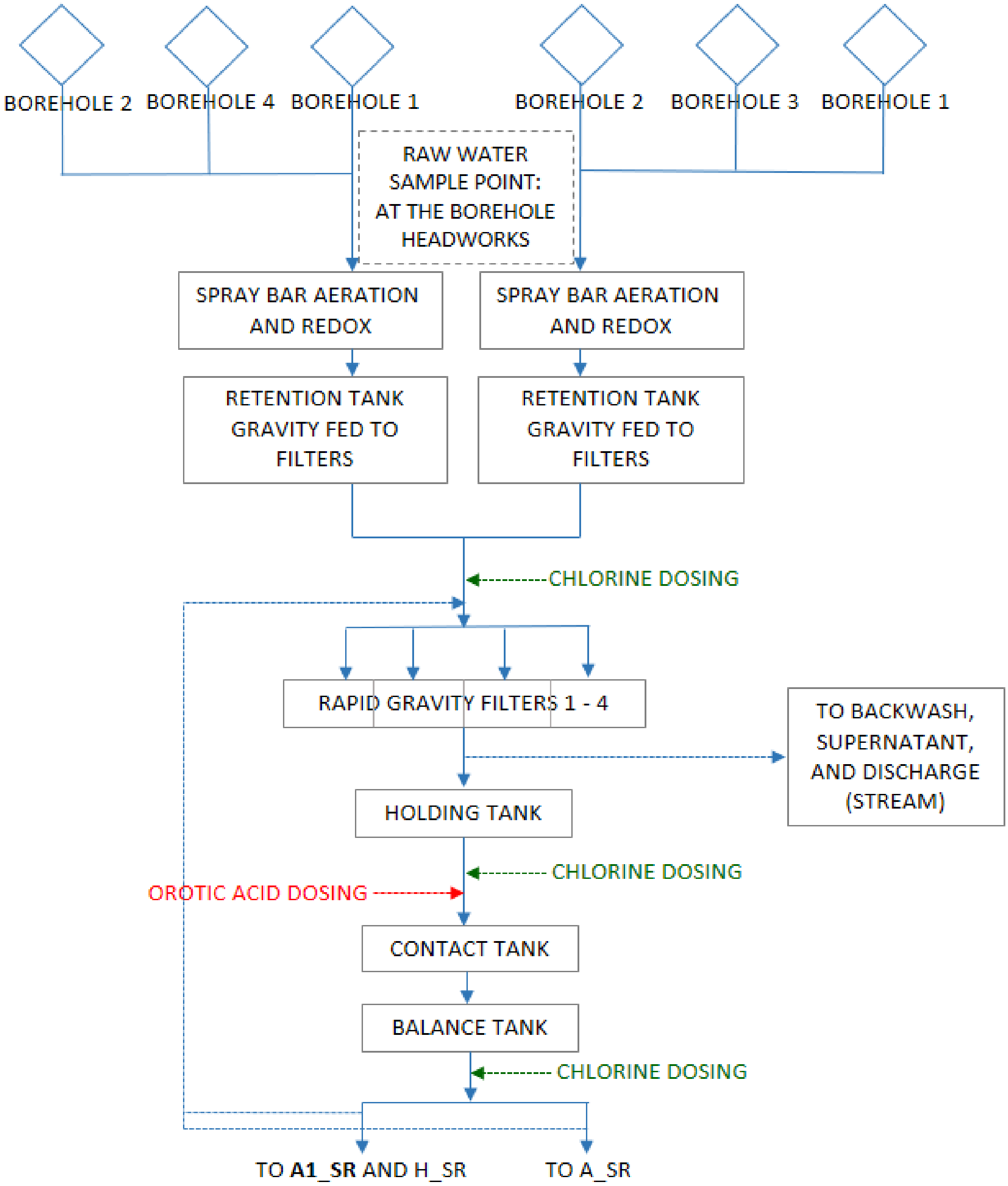


Figure 5.2 – **Water treatment works (M_WTW) process diagram for site A1.**

5.3.3. Service reservoir schematic and photos

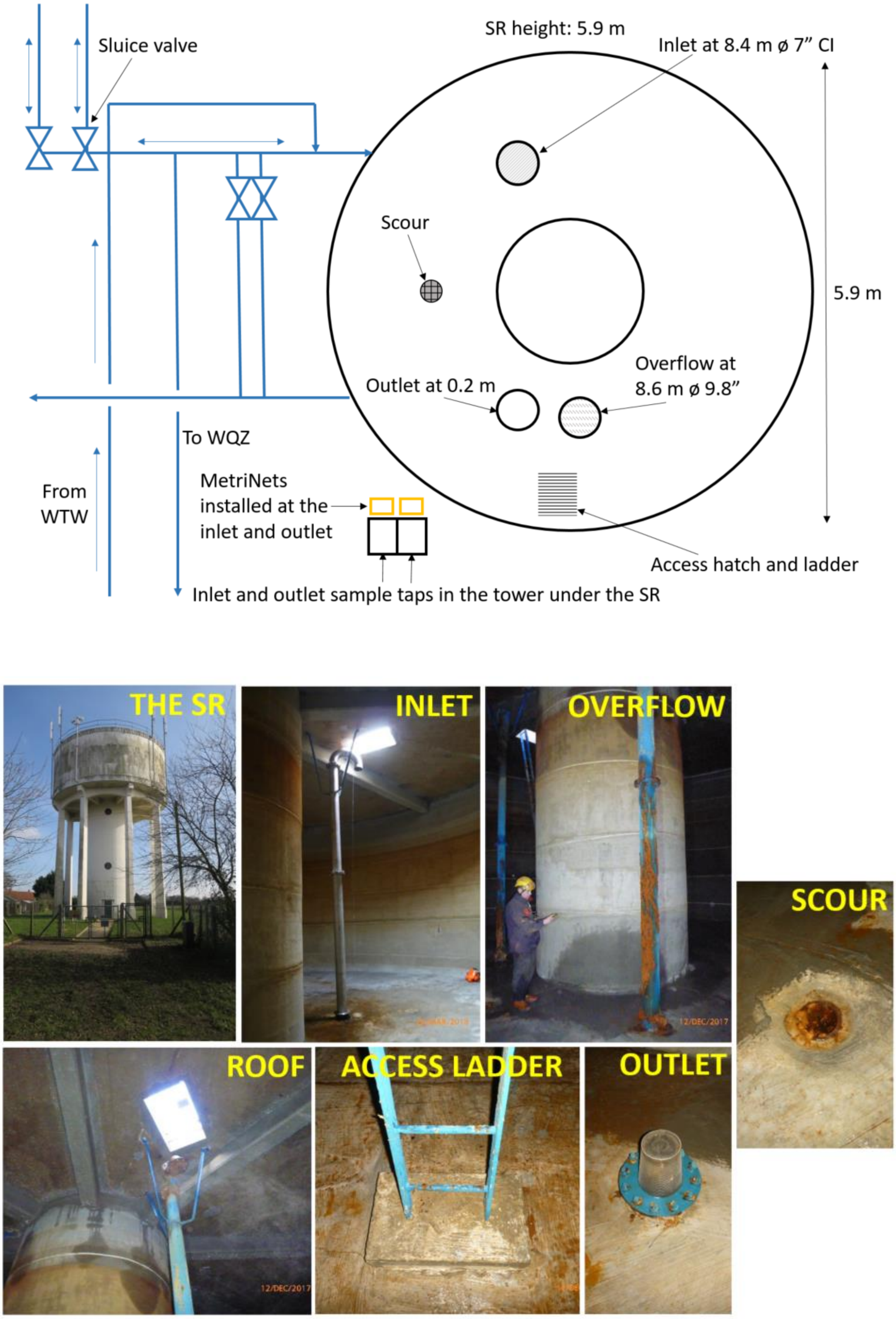


Figure 5.3 – **Schematic of A1 SR and collection of photos displaying the external and internal details of the SR.**

5.3.4. Timeline of sampling and events

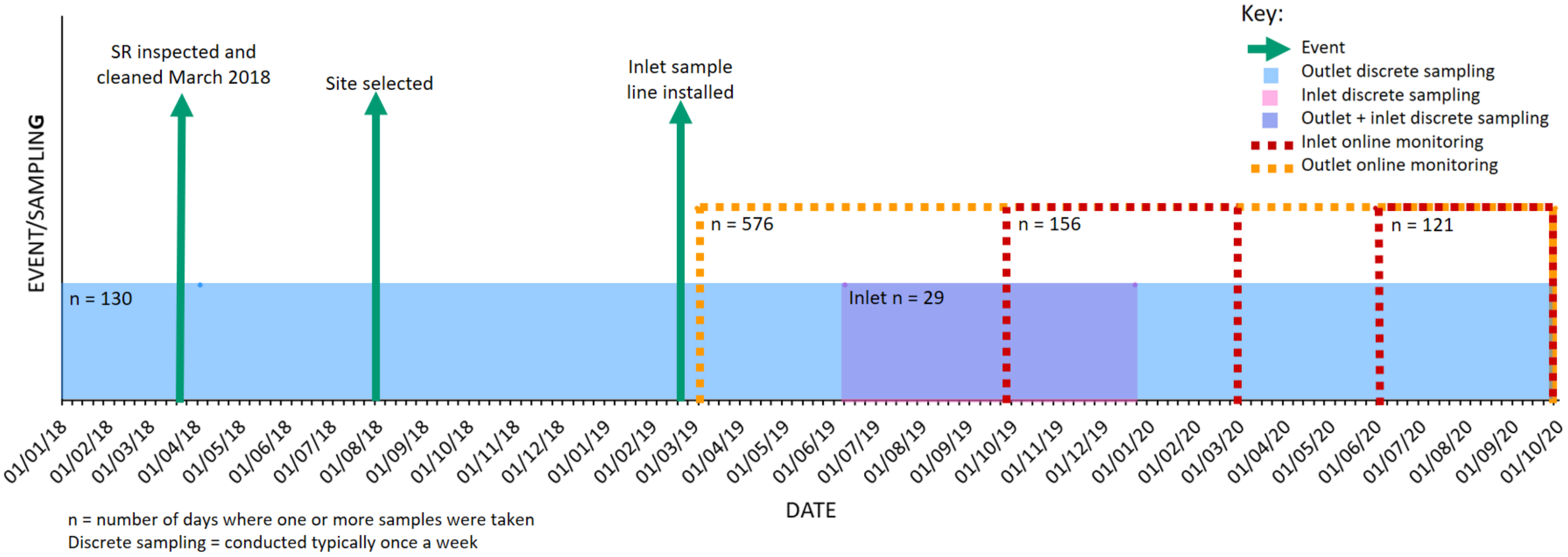


Figure 5.4 - **A timeline graph displaying periods of available sample data at the inlet and outlet of A1 SR and key significant events.**

5.4. Company B sites: B2, B5, and B6

5.4.1. B2

B2 SR is an underground, rectangular, twin-compartment, 90 ML reinforced concrete SR with an average water retention time of 31 hours, last inspected and cleaned in 2012 (Figure 5.7). It is fed by two 7.2 km trunk mains, one steel (49 inches in diameter) and one cement-lined ductile iron (35.4 inches in diameter) (Figure 5.5). The SR supplies a population of approximately 570,000 people. Treated water is river abstracted with free chlorine as the secondary residual disinfectant (Figure 5.6).

5.4.1.1. Network layout

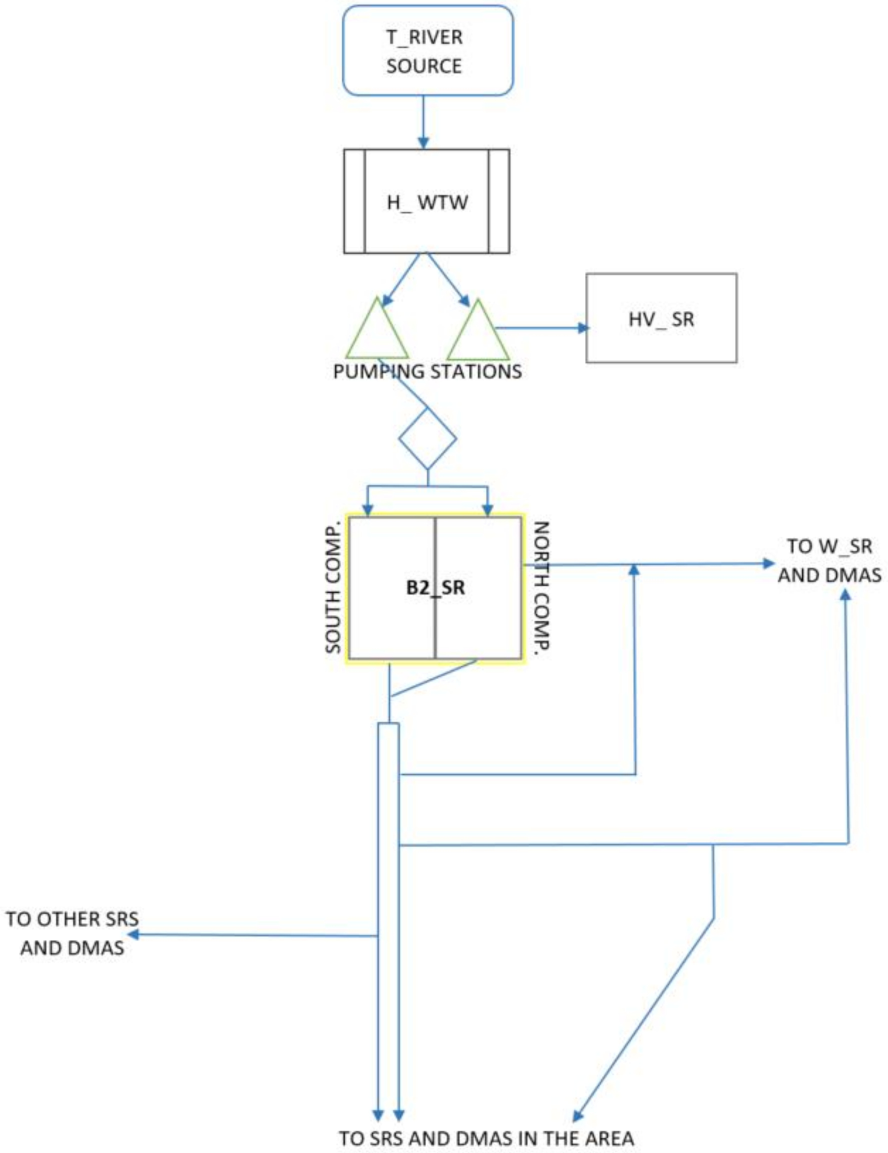


Figure 5.5 – Site B2 network layout.

5.4.1.2. Water treatment works process diagram

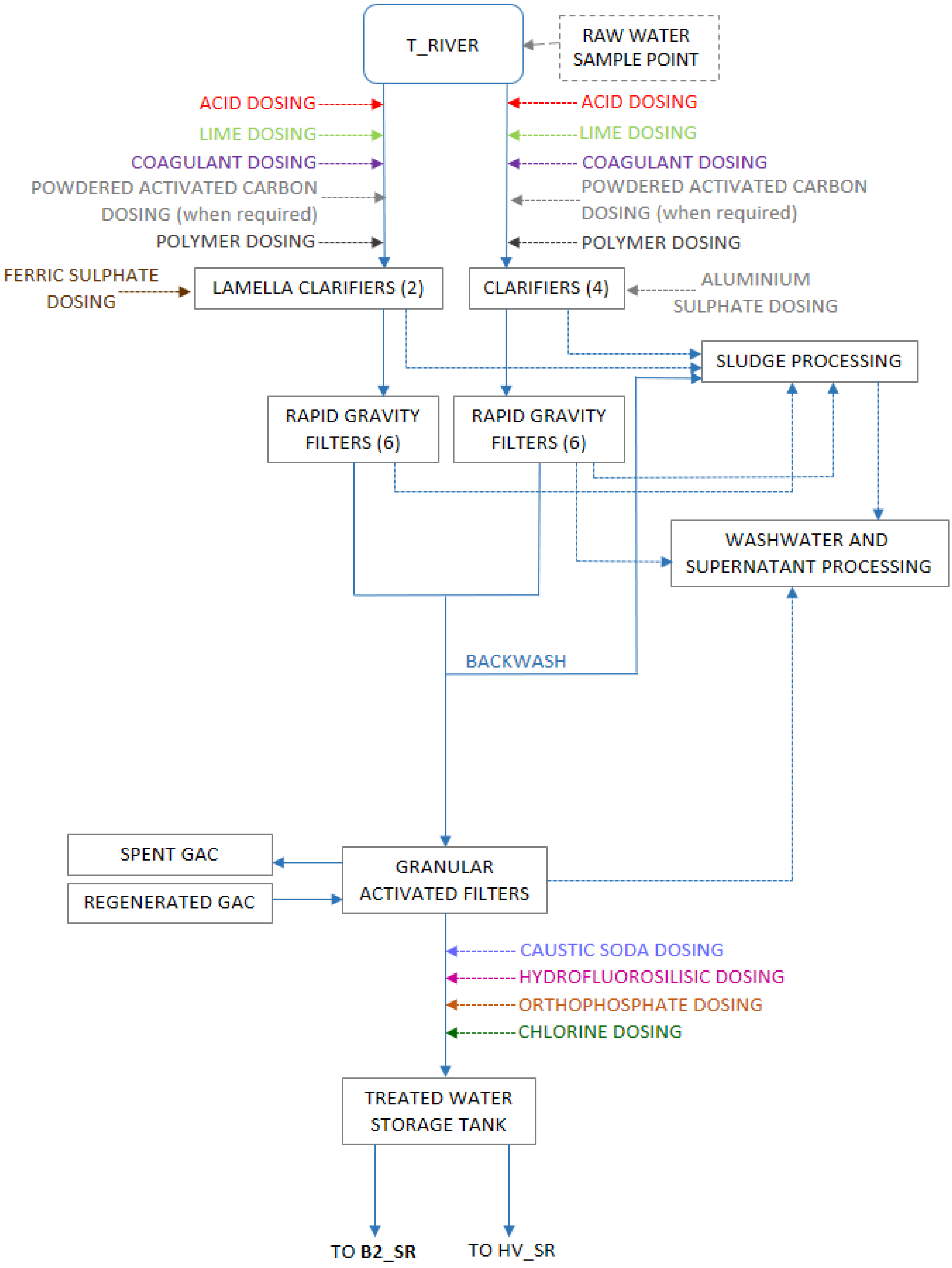


Figure 5.6 – Water treatment works (H_WTW) process diagram for site B2.

5.4.1.3. Service reservoir schematic and photos

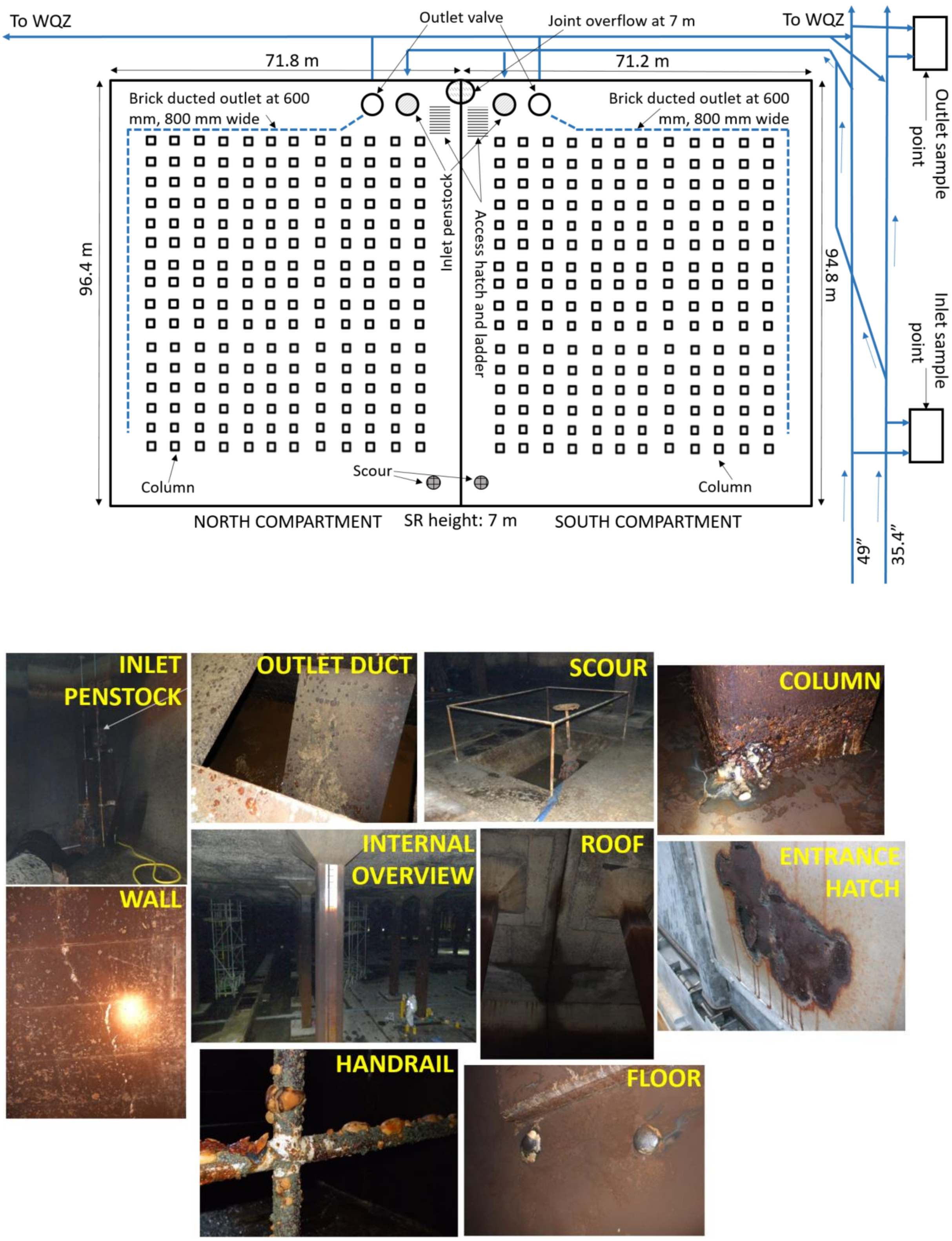
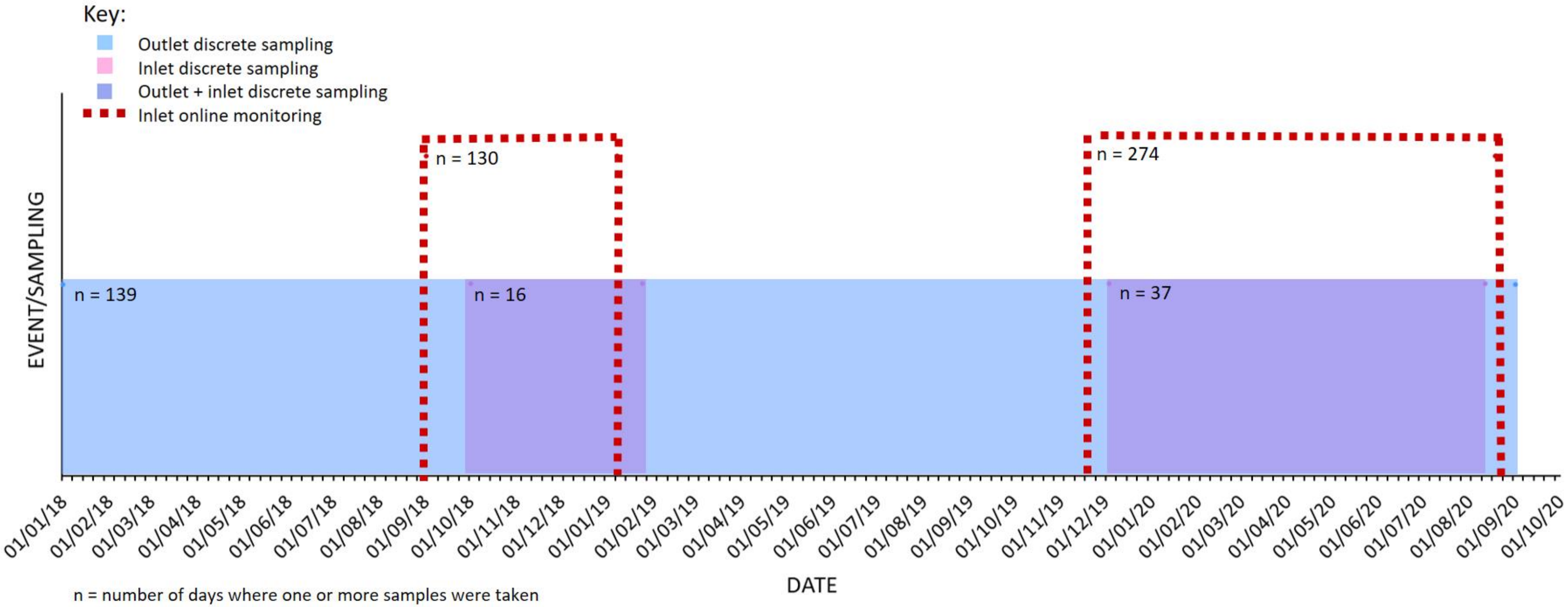


Figure 5.7 – A schematic of B2 SR and a collection of photos displaying the internal and external details of the SR.

5.4.1.4. Timeline of sampling and events



n = number of days where one or more samples were taken
Discrete sampling = conducted typically once a week

Figure 5.8 - A timeline graph displaying periods of available sample data at the inlet and outlet of B2 SR.

5.4.2. B5

B5 SR is an underground, rectangular, singular compartment, 0.04 ML glass reinforced plastic and laminate SR, last inspected and cleaned in May 2019 (Figure 5.10). It is fed by a 1.4 km ductile iron cement lined (DICL) trunk main (Figure 5.9). The SR supplies a population of approximately 2283 people. Treated water is reservoir abstracted with chloramine as the secondary residual disinfectant.

5.4.2.1. Network layout

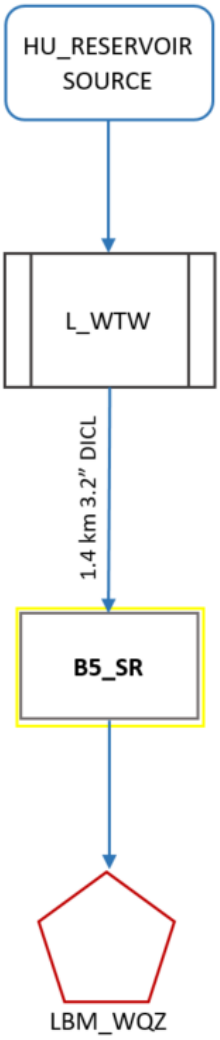


Figure 5.9 - **Site B5 network layout.**

5.4.2.2. Service reservoir schematic and photos

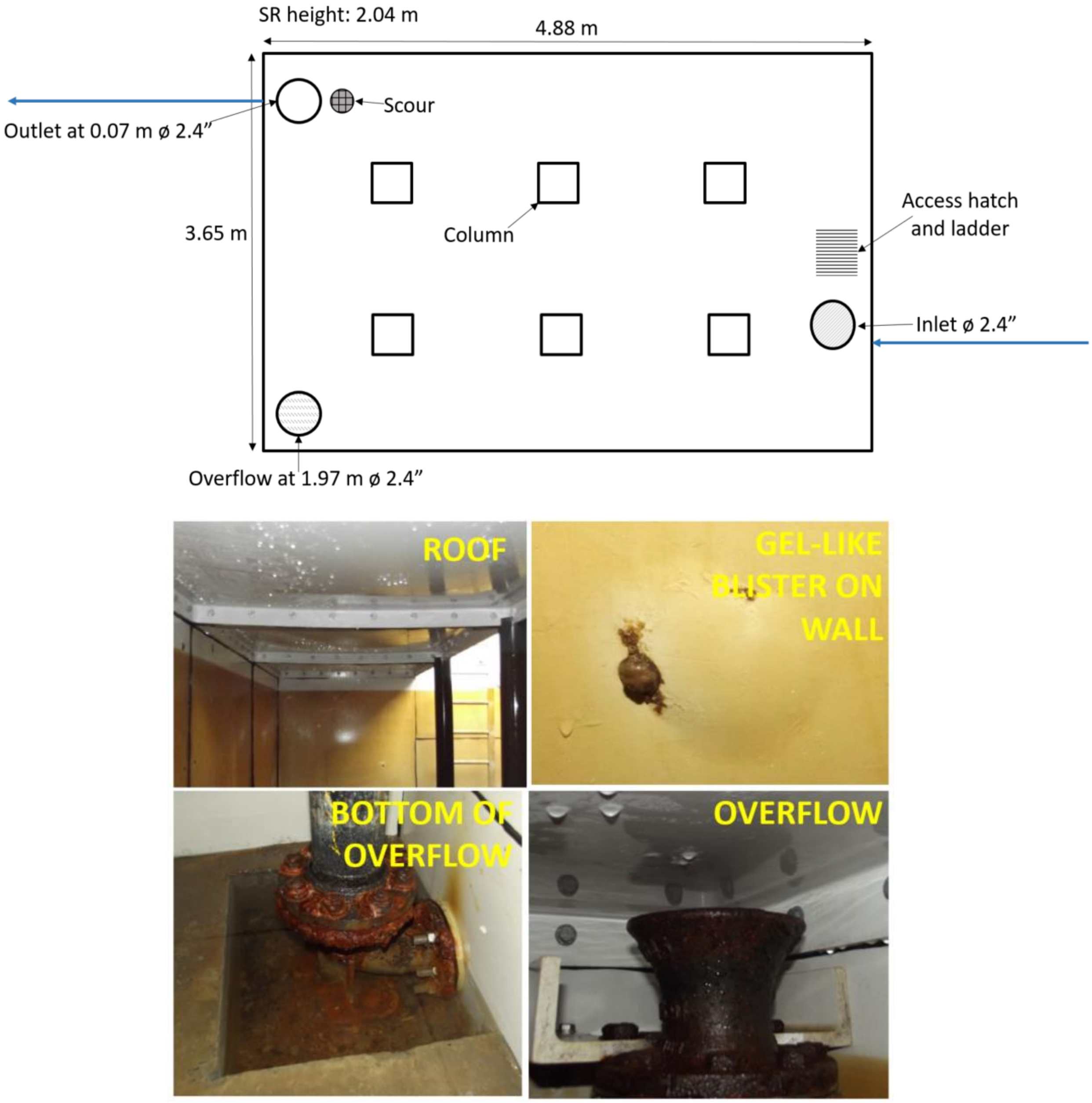


Figure 5.10 – Schematic of B5 SR and a collection of photos displaying the internal components of the SR.

5.4.3. B6

B6 SR is an underground, rectangular, twin-compartment, 9.4 ML reinforced concrete SR, last inspected and cleaned in May 2019 (Figure 5.12). It is fed by a 52 km trunk main, made from high performance polyethylene and ductile iron at different stages of the main (Figure 5.11). The SR supplies approximately 27,873 people. Treated water is both river and reservoir abstracted with free chlorine as the secondary residual disinfectant.

5.4.3.1. Network layout

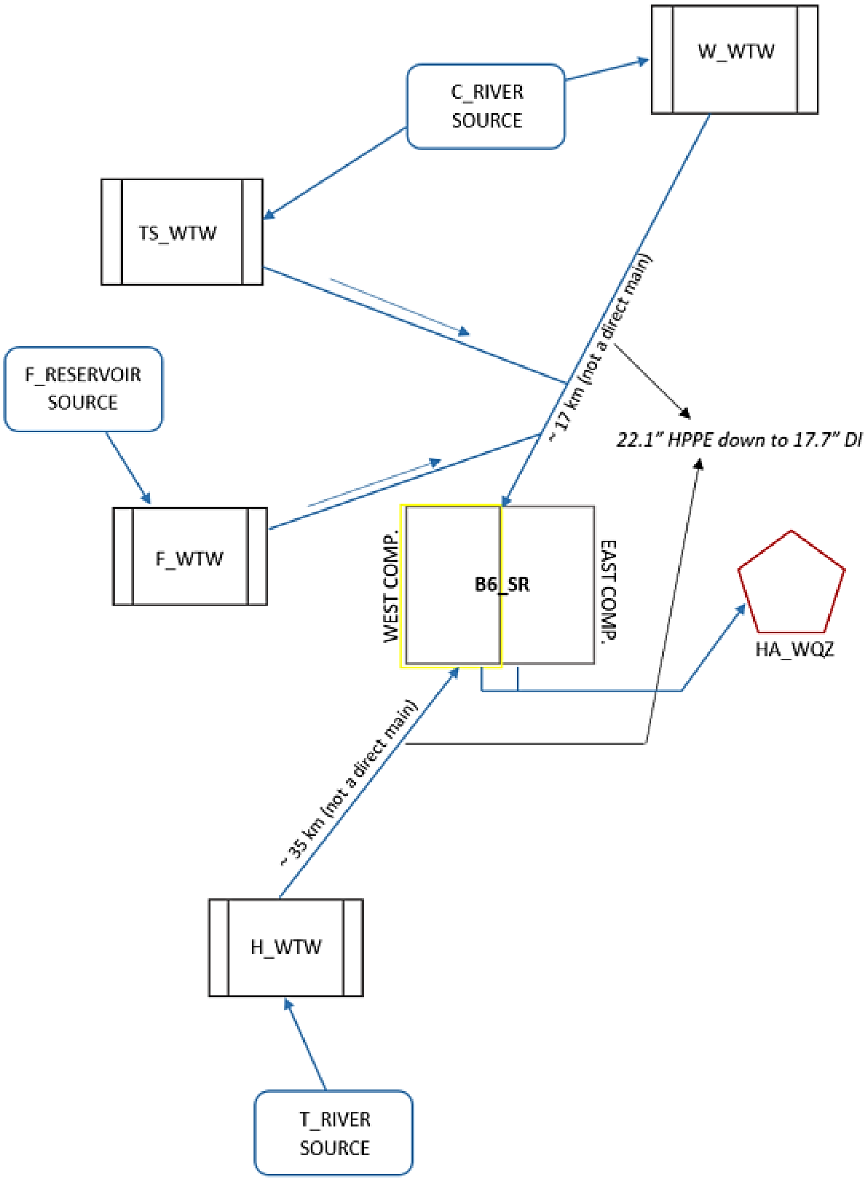


Figure 5.11 – Site B6 network layout.

5.4.3.2. Service reservoir schematic and photos

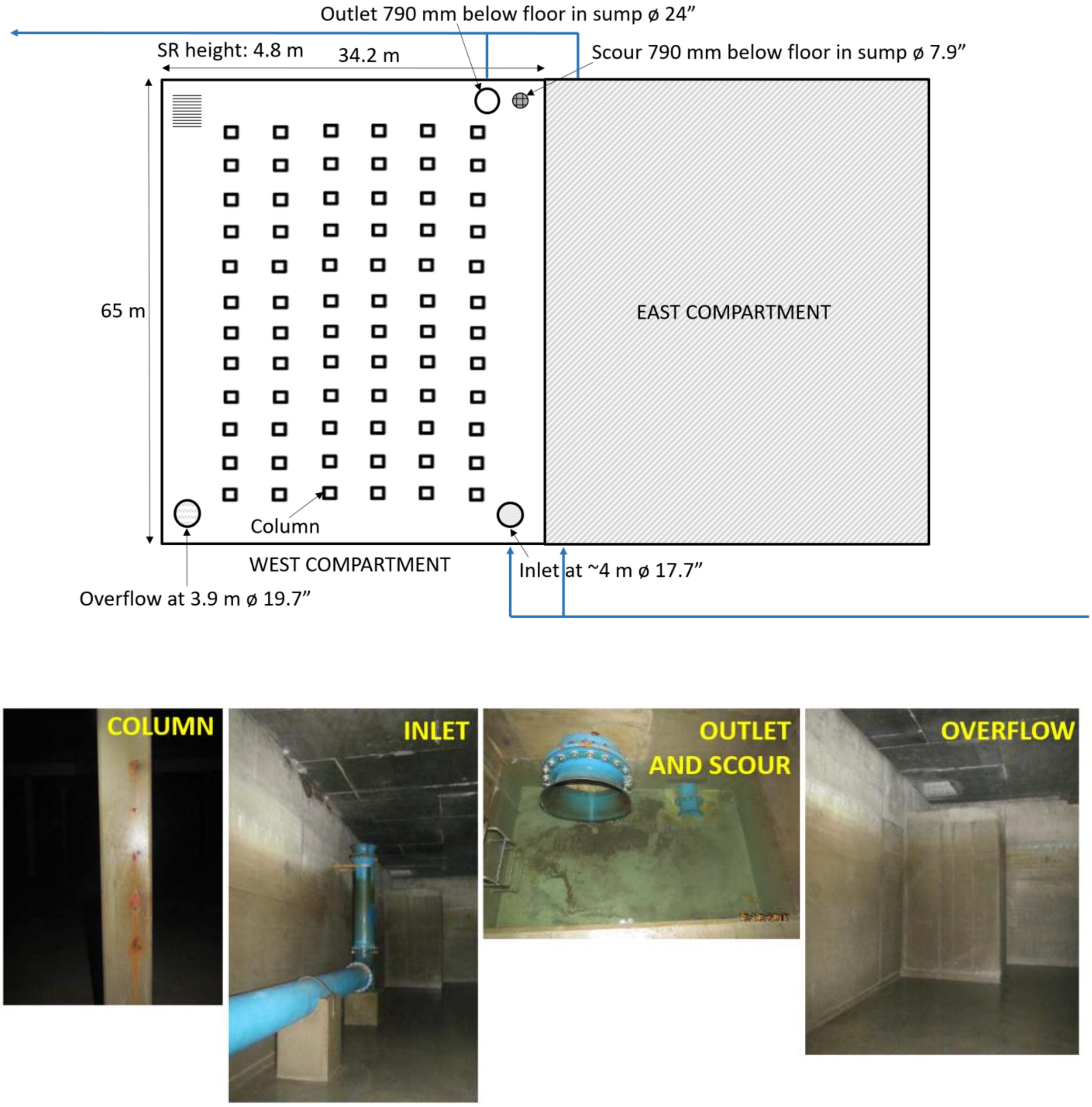


Figure 5.12 – A schematic of B6 SR and a few photos displaying some of the internal details of the SR.

5.5. Company C sites: C3, C7, C8, and C9

5.5.1. C3

C3 SR is an underground, rectangular, twin-compartment, 4.8 ML reinforced concrete SR with an average retention time of 41.3 hours, last inspected and cleaned in June (comp. 1) and July (comp. 2) 2018 (Figure 5.15). It is fed by a 50 km trunk main, which is steel for 22 km and unlined cast iron for the remaining 28 km (Figure 5.13). The SR supplies a population of approximately 4695 people. Treated water is reservoir abstracted with free chlorine as the secondary residual disinfectant, which is re-dosed on site at the inlet to the SR (Figure 5.14).

5.5.1.1. Network layout

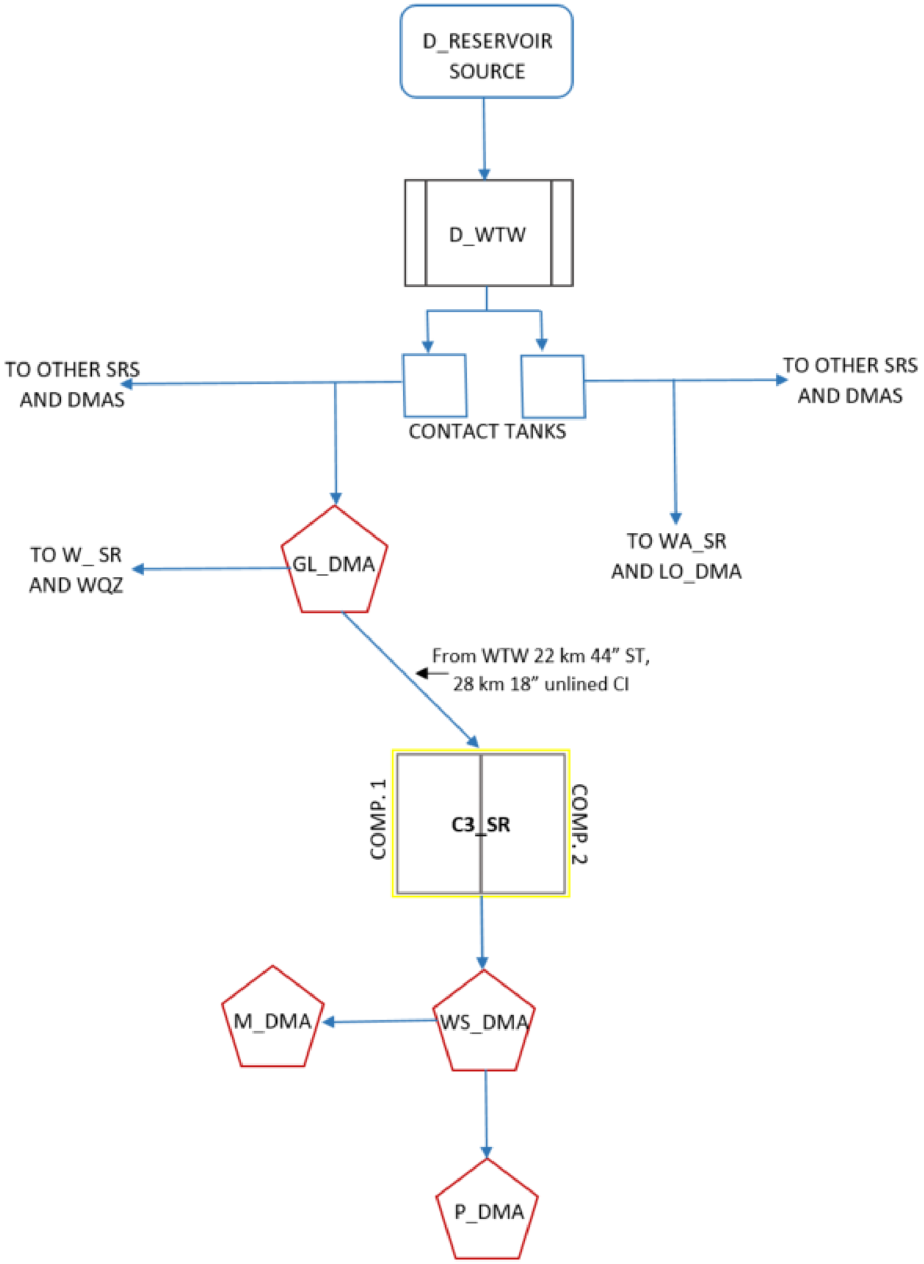


Figure 5.13 - Site C3 network layout.

5.5.1.2. Water treatment works process diagram

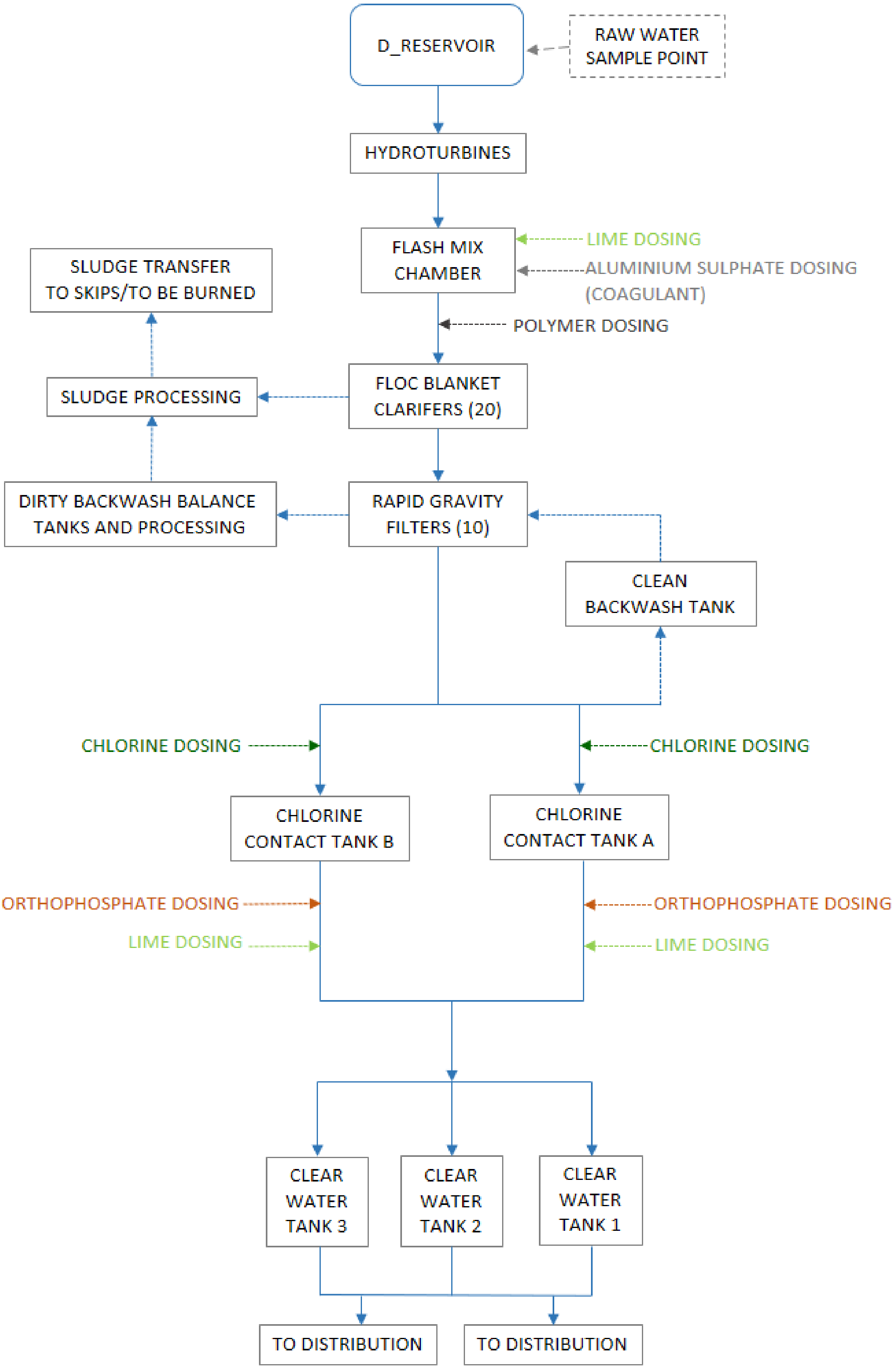


Figure 5.14 – Water treatment works (D_WTW) process diagram for site C3.

5.5.1.3. Service reservoir schematic and photos

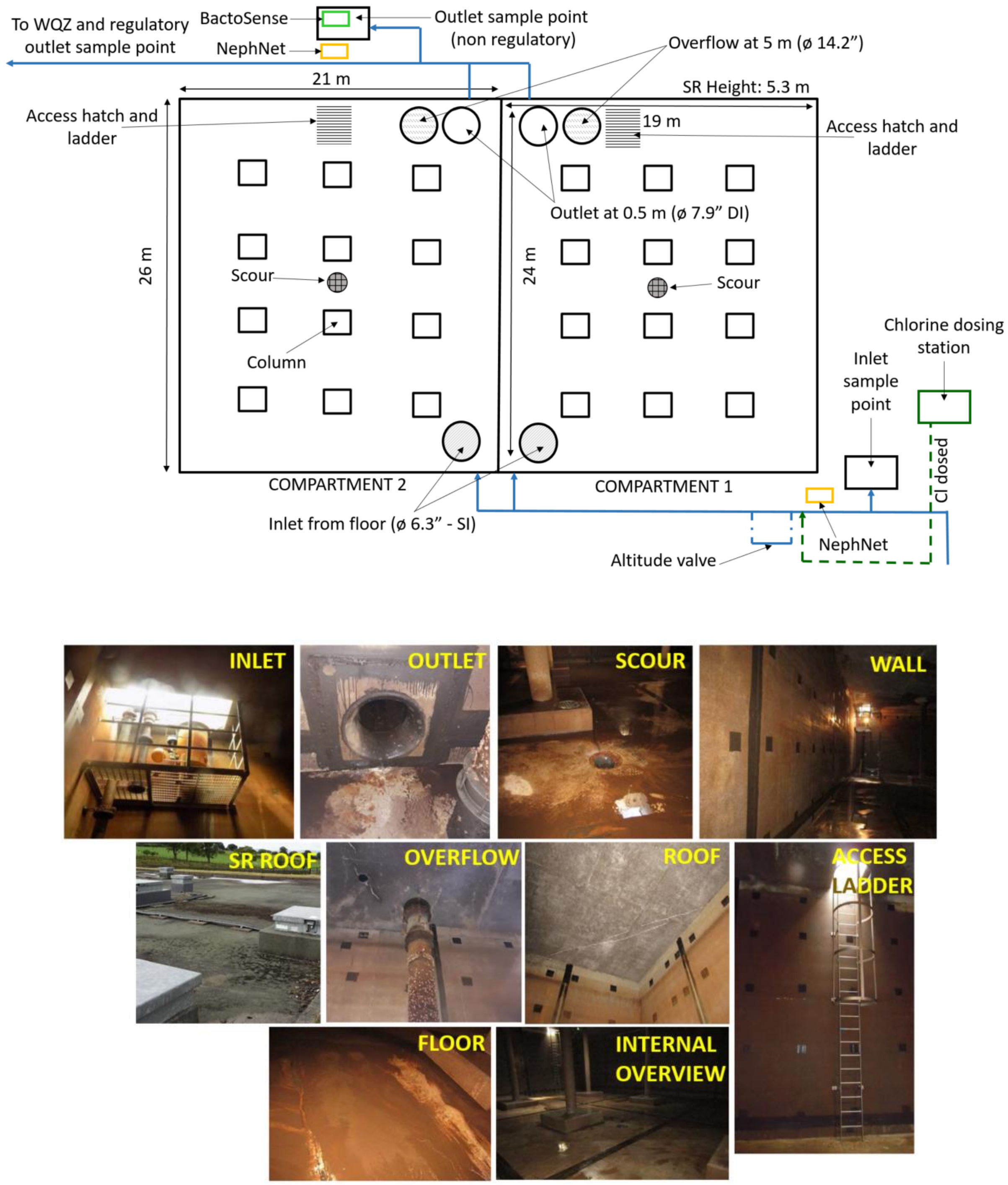
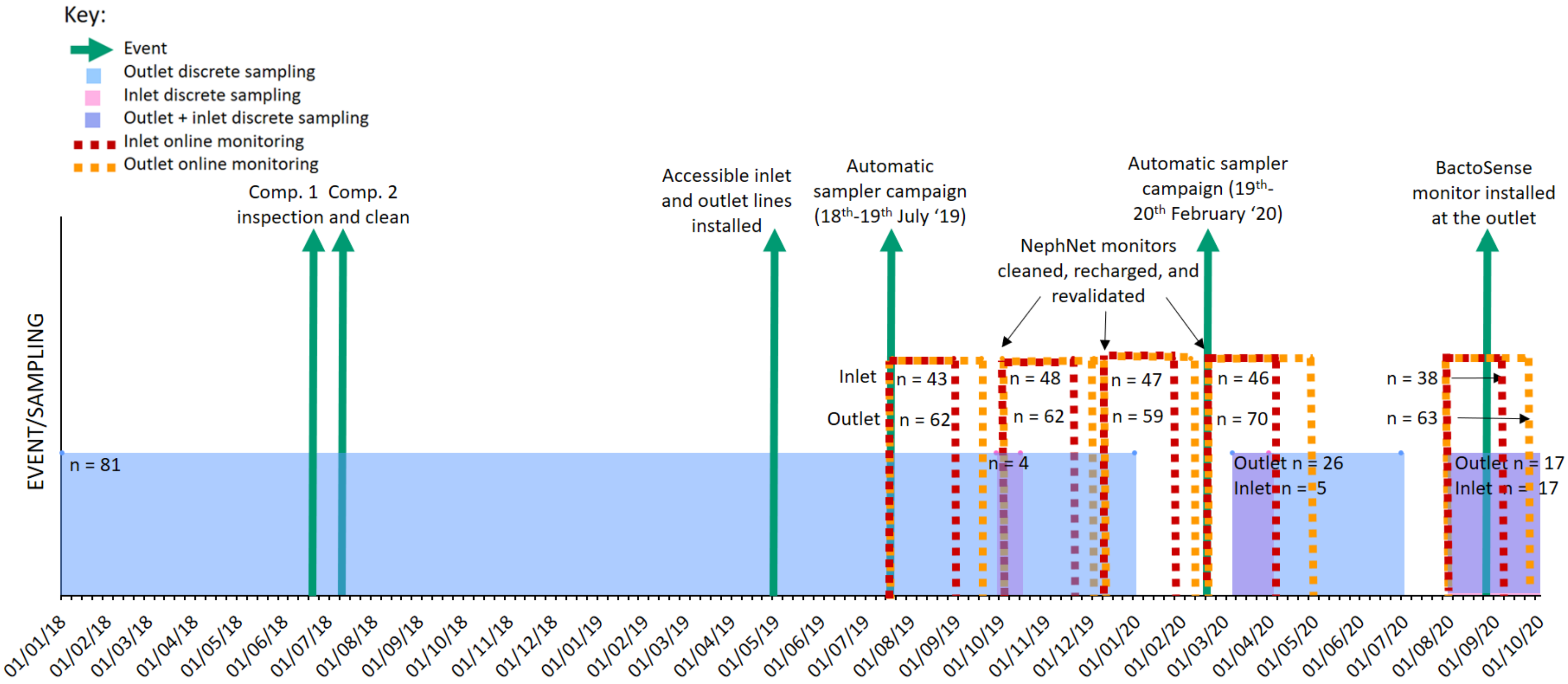


Figure 5.15 – **A schematic of C3 SR A collection of photos displaying the external and internal details of the SR.**

5.5.1.4. Timeline of sampling and events



n = number of days where one or more samples were taken
Discrete sampling = conducted typically once a week

Figure 5.16 - A timeline graph displaying periods of available sample data at the inlet and outlet of C3 SR and key significant events.

5.5.2. C7

C7 SR is an underground, rectangular, twin-compartment, 5.2 ML reinforced concrete SR with an average retention time of 64 hours, last inspected and cleaned in September 2019 (Figure 5.18). It is fed by a 0.51 km ductile iron trunk main. The SR supplies a population of approximately 5766 people (Figure 5.17). Treated water is reservoir abstracted with free chlorine as the secondary residual disinfectant.

5.5.2.1. Network layout

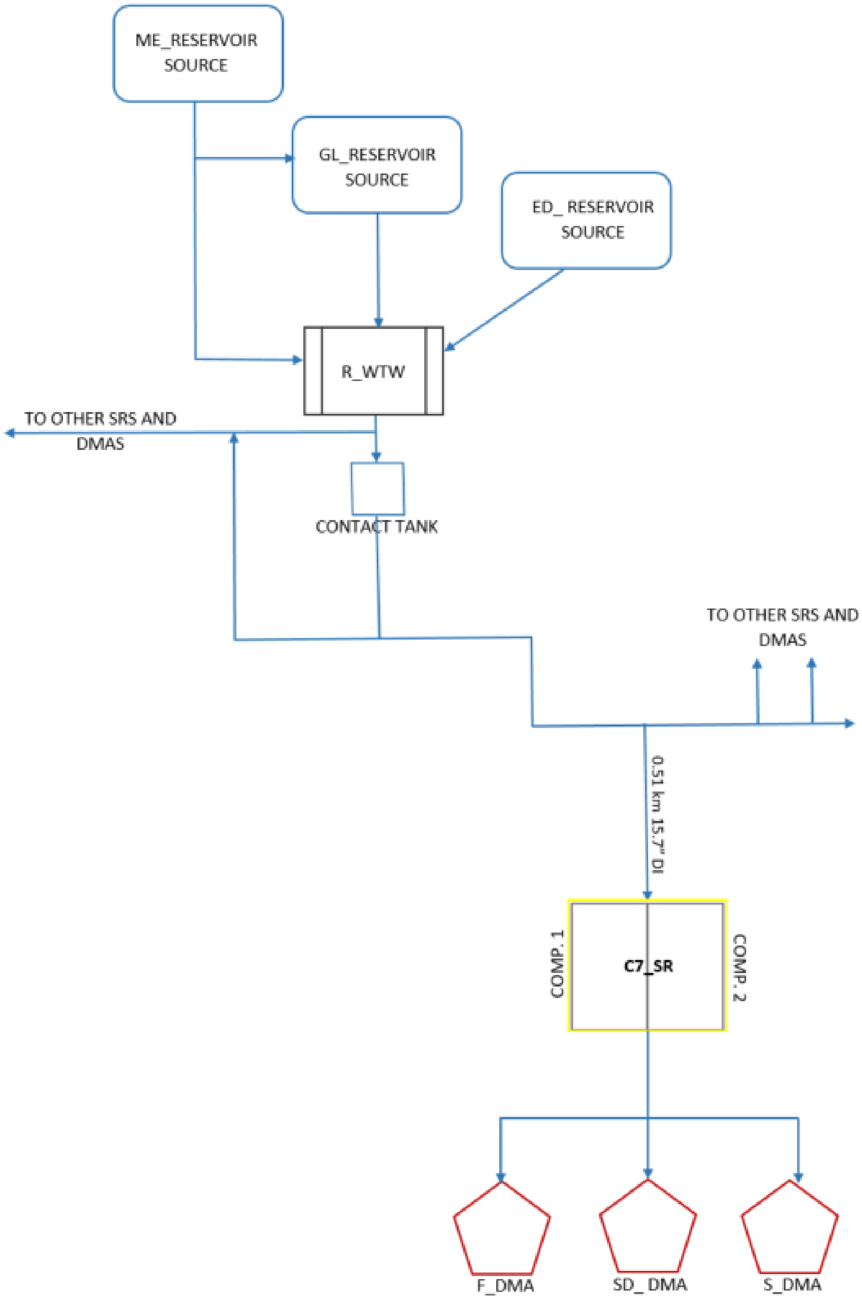


Figure 5.17 – **Site C7 network layout.**

5.5.2.2. Service reservoir schematic and photos

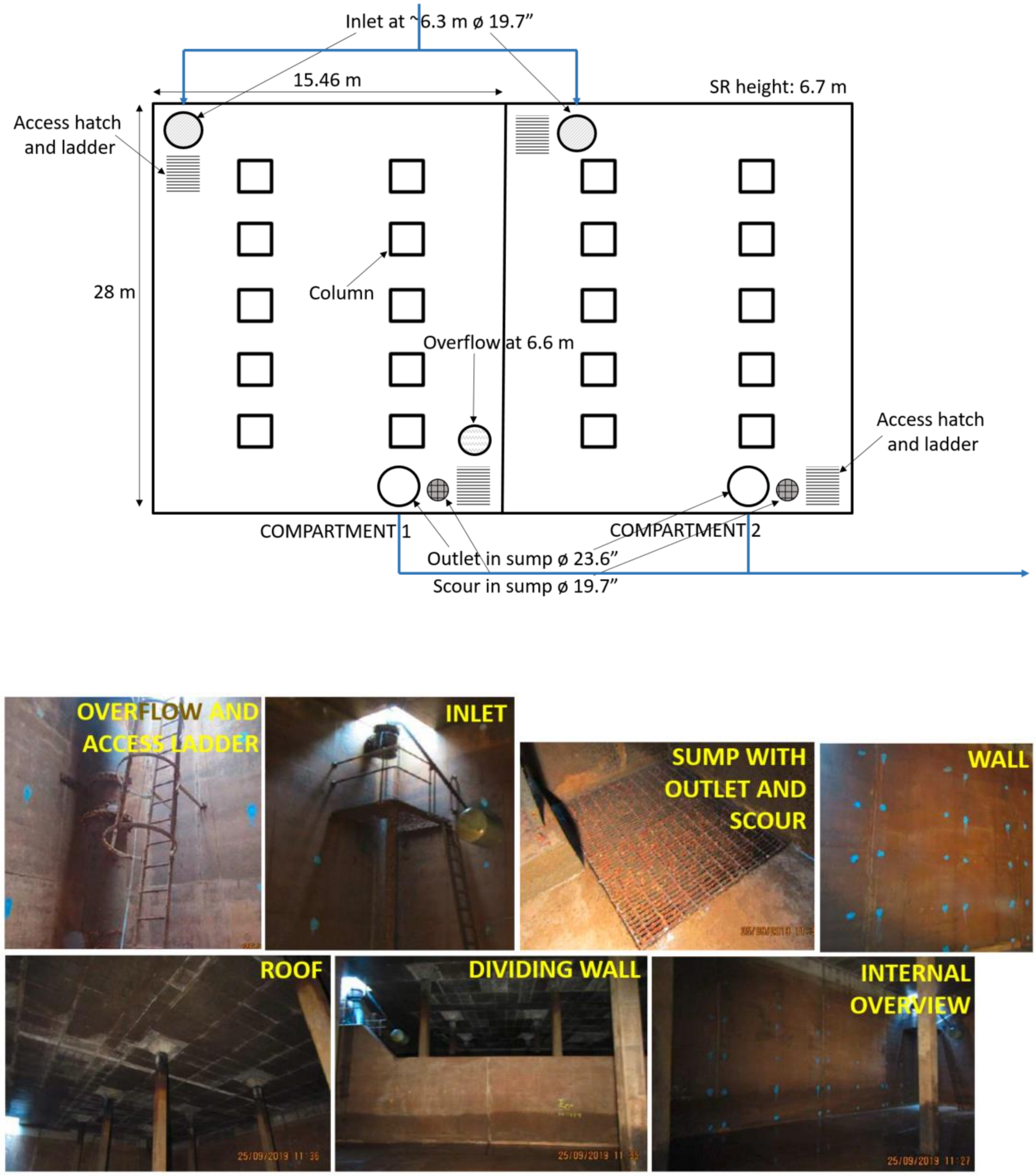


Figure 5.18 – **A schematic of C7 SR and a collection of photos displaying the internal details of the SR.**

5.5.3. C8

C8 SR is an underground, rectangular, twin-compartment, 0.8 ML SR with an average retention time of 82 hours, last inspected and cleaned in October 2019 (Figure 5.20). It is fed by a 1.1 km spun iron (SI) trunk main. The SR supplies a population of approximately 1000 people (Figure 5.19). Treated water is reservoir abstracted with chloramine as the secondary residual disinfectant.

5.5.3.1. Network layout (also for C9 service reservoir)

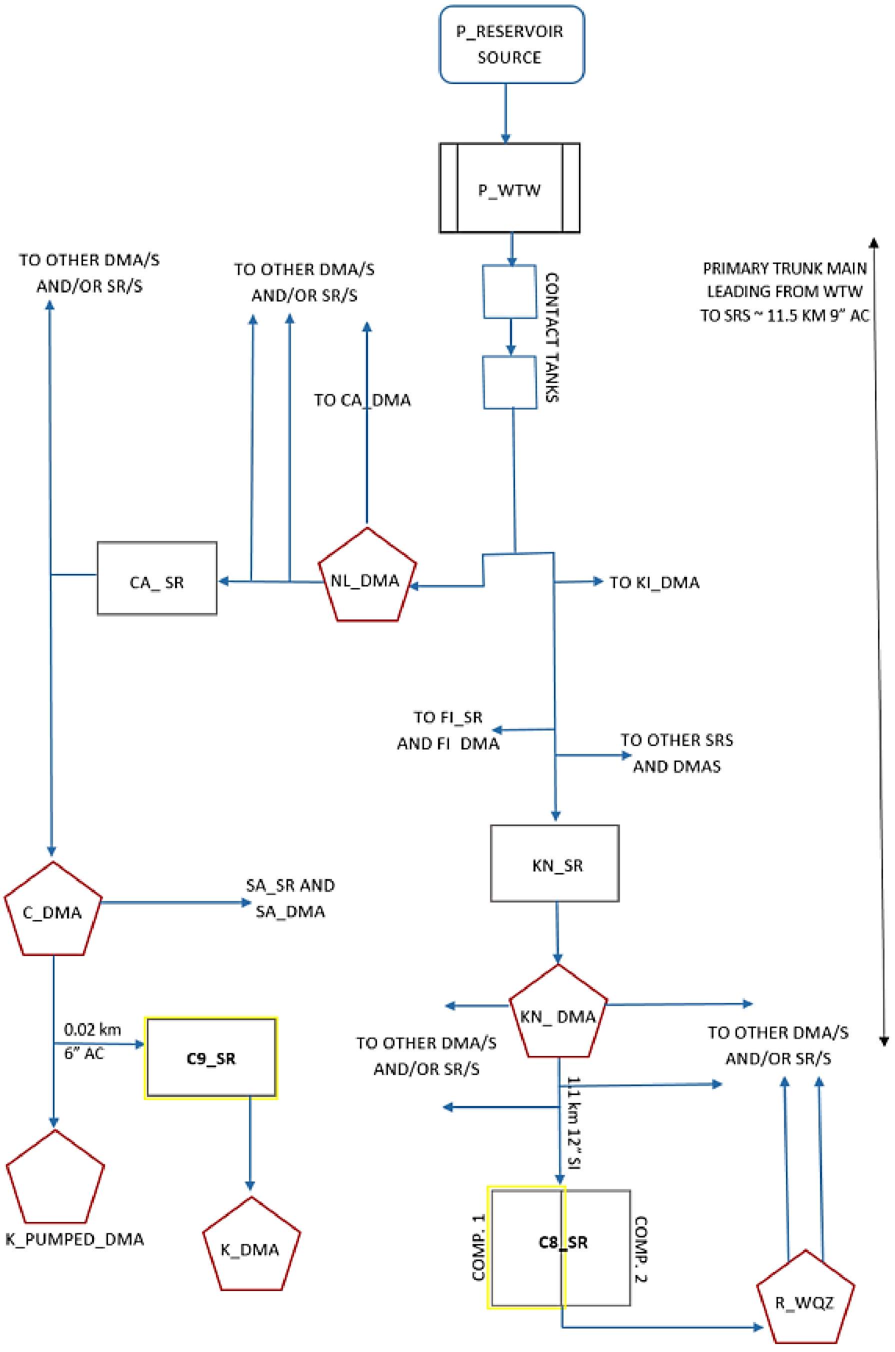


Figure 5.19 – **Network layout for sites C8 and C9.**

5.5.3.2. Service reservoir schematic and photos

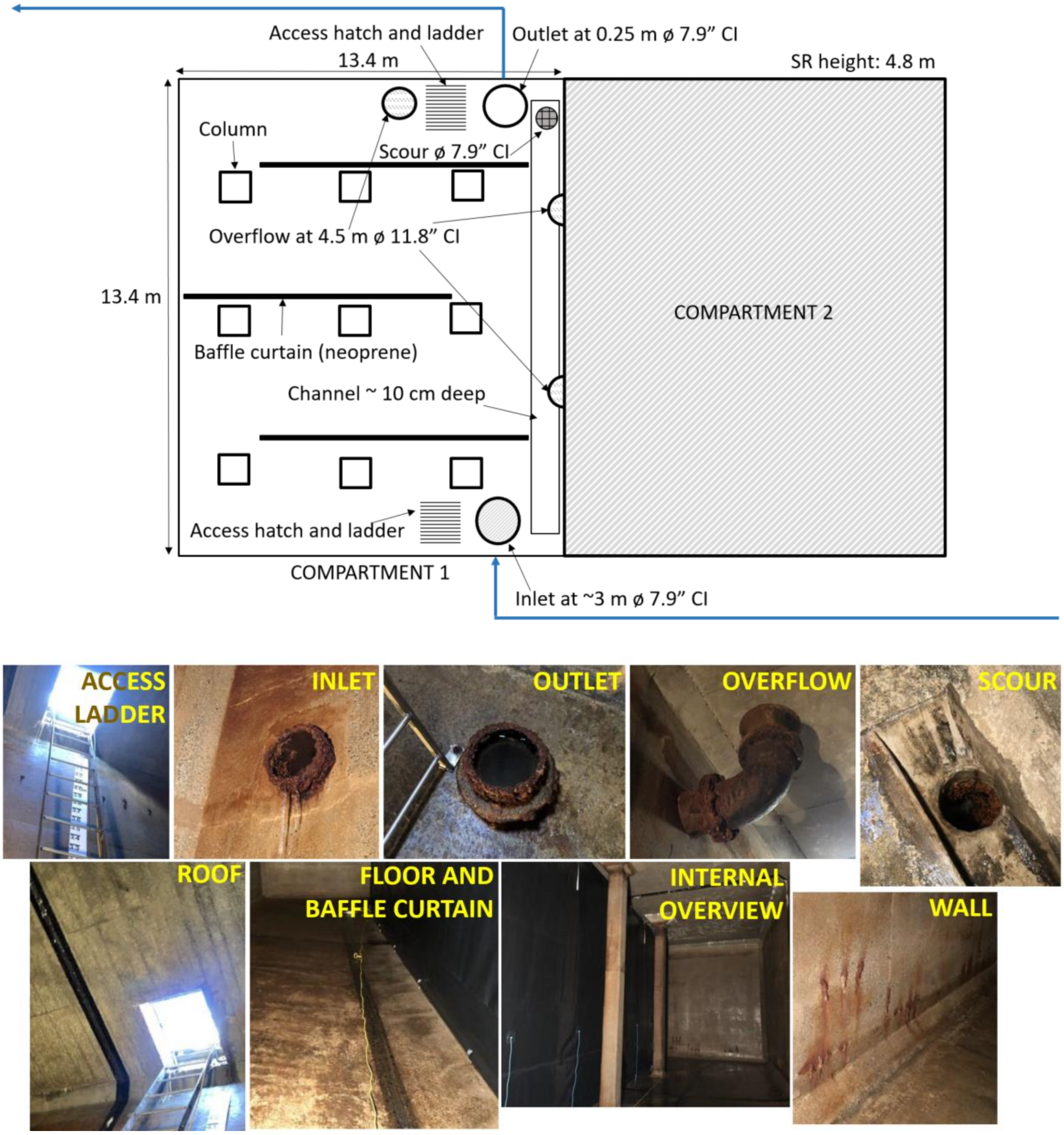


Figure 5.20 – A schematic of C8 SR and a collection of photos displaying the internal details of the SR.

5.5.4. C9

C9 SR is an underground (part exposed), circular, singular compartment, 0.4 ML concrete SR with an average retention time of 72 hours, last inspected and cleaned in October 2019 (Figure 5.21). It is fed by a 0.02 km asbestos cement trunk main, which taps off from an 11.5 km asbestos cement trunk main (Figure 5.19). The SR supplies a population of approximately 685 people. Treated water is reservoir abstracted, with chloramine as the secondary residual disinfectant.

5.5.4.1. Service reservoir schematic and photos

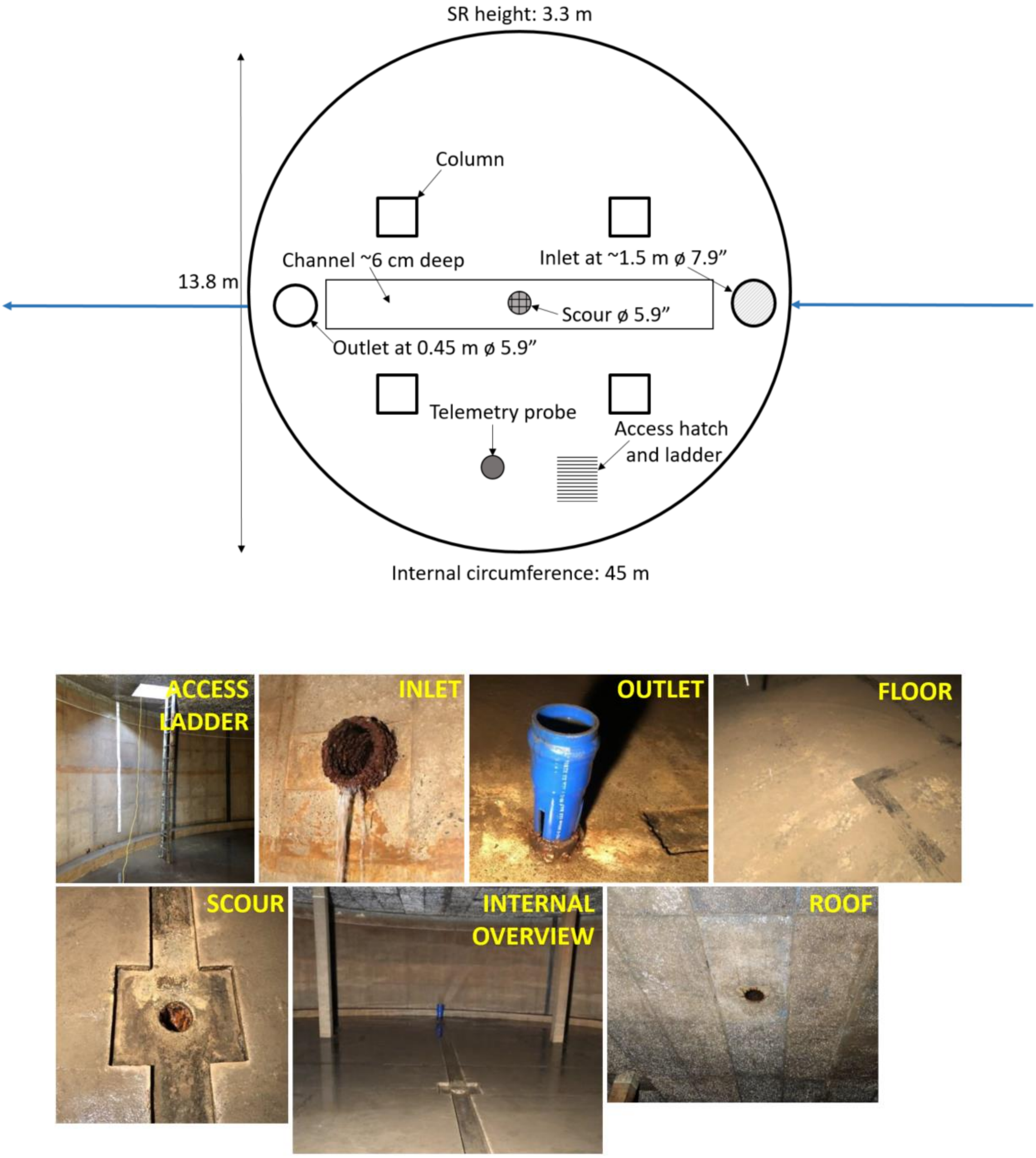


Figure 5.21 – A schematic of C9 SR and a collection of photos displaying the internal details of the SR.

5.6. Company D site: D4

D4 SR is an underground, rectangular, twin-compartment, 9.1 ML reinforced concrete (with a brick compartment-dividing wall) SR with an average retention time of 28 hours, last inspected and cleaned March (south comp.) and August (north comp.) 2019 (Figure 5.24). It is fed by a 0.22 km ductile iron cement lined trunk main. The SR feeds two SRs and two WQZs (Figure 5.22), which supply approximately 37,849 people between them. Treated water is reservoir abstracted with free chlorine as the secondary disinfectant and further UV dosing at the inlet of the SR (Figure 5.23).

5.6.1. Network layout

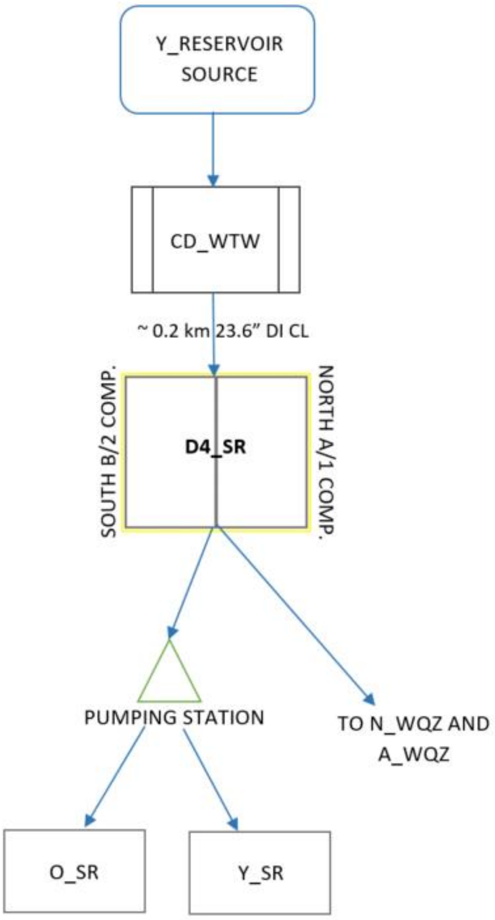


Figure 5.22 - **Site D4 network layout.**

5.6.2. Water treatment works process diagram

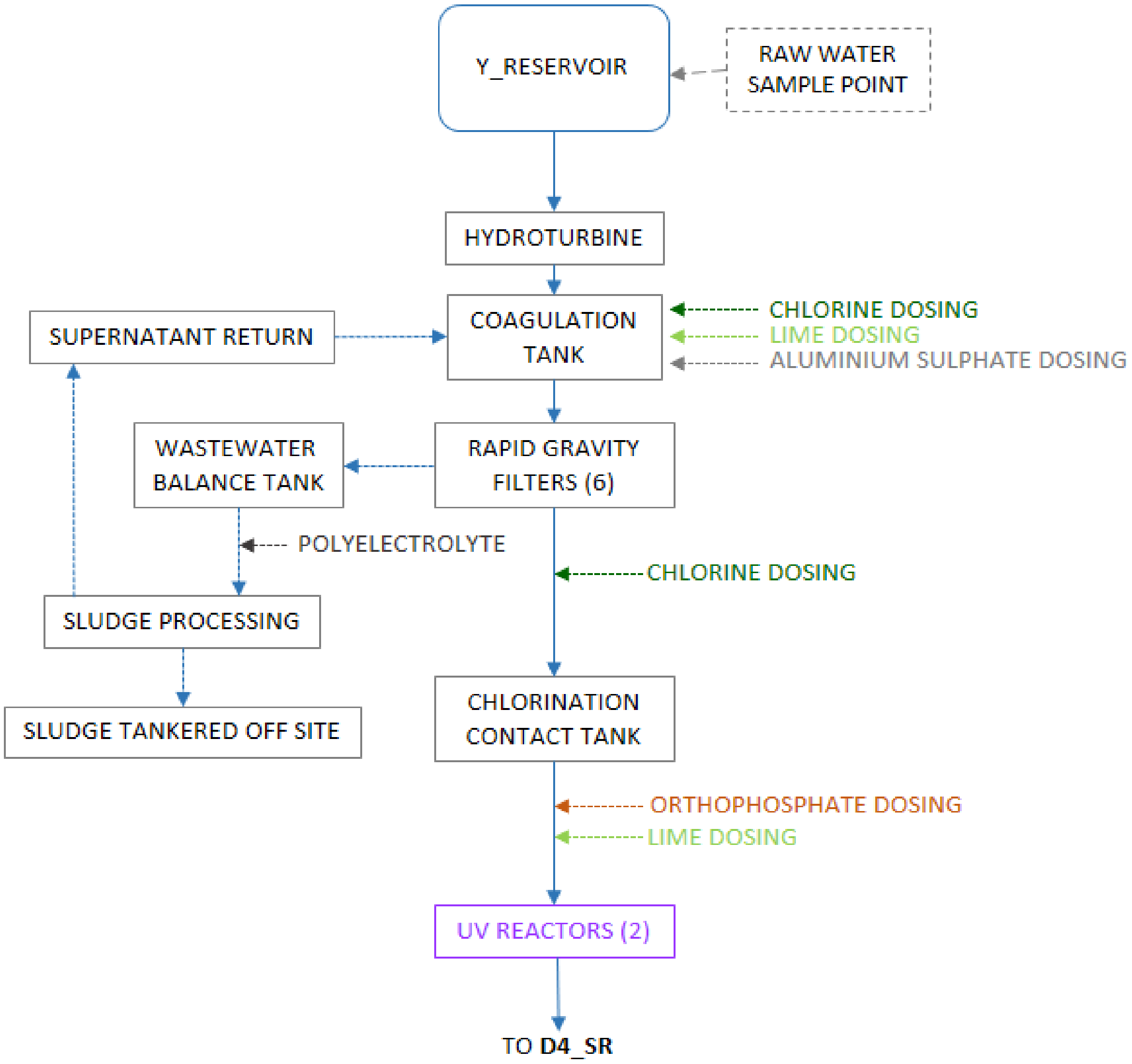


Figure 5.23 – Water treatment works (CD_WTW) process diagram for site D4.

5.6.3. Service reservoir schematic and photos

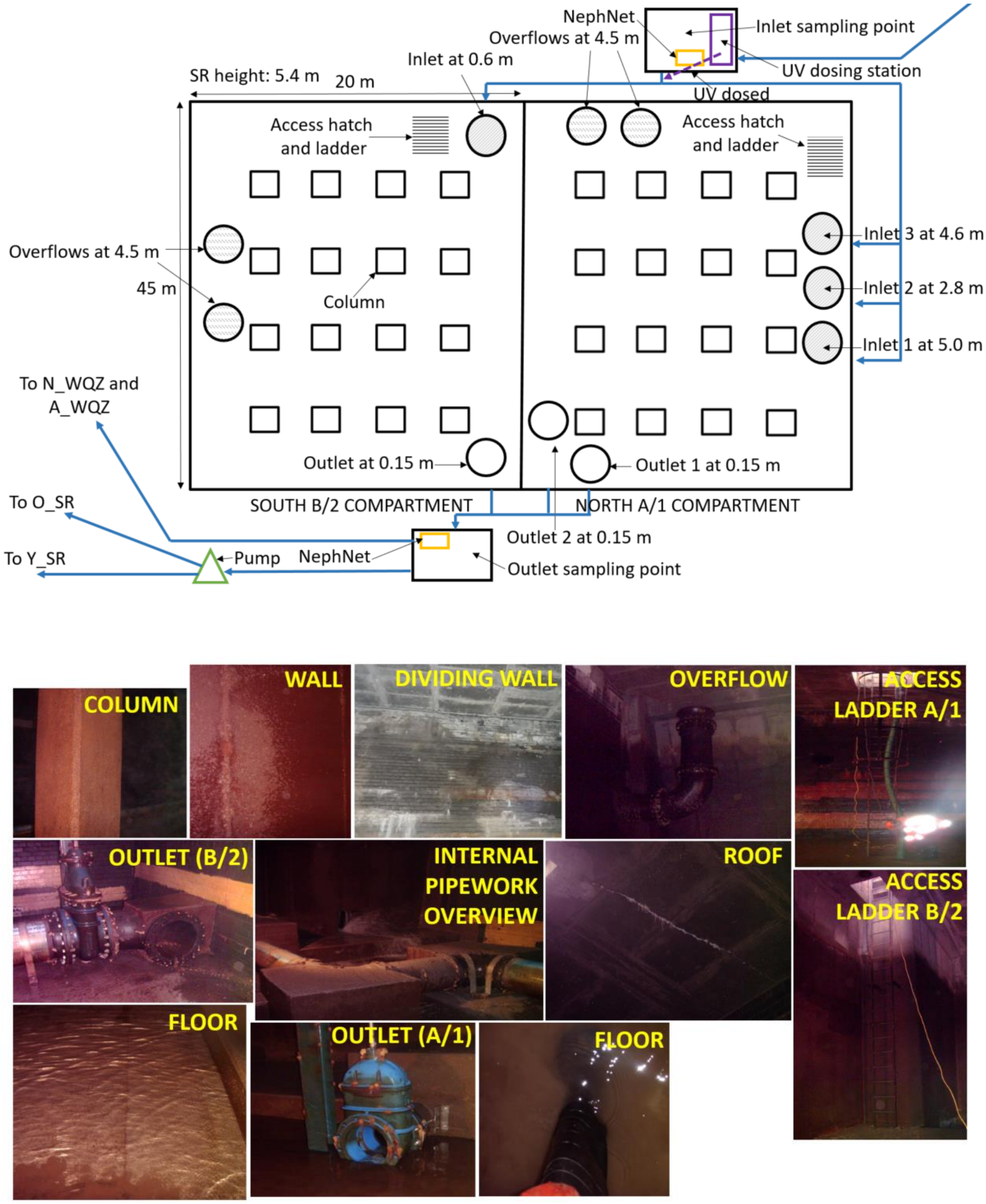
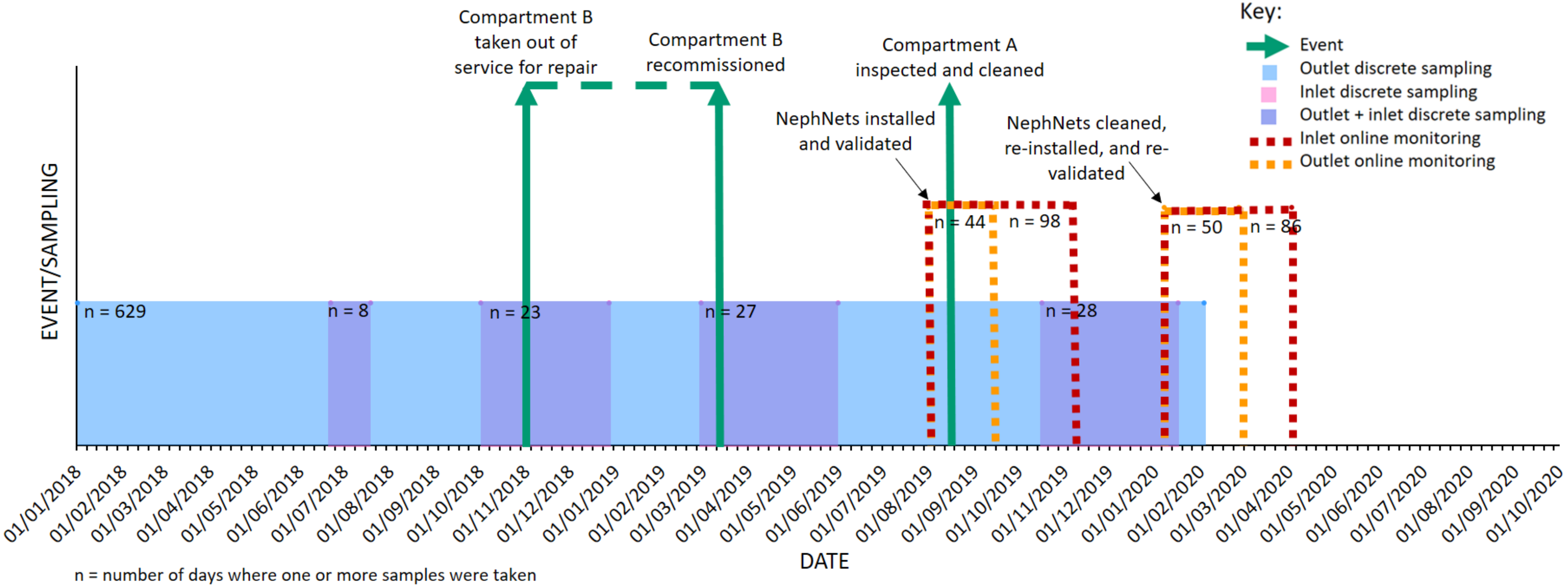


Figure 5.24 – **A schematic of D4 SR and a collection of photos displaying the internal details of the SR.**

5.6.4. Timeline of sampling and events



n = number of days where one or more samples were taken
Discrete sampling = conducted typically once a week

Figure 5.25 - A timeline graph displaying periods of available sample data at the inlet and outlet of D4 SR and key significant events.

Chapter 6: Results

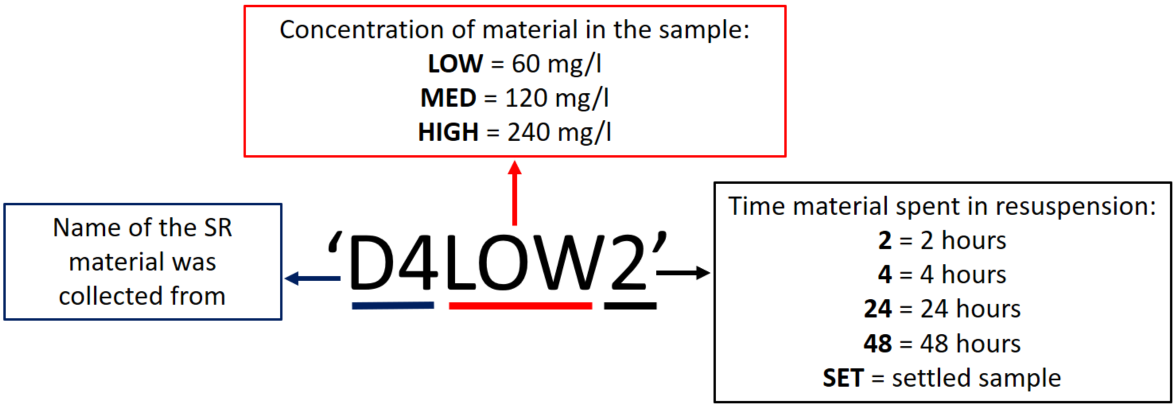
6.1. Analysis of Accumulated Material in Service Reservoirs

6.1.1. Introduction

This chapter presents results from analysis of accumulated material collected from six SRs (B5, B6, C7, C8, C9, and D4). Analysis was conducted in the form of two experiments, one with a focus on the effect of material resuspension on the surrounding water quality (B5, B6, and D4 SRs), and the other on the influence of location within SRs on the composition of accumulated material (C7, C8, and C9 SRs). These experiments were conducted to achieve **Objective 1** of the project.

6.1.2. Investigating the effect of material resuspension on surrounding water quality

Accumulated material collected from D4, B6, and B5 SRs was analysed for a broad selection of metals and elements, TOC, absorbance of UV light, and turbidity, results from which are presented in this section. Results from D4 and B6 SR samples are split into different concentrations of material (low, medium, and high) and different times in resuspension (2 hours, 4 hours, 24 hours, 48 hours, and settled). For full details of the experimental set up please see Chapter 4: Methodology and Methods. The naming convention for D4 and B6 samples is described below, using ‘D4LOW2’ as an example:



6.1.2.1. Metals and elements

D4 SR

Figures 6.1.1 and 6.1.2 present concentrations of the predominant metals found in D4 SR accumulated material samples from analysis for metals and elements. Aluminium data is presented separately in

Figure 6.1.1 as concentrations of this metal were a lot higher than other metals and data skewed the plot.

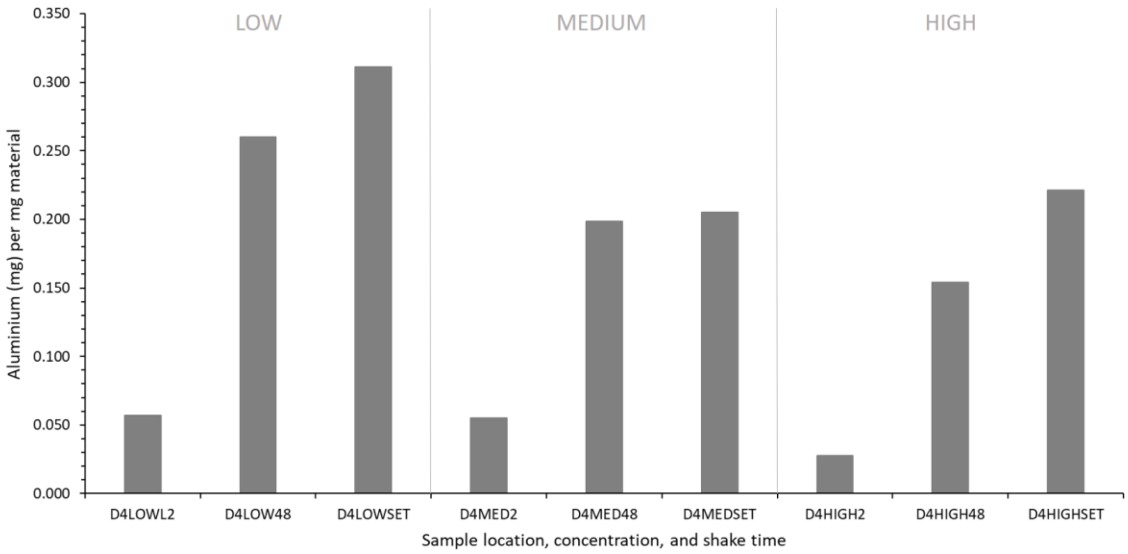


Figure 6.1.1 – Aluminium concentrations (mg) per mg of varying concentrations of material collected from D4 SR.

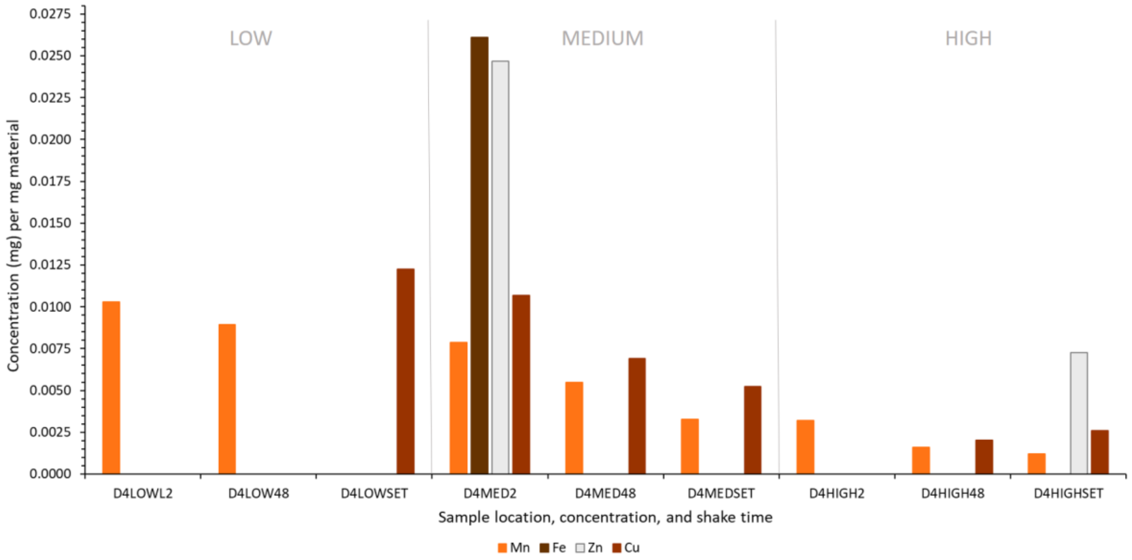


Figure 6.1.2 – Concentrations of total metals (mg) per mg of varying concentrations of material collected from D4 SR.

Results in Figure 6.1.1 suggest that aluminium concentrations increase with the duration of time material spends in contact with water, not necessarily with time in resuspension, as levels do not decrease in settled samples. The opposite effect can be observed with manganese concentrations, which decrease with duration of time material has been in contact with water (Figure 6.1.2). There is no clear relationship between resuspension time for copper and zinc.

B6 SR

Figure 6.1.3 presents concentrations of the predominant metals found in B6 SR accumulated material samples from analysis for metals and elements.

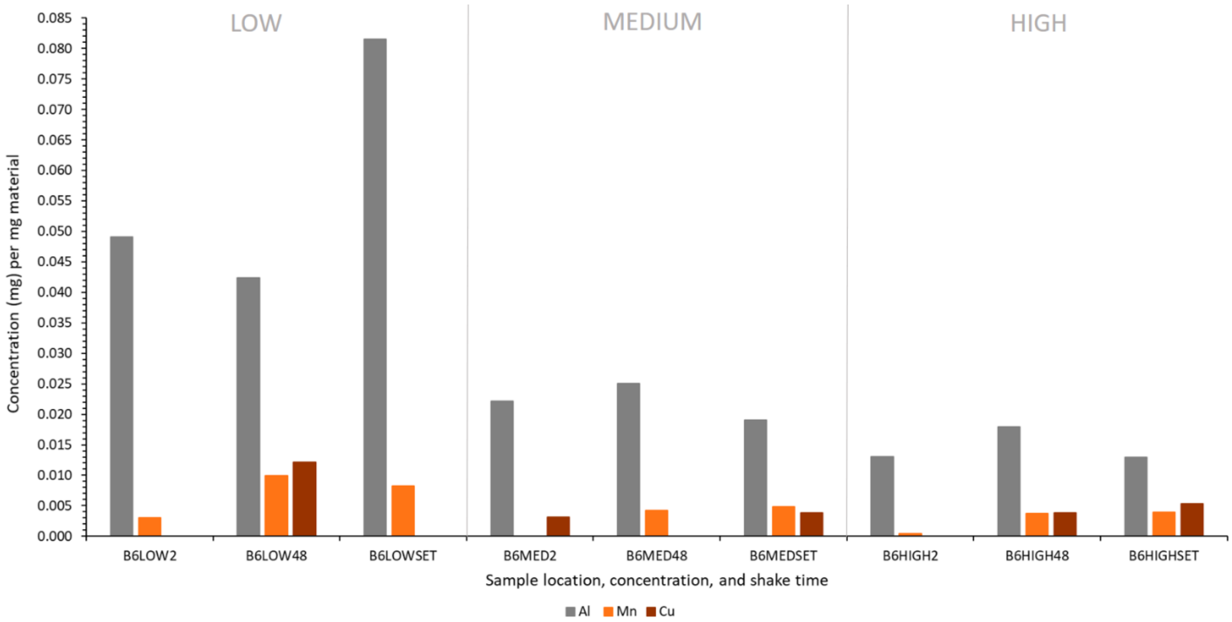


Figure 6.1.3 – Concentrations of total metals (mg) per mg of varying concentrations of material collected from B6 SR.

Results in Figure 6.1.3 suggest that there is no apparent relationship between time material spends in resuspension and the concentration of metals and elements in the surrounding water quality.

B5 SR

Figure 6.1.4 presents concentrations of the predominant metals found in the B5 SR accumulated material sample.

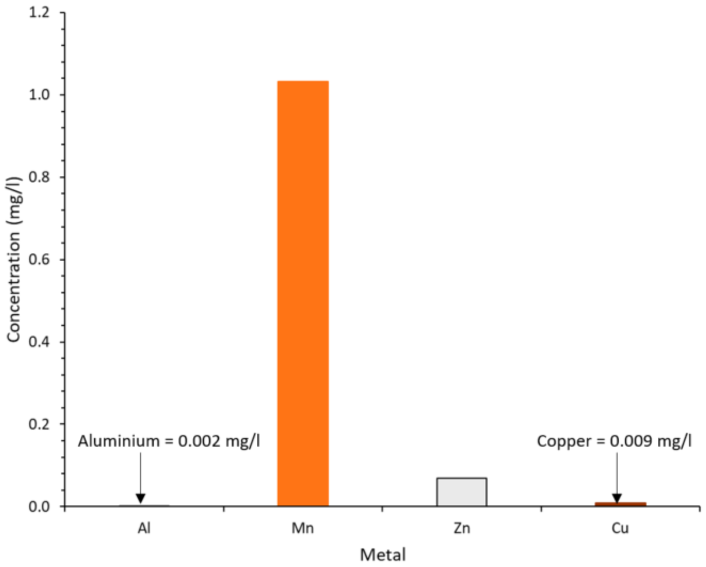


Figure 6.1.4 – **Concentration of metals (mg/l) in material collected from B5 SR.**

Figure 6.1.4 shows that the composition of the 'wet' B5 SR sample, which represented water that had been exposed to material for a long duration of time, in comparison to B6 and D4 samples that represented water that had not been previously exposed to material, had a much higher concentration of manganese, zinc, and copper.

Summary

Results from metals and elements analysis of SR accumulated material suggest that there is no reoccurring relationship between the time that material spends in resuspension and the concentration of metals and elements in the surrounding water. This effect varies between samples and parameters, which suggests that material is not homogenous in its composition of metals. Irrespective of concentration of material, metals and elements were released into the surrounding water.

Aluminium, manganese, and copper were the predominant metals found in accumulated material samples of all studied SRs, present in 100%, 89%, 63% of the samples respectively, with zinc and iron only present in 16% and 5% of the samples. It was interesting to observe that there was no iron present in the B6 SR sample, despite it being part supplied by a ductile iron trunk main (Chapter 5: Site Details - Figure 5.11). Although less pronounced, concentrations of certain metals and elements also differed between B6 and D4 SRs. Aluminium levels were higher in D4 SR accumulated material, which could be a result of carry-over of aluminium coagulant dosed at the supplying WTW of this SR, located only 0.2 km away from the WTW (Site Details: Chapter 5 – Figure 5.23). The concentration of all metals and elements in D4 and B6 accumulated material was below the UK health-based prescribed concentration values (PCVs)[4], whereas the concentration of manganese in the B5 sample breached PCV (set at 0.05 mg/l).

Magnesium and potassium were also present in all collected material samples, but as they were not the key parameters of interest in this research, data is not included here but can be found in Appendix 3, Figures a and b.

6.1.2.2. Absorbance (UV) and total organic carbon

Absorbance (cm^{-1}) of accumulated material from D4, B6, and B5 SRs was measured across wavelengths 200 to 800 nm. Wavelength UV254 was used to calculate specific ultraviolet absorbance (SUVA), results from which are presented below in Table 6.1.1, alongside dissolved organic carbon (DOC) concentrations in material samples. Total and dissolved organic carbon are interchangeable in this analysis as all of the carbon measured by the analytical instrument is dissolved.

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[4] A table containing PCVs for metals and elements analysed in accumulated material in this project can be found in Appendix 4, Table f.

Table 6.1.1 – Dissolved organic carbon (DOC) (mg/l), UV254 wavelength (cm^{-1}), and SUVA (L/mg-m) values in varied concentrations of 'dry' material samples collected from D4 and B6 SRs and in a 'wet' material sample collected from B5 SR.

Sample name	DOC (mg/l)	UV254 (cm-1)	SUVA (L/mg-m)
D4LOWL2	0.21	0.0056	2.71
D4LOW4	0.20	0.0056	2.82
D4LOW24	0.21	0.0064	3.09
D4LOW48	0.18	0.0070	3.94
D4LOWSET	0.69	0.0074	1.08
D4MED2	0.19	0.0062	3.33
D4MED4	0.21	0.0070	3.30
D4MED24	0.18	0.0076	4.34
D4MED48	0.18	0.0082	4.50
D4MEDSET	0.73	0.0083	1.14
D4HIGH2	0.27	0.0065	2.43
D4HIGH4	0.25	0.0061	2.44
D4HIGH24	0.24	0.0079	3.27
D4HIGH48	0.27	0.0080	2.93
D4HIGHSET	0.75	0.0105	1.40
B6LOWL2	0.26	0.0044	1.66
B6LOW4	2.31	0.0060	0.26
B6LOW24	0.17	0.0036	2.13
B6LOW48	0.18	0.0034	1.88
B6LOWSET	0.77	0.0033	0.43
B6MED2	0.19	0.0032	1.67
B6MED4	0.18	0.0027	1.48
B6MED24	0.17	0.0040	2.42
B6MED48	0.22	0.0035	1.65
B6MEDSET	0.91	0.0045	0.49
B6HIGH2	0.16	0.0041	2.53
B6HIGH4	0.17	0.0038	2.21
B6HIGH24	0.21	0.0040	1.96
B6HIGH48	0.21	0.0040	1.92
B6HIGHSET	0.77	0.0087	1.14
B5	3.53	0.3567	10.10

Results show that settled samples from both D4 and B6 SRs had lower SUVA values (mean 0.95 L/mg-m) than the other samples in resuspension (mean 2.54 L/mg-m). Based on current literature, this could suggest that settled samples are likely to have lower DBP formation, NOM content, and chlorine demand in comparison to the other samples. As for DOC concentrations, where SUVA was at its lowest, DOC concentrations were at their highest in settled samples from both D4 and B6 SRs. Duration of time material spent in resuspension did not otherwise appear to influence the concentration of SUVA or DOC in the surrounding water.

When comparing between all the SRs, SUVA was higher on average in D4 SR samples (mean SUVA 2.84 L/mg-m) in comparison to B6 SR samples (mean SUVA 1.59 L/mg-m). However, by far the highest SUVA was in the B5 SR 'wet' sample (10.10 L/mg-m). The water in this sample was exposed to material for a longer duration of time than the 'dry' material samples from B6 and D4 SRs, was unfiltered, and collected from a chloraminated network. DOC levels were similar in both B6 and D4 SR samples, irrespective of concentration of material. In comparison, the 'wet' B5 SR sample had a much higher DOC concentration of 3.53 mg/l. This observation aligns with the results for the B6 and D4 SR settled material samples as these had the longest contact time between material and water out of all analysed 'dry' material samples. This could suggest that perhaps the dissolving process resulting in the release of DOC is a very slow reaction, which takes weeks rather than hours or days.

6.1.2.3. Turbidity

Results for turbidity analysis in D4 and B6 SR samples did not indicate that there was any influence of duration of time material spent in resuspension or its concentration in samples on turbidity values. With the exception of one 'B6 LOW 48' sample, turbidity values were also within a similar range in both D4 (mean 0.17 NTU) and B6 (mean 0.16 NTU) SR material. The highest turbidity was observed in the 'wet' B5 SR sample at 1.7 NTU. Data can be seen in Figures c and d in Appendix 3.

6.1.3. Investigating the influence of sampling location within service reservoirs on the composition of accumulated material and the effect of its resuspension on disinfectant demand

Accumulated material collected from C7, C8, and C9 SRs was analysed for a broad selection of metals and elements, TOC, absorbance of UV light, fluorescence, turbidity, and chlorine demand, results from which are presented in this chapter. Samples were collected from different locations within the SR: around the inlet, from the middle of the tank, around the outlet, under probe (C9 SR only), and under ladder (C9 SR only); which is reflected in the way data is presented. For full details of the experimental set up please see Chapter 4: Methodology and Methods.

6.1.3.1. Metals and elements

Figure 6.1.5 presents concentrations of the predominant metals found in material samples collected from C7, C8, and C9 SRs. Results from sample 'C7 SR middle of compartment 2' were much higher than in material samples from other SRs. This was also the only sample where arsenic (0.0010 mg/l), lead (0.0007 mg/l), and uranium (0.0001 mg/l) were identified.

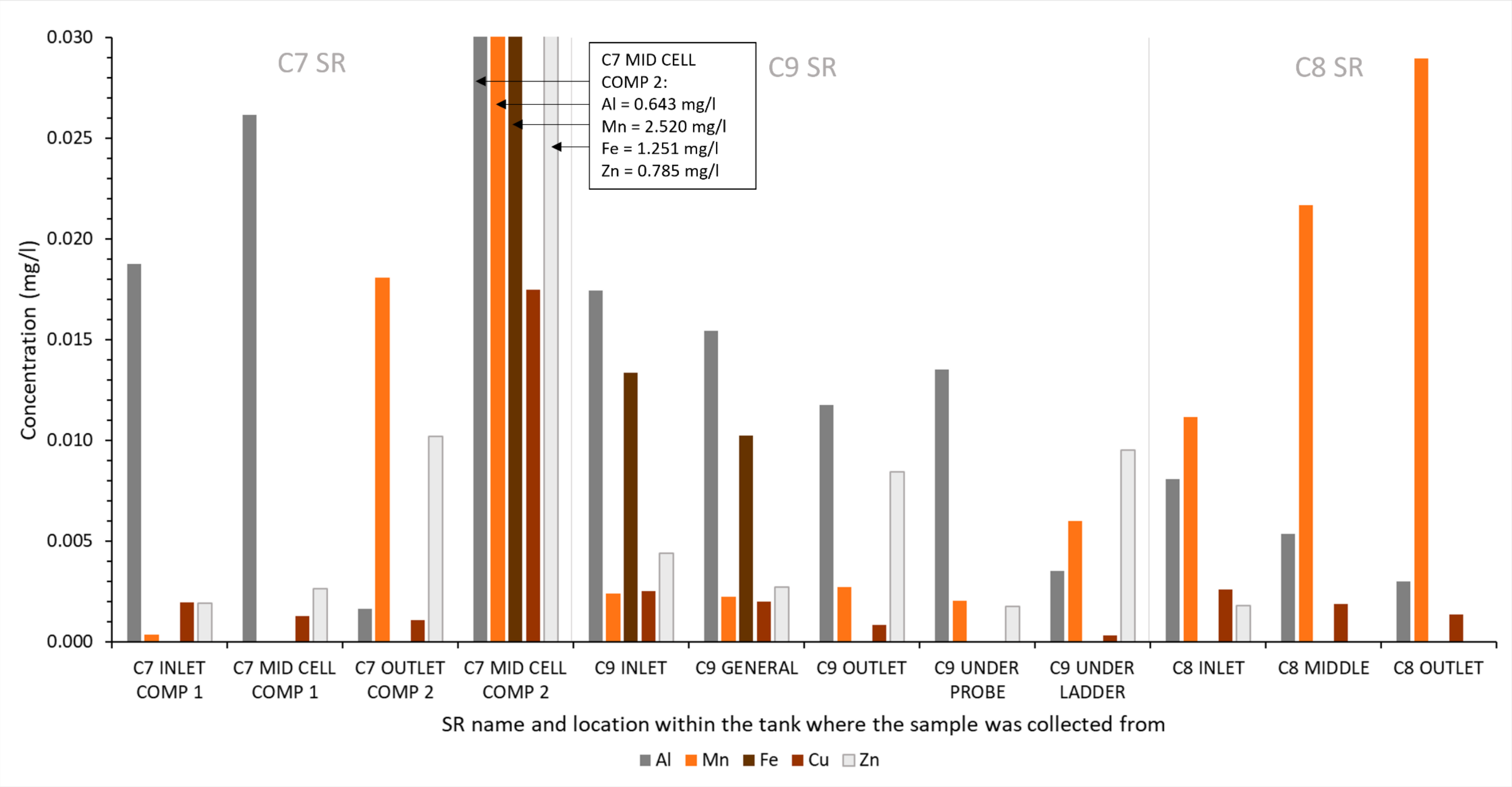

Figure 6.1.5 – **Total metals (mg/l) in material samples collected from different locations within C7, C8, and C9 SRs.**

Results from Figure 6.1.5 suggest that copper decreased with travel through all studied SRs and aluminium decreased with travel through C9 and C8 SRs, whereby concentrations were highest in samples collected around SR inlets and lowest in those collected around SR outlets. The potential influence of sampling location on other metals is less obvious. Although, there may be a potential influence of sampling under the ladder in C9 SR as manganese levels are higher in this sample than anywhere else in that SR.

Excluding the results from sample 'C7 SR MID COMP. 2', aluminium was the most dominant metal, present in 100% of the samples, followed by manganese in 91%, copper in 91%, zinc in 82%, and iron in just 18% of the samples. These results match that of metals and elements analysis on B6, D4, and B5 SR material, where aluminium was present in 100%, manganese in 89%, copper in 63%, zinc in 16%, and iron in 5% of the samples (Figures 6.1.1 to 6.1.4).

Iron was present in the only SR (C9) that was not directly fed by an iron trunk main (Chapter 5: Site Details – Figure 5.19). No metal concentrations breached UK PCVs in any of the samples other than 'C7 MID COMP. 2', an outlier sample in which manganese, aluminium, and iron concentrations all breached PCVs, set at 0.2 mg/l for aluminium and iron, and 0.05 mg/l for manganese (Figure 6.1.5). This sample was also the only sample that contained arsenic, uranium, and lead. Although not confirmed, it is suspected that this sample was exposed to a biocide solution, used as part of the cleaning process of SRs, prior to collection. This solution is used to strip biofilm and other accumulated materials off concrete and metal structures and in SRs is sprayed onto walls and internal structures. It is likely that this particular sample was impacted by the removal of a large area of biofilms and the resulting effluent ending up in the collected sample, which could explain these large concentrations and the detectable presence of arsenic, uranium, and lead. These results suggest that some of the metals and elements that enter SRs may accumulate in small concentrations in biofilms and are not present in their loose, particulate forms in accumulated material, e.g., iron.

Magnesium and potassium were also present in all collected material samples, but as they were not the key parameters of interest in this research, data is not included here but can be found in Appendix 3 (Figure e).

6.1.3.2. Absorbance (UV) and total organic carbon

Absorbance (cm^{-1}) of accumulated material from C7, C8, and C9 SRs was measured across wavelengths 200 to 800 nm. Wavelength UV254 was used to calculate specific ultraviolet absorbance (SUVA), results from which are presented below Table 6.1.2, alongside dissolved organic carbon (DOC) concentrations in material samples. Total and dissolved organic carbon are interchangeable in this analysis as all of the carbon measured by the analytical instrument is dissolved.

Table 6.1.2 – **Dissolved organic carbon (DOC) (mg/l), UV254 wavelength (cm^{-1}), and SUVA (L/mg-m) values in material samples collected from various locations within C7, C8, and C9 SRs.**

Sample name	DOC (mg/l)	UV254 (cm-1)	SUVA (L/mg-m)
C7 INLET COMP 1	1.54	0.0270	1.75
C7 MID COMP 1	1.48	0.0250	1.69
C7 MID COMP 2 DILUTED	4.28	0.0527	1.23
C7 OUTLET COMP 2	2.51	0.0350	1.39
C9 INLET	3.98	0.0780	1.96
C9 GENERAL	3.90	0.0750	1.92
C9 OUTLET	3.97	0.0790	1.99
C9 UNDER PROBE	3.79	0.0750	1.98
C9 UNDER LADDER	4.86	0.0990	2.04
C8 INLET	4.47	0.0861	1.93
C8 MIDDLE	3.87	0.0760	1.96
C8 OUTLET	3.88	0.0742	1.91

Results suggest that SUVA was higher in chloraminated system SRs, C8 (mean 1.93 L/mg-m) and C9 (mean 1.98 L/mg-m), in comparison to C7 SR (mean 1.52 L/mg-m), which is located in a chlorinated system. The same observation can be made for DOC, whereby concentrations were higher in samples from SRs located in a chloraminated system. It is important to highlight that both C8 and C9 SRs are located in the same network, it is therefore difficult to distinguish whether the difference in SUVA and DOC between these SRs and C7 SR samples is related to the different secondary disinfectant used or to the specific network the two SRs are in.

C7 is the only SR where there is some variability in SUVA values across different sampling locations, whereby SUVA decreases with distance from SR inlet (highest SUVA value at the inlet and lowest value at the outlet). Similarly, results show that there was no influence of sampling location within SRs on DOC concentrations and that measured DOC levels were average in terms of DWDS expected levels, which range from 0.05 to 12.2 mg/l (Symons et al., 1975).

Even after the sample had a five-factor dilution, the concentration of DOC in the material sample collected from the middle of compartment 2 in C7 SR was 21.4 mg/l, which is much higher than the DWDS average. As previously mentioned, it is suspected that this sample came into contact with a biocide solution used to strip biofilm and material off SR internal structures, which could potentially indicate that DOC adheres to internal surfaces, e.g., through assimilation into biofilms.

6.1.3.3. Fluorescence

Figures 6.1.6 to 6.1.8 present the output of fluorescence analysis in the form of excitation and emission matrices (EEMs) for material samples collected from different locations within C7, C9, and C8 SRs respectively.

C7 SR

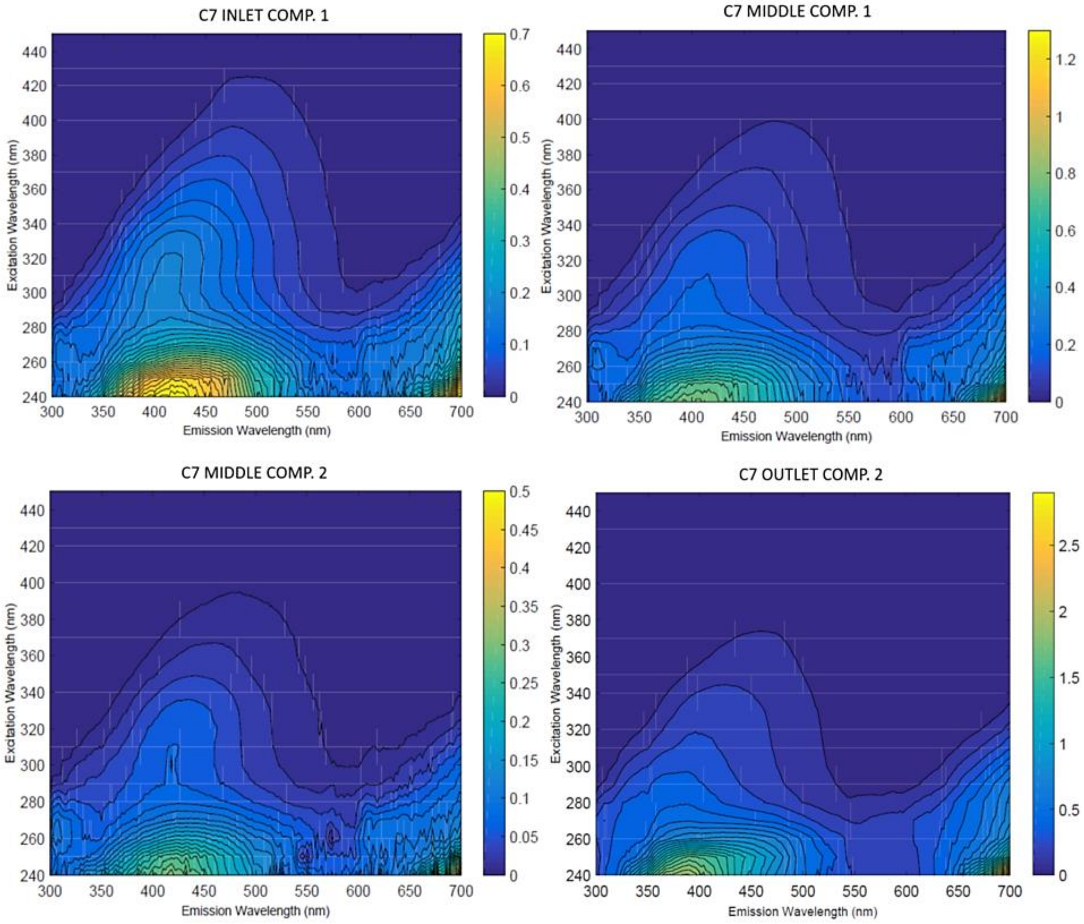

Figure 6.1.6 – Excitation and emission matrices for material samples collected from different locations within C7 SR.

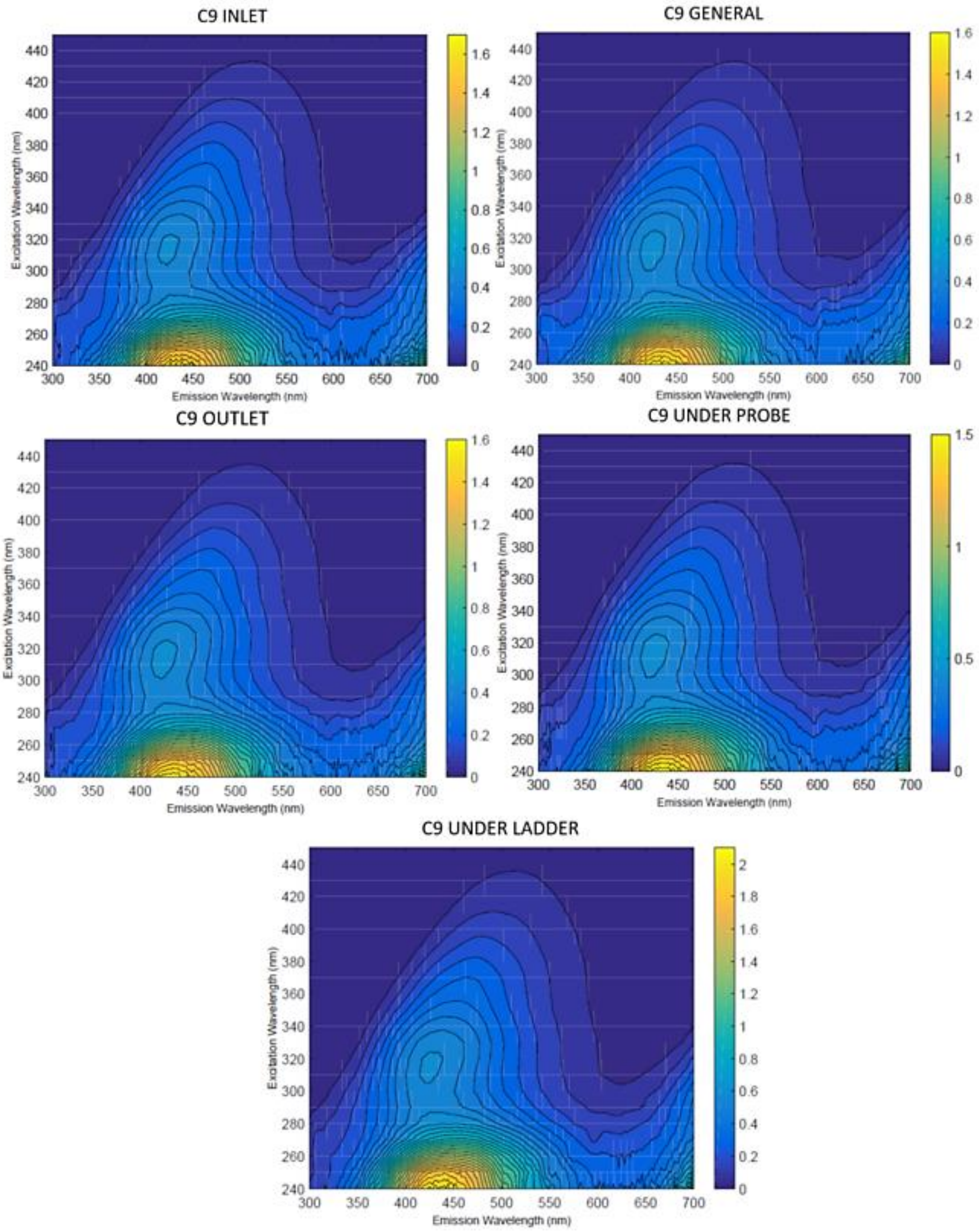

Figure 6.1.7 – Excitation and emission matrices for material samples collected from different locations within C9 SR.

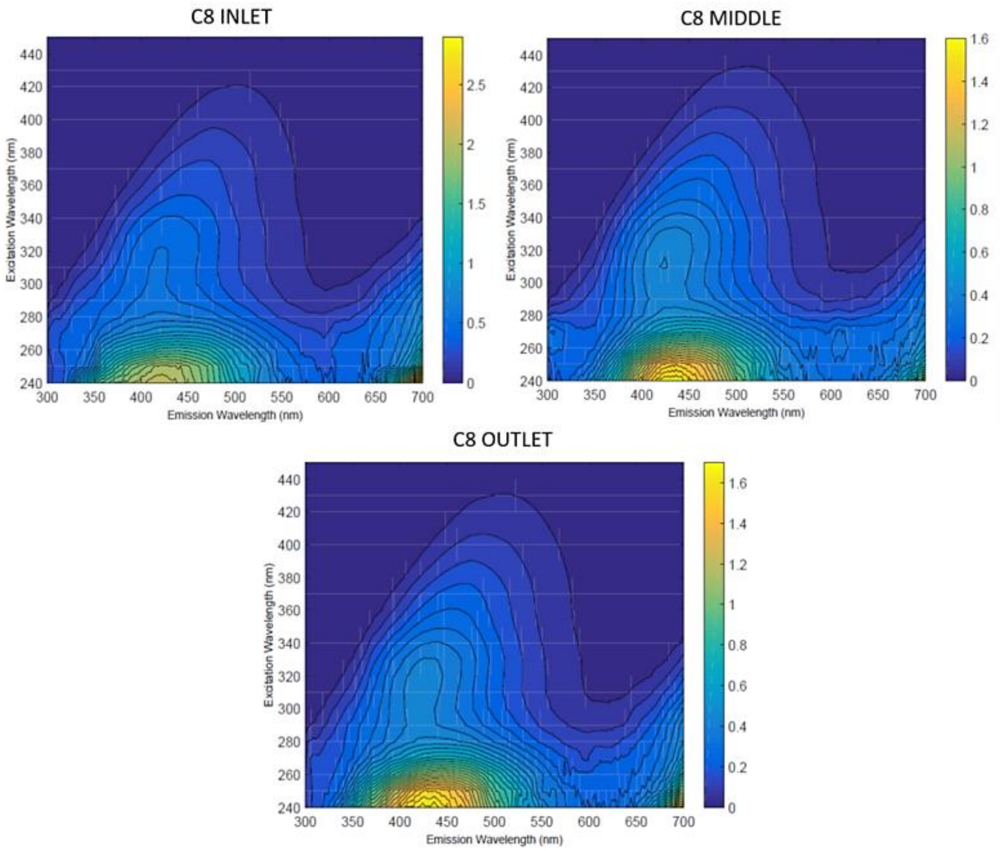

Figure 6.1.8 – **Excitation and emission matrices for material samples collected from different locations within C8 SR.**

Results show that the range of the excitation peak in EEMs for material collected from C7, C8, and C9 SRs (Figures 6.1.6 to 6.1.8) is similar across all samples and falls within the range of 350 to 500 nm for the emission wavelength and 240 to 260 nm for the excitation wavelength. Based on papers by Gabor et al. (2014) and Wasswa et al. (2019), these results indicate that the predominant fluorophore (material) is made up of humic-like compounds. The intensity of the excitation peak is low, which indicates that samples are low in organic content, which suggests a low microbial presence.

C7 appears to be the only SR that had some variability in the intensity of the excitation peak, which decreased in intensity with distance from SR inlet to SR outlet (Figure 6.1.6). The intensity of the excitation peak in most C7 SR samples was also lower in comparison to material samples from C8 and C9 SRs, which are located in a chloraminated system (Figures 6.1.7 and 6.1.8).

6.1.3.4. Turbidity

Figure 6.1.9 presents results from turbidity analysis of material samples collected from C7, C8, and C9 SRs.

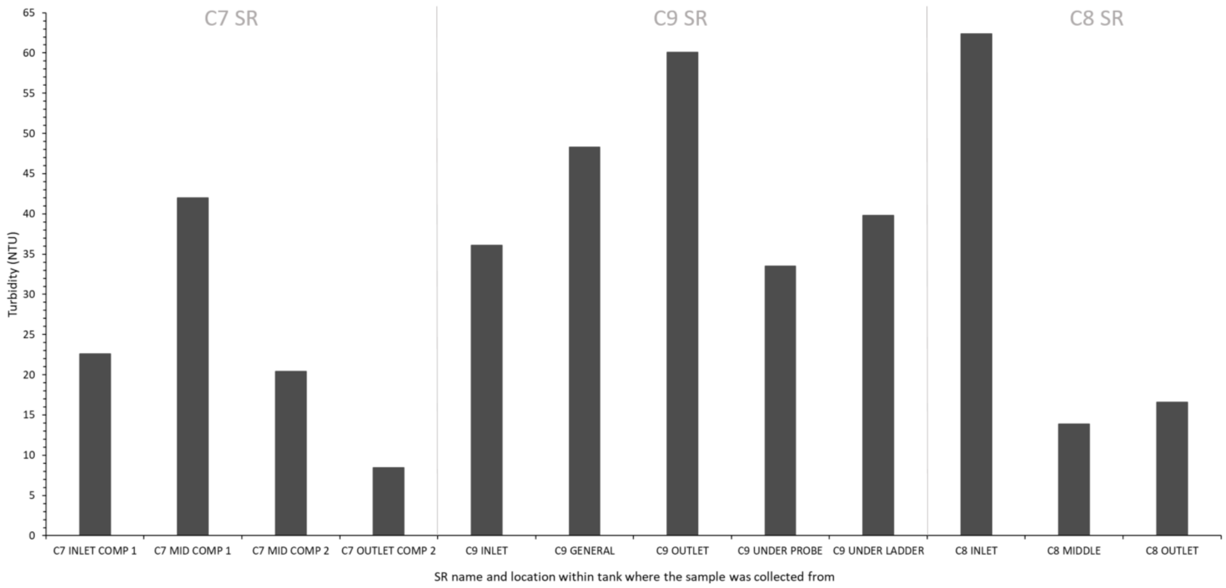

Figure 6.1.9 – Turbidity (NTU) in material samples collected from different locations within C7, C8, and C9 SRs.

Results do not seem to show any clear relationships between sampling location within SRs and corresponding turbidity values (Figure 6.1.9). Turbidity was, however, high in all samples (ranging from 9 to 62 NTU) and breached UK PCV (set at 4 NTU at consumers' taps), even after 30 hours of settling time.

6.1.3.5. Chlorine demand

Figures 6.1.10 to 6.1.12 present results from analysis of chlorine decay rate exerted by resuspended material samples collected from different locations within C7, C9, and C8 SRs respectively.

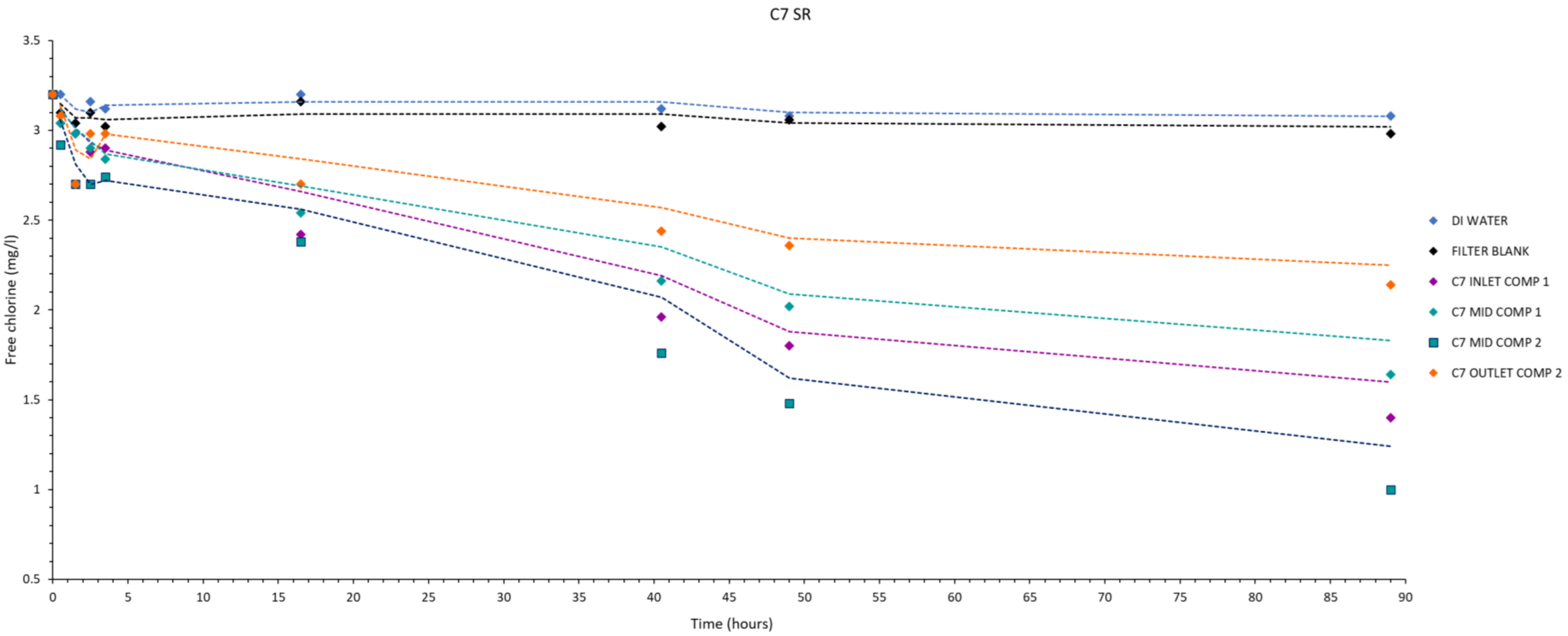

Figure 6.1.10 – Chlorine decay rates with two-period moving average trendlines across 90 hours with a starting chlorine concentration of 3.2 mg/l for material samples collected from different locations within C7 SR.

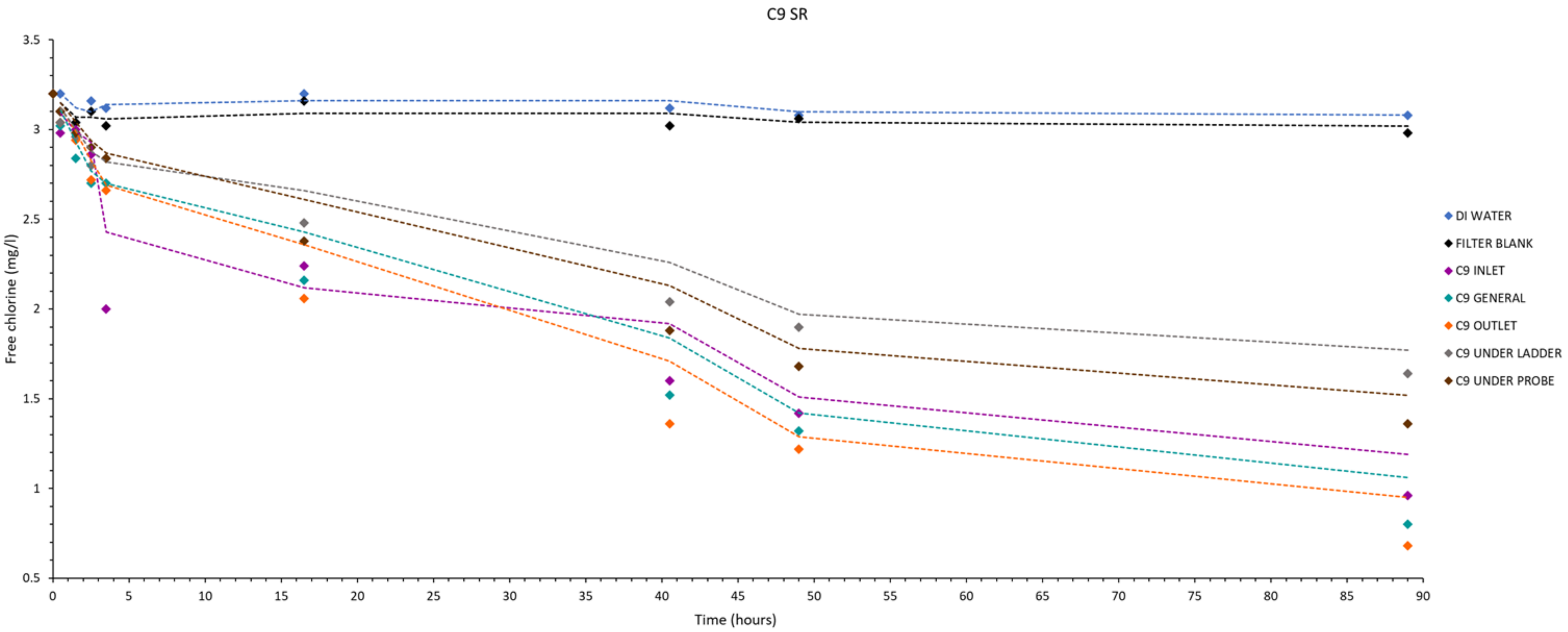

Figure 6.1.11 – Chlorine decay rates with two-period moving average trendlines across 90 hours with a starting chlorine concentration of 3.2 mg/l for material samples collected from different locations within C9 SR.

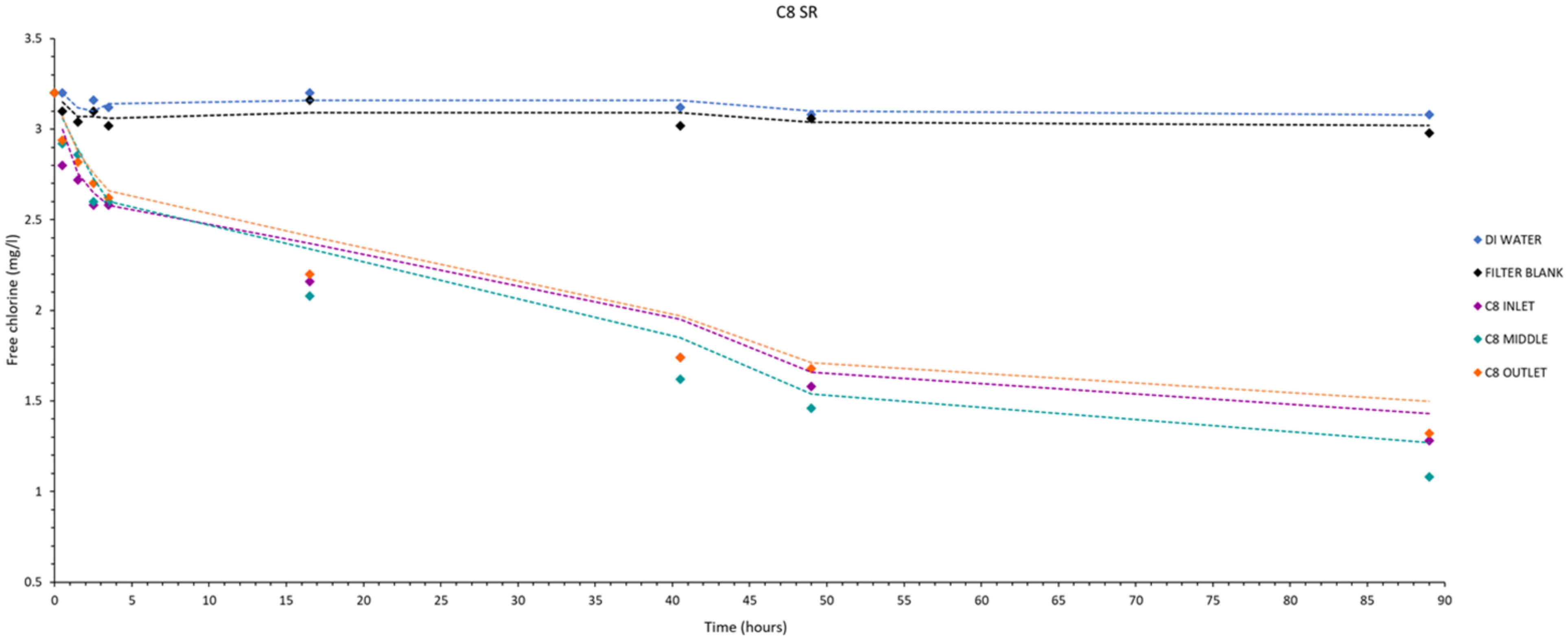

Figure 6.1.12 – Chlorine decay rates with two-period moving average trendlines across 90 hours with a starting chlorine concentration of 3.2 mg/l for material samples collected from different locations within C8 SR.

Results show that there was a slight difference in chlorine decay rate between SRs and sampling locations within them. Chlorine demand was highest in C9 SR samples, which increased with travel through the SR (lowest decay rate at the inlet, highest at the outlet) (Figure 6.1.12). In the same SR, samples collected from under the ladder and probe exerted the least chlorine demand. The lowest chlorine decay rate was exerted by C7 SR material, which also varied between the samples, with the 'C7 MID COMP. 2' sample, that was likely exposed to a biocide solution, exerting the highest demand, and 'C7 OUTLET COMP. 2' sample, which needed to be weighed using a filter, exerting the lowest demand (Figure 6.1.10). There was very little difference between sampling locations in C8 SR (Figure 6.1.11). Overall, there was a slightly steeper chlorine decay curve in SRs located in a chloraminated system (C8 and C9). In general, irrespective of the supposed low organic content of collected material samples, they all exerted a high chlorine demand in that average hourly decay rate was 0.02 mg/l (0.48 mg/l across 24 h), with a starting chlorine concentration of 3 mg/l and just 50 mg/l of material. Typical residual chlorine levels leaving UK WTW are 0.05 mg/l (DWI 2010), which, based on the above results, would rapidly drop to zero at SR outlets if material resuspends.

6.1.4. Summary

SR accumulated material collected in this project was low in organic content, which suggests a low microbial presence, but exerted a high chlorine demand and sometimes breached PCV for turbidity and metals upon resuspension. The majority of collected samples also had negligible levels of iron in their composition, a metal that does not seem to settle as loose deposits in SRs, unlike Al, Mn, Cu, Zn, which were the predominant metals found in all samples.

6.2. Using Historical Data to Understand the Impact of Service Reservoirs on Water Quality

6.2.1. Changes in water quality with transport through distribution systems

This chapter presents results from the assessment of site-specific historical water quality data collected, where available, at all stages of the DWDS for project sites B2, C3, and D4. This was done to achieve **Objective 2** of the project.

As expected, total and free chlorine decreased steadily with travel through the DWDS across all project sites. This data is therefore not included in this chapter but can be found in Appendix 3 (Figures f and g). Post treatment, aluminium concentrations did not vary between different network stages for all project sites and so data is not included here but can be found in Appendix 3 (Figures h to j). The same lack of change in parameter concentrations post treatment was observed for manganese, TOC, and turbidity in the C3 network, data for which is also in Appendix 3 (Figures k to m). pH data was available for C3 and D4 networks, but aside from adding to the completeness of the dataset, this parameter did not provide much information on network or SR performance, it is therefore not included here, but can be found in Appendix 3 (Figures n and o).

Results from all the presented figures below are discussed in the summary section (6.2.1.4.) of this chapter.

6.2.1.1. B2

Figures 6.2.1 to 6.2.3 present historical iron, manganese, and turbidity concentrations at different stages of the B2 DWDS.

6.2.1.1.1. Iron

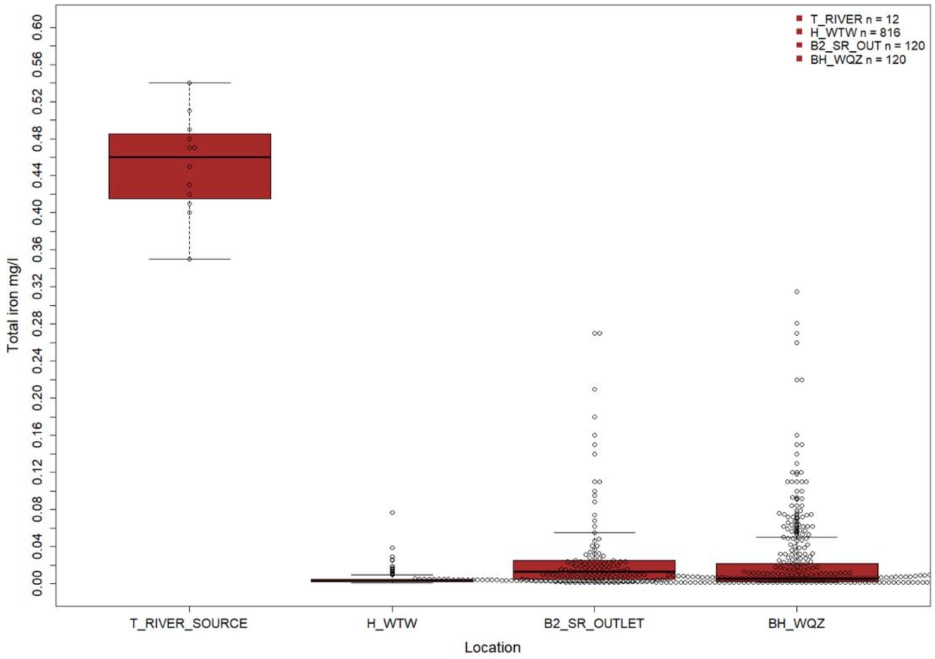

Figure 6.2.1 – Total iron at different stages of the B2 DWDS across 2007 to 2010, and 2017. Averages: source water 0.452 mg/l, WTW 0.004 mg/l, SR outlet 0.029 mg/l, and WQZ 0.024 mg/l.

6.2.1.1.2. Manganese

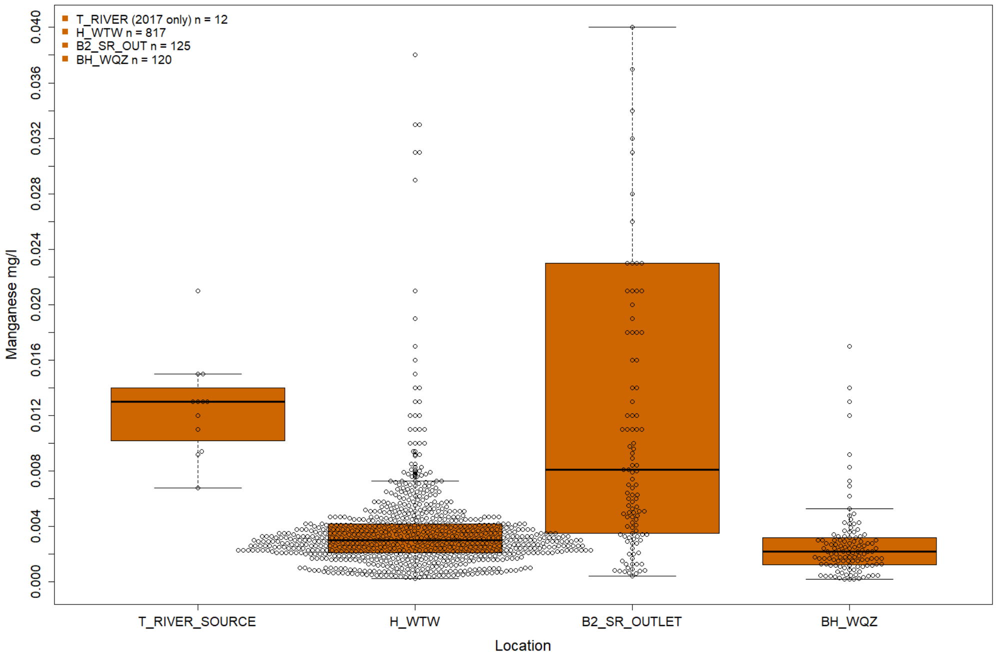

Figure 6.2.2 – **Total manganese (mg/l) at different stages of the B2 DWDS across 2007 to 2010, and 2017. Source water data is for 2017 only. Averages: source water 0.013 mg/l, WTW 0.005 mg/l, SR outlet 0.041 mg/l, and WQZ 0.004 mg/l.**

6.1.2.1.3. Turbidity

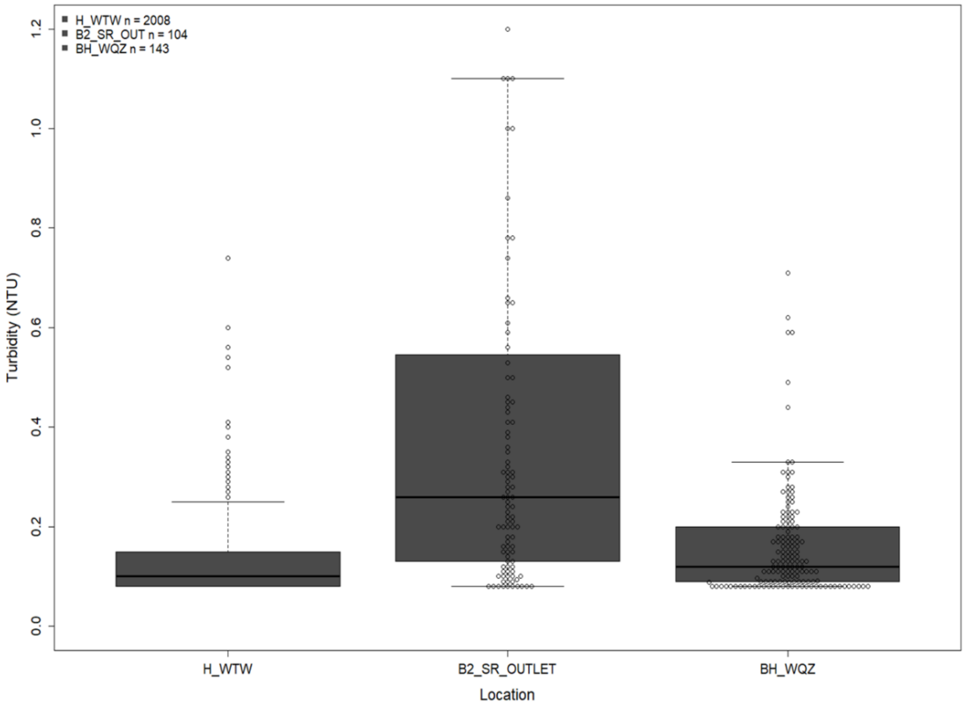

Figure 6.2.3 – **Turbidity (NTU) at different stages of the B2 DWDS across 2007 to 2010, 2014, and 2017. Averages: WTW 0.12 NTU, SR outlet 0.59 NTU, and WQZ 0.16 NTU.**

6.2.1.2. C3: Iron

Figure 6.2.4 presents historical total iron concentrations at different stages of the C3 DWDS.

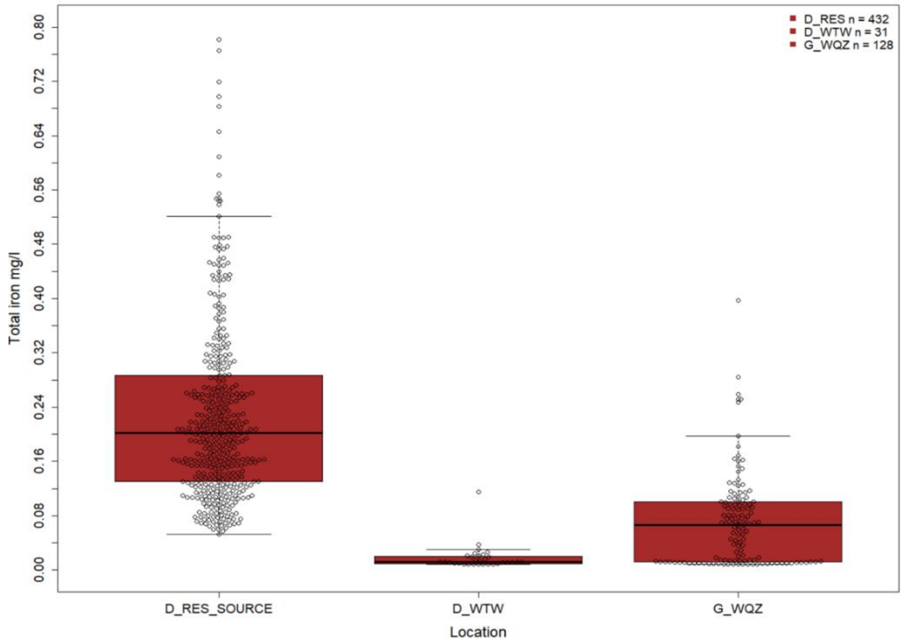

Figure 6.2.4 – Total iron (mg/l) at different stages of the C3 DWDS across 2008 to 2017. Averages: source water 0.283 mg/l, WTW 0.018 mg/l, and WQZ 0.070 mg/l.

6.2.1.3. D4: Turbidity

Figure 6.2.5 presents historical turbidity values at different stages of the D4 DWDS.

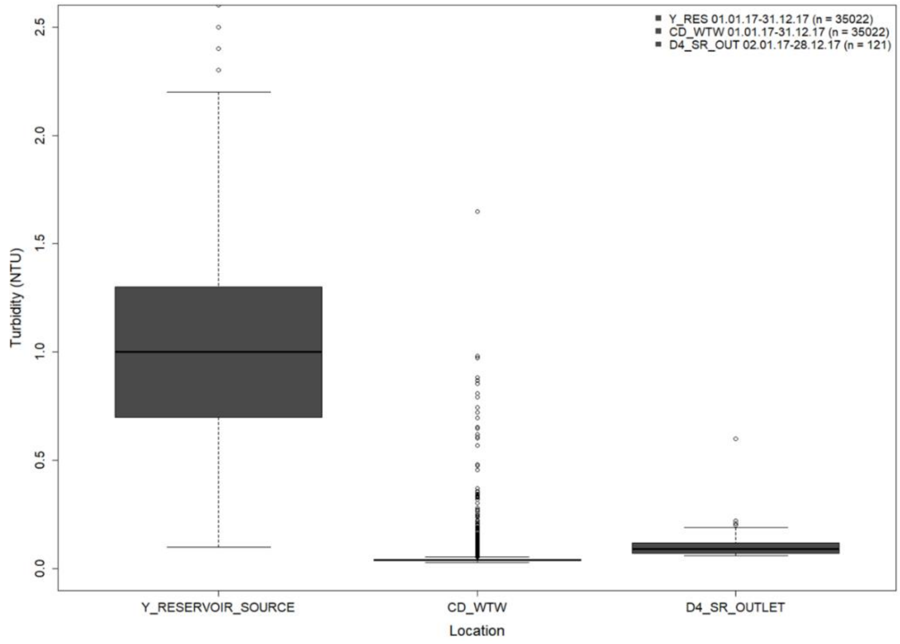

Figure 6.2.5 – Turbidity (NTU) at different stages of the D4 DWDS across 2017. Averages: source water 1.1 NTU, WTW 0.04 NTU, and SR outlet 0.10 NTU.

6.2.1.4. Summary

Where SR outlet data was available for parameters other than the regulatory disinfectant residual and bacteria (predominantly in the B2 network), results show that there is a change in concentration of these parameters between the SR outlet and the upstream network (Figures 6.2.1, 6.2.2., 6.2.3, and 6.2.5). This is particularly evident in the B2 network where values for iron, and especially manganese and turbidity were higher at the SR outlet in comparison to that at the outlet of the supplying WTW (Figures 6.2.1 to 6.2.3). Manganese and turbidity levels (Figures 6.2.2 and 6.2.3) were also a lot more variable at the B2 SR outlet in relation to other network stages.

Although the additional sampling campaigns for non-regulated parameters conducted by water utilities at SR outlets indicate that water quality changes between WTW and SR outlets, highlighting potential network issues, without SR inlet monitoring, it is unclear whether these observed changes can be attributed to the SR itself, the upstream network (e.g., trunk main supplying the SR), or both.

Regarding how concentrations of individual water quality parameters changed with travel through the DWDS after treatment, iron was consistent in that concentrations increased post treatment with travel through B2 and C3 DWDSs (Figures 6.2.1 and 6.2.4).

6.2.2. Relationship between SR construction age and the likelihood of bacteriological failure occurrence

This section presents results from a comparison analysis carried out on company-wide operational SR construction age data against the number of SRs with one or more bacteriological failures at the outlet between 2012 to 2018. Analysis was conducted on data collected from three of the four project water utilities to assess whether there is a potential relationship between the duration of time a SR has been in service against the likelihood of it experiencing a bacteriological failure, with the assumption that older SRs are more likely to fail.

Figure 6.2.6 shows the percentage of operational service reservoirs with a known construction age that had one or more bacteriological failures at the outlet between 2012-2018 for data collected from three water utilities. Table 6.2.1 contains the raw data used for analysis; Company B data is split into two categories as there are two distinct geographical regions covered by this utility, with highly varying topographies.

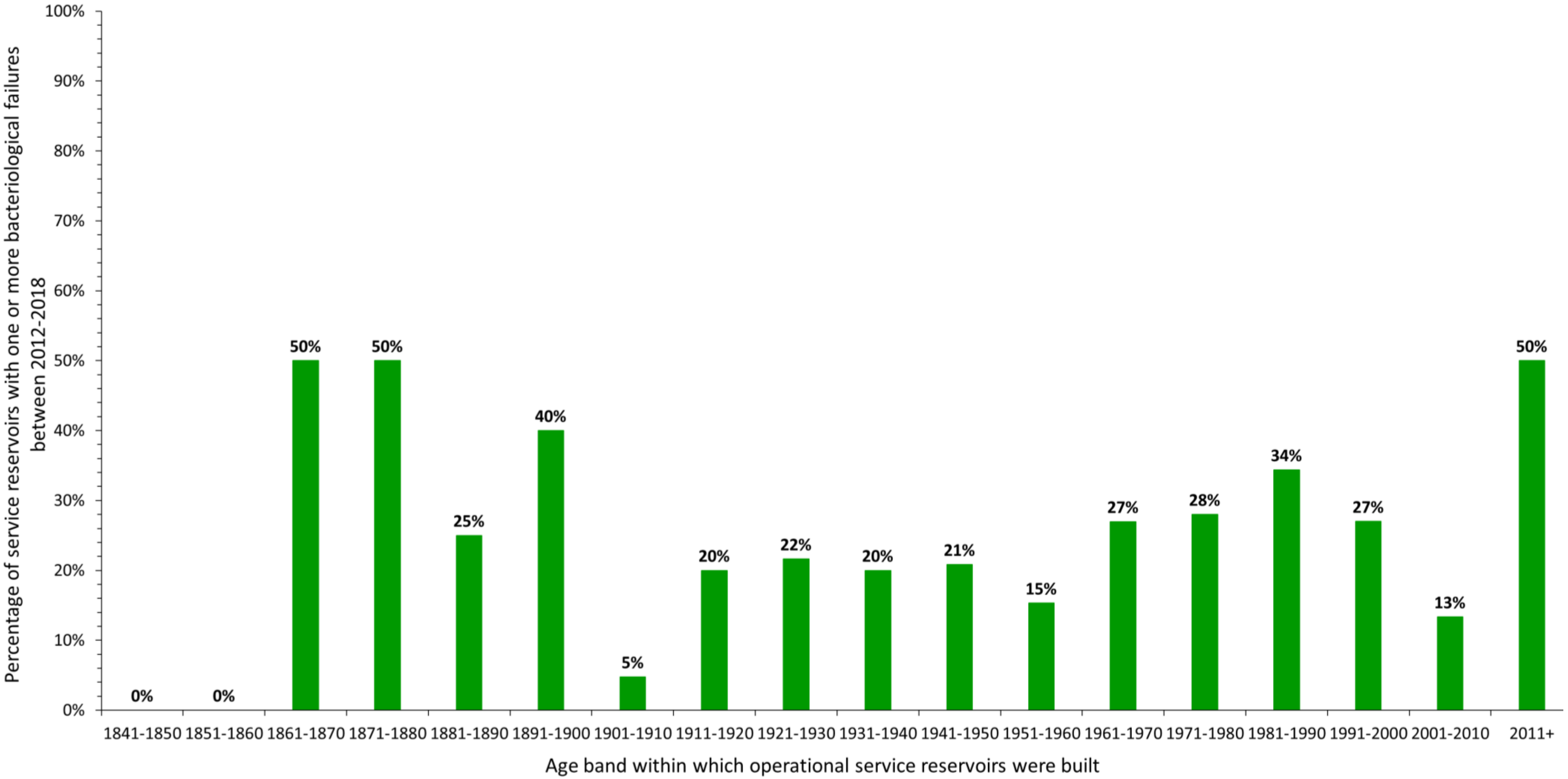

Figure 6.2.6 – The percentage of operational service reservoirs with a known construction age that had one or more bacteriological failures at the outlet between 2012-2018 from data collated across three water utilities.

Table 6.2.1 – The number of operational service reservoirs categorised by construction age across three water utilities and the quantity of those service reservoirs that had one or more identified bacteriological failures between 2012 to 2018.

	Number of operational service reservoirs					**No. of service reservoirs with 1≥ bacteriological failures 2012-2018**				
Year built	**Company A**	**Company B (1)**	**Company B (2)**	**Company C**	**Total**	**Company A**	**Company B (1)**	**Company B (2)**	**Company C**	**Total**
1841-1850	NA	NA	NA	2	**2**	NA	NA	NA	0	**0**
1851-1860	NA	1	0	NA	**1**	NA	0	0	NA	**0**
1861-1870	NA	1	0	1	**2**	NA	1	0	0	**1**
1871-1880	2	0	1	1	**4**	0	0	1	1	**2**
1881-1890	2	2	1	3	**8**	0	0	1	1	**2**
1891-1900	3	4	1	2	**10**	1	2	0	1	**4**
1901-1910	11	1	0	9	**21**	0	0	0	1	**1**
1911-1920	3	7	0	5	**15**	0	3	0	0	**3**
1921-1930	11	5	7	14	**37**	1	1	3	3	**8**
1931-1940	22	8	11	19	**60**	3	2	1	6	**12**
1941-1950	23	15	4	54	**96**	0	6	1	13	**20**
1951-1960	99	33	21	154	**307**	11	8	2	26	**47**
1961-1970	79	45	27	179	**330**	11	20	8	50	**89**
1971-1980	31	32	6	106	**175**	5	13	1	30	**49**
1981-1990	16	20	5	87	**128**	3	12	2	27	**44**
1991-2000	11	18	6	128	**163**	1	10	3	30	**44**
2001-2010	3	5	6	46	**60**	1	0	0	7	**8**
2011+	1	1	0	NA	**2**	0	1	0	NA	**1**
Total	**317**	**198**	**96**	**810**		**37**	**79**	**23**	**196**	
No known construction age	5	13	2	654		0	6	2	466	

Results in Figure 6.2.6 suggest that there is no correlation between the duration of time an operational SR (with a known construction age) has been in service and the occurrence of bacteriological failures. It is important to highlight that there were some operational SRs that experienced one or more bacteriological failures between 2012-2018, but as they were without a known construction age, they were not included in the analysis above. For Company C data, the inclusion of these SRs could affect observations made in Figure 6.2.6, as the number of Company C SRs without a known age was 654, out of which 466 had experienced a bacteriological failure between 2012-2018. However, the inclusion of similar data for Company B (both networks) is unlikely to influence above observations as there were only 2 SRs in network 2 and 13 in network 1, out of which 2 and 6 experienced bacteriological failures respectively. Company A had only 5 SRs without a known age, none of which has experienced a bacteriological failure between 2012-2018 (Table 6.2.1).

Also of interest is that records show only 4% of operational SRs with a known construction age are older than 100 years old and it is likely that many older SRs are no longer in operation or have been rebuilt (Table 6.2.1). Based on acquired data, it appears that there was either an increase in construction of SRs or improved record keeping from the 1950's onwards, predominantly between 1950's to 1970's for most project water utilities (Table 6.2.1). This observation is supported by UKWIR (2019), who highlight that there is a peak in the number of SRs constructed between 1950 and 1980, with nearly 60% of those currently in operation constructed by 1970.

6.3. Assessing Service Reservoir Performance Using Incoming and Outgoing Water Quality Composition and Material Loading

6.3.1. Changes in Water Quality Composition with Transport through Service Reservoirs

6.3.1.1. Introduction

This chapter presents results from analysis of discrete and continuous monitoring data for a variety of regulated and non-regulated water quality parameters collected in project networks (A1, B2, C3, and D4). The aim of this chapter is to achieve **Objectives 3** and **4** of the project.

Discrete iron and manganese data collected in the B2 network presented in this chapter (Figures 6.3.4 and Figure 6.3.7) forms a part of the following publication: **Doronina, A.V.**, Husband, S.P., Boxall, J.B., Speight, V.L. **2020.** The operational value of inlet monitoring at service reservoirs. Urban Water Journal 17(8):35-744.

6.3.1.2. Regulated parameters

6.3.1.2.1. Chlorine

Sampling for chlorine at SR outlets alone does not provide much information about asset performance, however, sampling for chlorine at SR inlet and outlet can potentially be used to determine chlorine decay rate with travel through these assets. To do this, it is important to consider water retention times and thus continuous data would be more suited for this analysis in comparison to discrete data, which is typically sampled once a week at a similar time of day at both the SR inlet and outlet. Discrete sampling makes it impossible to account for the influence of residence times on outgoing chlorine levels, which can be seen in Figure 6.3.13 of this chapter, where paired discrete chlorine data was used to assess whether chlorine can be used as a measure of SR performance. In this figure, there are instances where chlorine residual is higher at the outlet in comparison to the inlet of SRs where no additional chlorine is boosted on site. This could suggest that, in some samples, chlorine measured at the outlet is from a period of higher residual at the inlet in comparison to the same day paired sample that this value is being compared with. For instance, if on Monday, sampled incoming chlorine is 1.5 mg/l and the decay rate is 0.5 mg/l through the SR across a period of a turnover of 24 hours, the value at the outlet should be 1.0 mg/l same time on Tuesday. Because of the nature of discrete sampling, sampling chlorine at the inlet and outlet of the SR on the same day would mean that the collected outlet sample is actually from chlorine dosed the previous day. Therefore, if upon sampling chlorine on Tuesday incoming chlorine was 0.8 mg/l at the inlet but 1.0 mg/l at the outlet, this would not be an accurate representation of chlorine decay through the SR.

Within this project, continuous chlorine data was available at one of the four project SRs (A1). To account for the influence of retention time on chlorine decay rate, the intention was to adjust the data collected at the outlet of the SR in accordance with the average retention time of the asset. However, this data could not be used to determine chlorine decay rate through the SR because both total and free chlorine residual was recording higher at A1 SR outlet in comparison to the inlet (Figure 6.3.1). Initially, it was assumed that there was a fault with the MetriNet monitors as there is no chlorine boosting at the inlet of this SR. However, discrete chlorine sample data also showed that chlorine residual was higher at the SR outlet (Figure 6.3.2). Therefore, a further investigation was conducted to find an explanation for this observation.

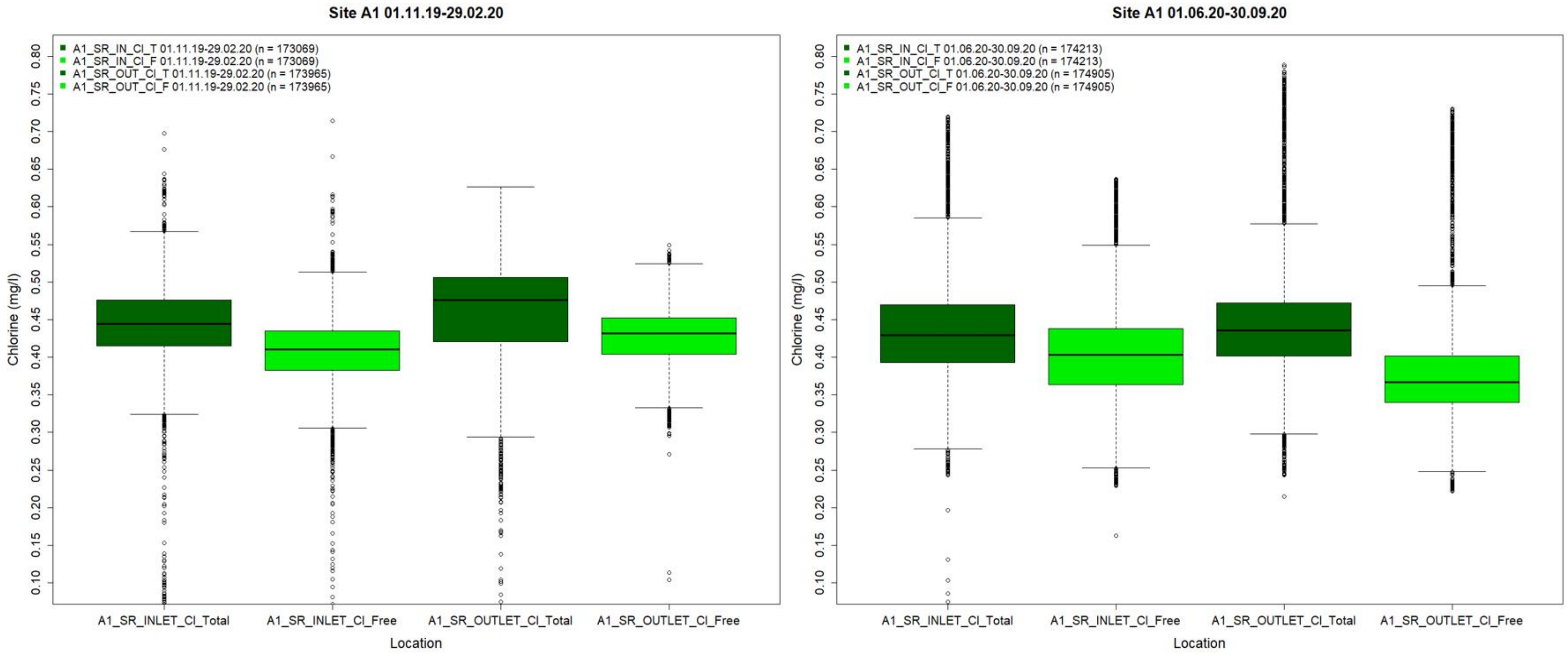

Figure 6.3.1 - **Continuous (MetriNet) total and free chlorine concentrations at the inlet and outlet of the A1 SR across 01.11.19 to 29.02.20 and 01.06.20 to 30.09.20.**

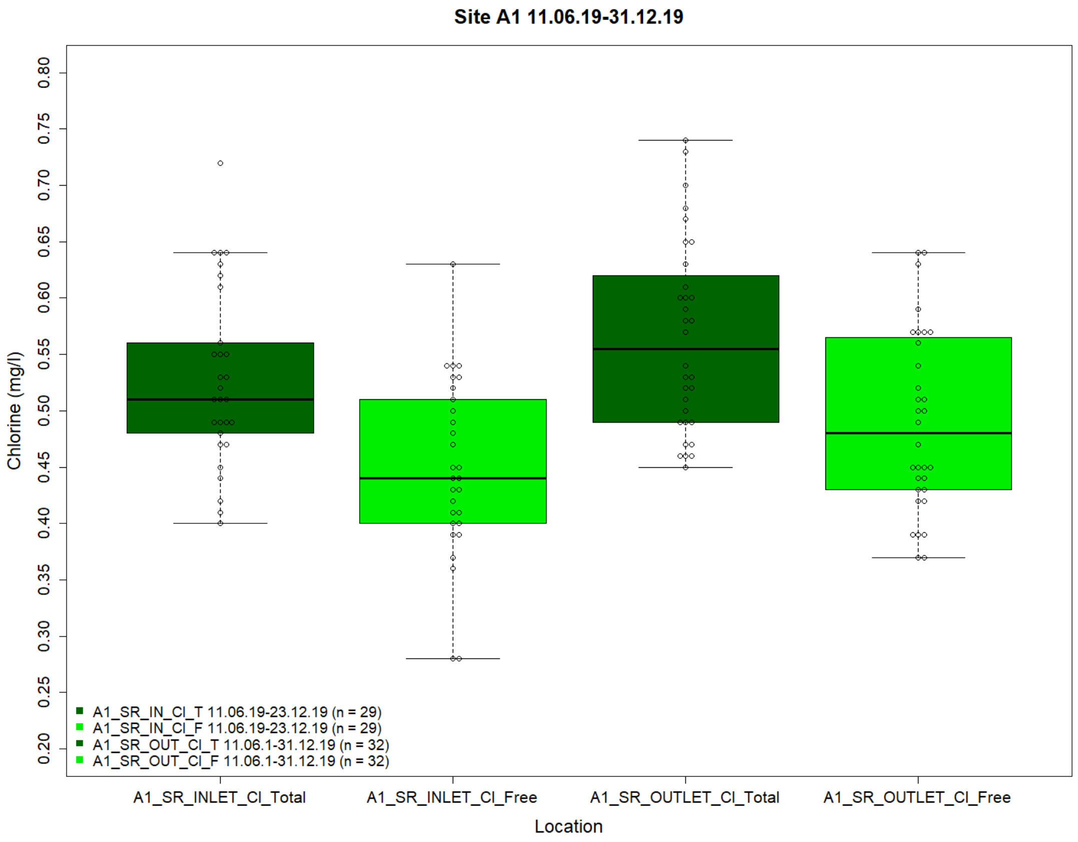

Figure 6.3.2 - Discrete total and free chlorine concentrations at the A1 SR across 11.06.19 to 31.12.19. Average chlorine residual at the supplying WTW during this time: 0.67 mg/l (total) and 0.57 mg/l (free).

The configuration of the A1 SR is such that the inlet and outlet pipes are located on opposing sides of the SR (Chapter 5: Site Details – Figure 5.3). However, sample collection points for both the SR inlet and outlet are located on the same side of the SR. A 15 mm copper inlet sample line taps off the inlet trunk main and runs for 11 m to the discrete inlet sample tap and 7 m to the inlet continuous online MetriNet monitor. It was calculated that it takes approximately 6 minutes for water to travel from the inlet trunk main to the MetriNet monitor and approximately 9 minutes to the inlet sample tap. The suggestion is that there is greater chlorine decay with transport through the small diameter sample line in comparison to transport through the SR. Firstly, the velocity in the sample line will be low (200-250 ml/m), with low turnover rates, which can result in stagnant conditions and longer contact times between water and the interior surface of the sample line, which can lead to the depletion of disinfectant residual (Kerneis et al., 1995; Kirmeyer et al., 1999). Secondly, the inlet sample line is located inside a closed building (Chapter 5: Site Details – Figure 5.3), where temperatures are likely to be higher than the ambient air temperature outside. Additionally, the smaller volume of water in the sample line will require less energy to heat than the water travelling through the SR. At higher temperatures, disinfection residual decreases (García-Ávila et al., 2020). The difference between continuous inlet and outlet chlorine data is less prominent than discrete inlet and outlet chlorine data

(Table 6.3.1), which could be explained by the shorter amount of time it takes for water to travel to the MetriNet monitor in comparison to the discrete sampling tap.

It would not have been possible to observe the influence of the length of the sample line on chlorine decay and sample validity without both inlet and outlet chlorine monitoring at the SR.

Table 6.3.1 - **Average differences between discrete and continuous total and free chlorine data between A1 SR inlet and outlet.**

Data	Chlorine type	Average chlorine (mg/l)		Difference between SR inlet and outlet chlorine (mg/l)
		SR inlet	SR outlet	
Discrete	Total	0.53	0.56	+ 0.03
	Free	0.45	0.49	+ 0.04
Continuous 01.11.19-29.02.20	Total	0.45	0.47	+ 0.02
	Free	0.41	0.43	+ 0.02
Continuous 01.06.20-30.09.20	Total	0.43	0.44	+ 0.01
	Free	0.40	0.37	- 0.03

SR chlorine data can also be used to determine the effectiveness of a SR clean by measuring the amount of chlorine decay through the SR pre and post clean. For example, C3 SR was inspected and cleaned in June/July 2017. Figure 6.3.3 below shows total and free chlorine levels at the SR outlet pre and post clean. It appears that SR outlet chlorine increased after the clean, which could suggest that cleaning the SR decreased the rate of chlorine decay with travel through it, potentially in relation to the removal of material accumulated within. A Wilcoxon-Mann-Whitney U test demonstrated that this observed difference in chlorine residual pre and post clean was statistically significant; total chlorine (W = 141, p-value = 0.00004) and free chlorine (W = 199, p-value = 0.0016).

Without inlet chlorine data, it is difficult to establish whether the increase in outlet chlorine residual is related directly to the clean or is influenced by a change in chlorine residual at the inlet. However, chlorine is dosed at the inlet of C3 SR, and as there was no known change in dosing regime during the time of data collection, there is confidence that the higher outlet residual is related to the SR clean. Undoubtedly, having both inlet and outlet chlorine data would give greater confidence in the determination of the effectiveness of a SR clean.

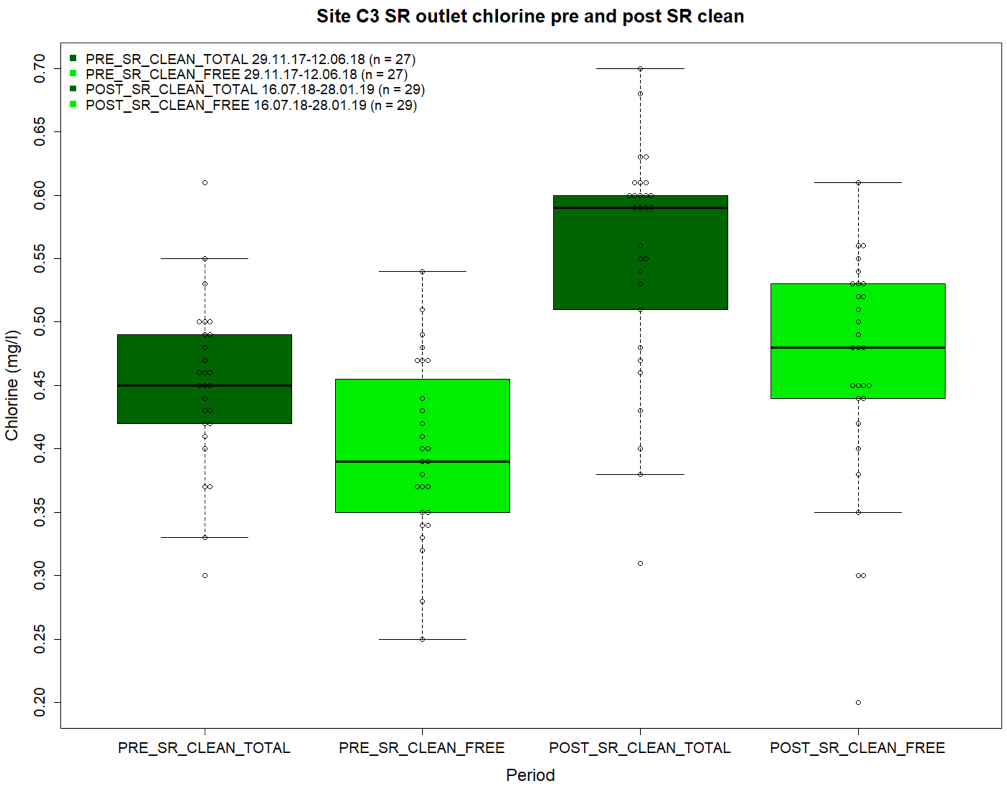

Figure 6.3.3 – **Total and free chlorine data at the outlet of C3 SR pre and post its clean (20.06.18 – 11.07.18).**

6.3.1.2.2. Bacteriological indicators

Bacteriological indicator samples for parameters like coliforms, colony counts, and *Escherichia coli* at SRs can capture bacteriological events but, in this project, did not show trends in microbiological prevalence over time. However, the addition of sampling for bacteriological indicators at the inlet of SRs could help to determine whether the SR was the cause of an event, which could in turn reduce investigation costs.

6.3.1.3. Non-regulated parameters

6.3.1.3.1. Iron

Iron is not currently a regulated parameter at SRs in the UK. Results from sampling for iron at both the SR inlet and outlet have shown that this data can be used to obtain information on SR and upstream network performance.

For example, Figure 6.3.4 shows discrete total iron data collected across 2018 to 2020 in the B2 DWDS. Monitoring iron only at WTW and SR outlet could lead to the assumption that the B2 SR is the cause of water quality deterioration as it is contributing elevated iron concentrations into the downstream network. However, with the addition of inlet monitoring, it can be observed that the deterioration is also occurring upstream of the SR, post treatment, thus identifying the supplying trunk mains (one steel and one ductile iron) as the initial source of elevated iron in the network. This information could justify network maintenance programmes, such as trunk main conditioning and/or SR clean, and monitoring iron levels pre and post could be used to evaluate the benefit of the interventions and inform future maintenance strategies or scheduling.

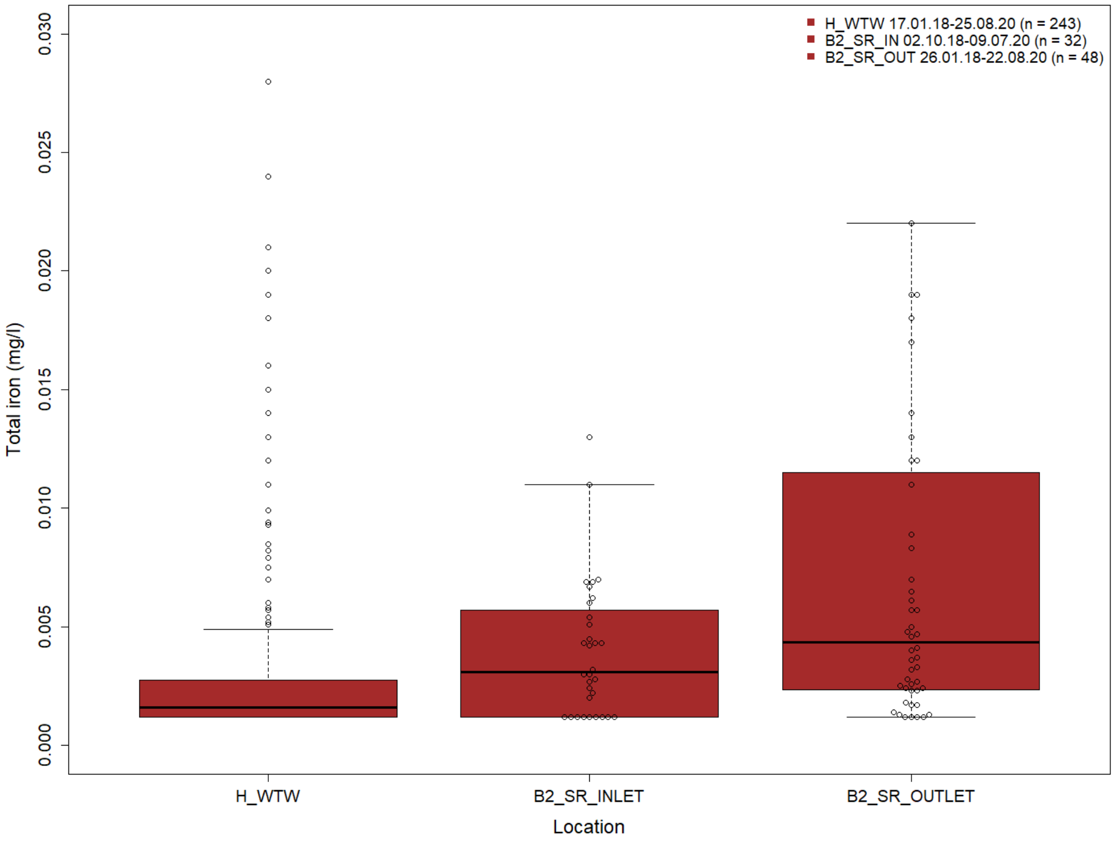

Figure 6.3.4 – Discrete total iron data across the B2 DWDS 17.01.18 to 25.08.20. Figure adapted from Doronina et al. (2020).

It is important to highlight that some of the data presented in Figure 6.3.4 did not always overlap in time. Nevertheless, the collected iron data provides an insight into upstream network and SR performance, which is currently not possible to observe without iron sampling at SRs. Furthermore, when splitting the data up into two overlapping and comparable time periods (see Appendix 3, Figure p), the same observation can be made as when the two time periods are combined in one plot. In the first time period, iron concentration at the WTW outlet is lower than at the SR inlet, and in the second time period iron is lower at SR inlet in comparison to SR outlet.

Iron was also sampled in the C3 DWDS and provides another example of how monitoring for iron at SRs is valuable in obtaining information on network performance. It can be seen in Figure 6.3.5 that iron levels increase between WTW outlet and C3 SR inlet, to the extent that by the time water reaches the SR, it frequently breaches PCV for iron. C3 SR is fed by a 50 km trunk main, which is unlined cast iron for 28 km of those and, like with the B2 site, the trunk main is likely contributing iron into the downstream network. Most of this iron appears to travel through the SR, posing a risk to the safety of the water supply in the downstream WQZ. Without iron monitoring at this SR, it would be impossible to make the above observations. Since this and other project data was shared with Company C, a plan for the proactive management of the C3 DWDS in the form of conditioning of the supplying trunk main has been put into action and a routine monitoring programme for iron implemented.

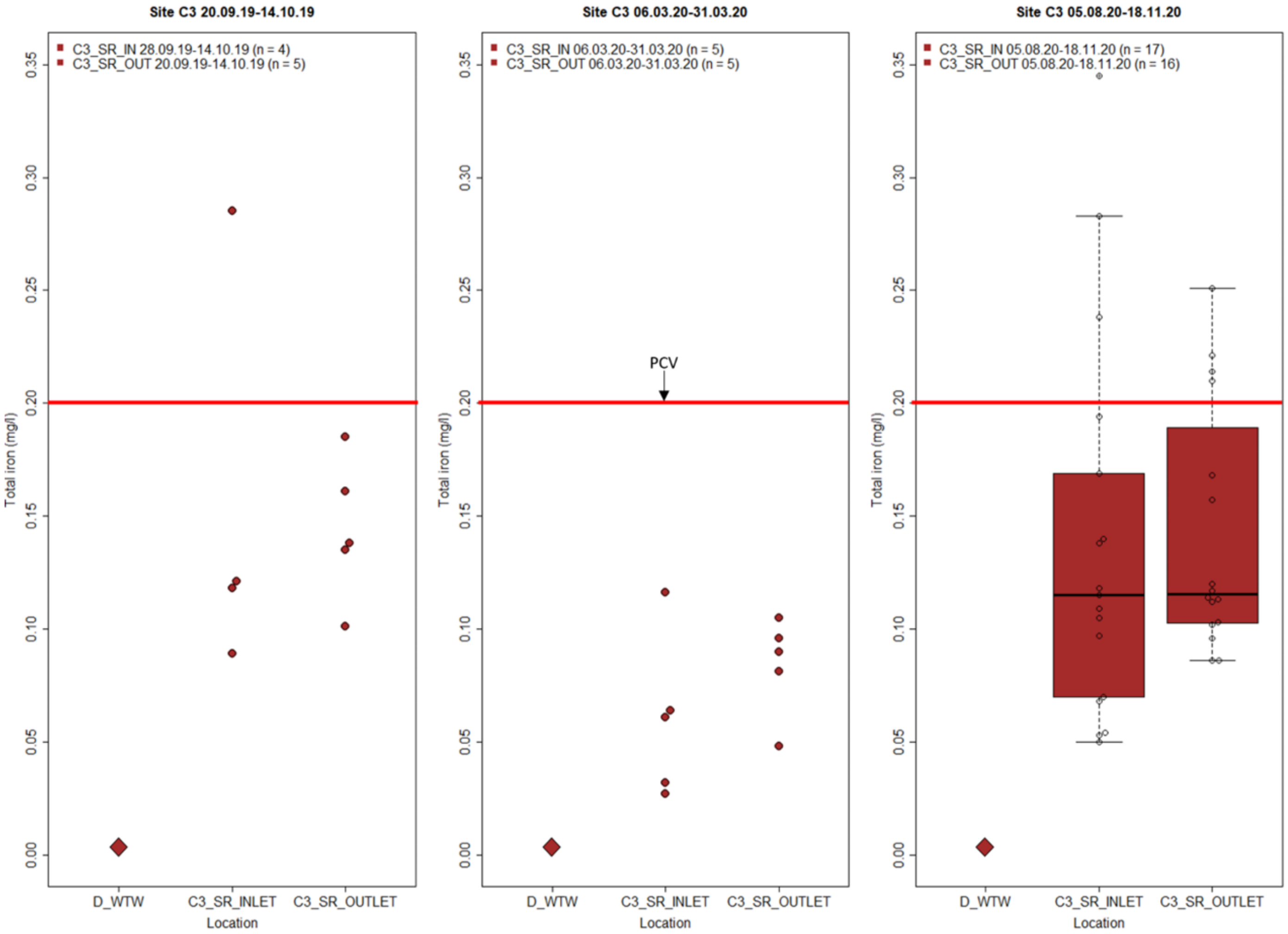

Figure 6.3.5 – Discrete total iron concentrations (mg/l) at the WTW and SR of the C3 DWDS across three separate time periods. All values at the WTW were below the minimum detection limit of 0.007 mg/l and are represented here as limit of detection/2 (0.0035 mg/l). The red line at the 0.2 mg/l mark indicates the UK prescribed concentration value (PCV) for iron in drinking water.

Another way iron was monitored at a project SR was via automatic sampling. Two 24-hour automatic sampling campaigns were conducted at C3 SR, one in July 2019 and one in February 2020 (Figure 6.3.6).

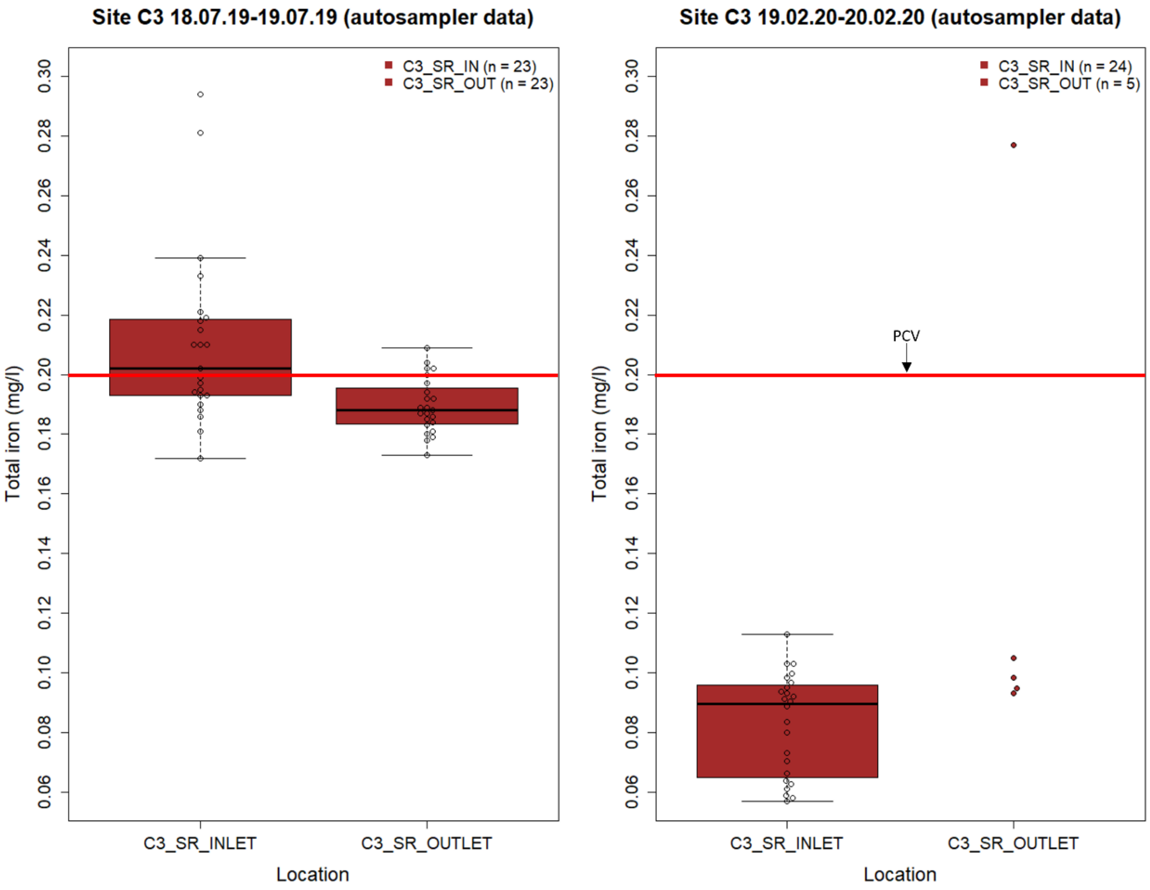

Figure 6.3.6 – Discrete total iron concentrations (mg/l) at the inlet and outlet of the C3 SR from two 24-hour automatic sampling campaigns, one in July 2019 and one in February 2020. The red line at the 0.2 mg/l mark indicates the UK prescribed concentration value (PCV) for iron in drinking water.

Results show that, as with discrete iron sampling at this SR, iron levels breach PCV in July 2019. Automatic sampling campaigns have also captured a potential effect of seasonal temperature changes on iron levels at the SR whereby iron levels were higher at both the SR inlet and outlet in July (a warm weather month) in comparison to February (a cold weather month). This observation is supported by findings in Chapter 6.4., section 6.4.4, on the influence of seasonal changes in temperature on SR performance, where iron levels were observed to be higher at the inlet and outlet of all project SRs in warmer weather (Tables 6.4.3 and 6.4.4).

6.3.1.3.2. Manganese

Like iron, manganese is also not a regulated parameter at SRs in the UK. Results from discrete manganese sampling conducted at SRs in this project have been valuable in demonstrating how manganese changes with travel through SRs and how this behaviour varies between different systems and seasons, providing useful information on SR and network performance.

For example, manganese data collected in the B2 DWDS shows that the supplying WTW is contributing manganese into the downstream network, which then appears to travel through the network without much settling, with the SR having limited influence on manganese levels (Figure 6.3.7). This information could potentially be used to support the need for the improvement of manganese removal processes at the supplying WTW, which is in the process of happening in this specific system.

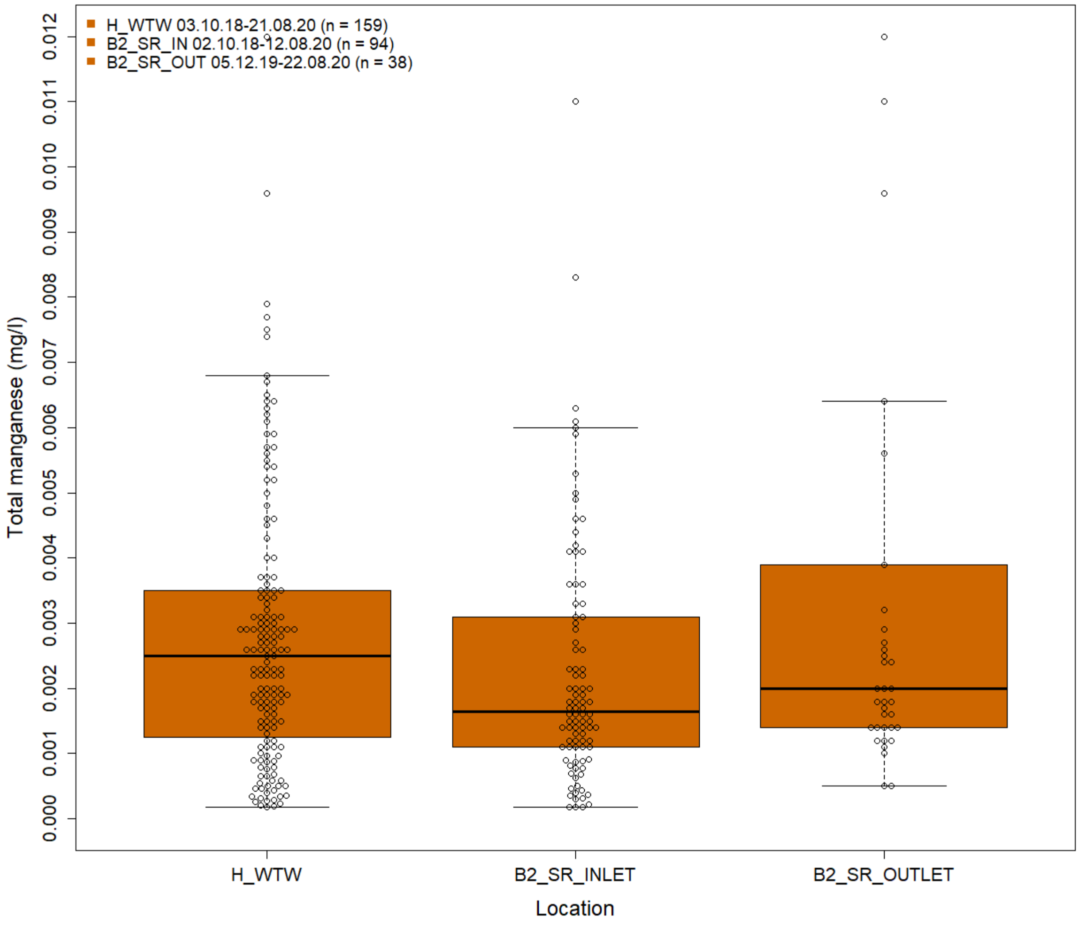

Figure 6.3.7 – Discrete total manganese data across the B2 DWDS 02.10.18 to 22.08.20. Figure adapted from Doronina et al. (2020).

At the C3 SR, results from the two automatic sampling campaigns show that, like with iron samples, there is a potential effect of seasonal temperature changes on manganese levels at the SR, with higher concentrations at both the inlet and outlet in July (a warm weather month) in comparison to February (a cold weather month) (Figure 6.3.8). This observation is also supported by findings in Chapter 6.4., section 6.4.4 on the influence of seasonal changes in temperature on SR performance, which show that manganese levels were higher at the inlet and outlet of all SRs in warmer weather (Tables 6.4.3 and 6.4.4).

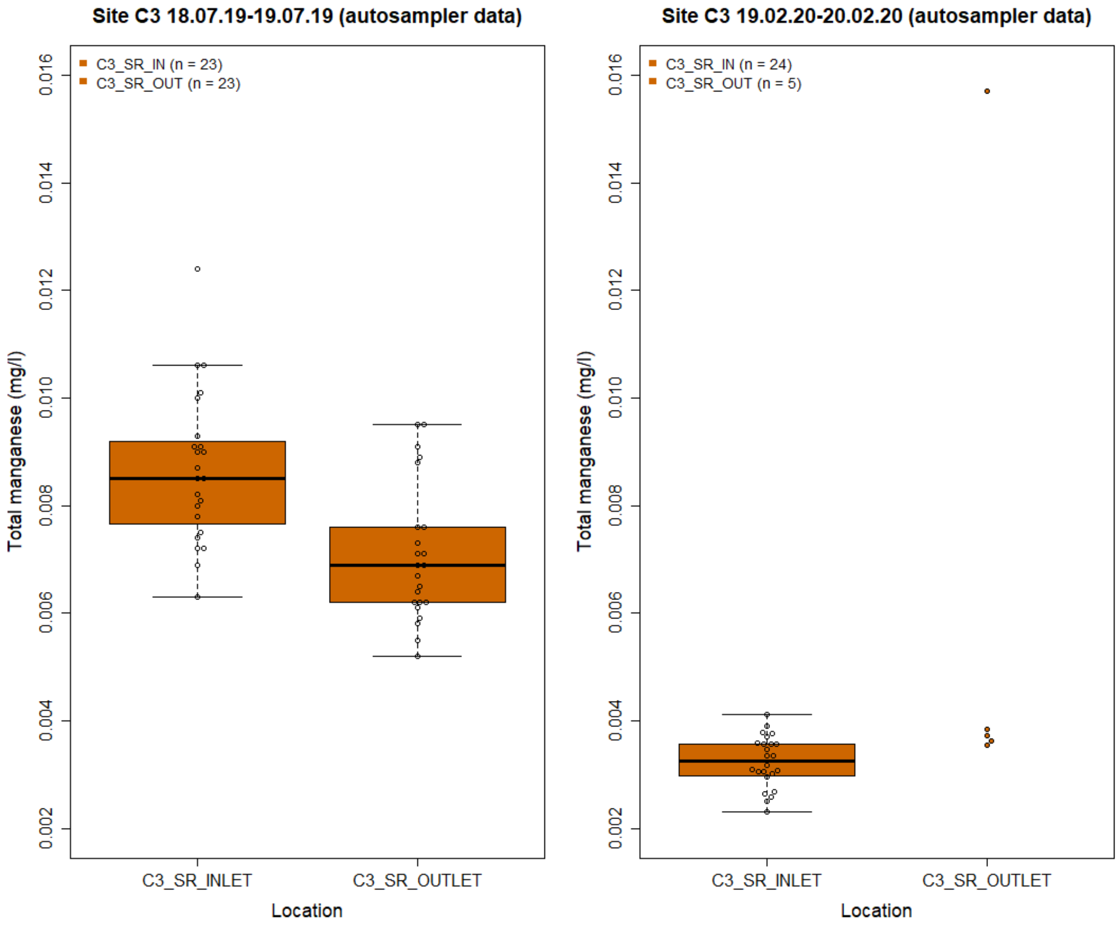

Figure 6.3.8 – Discrete total manganese concentrations (mg/l) at the inlet and outlet of the C3 SR from two 24-hour automatic sampling campaigns, one in July 2019 and one in February 2020.

Discrete manganese sampling was carried out throughout the duration of a clean at the D4 SR, enabling the investigation on whether cleaning this SR made a difference to its performance with respect to outlet manganese levels. Results in Figure 6.3.9 show that pre clean manganese levels were higher at the SR outlet in comparison to the SR inlet. During and post clean, manganese levels became lower at the SR outlet in comparison to SR inlet, irrespective of the concentration of incoming manganese. This switch in source to sink behaviour of the SR suggests that cleaning may have potentially improved SR performance with respect to manganese.

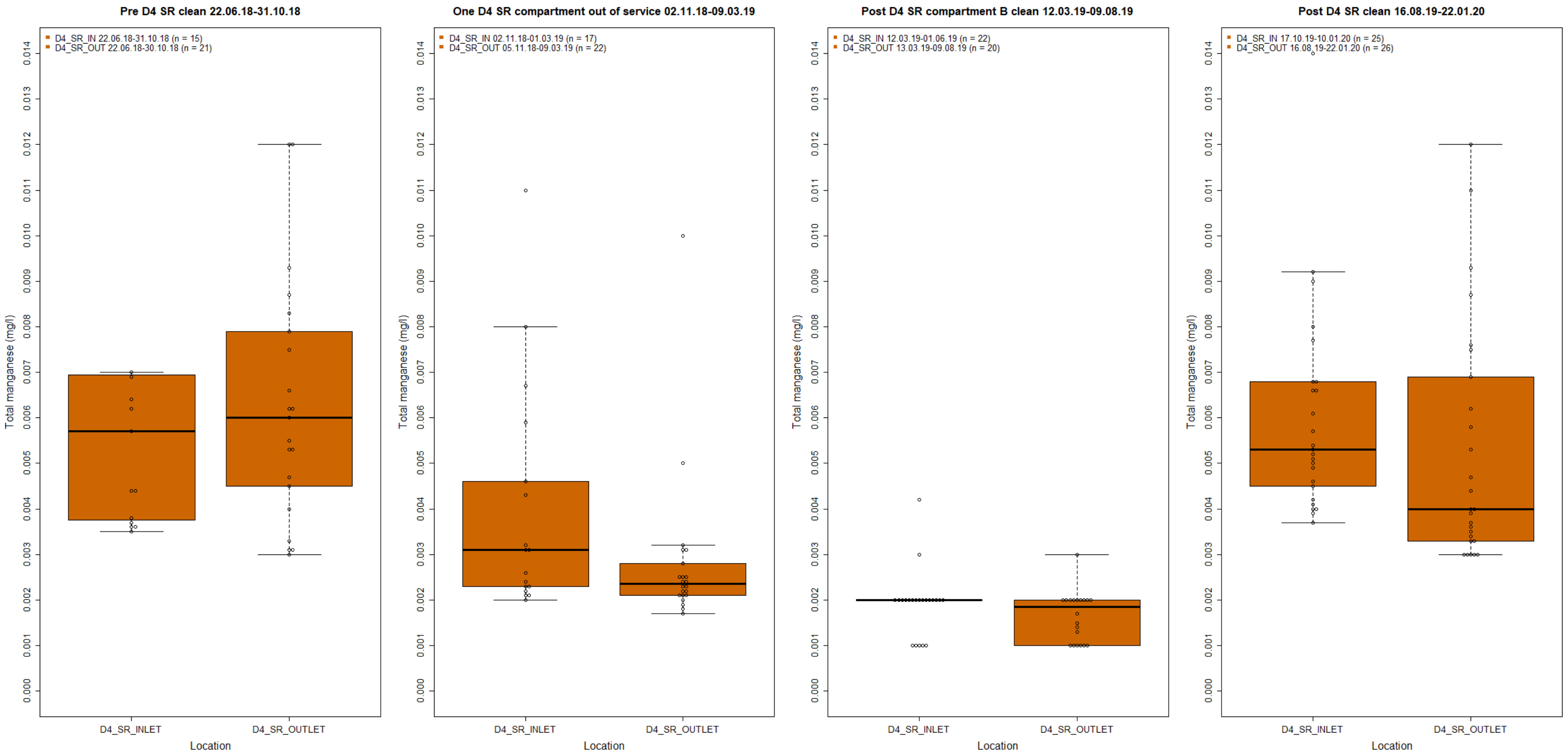

Figure 6.3.9 - **Discrete total manganese concentrations (mg/l) at the D4 SR across four time periods; pre D4 SR clean, with one compartment out of service, post D4 compartment B clean, and post entire D4 SR clean.**

6.3.1.3.3. Turbidity

Monitoring turbidity at the inlet and outlet of project SRs has arguably been the most valuable parameter in terms of the information it has provided on SR and upstream asset performance. For example, discrete turbidity sampling in the A1 DWDS has shown that turbidity increases post WTW and pre SR inlet, and decreases again with travel through the SR (Figure 6.3.10). Without inlet monitoring, it could be presumed that turbidity is not changing with travel between WTW and SR outlet, when in fact the SR is acting as a beneficial network stage by sinking suspended material. A1 DWDS is a groundwater source fed system, with low initial and background turbidity levels, yet results demonstrate that even under these conditions water quality deterioration occurs in the network.

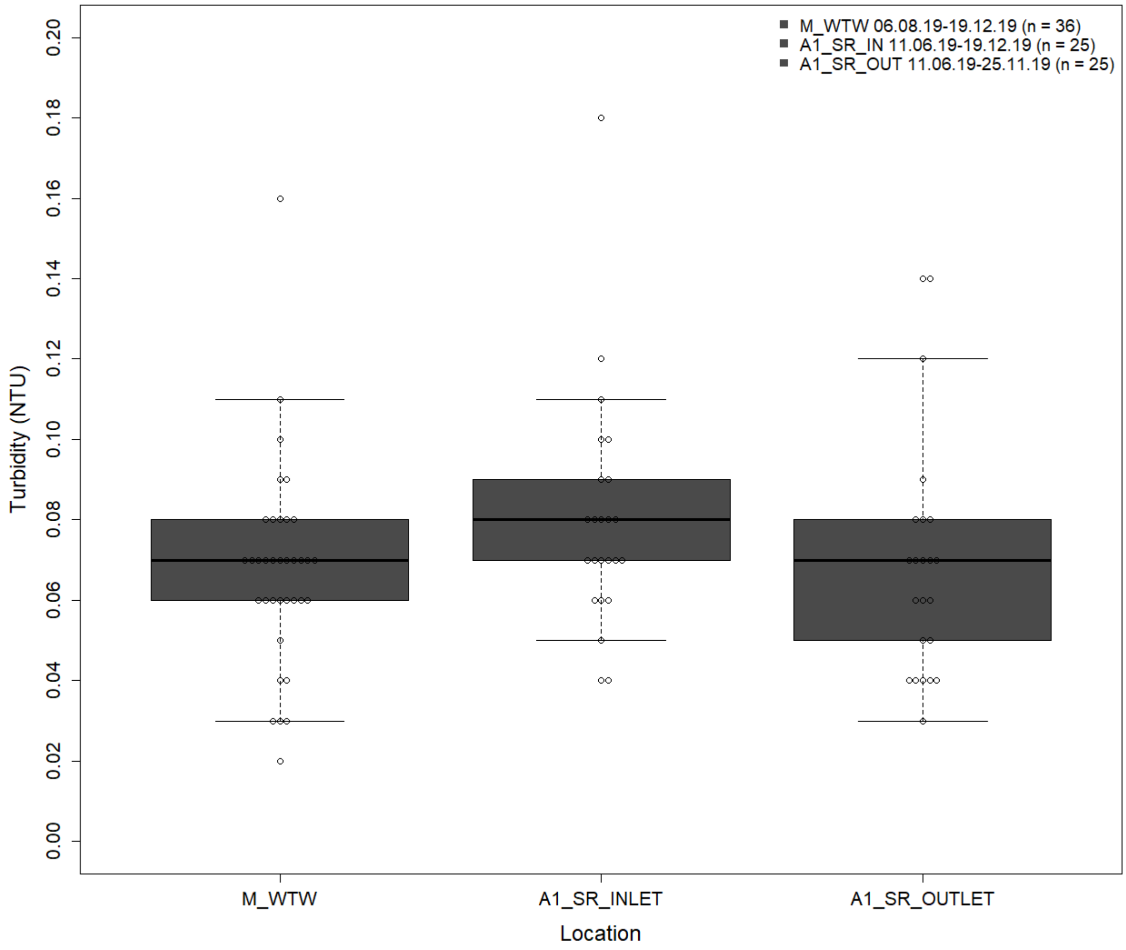

Figure 6.3.10 – Discrete turbidity (NTU) data in the A1 DWDS 11.06.19 to 19.12.19.

In the D4 DWDS, continuous turbidity sampling helped to reveal ineffective operation of an upstream asset. During monitoring at the D4 SR, it was observed that there were regular increases in the concentration of incoming turbidity (Figure 6.3.11).

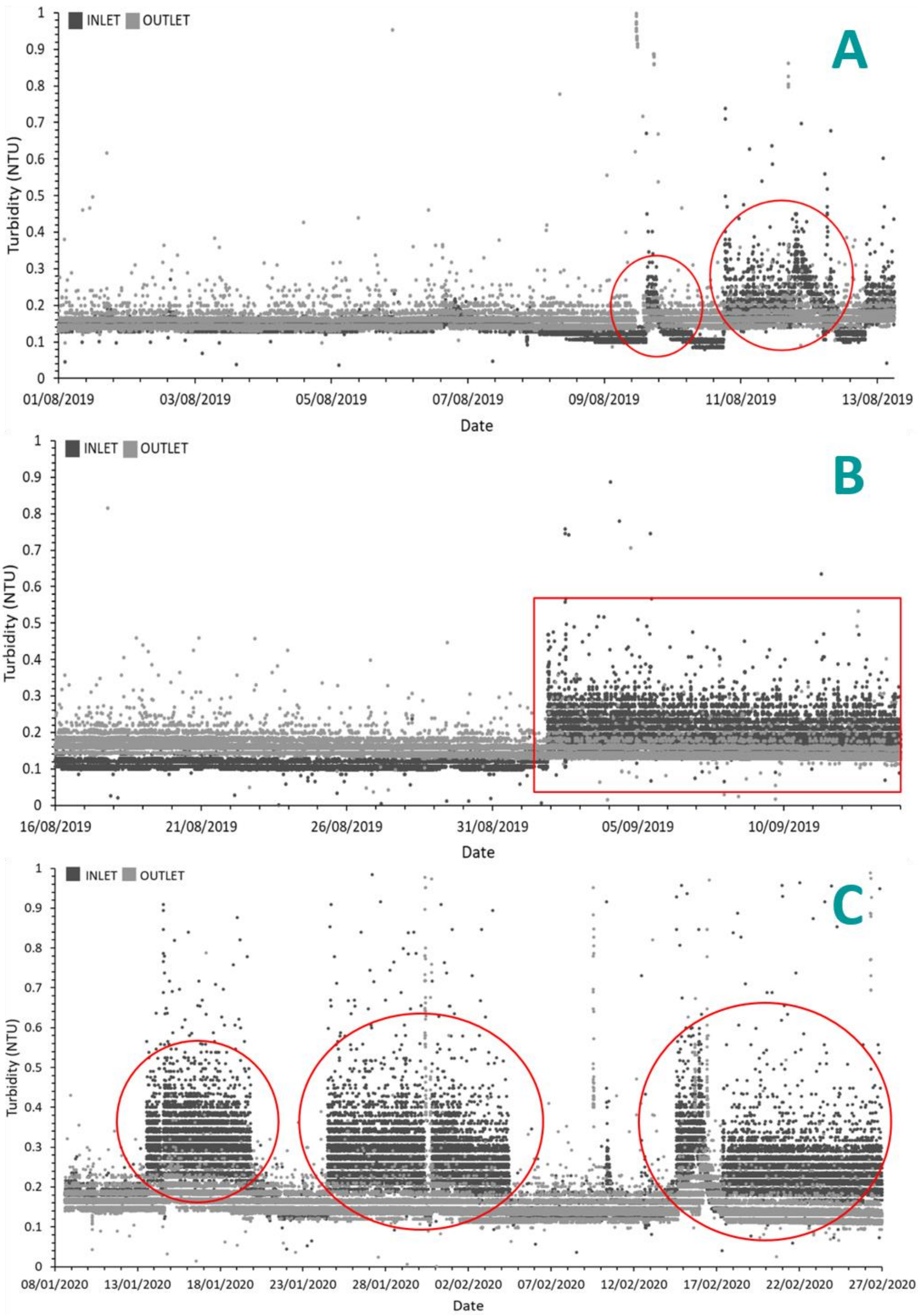

Figure 6.3.11 – Continuous (NephNet) turbidity (NTU) values at the inlet and outlet of D4 SR across (A) two weeks in August 2019, (B) mid-August to mid-September 2019, and (C) January and February 2020. Data circled in red highlights time periods where there was a sudden step change in incoming turbidity.

These spikes in turbidity were not related to inlet flow and, upon further investigation, it was established that this change in water quality was likely related to excess material coming into the SR from the WTW, specifically from excess lime dosing. More data is needed to confirm this assumption, but from the data that is available, the conclusions are that:

- Incoming material is unlikely to be related to faulty filter flushing or backwash at the WTW as this would be reflected in an increase in flow cytometry cell counts at the D4 SR inlet during periods of increased inlet turbidity, which, based on available flow cytometry data is not the case.
- No other parameters at the inlet of the D4 SR showed the same pattern as inlet turbidity. Therefore, it is unlikely that this incoming material is related to carry-over of other materials, such as metals, from the WTW.
- There is evidence of lime build up in the trunk main supplying the D4 SR:
    - In 2014, a D4 SR inspection report stated that there were “observable lime deposits on SR walls”.
    - In 2018, during installation of the UV dosing plant at the inlet of the D4 SR, it was stated that the “trunk main needed to be flushed because it was filled with lime”.
- Company D project staff advised me that CD_WTW is known to have issues with pH adjustment, which is corrected using lime (Chapter 5: Site Details – Figure 5.23). A correlation analysis was conducted between WTW outlet pH and SR inlet turbidity to see whether there is a relationship between the two parameters, especially as CD_WTW is located just 0.2 km away from D4 SR inlet. Results show that when the pH is higher at the WTW outlet, turbidity at the inlet of the SR is also higher, which may potentially reflect lime dosing adjustment (lime increases pH). This observation was supported by Spearman’s rank order correlation analysis, which showed that there was a very strong significant positive correlation between the two parameters ($r = 0.467$, $df = 6809$, p-value = 2.2^{e-16}).

Without continuous inlet monitoring at the inlet of D4 SR, it would not have been possible to observe that the supplying WTW is overdosing lime, especially as the SR is acting as a sink of this excess material and turbidity data at the SR outlet does not reflect the increases in turbidity at the inlet (Figure 6.3.11).

In this project, continuous turbidity data has also enabled the development of a quantifiable way to measure SR performance over time, which is described below in section 6.3.2.2. of this chapter.

6.3.1.3.4. Relationship between turbidity and other parameters in the DWDS

Turbidity is often associated with the presence of other parameters, like iron and manganese. Using data collected in this project, it was investigated whether turbidity can be used as a surrogate measure for other parameters at SRs. Table 6.3.2 below presents results from correlation analysis between:

- Discrete turbidity and iron (Fe) at the inlet and outlet of A1, B2, C3, and D4 SRs.
- Discrete turbidity and manganese (Mn) at the inlet and outlet of B2, C3, and D4 SRs.
- Discrete turbidity and total cell count at the inlet and outlet of B2 and C3 SRs.
- Continuous SR outlet turbidity and total cell count at the C3 SR.
- Discrete turbidity and intact cell count at the inlet and outlet of B2 and C3 SRs.
- Continuous SR outlet turbidity and intact cell count at the C3 SR.

The full version of Table 6.3.2, which includes descriptive statistics, can be found in Appendix 3, Table e.

Table 6.3.2 – Results from correlation analyses between turbidity and other parameters (iron, manganese, and cell count) at the inlet and outlet of project SRs (A1, B2, C3, and D4). Cells in green highlight statistically significant relationships.

	SR INLET			
Site name	NTU vs Mn	NTU vs Fe	NTU vs TCC	NTU vs ICC
A1	NA	r = 0.34, p = 0.0997	NA	NA
B2	r = 0.62, p = 0.0016	r = 0.56, p = 0.0053	r = -0.05, p = 0.8243	r = -0.21, p = 0.3295
C3	r = 0.73, p = 3.206^{e-11}	r = 0.77, p = 2.315^{e-13}	r = 0.58, p = 0.0300	r = 0.64, p = 0.0133
D4	r = 0.05, p = 0.7936	r = -0.03, p = 0.9489	NA	NA

	SR OUTLET			
Site name	NTU vs Mn	NTU vs Fe	NTU vs TCC	NTU vs ICC
A1	NA	r = 0.31, p = 0.1270	NA	NA
B2	r = 0.71, p = 0.0032	r = 0.67, p = 0.0005	r = -0.14, p = 0.4713	r = -0.17, p = 0.3853
C3	r = 0.65, p = 1.259^{e-06}	r = 0.41, p = 0.0049	r = -0.18, p = 0.4837 (disc.)/r = -0.06, p = 0.4284 (cont.)	r = 0.34, p = 0.1874
D4	r = -0.19, p = 0.3010	r = 0.22, p = 0.4580	r = -0.12, p = 0.6938	r = 0.51, p = 0.2964

Results show that there was a strong positive correlation between turbidity and iron and turbidity and manganese at both the inlet and outlet of B2 and C3 SRs. There was also a positive correlation between turbidity and cell count (both total and intact) at the inlet of C3 SR.

Results suggest that in some instances turbidity can be used as an indicator for the presence of iron, manganese, and high cell count, but this relationship is dependent on other factors as significance was seen at some SRs, but not others. The two project SRs (B2 and C3) where a significant relationship was observed between turbidity and metals differ from the other sites in that they are both fed by steel and cast/ductile iron trunk mains, whereas the other two SRs (A1 and D4) are fed by plastic or cement lined trunk mains. Based on this, it is proposed that trunk main material could be a key factor in influencing whether turbidity can be used as a surrogate measure for iron and manganese, as long as there is evidence to show that these metals are present in the turbidity in that part of the system. Significance of the relationship between turbidity and metals was much stronger at C3 SR in comparison to B2 SR and C3 was the only SR with a significant relationship for cell count at the inlet. It is likely that there was no significant relationship between turbidity and cell count at the outlet of C3 SR because chlorine is dosed at the inlet, which could be significantly reducing cell count at the outlet. Average manganese, iron, and cell count was higher at both the inlet and outlet of the C3 SR (see Table e in Appendix 3), which is likely to be a contributing factor to the stronger significance of the relationship between turbidity with metals and cells at this SR. The reason for higher concentrations of metals and cells at C3 SR in comparison to B2 SR may be to do with the length of their supplying trunk mains, which is 7.2 km for B2 SR and a longer 50 km for C3 SR. It can therefore be inferred that both the material and the length of the supplying main could influence whether and to what extent turbidity can be used as a surrogate measure for metals and cell count, in that a significant relationship between these parameters is more likely to be seen in steel/iron and longer mains.

6.3.1.3.5. Flow cytometry (cell count)

Flow cytometry data has been a valuable bacteriological measure of SR performance in this research. Results have shown that, throughout the course of project sampling, all SRs where flow cytometry monitoring was conducted (B2, C3, and D4) acted as sinks of cell counts (total and intact), making them a beneficial treatment stage in the DWDS. The main example of this can be seen in the B2 DWDS (Figure 6.3.12).

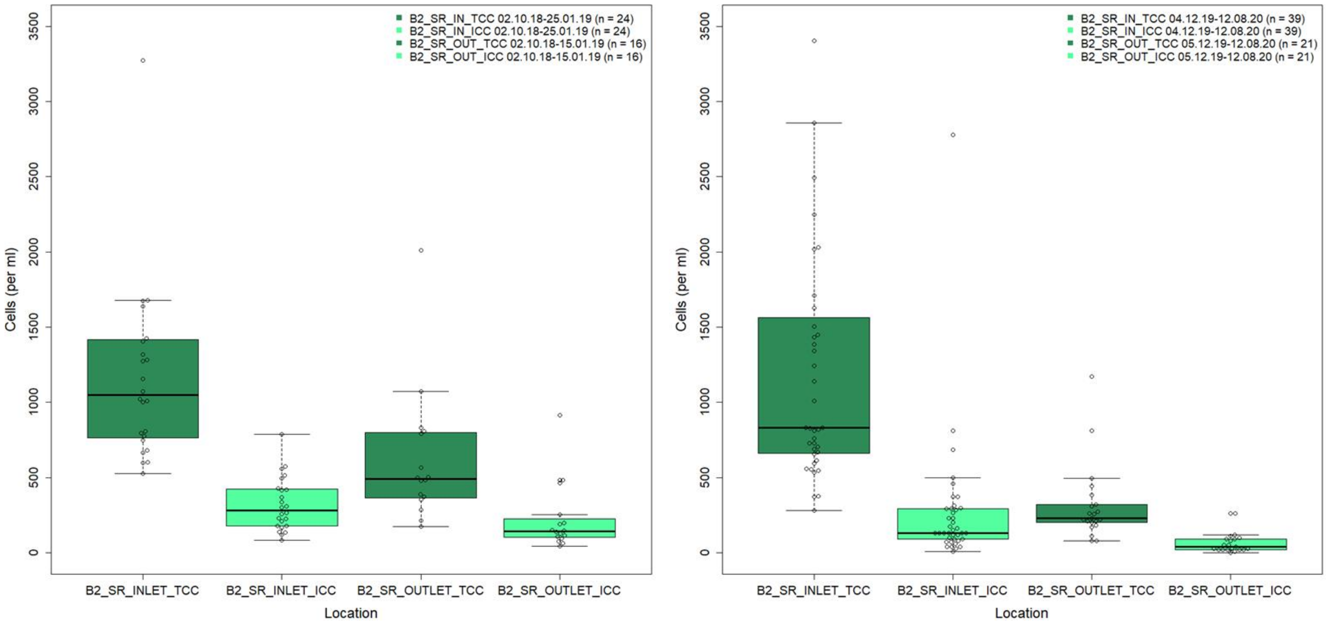

Figure 6.3.12 – **Discrete total and intact cell counts (per ml) at B2 SR across two time periods, 02.10.18 to 15.01.19 and 04.12.19 to 12.08.20.**

Chlorine is dosed at the inlet of C3 SR, which likely has a significant effect on cell count decrease with travel through the SR, making it impossible to distinguish the influence the SR has on this decrease independent of chlorine boosting. Even though D4 SR appears to be a sink for total and intact cells, cell count numbers at this SR are extremely low in comparison to those in B2 and C3 systems. For this reason, and the chlorine dosing at C3 SR, flow cytometry data at both C3 and D4 SRs is not included here, but can be found in Chapter 6.4.2., Figure 6.4.3 (C3 SR) and Appendix 3, Figure q (D4 SR).

6.3.1.4. Summary

Results have shown that there is value in sampling for both regulated parameters (chlorine and bacteriological indicators) and non-regulated parameters (specifically iron, manganese, turbidity, and flow cytometry) at *both* the inlet and outlet of SRs. Carrying out such sampling can provide information not only on the performance of SRs and how it can change with operational interventions (e.g., SR cleans), but on the performance of the upstream network. Results also showed that in single supply source systems (like the ones in this project), pH, conductivity, temperature, and aluminium were good for completeness of the dataset, but were not as informative on changes in SR performance as the other mentioned parameters. Therefore, data for these parameters is not reported here, but descriptive summary statistics of this data can be found in Table g, Appendix 5.

6.3.2. Assessing and Quantifying Service Reservoir Performance; Sink or Source of Material?

This section is divided into two parts. The first, presents results from the assessment of SR performance using mass balance of discrete water quality sample data, and the other presents results from a metric developed to assess and quantify SR performance using continuous turbidity monitoring data, applied to three project SRs (A1, C3, and D4). For full details on both the discrete data method and continuous data model and metric, please refer to Chapter 4: Methodology and Methods.

6.3.2.1. Discrete data

In this section, discrete water quality sample data collected at the inlet and outlet of project SRs is used to describe SR performance in terms of the percentage difference in parameter value between the inlet and outlet. A negative percentage indicates that the SR is acting as a sink of that parameter and a positive percentage indicates the SR is acting as a source. Except for chlorine, where percentage change closest to 0 is indicative of better performance.

6.3.2.1.1. Chlorine (free)

Figure 6.3.13 presents percentage differences in free chlorine concentrations between the inlet and outlet of B2 (yellow triangles) and D4 (pink squares) SRs across 2018 to 2020.

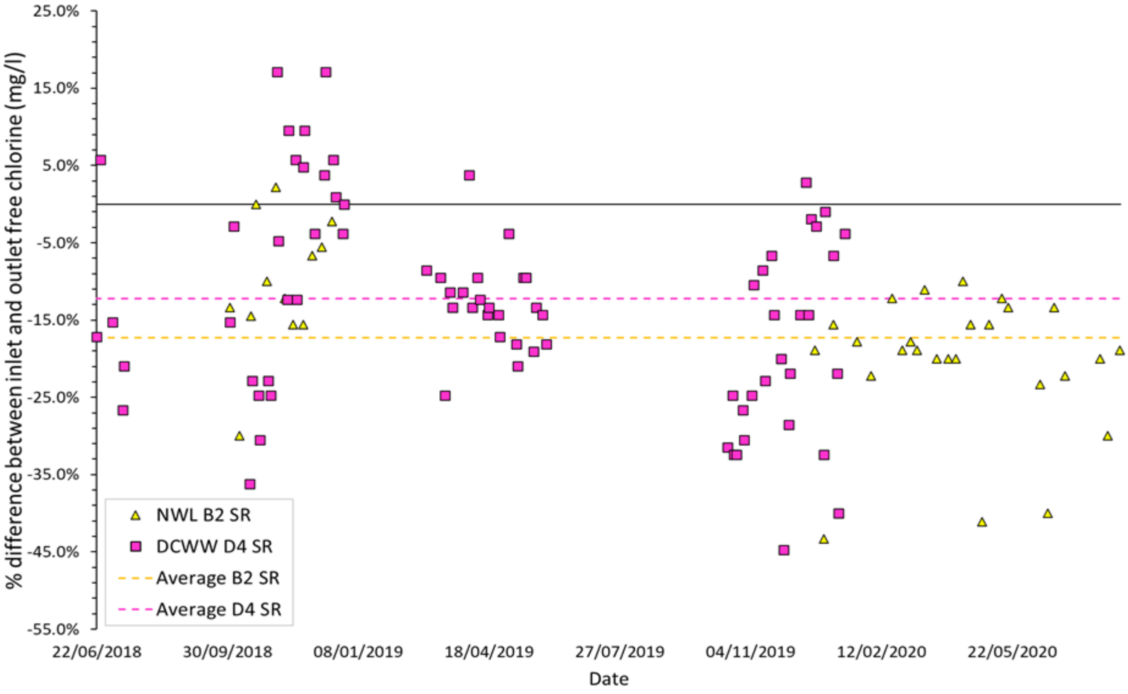

Figure 6.3.13 – Percentage difference in free chlorine (mg/l) between the inlet and outlet of B2 and D4 SRs across 2018 to 2020. The dashed lines represent the average percentage difference across this time.

Although the averages in Figure 6.3.13 indicate that chlorine decays through the two SRs by 12-17%, it is suspect that there are data points showing a percentage increase in free chlorine as there is no additional disinfectant dosing at either B2 or D4 SRs. This phenomenon is likely related to SR residence times, which affect chlorine decay, but which cannot be accounted for with discrete sampling (discussed in more detail in section 6.3.1.2.1.). This suggests that using discrete chlorine data to describe SR performance is unreliable as this type of sampling is unable to accurately capture changes in SR performance over time. It is unlikely that the recorded residual chlorine measurements are incorrect as chlorine samples were collected and measured on site using an accredited chlorine monitor with an accuracy of ±5%, and which is stipulated by regulation to be calibrated and working correctly at the time each sample is analysed (DWI, 2005).

6.3.2.1.2. Flow cytometry total and intact cell count

Figures 6.3.14 and 6.3.15 present percentage differences in total and intact cell counts between the inlet and outlet of B2 (yellow triangles), C3, (blue diamonds), and D4 (pink squares - TCC only) SRs across 2018 to 2020.

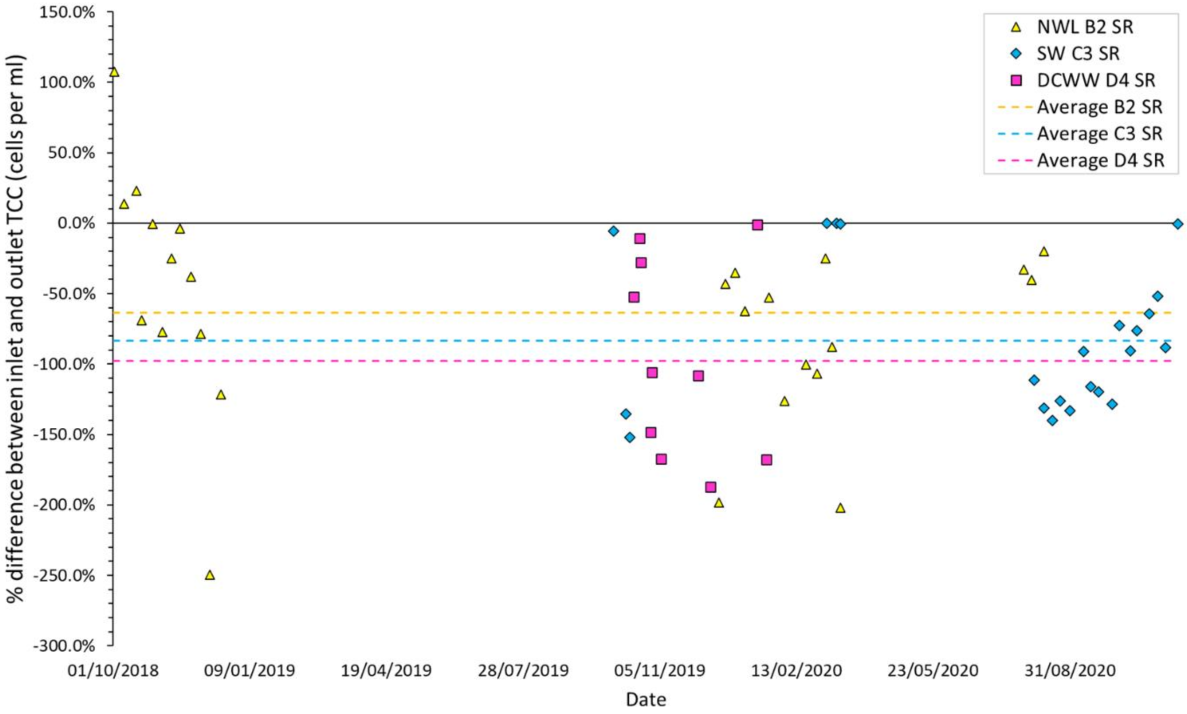

Figure 6.3.14 – Percentage difference in total cell count (per ml) between the inlet and outlet of B2, C3, and D4 SRs across 2018 to 2020. The dashed lines represent the average percentage difference across this time.

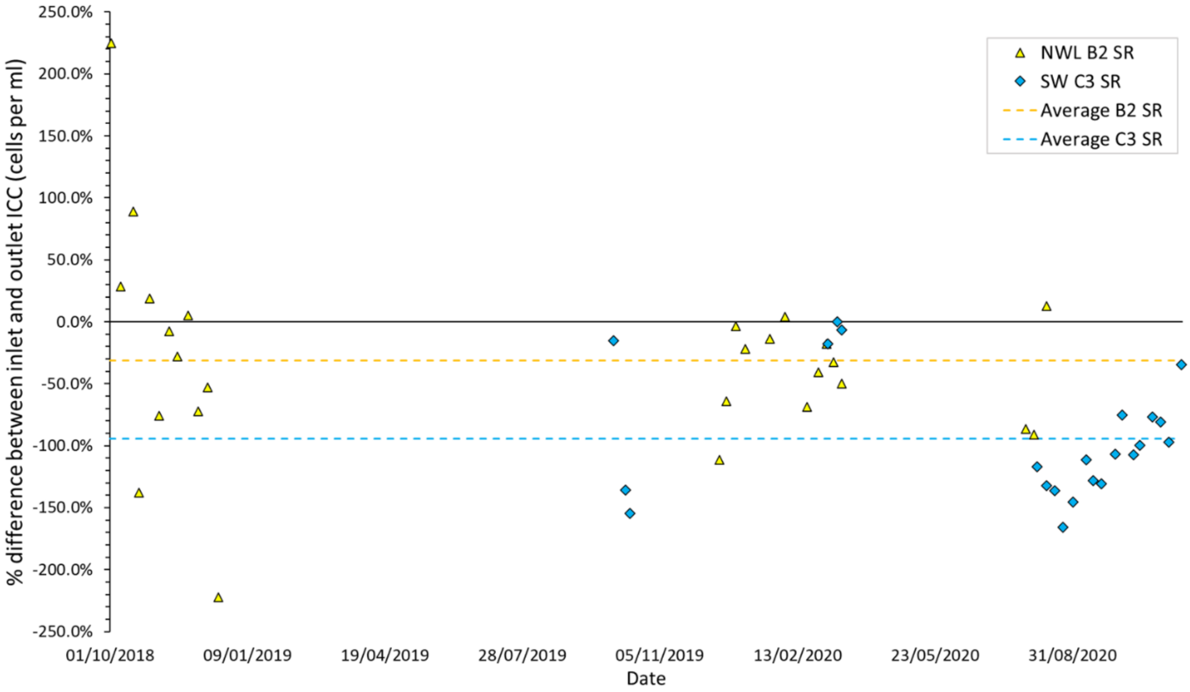

Figure 6.3.15 – Percentage difference in intact cell count (per ml) between the inlet and outlet of B2 and C3 SRs across 2018 to 2020. The dashed lines represent the average percentage difference across this time.

Figures 6.3.14 and 6.3.15 show that all SRs acted as sinks of cells, both total and intact. Results suggest that the greatest sink of total cells was D4 SR, however, it is important to highlight that initial cell count values at the inlet of this SR are very low and are much lower than at B2 or C3 SRs (see Table 6.3.3 below). Therefore, what appears to be a great percentage difference in TCC between D4 SR inlet and outlet is actually not that drastic (e.g., going from 10 cells to 1 is not as notable as a decrease from 100,000 cells to 10,000). Care should be taken when using flow cytometry data to cross compare the performance of multiple SRs in this way as it can lead to false assumptions about the results.

6.3.2.1.3. Iron

Figure 6.3.16 presents percentage differences in total iron concentrations between the inlet and outlet of A1 (green circles) and C3 (blue diamonds) SRs across 2019 to 2020.

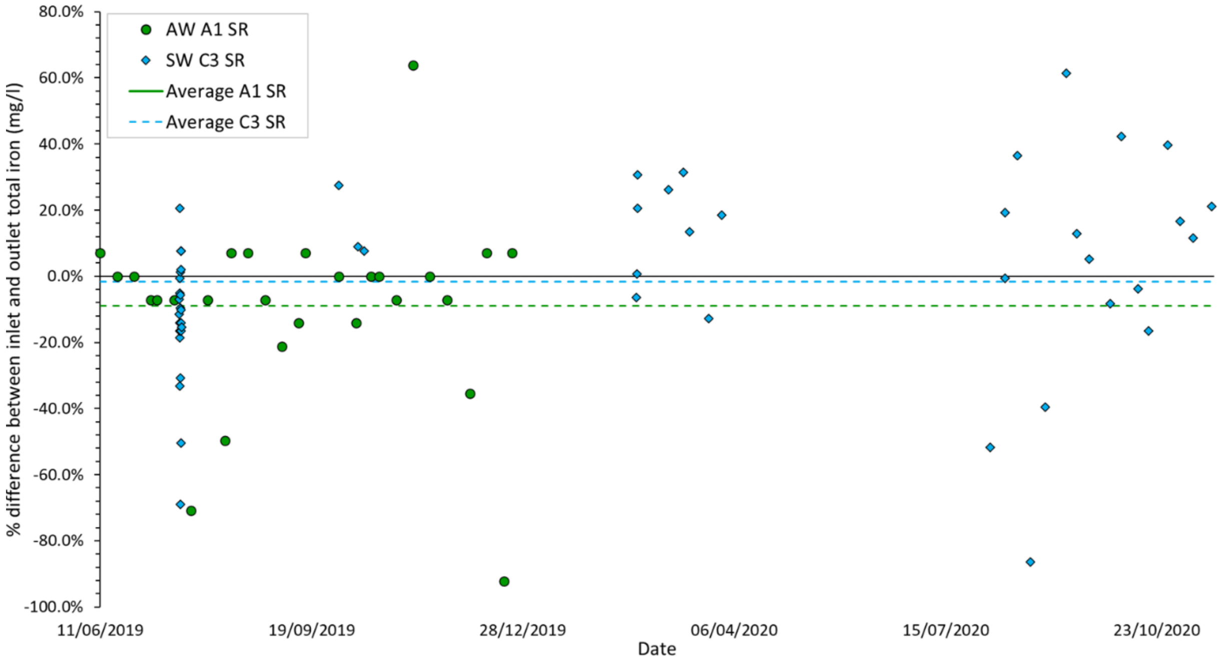

Figure 6.3.16 – Percentage difference in total iron (mg/l) between the inlet and outlet of A1 and C3 SRs across 2019 to 2020. The dashed lines represent the average percentage difference across this time.

Results in Figure 6.3.16 show that percentage differences in total iron concentrations are very sporadic and do not provide a clear understanding of SR performance over time at either the A1 or C3 SR.

6.3.2.1.4. Manganese

Figure 6.3.17 presents percentage differences in total manganese concentrations between the inlet and outlet of B2 (yellow triangles), C3 (blue diamonds), and D4 (pink squares) SRs across 2018 to 2020.

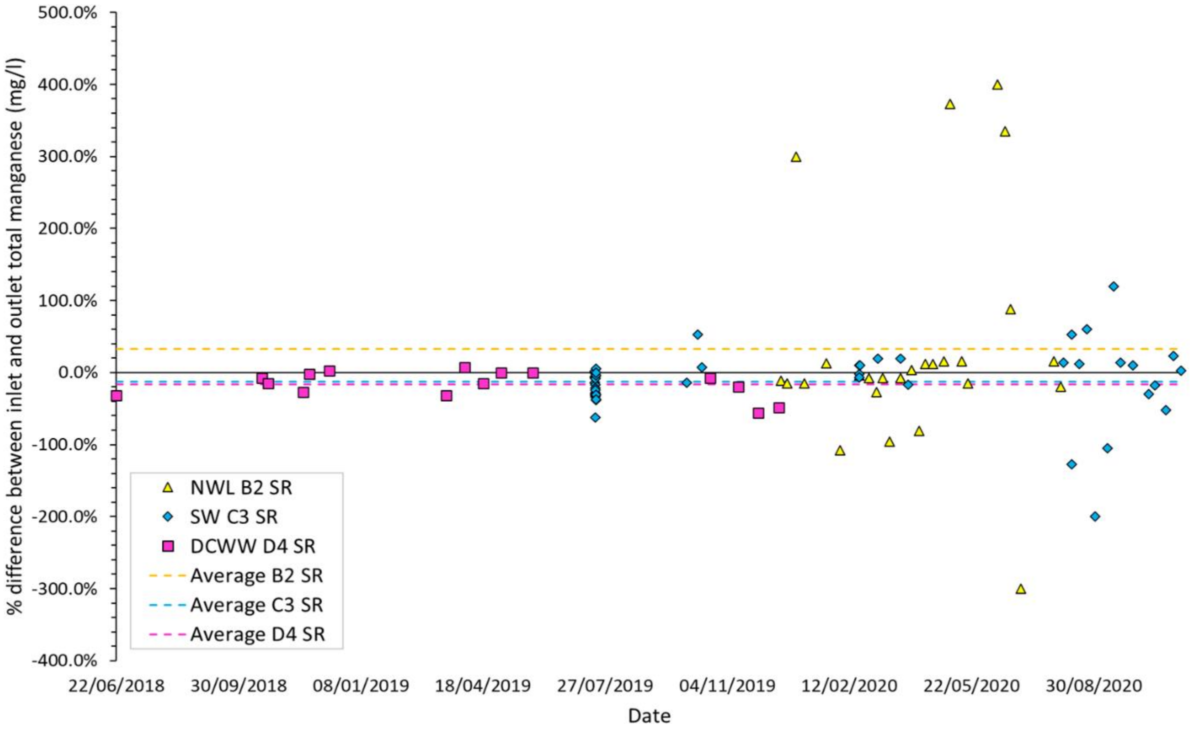

Figure 6.3.17 – Percentage difference in total manganese (mg/l) between the inlet and outlet of B2, C3, and D4 SRs across 2018 to 2020. The dashed lines represent the average percentage difference across this time.

As with total iron data above, percentage differences in total manganese (Figure 6.3.17) are also sporadic and hard to use to establish SR performance changes over time, with varying behaviour between SRs.

6.3.2.1.5. Temperature

Figure 6.3.18 presents percentage differences in temperature between the inlet and outlet of A1 (green circles), B2 (yellow triangles), and D4 (pink squares) SRs across 2018 to 2020.

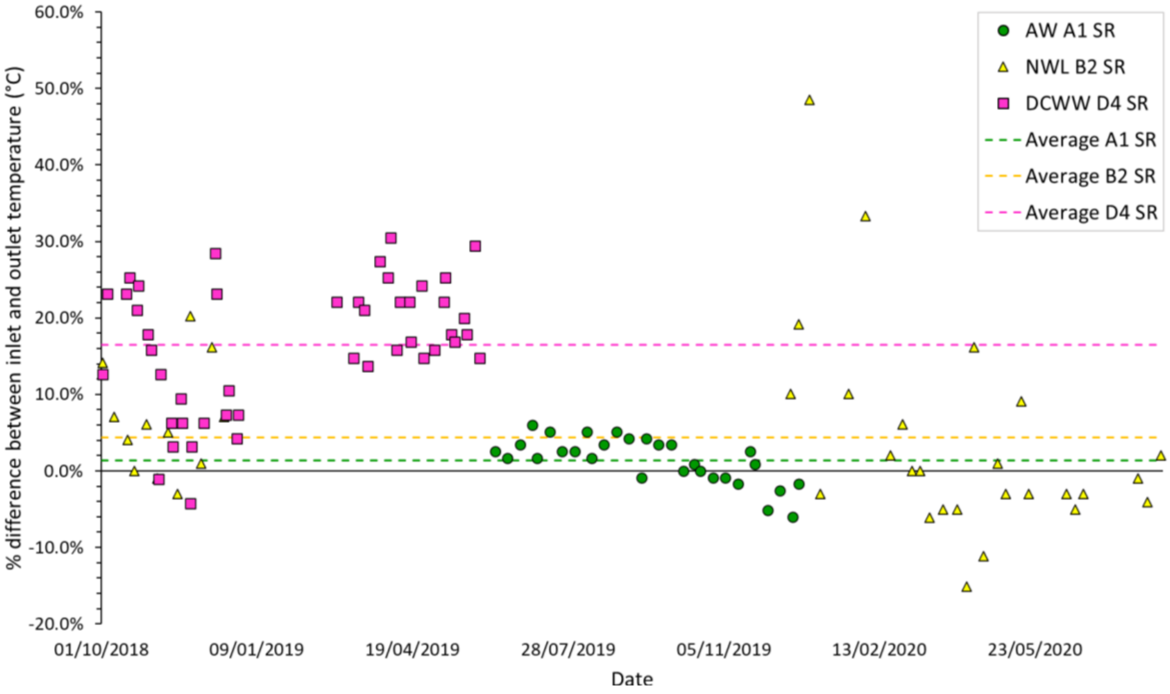

Figure 6.3.18 – Percentage difference in temperature (°C) between the inlet and outlet of A1, B2, and D4 SRs across 2018 to 2020. The dashed lines represent the average percentage difference across this time.

It was interesting to observe that percentage differences in temperature between SR inlets and outlets presented in Figure 6.3.18 showed that all SRs increased the temperature of bulk water as it travelled through them. There is an assumption in industry that because the majority of SRs in the UK are buried underground, they are not affected by changes in temperature and water quality issues associated with higher temperatures (e.g., thermal stratification). Results above contradict this assumption, as both B2 and D4 SRs are buried underground and are heating up the water temperature by an average of 5% (B2) and 17% (D4). The difference in percentage change in temperature may also be influenced by ambient temperature in the area the SRs are located in. For instance, D4 SR is located further south than B2, which could explain the average 12% difference in temperature increase between the two SRs. Other factors may also be in effect, such as the volume of the SR, whereby larger volumes of water require more energy to heat (B2 is 81 ML bigger than D4).

It is important to highlight that the difference in temperature between the inlet and outlet of the A1 SR is likely to be higher than is presented in Figure 6.3.18. At this site, the length and diameter of the inlet sample line affected chlorine residual levels recorded at the inlet (see section 6.3.1.2.1.) and the same sample line may be heating the water faster than it heats with travel through the SR. This is especially likely as the inlet sample line is located inside an enclosed building, where surrounding air temperature is likely to be higher than the air temperature around the A1 SR, an overground water tower (Chapter 5 – Site Details: Figure 5.3).

6.3.2.1.6. Turbidity

Figure 6.3.19 presents percentage differences in turbidity between the inlet and outlet of A1 (green circles) and C3 (blue diamonds) SRs across 2019 to 2020.

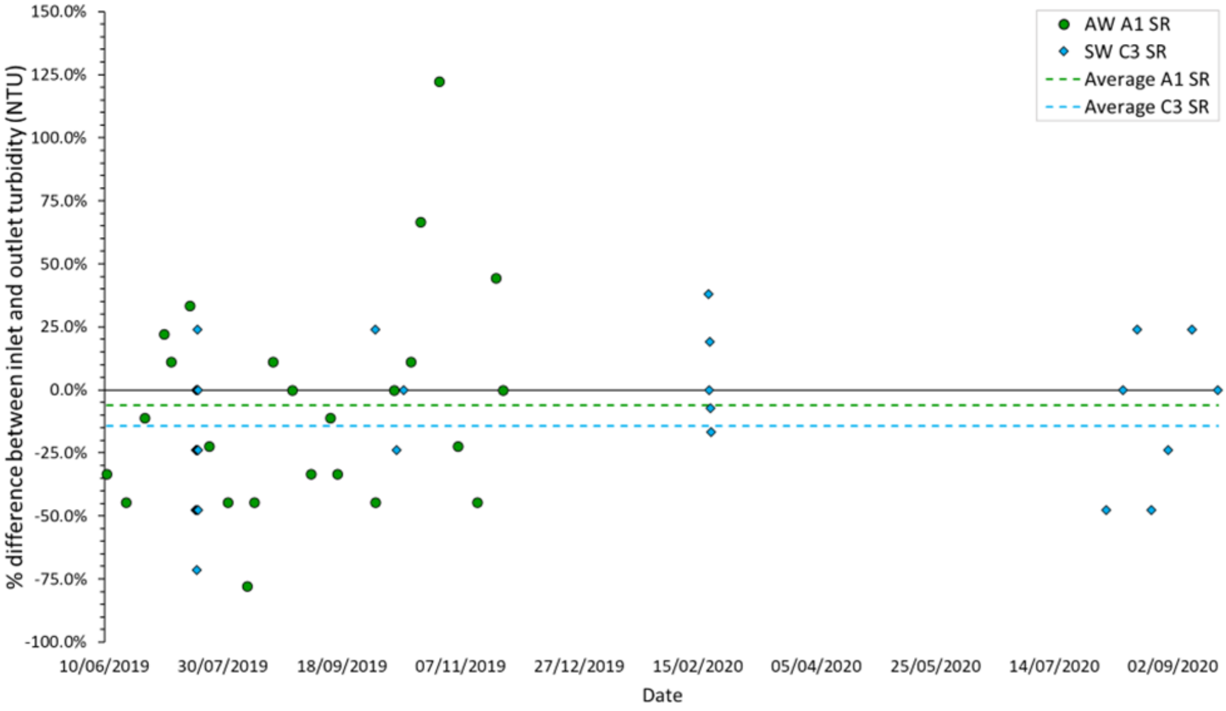

Figure 6.3.19 – Percentage difference in turbidity (NTU) between the inlet and outlet of A1 and C3 SRs across 2019 to 2020. The dashed lines represent the average percentage difference across this time.

As with iron and manganese data, results in Figure 6.3.19 show that percentage differences in turbidity between the SR inlet and outlet are sporadic, without a clear pattern of performance at both the A1 and C3 SR.

Summary

Table 6.3.3 contains descriptive statistics, average percentage differences, and statistical analysis on all the data presented in Figures 6.3.13 to 6.3.19 with the addition of TOC at C3 SR. Average percentage differences highlighted in blue indicate that the parameter decreased with travel through the SR, those highlighted in red indicate that the parameter increased with travel through the SR, and values highlighted in grey indicate that no notable change (< 5%) occurred.

Table 6.3.3 – Descriptive statistics and statistical analysis on the differences between paired discrete water quality samples at the inlet and outlet of project SRs across 2018 to 2020.

Difference in sampled water quality parameters between the inlet and outlet of project service reservoirs across 2018-2020 (paired samples)										
Parameter	SR	n	Mean	Median	SD	RNG	Average % difference (outlet-inlet)	Test (T/W)	p-value	Statistically signifcant (Y/N)
Chlorine (total) (mg/l)	**B2**	38	-0.164	-0.150	0.090	0.380	**-16.1%**	T	3.842^e-13	Y
	D4	79	-0.132	-0.140	0.133	0.650	**-11.3%**	W	1.128^e-09	Y
Chlorine (free) (mg/l)	**B2**	39	-0.155	-0.140	0.088	0.410	**-17.3%**	W	1.325^e-07	Y
	D4	79	-0.138	-0.140	0.135	0.650	**-12.3%**	W	5.657^e-10	Y
Flow cytometry (TCC) (cells per ml)	**B2**	26	-743	-562	883	4181	**-63.5%**	W	8.804^e-05	Y
	C3	22	-123944	-134926	77958	226000	**-83.4%**	W	6.412^e-05	Y
	D4	10	-48	-52	34	91	**-97.6%**	T	0.002	Y
Flow cytometry (ICC) (cells per ml)	**B2**	25	-71	-72	181	993	**-31.4%**	W	0.01	Y
	C3	22	-112262	-127400	59805	197600	**-94.4%**	W	4.768^e-07	Y
Iron (mg/l)	**A1**	27	-0.001	-0.001	0.004	0.022	**-8.9%**	W	0.068	N
	C3	52	-0.002	-0.001	0.043	0.231	**-1.6%**	W	0.982	N
Manganese (mg/l)	**B2**	27	0.0008	-0.0001	0.0040	0.0182	**32.4%**	W	0.923	N
	C3	48	-0.0010	-0.0005	0.0037	0.0249	**-12.5%**	W	0.033	Y
	D4	15	-0.0007	-0.0006	0.0008	0.0026	**-16.7%**	W	0.006	Y
Temperature (°C)	**A1**	29	0.17	0.20	0.35	1.40	**1.4%**	W	0.015	Y
	B2	38	0.43	0.10	1.18	6.30	**4.4%**	W	0.064	N
	D4	46	1.57	1.65	0.80	3.30	**16.5%**	W	5.366^e-09	Y
Total organic carbon (mg/l)	**C3**	25	-0.01	0.00	0.09	0.30	**-0.7%**	W	0.664	N
Turbidity (NTU)	**A1**	24	-0.005	-0.010	0.039	0.180	**-6.0%**	W	0.258	N
	C3	38	-0.059	-0.100	0.104	0.460	**-14.2%**	T	0.001	Y

Results show that using discrete water quality sample data to assess SR performance with changes over time can be difficult due to the sporadic nature of such datasets, which can make it challenging to interpret the data and lead to false assumptions about performance. Additionally, it is difficult to account for retention times when using this type of infrequent sampling. However, results also show that discrete data can provide useful information about overall SR performance. For instance, average percentage differences between parameters at the inlet and outlet of project SRs presented in Table 6.3.3 show a pattern of sink or source behaviour for certain parameters across all sites such that:

- **Chlorine decreased** with travel through B2 and D4 SRs.
- Flow cytometry total and intact **cell count decreased** with travel through B2, C3, and D4 SRs.
- **Total organic carbon did not change** with travel through C3 SR.
- **Turbidity decreased** with travel through A1 and C3 SRs.
- Changes in **manganese and iron** were **site specific.**

6.3.2.2. Continuous online monitoring data

The SR performance metric defines SR performance in terms of net material loading (NTU), whereby values < 0 indicate that the SR is acting as a sink of material and is performing well and values > 0 indicate that the SR is acting as a source of material and is performing badly. Figures 6.3.20 to 6.3.22 present results from the application of this metric to continuous turbidity data collected at three project SRs: A1, C3, and D4 respectively.

6.3.2.2.1. A1 SR

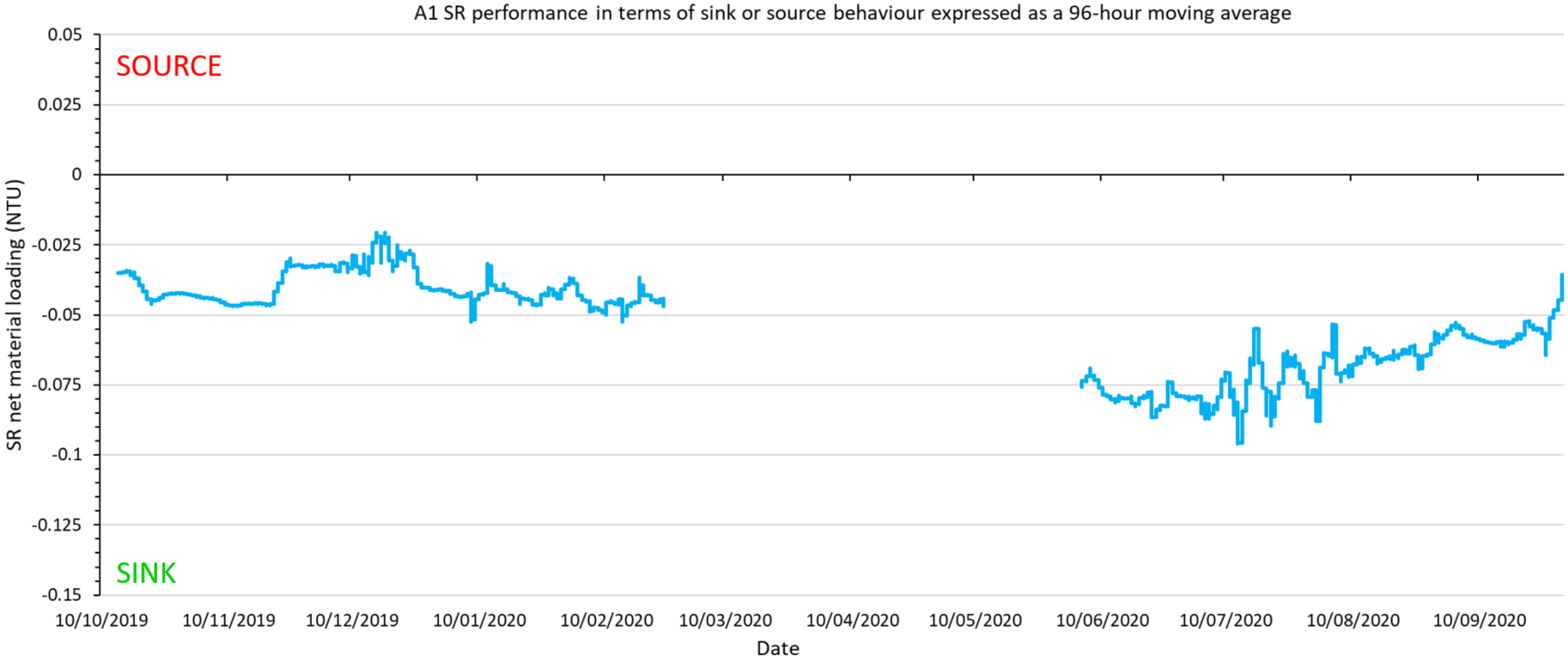

Figure 6.3.20 – Two time periods of continuous A1 SR net material loading (NTU) data from October 2019 to September 2020, plotted as a 96-hour moving average. This plot describes the performance of the A1 SR in terms of it acting as a sink or source of material (NTU).

A1 SR performance data presented in Figure 6.3.20 is split into two time periods of continuous MetriNet turbidity data across 2019 to 2020. The first time period falls between October 2019 and February 2020 (colder weather months) and the second time period falls between June and August 2020 (warmer weather months). A1 SR is a groundwater site, which is often associated with stable water quality conditions in the DWDS. This is reflected in the largely unvarying A1 SR net material loading across a year of data collection. Nevertheless, the performance metric reveals a seasonal temperature effect, whereby the SR is acting more of a sink in warmer months. The average performance value of this SR was -0.054 NTU.

6.3.2.2.2. C3 SR

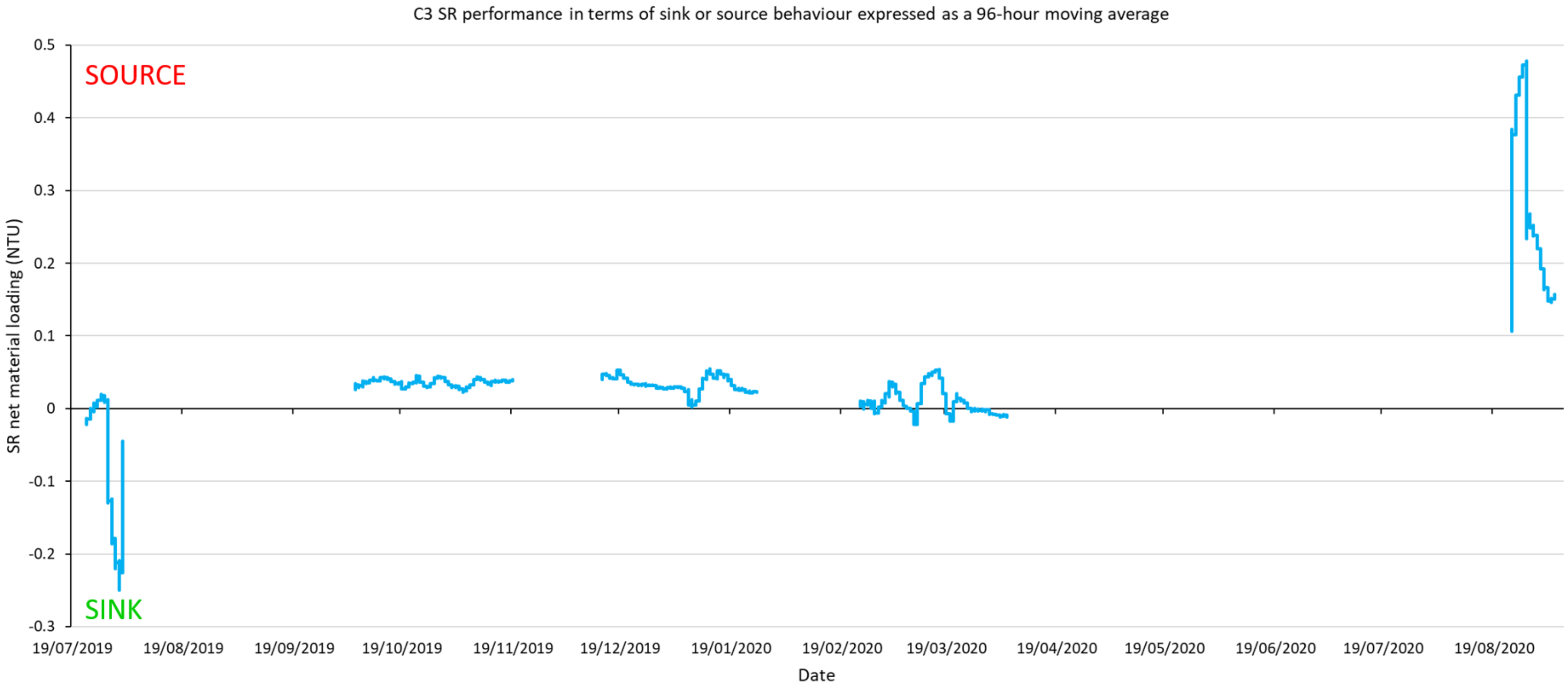

Figure 6.3.21 – Five time periods of continuous C3 SR net material loading (NTU) data from July 2019 to August 2020, plotted as a 96-hour moving average. This plot describes the performance of the C3 SR in terms of it acting as a sink or source of material (NTU).

C3 SR performance data presented in Figure 6.3.21 is split into five time periods of continuous NephNet turbidity data across 2019 to 2020. Data shows that the SR gradually becomes more and more of a source of material over time. Having been cleaned only a year prior to the commencement of this data collection, it was unexpected that the SR would switch to source behaviour so quickly after the clean. Upon further investigation, it has been established that the supplying 50 km trunk main, of which 28 km is unlined cast iron (Chapter 5: Site Details – Figure 5.13) is the likely source of material and proactive management measures are being taken to flow condition said trunk main to remove some of the accumulated material within it. The average performance value of this SR was 0.038 NTU.

6.3.2.2.3. D4 SR

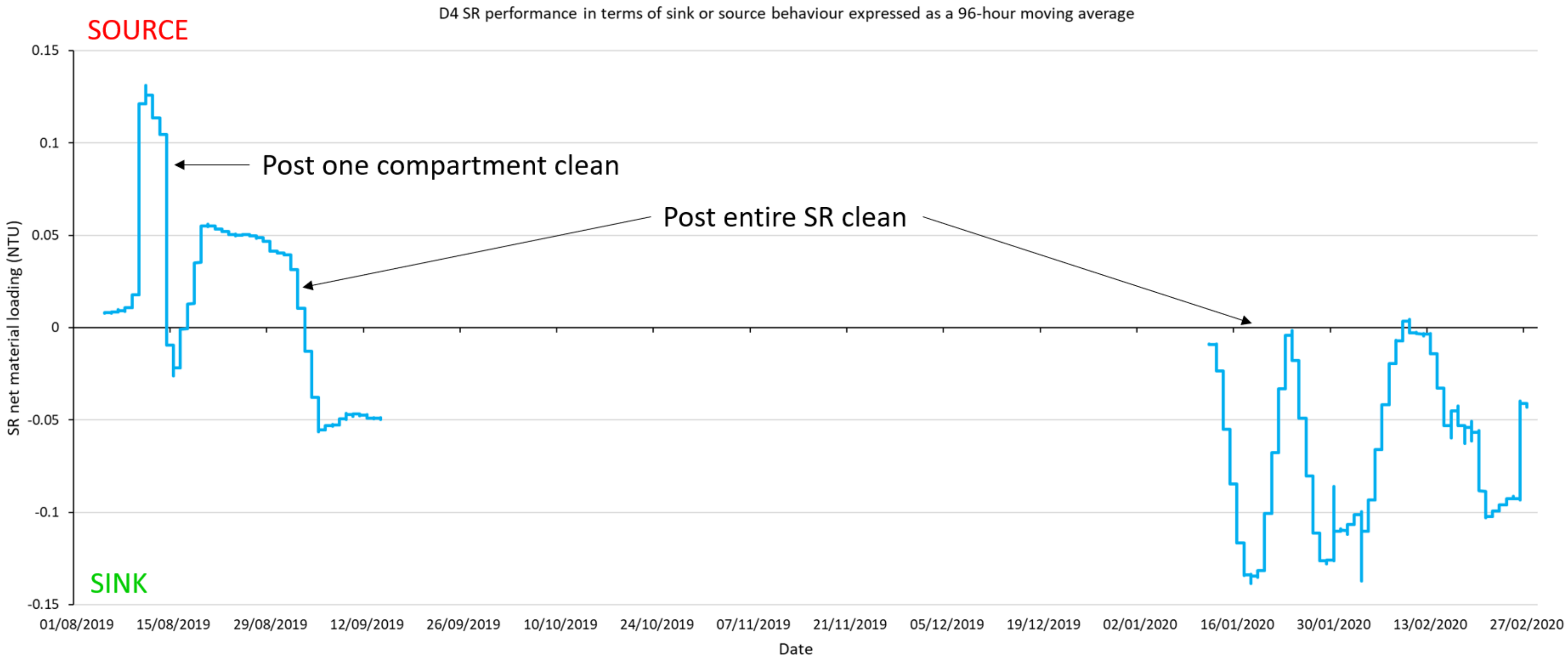

Figure 6.3.22 – Two time periods of continuous D4 SR net material loading (NTU) data from August 2019 to February 2020, plotted as a 96-hour moving average. This plot describes the performance of the D4 SR in terms of it acting as a sink or source of material (NTU). The D4 SR was cleaned during the time that this data was collected and the time periods are labelled to indicate which stage of the cleaning process data was collected from.

D4 SR performance data presented in Figure 6.3.22 is split into two time periods of continuous NephNet turbidity data across 2019 to 2020. Data was collected during a SR clean, after which the SR switches from a source to a sink of material, suggesting that the clean improved performance. The regular drastic variation in performance in the second time period was considered suspect and was investigated further. Upon investigation, it was discovered that the supplying WTW is not operating very efficiently and is overdosing lime at regular intervals, resulting in excess lime entering the downstream network (discussed in more detail in section 6.4.2.1.). As D4 SR appears to be buffering the incoming material, it would not have been possible to capture the negative effect of lime overdosing without SR inlet monitoring or the performance metric. The average performance value of this SR was -0.029 NTU.

Statistical analysis was conducted on the difference between continuous turbidity values at the inlet and outlet of project SRs to establish whether the observed differences were as a result of genuine water quality changes with travel through the SRs or due to chance. Results, which are presented alongside descriptive statistics on the data in Table 6.3.4 below, show that the differences in turbidity at the inlet and outlet of project SRs were statistically significant at all sites, meaning that the observed changes are very unlikely to have resulted by chance.

Table 6.3.4 – Descriptive statistics and statistical analysis of the difference between continuous turbidity samples at the inlet and outlet of project service reservoirs across 2019-2020 (paired samples).

Service Reservoir	n	Mean	Median	SD	RNG	Test (T/W)	p-value	Statistically signifcant (Y/N)
A1	377081	-0.055	-0.050	0.132	29.330	W	2.2^e-16	Y
C3	242942	0.039	0.038	0.301	31.323	W	2.2^e-16	Y
D4	131109	-0.028	-0.021	0.283	23.494	W	2.2^e-16	Y

6.3.2.3. Summary

Results show that it is difficult to capture real-time events or trends in SR performance over time when using discrete sampling alone. However, this type of data collection is useful in providing information about overall SR performance with respect to sink or source behaviour. Using continuous turbidity sampling has proven to be an effective way to quantify SR performance in real-time, which can also be used to provide information on the performance of the upstream network. Continuous sampling is also better at accounting for residence times of SRs, which is very difficult to do with discrete data. However, using discrete and continuous data in conjunction with one another provides the most comprehensive overview of SR performance. For instance, Figure 6.3.21 shows that C3 SR becomes more and more of a source of material over time, especially during the fifth period of sampling in August/September 2020. When looking at discrete sample data for the percentage differences in iron

(Figure 6.3.16), manganese (Figure 6.3.17), and cell counts (Figures 6.3.14 and 6.3.15) between the inlet and outlet of C3 SR, it also appears that the SR is either becoming a source of these parameters or their values are at their highest during this time. Irrespective of approach, results clearly show that monitoring water quality at ***both*** the inlet and outlet of SRs is vital in allowing for the effective assessment of SR performance and is especially valuable with regards to the application of the sink or source model.

6.4. Assessing the Impact of Operational Practices, Seasonality, and Site Differences, on Service Reservoir Performance

6.4.1. Introduction

This chapter presents results from the identification and assessment of various operational, network, and seasonal factors that had an influence on the performance of four main project SRs (A1, B2, C3, and D4), done to achieve **Objective 5** of the project. The chapter is split into three main sections:

1. Operational practices and management
2. Finished water type
3. Seasonality: temperature changes

6.4.2. Operational practices and management

6.4.2.1. WTW operation

This section presents observations from a case study in the D4 network where the operation of the supplying WTW had an effect on the performance of the SR. Continuous turbidity monitoring at D4 SR showed that there were increases in the concentration of incoming turbidity at regular intervals throughout the course of sampling (Chapter 6.3. – Figure 6.3.11). It was later established that the supplying WTW is contributing excess material into the SR as a consequence of lime overdosing during treatment. For full details of the event, please see Chapter 6.3., section 6.3.1.3.3.

Continuous online turbidity data at the SR suggested that the SR is buffering and acting as a sink for the additional incoming material, as there were no increases in turbidity at the outlet of D4 SR (see Figure 6.3.11 in Chapter 6.3.). This observation is supported by the SR performance metric (Chapter 6.3 - Figure 6.3.22), which shows that during periods of lime overdosing the SR is acting as a sink of this excess material. However, it also appears that with each increase in turbidity, the SR is acting as less and less of a sink and is gradually moving towards becoming a source of material. It can therefore be proposed that the operation of a WTW can have a direct effect on SR performance, in this instance; overdosing lime at the WTW is negatively impacting SR performance as the SR will likely become a source sooner than would have been without additional material to buffer, negating the positive effects of a recent SR clean.

6.4.2.2. Hydraulic regimes

This section describes the impact of an operational (hydraulic) event that occurred at C3 SR on SR performance with respect to incoming and outgoing water quality.

On the 11.03.20-12.03.20, C3 SR was filled to a maximum level (SR height 4.97 m) after which incoming flow was adjusted to a steady fill rate of 36 l/s from midday on the 12.03.20 until midday of the 17.03.20 (Figure 6.4.1). This is approximately 20 l/s less than the maximum inlet flow during the normal regime, which is also usually pumped. Inlet flow regime was restored to normal on the 18.03.20.

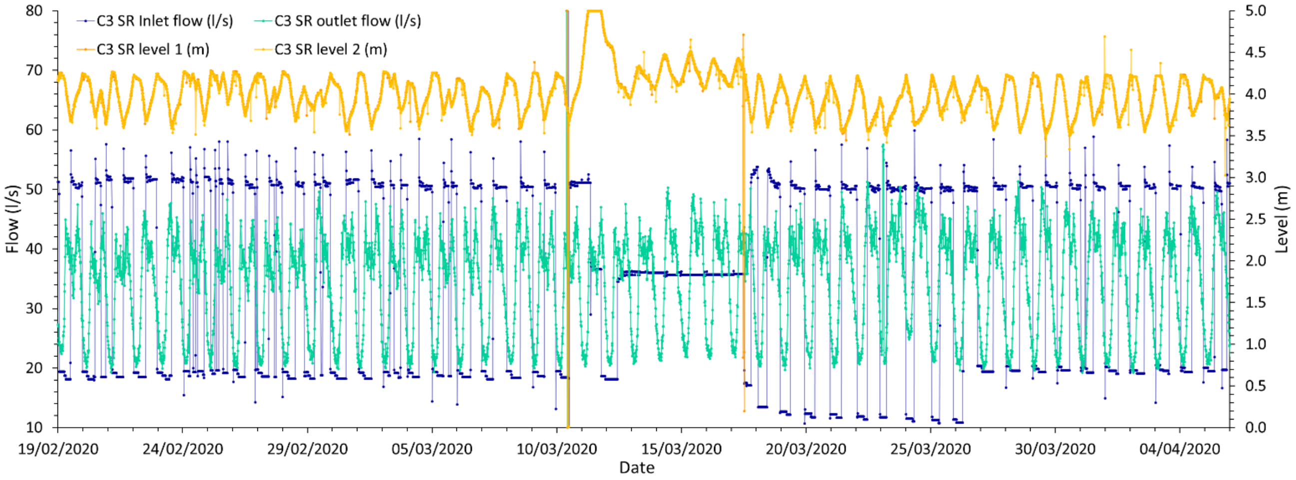

Figure 6.4.1 – Flow and level data at C3 SR between 19.02.20-06.04.20.

The operational change in inlet flow on the 11.03.20-17.03.20 had a pronounced effect on the concentration of several water quality parameters that were sampled at the inlet and outlet of C3 SR during and around this time (Table 6.4.1). There were no other hydraulic changes or events that could have contributed to the changes seen in C3 SR water quality at least a month pre and post the described operational event.

Table 6.4.1 - Changes in concentrations of sampled water quality parameters at the inlet and outlet of C3 SR pre and post the operational event on the 11.03.20-17.03.20. Numbers highlighted in blue indicate a decrease and in red an increase in percentage change in parameter values pre and post event.

Location	Parameter	Pre-event Mean[5]	Event Mean	% Change	Post-event mean[6]	% Difference In/Out Pre-event	% Difference In/Out Event	% Difference In/Out Post Event
INLET	NTU	0.16	0.06	-63	0.21			
	TCC	152352	6200	-96	172430			
	ICC	117360	5300	-95	137945			
	TOC mg/l	1.26	0.75	-40	1.28			
	Conductivity µS/cm	77	65	-16	78			
	$\mathrm{Fe_{Total}}$ mg/l	0.135	0.030	-78	0.138			
	$\mathrm{Mn_{Total}}$ mg/l	0.007	-	-	0.010			
	$\mathrm{Cl_{Total}}$ mg/l	-	-	-	-			
	$\mathrm{Cl_{Free}}$ mg/l	-	-	-	-			
OUTLET	NTU	0.17	0.09	-47	0.31	6	33	32
	TCC	18687	5800	-69	27390	-715	-7	-530
	ICC	3580	1400	-61	8105	-3178	-278	-1601
	TOC mg/l	1.27	0.80	-37	1.27	1	7	-1
	Conductivity µS/cm	81	60	-26	82	5	-8	5
	$\mathrm{Fe_{Total}}$ mg/l	0.138	0.065	-53	0.142	2	54	3
	$\mathrm{Mn_{Total}}$ mg/l	0.007	0.002	-71	0.008	0	-	-25
	$\mathrm{Cl_{Total}}$ mg/l	0.59	0.66	12	0.66	-	-	-
	$\mathrm{Cl_{Free}}$ mg/l	0.49	0.56	14	0.52	-	-	-

Recorded data in Table 6.4.1 was plotted graphically as line/scatter graphs, box plots, or both, which includes: inlet and outlet turbidity against flow, flow cytometry cell counts, TOC, conductivity, iron, manganese, and chlorine residual in Figures 6.4.2 to 6.4.8.

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[5] For all available data pre-event

[6] For all available data post-event

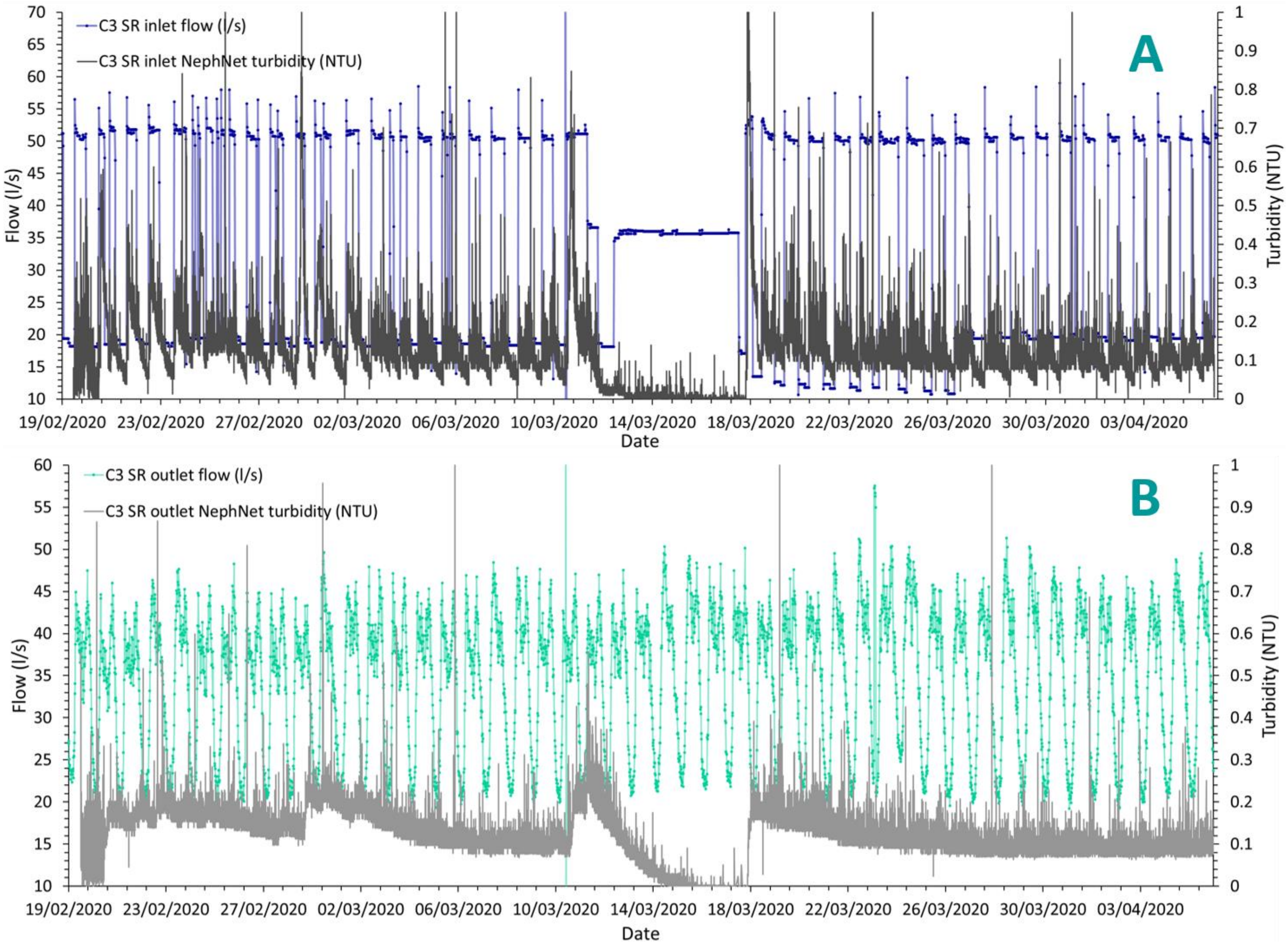


Figure 6.4.2 – (A) C3 SR inlet flow and continuous (NephNet) inlet turbidity and (B) C3 SR outlet flow and continuous (NephNet) outlet turbidity 19.02.20-04.04.20. This time-period captures an operational change in inlet flow between 11.03.20-17.03.20 and its effect on incoming and outgoing turbidity levels. NB: The drop in turbidity on the 19.02.20-20.02.20 is related to the installation of the NephNet monitors at both the inlet and outlet of C3 SR.

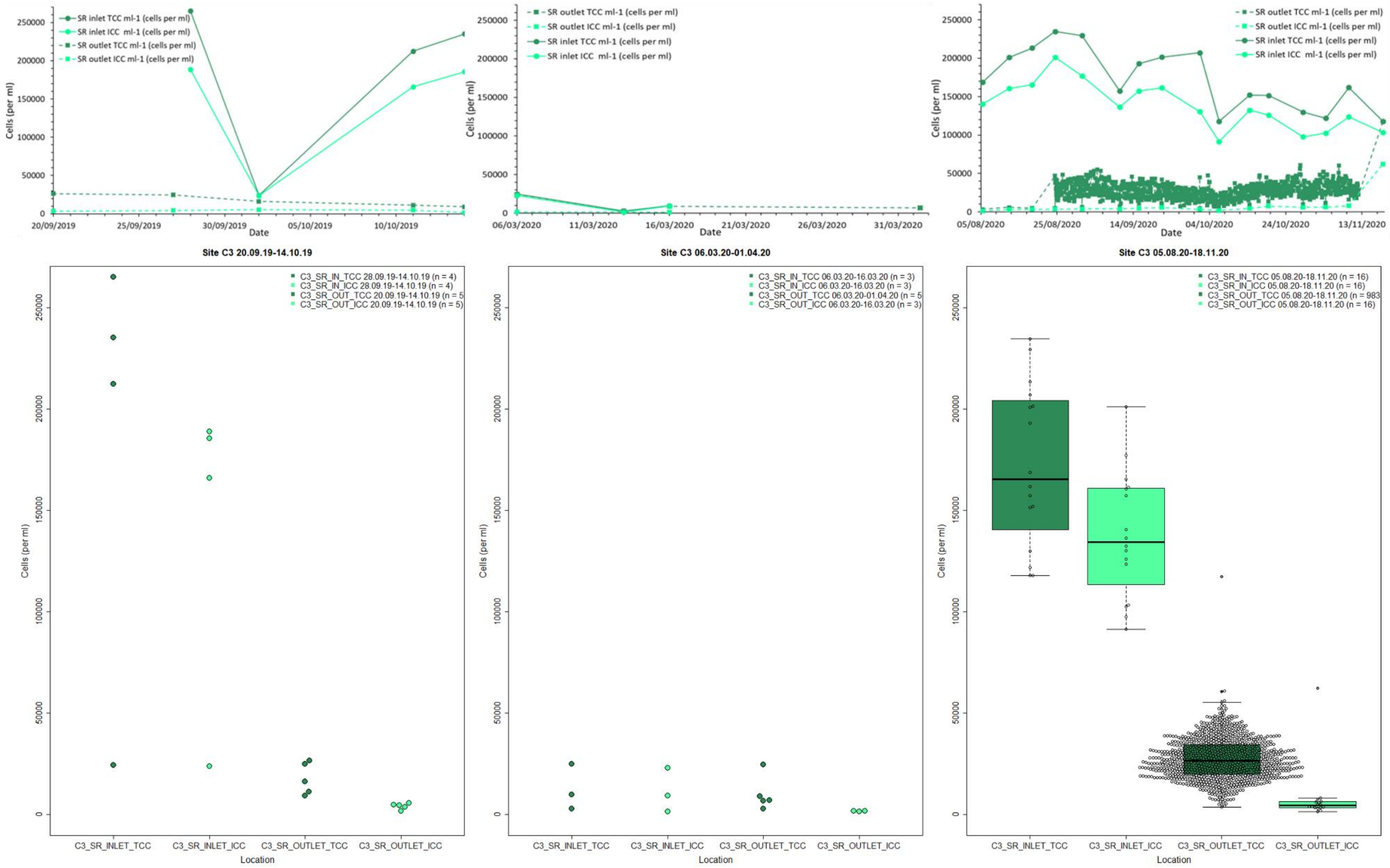
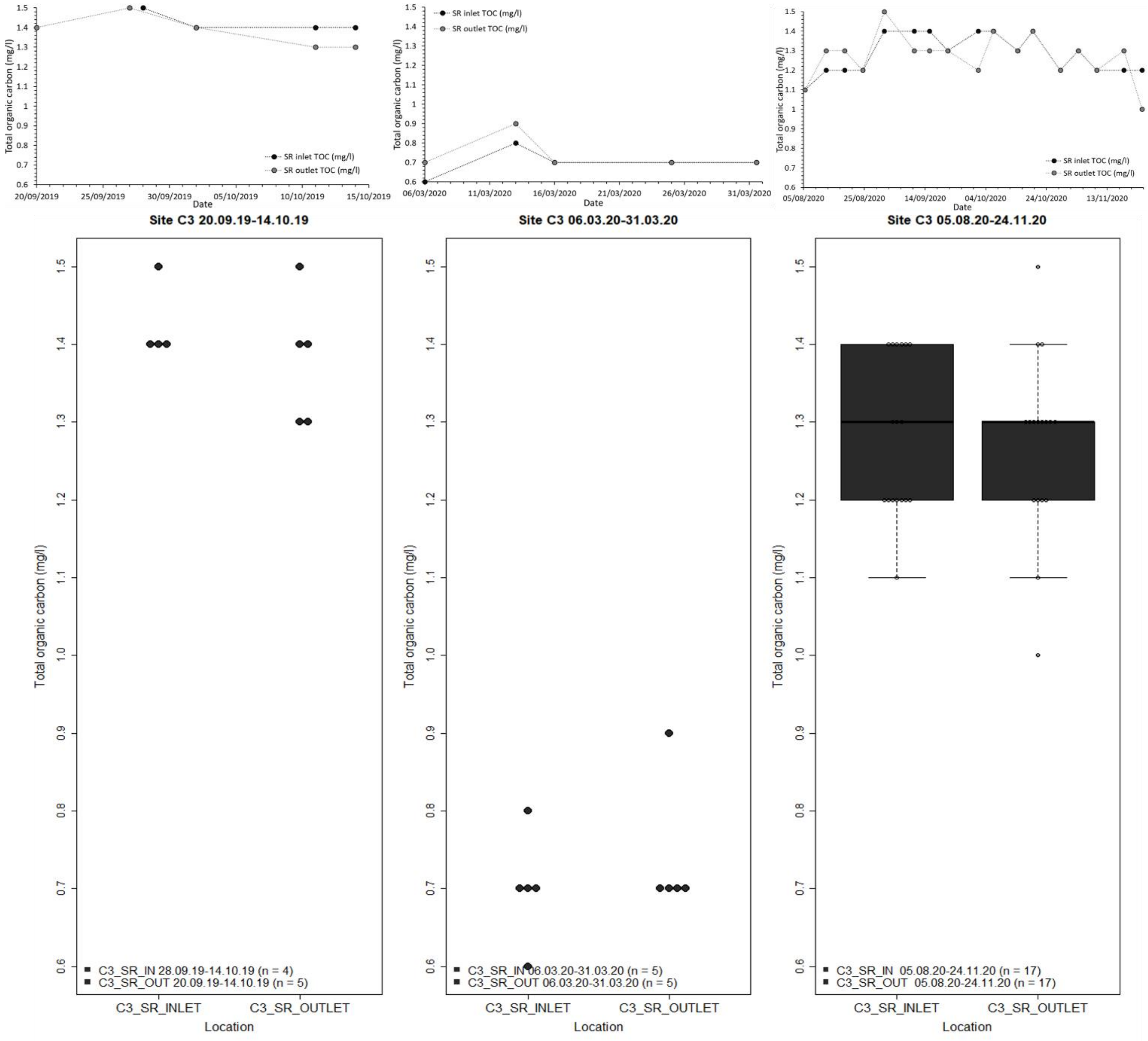


Figure 6.4.3 - Discrete flow cytometry data at the C3 SR inlet and outlet across three separate time-periods between 20.09.19-18.11.20 and continuous outlet 'BactoSense' flow cytometry data at the outlet of C3 SR between 24.08.20-12.11.20.


Site C3 20.09.19-14.10.19

Site C3 06.03.20-31.03.20

Site C3 05.08.20-24.11.20

Figure 6.4.4 - Discrete total organic carbon data at the C3 SR inlet and outlet across three separate time-periods between 20.09.19-24.11.20.

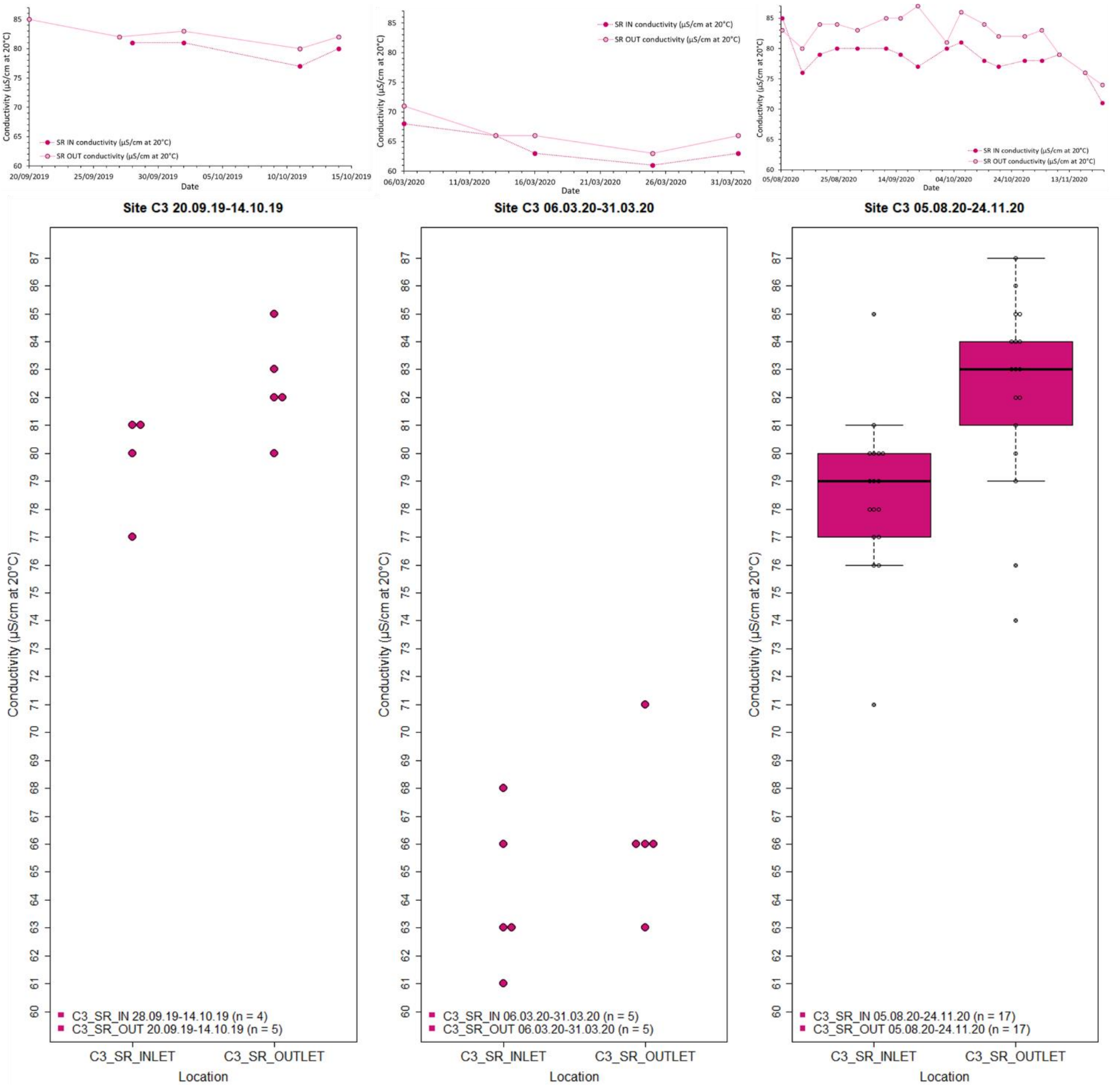


Figure 6.4.5 - **Discrete conductivity data at the C3 SR inlet and outlet across three separate time-periods between 20.09.19-24.11.20.**

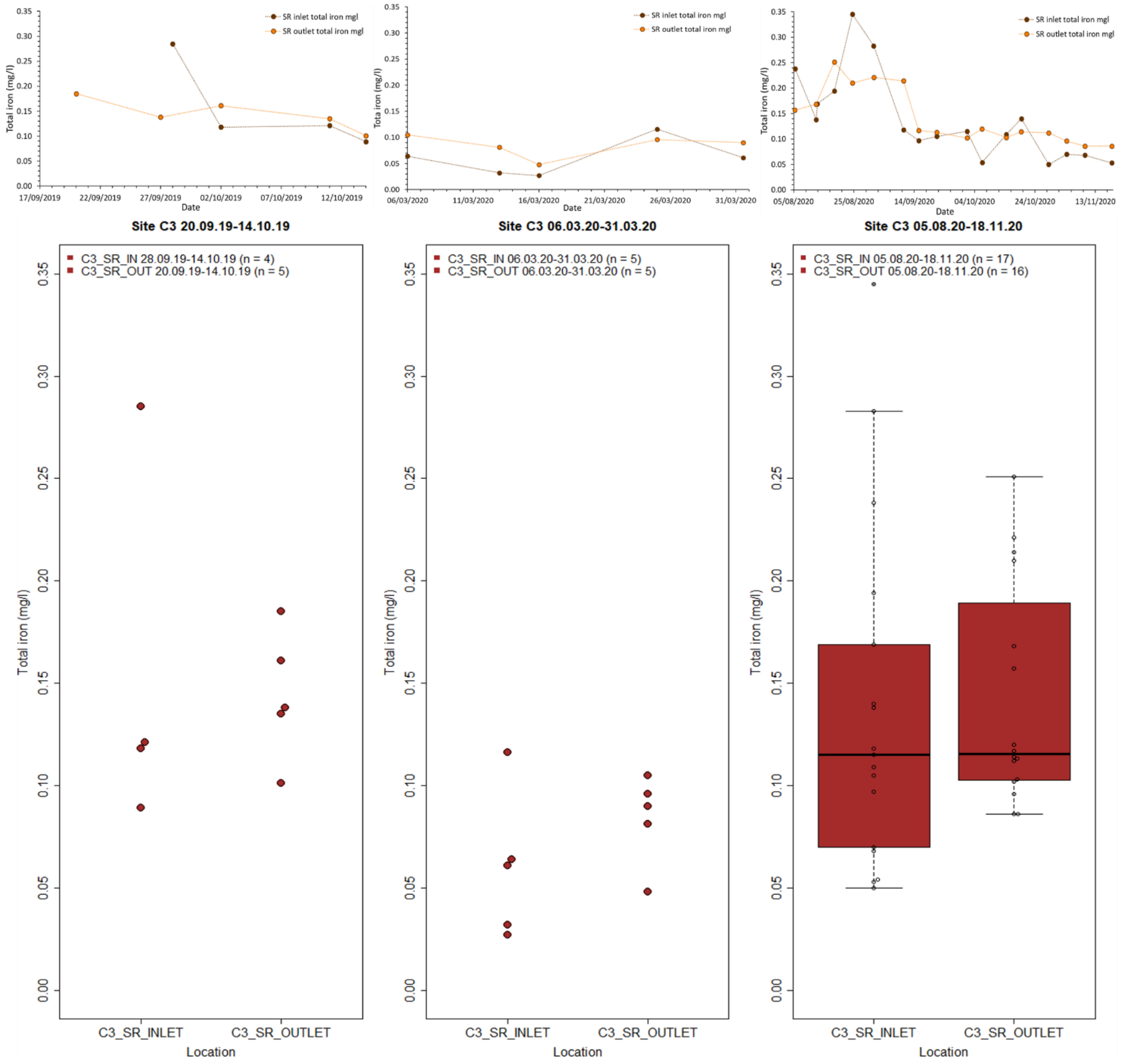
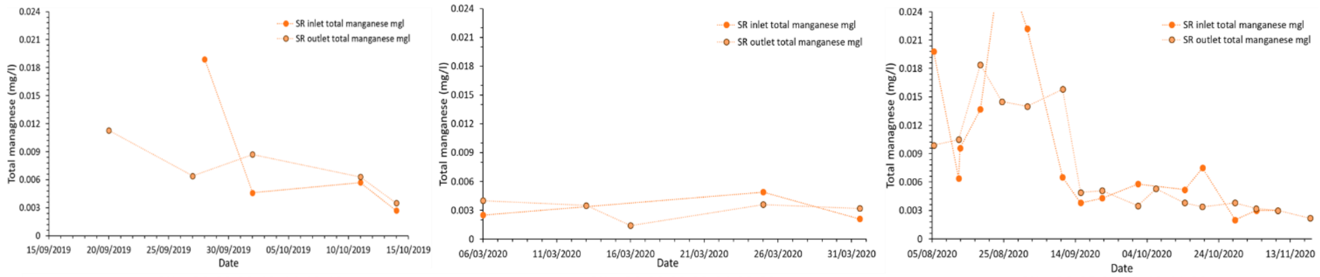


Figure 6.4.6 - **Discrete total iron data at the C3 SR inlet and outlet across three separate time-periods between 20.09.19-18.11.20.**



Site C3 20.09.19-14.10.19 **Site C3 06.03.20-31.03.20** **Site C3 05.08.20-18.11.20**

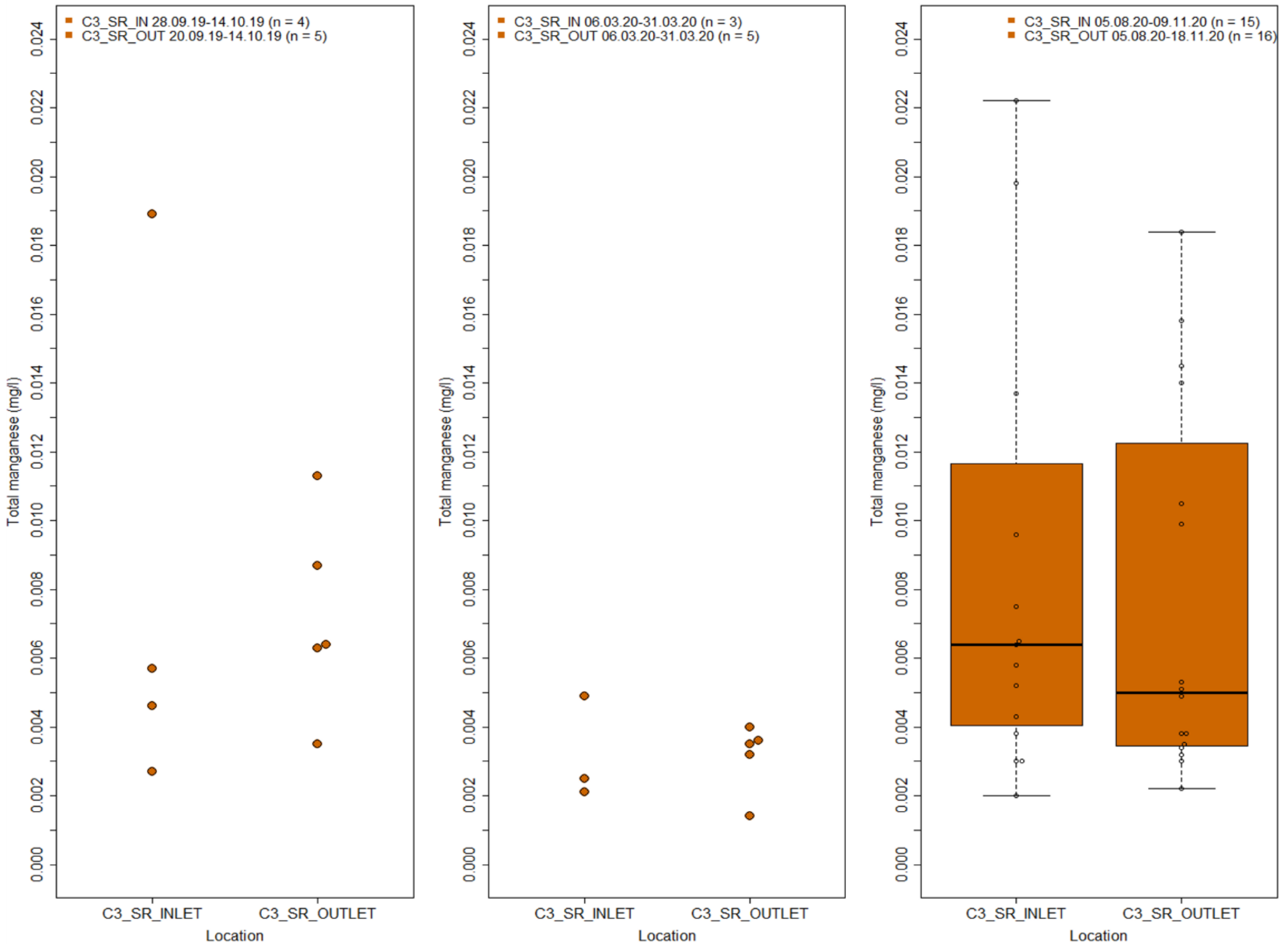
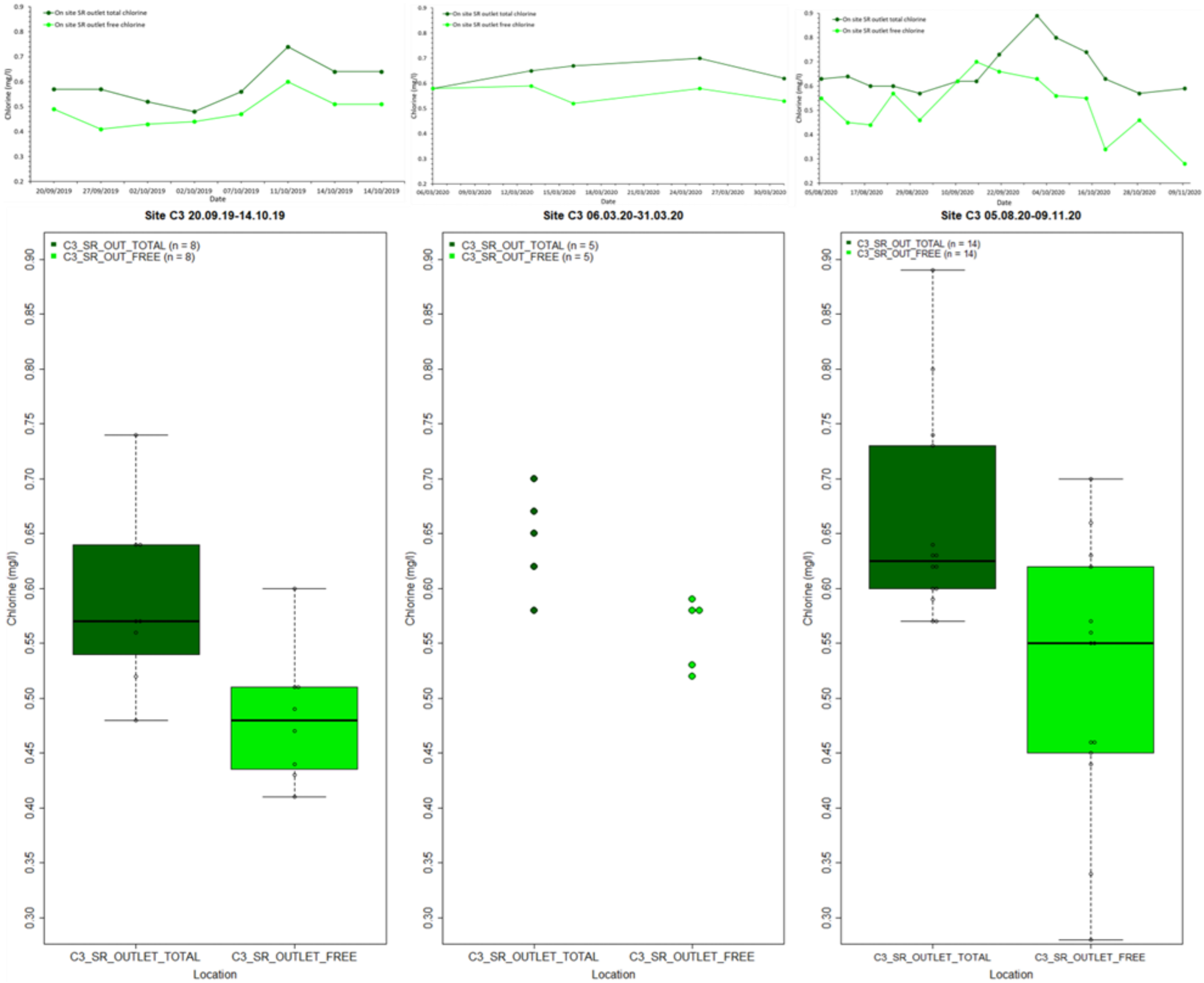


Figure 6.4.7 - **Discrete total manganese data at the C3 SR inlet and outlet across three separate time-periods between 20.09.19-18.11.20.**


Site C3 20.09.19-14.10.19

Site C3 06.03.20-31.03.20

Site C3 05.08.20-09.11.20

Figure 6.4.8 – Discrete total and free chlorine concentrations (mg/l) at the outlet of the C3 SR across three time periods between 20.09.19 to 09.11.20.

Results show that during the sudden change in inlet flow, values for the following parameters dropped at both the inlet and outlet of the SR (exact values in Table 6.4.1), irrespective of the outlet flow staying the same as normal (Figure 6.4.1):

- Continuous inlet and outlet turbidity (NTU)
- Flow cytometry (TCC and ICC) (cells per ml)
- TOC (mg/l)
- Conductivity (µS/cm at 20°C)
- Total iron (mg/l)
- Total manganese (mg/l)

The exception to these parameters was residual total and free chlorine at the SR outlet, which increased during the event. As there was no known change in the inlet chlorine dosing regime during this time, it is likely that the increase in residual is related to the decrease in concentration of incoming parameters, which chlorine would normally react with (e.g., metals, TOC, cells).

Although there was an improvement in water quality at the SR in that concentrations of deterioration-causing water quality parameters were reduced, which is especially beneficial at the SR outlet, the performance of the SR itself became worse during this time. Figure 4.25 in section 4.5.3. clearly demonstrates that the SR became more of a source of material during the event (day 20-25 on the figure), which coincides with the results from collected turbidity, iron, TOC, and cell count data, whose change in percentage difference between inlet and outlet during the event indicates an increase in source behaviour (Table 6.4.1). The reason why the source/sink model shows that performance became worse is likely related to the retention time of the SR (average 41 hours), which meant that there was a time lag between the drop in the concentration of incoming turbidity values before their subsequent drop at the outlet. The performance metric compares values at the inlet and outlet at the same point in time and, although a moving average is applied to smooth out the potential effects of SR retention time on performance, not shifting outlet data by the retention time makes it difficult to accurately incorporate residence time effects of the SR into the calculation. Although this can be seen as a potential limitation of the metric, the metric is nevertheless able to capture a shift in SR performance unrelated to normal operation and alert to an event in the network that may otherwise go unnoticed, which is part of the requirements for the metrics’ intended usage. This can also be seen in section 6.4.2.1., where the application of the metric alerted to unusual behaviour in D4 SR performance, which was later linked to ineffective operation of the supplying WTW. Although the change in the operation of the fill/drain cycle did not improve SR performance in terms of sink/source behaviour, performance did improve in terms of the reduction in chlorine decay with travel through the SR.

It is important to highlight that looking at the timeline scatter graphs on top of raw data box plots, the concentrations for cell counts, TOC, and conductivity were already lower on the 06.03.20 (in comparison to the other two time periods) prior to the beginning of the inlet flow change on the 11.03.20 (Figures 6.4.3 to 6.4.5). It is possible that there was a seasonal temperature effect on the concentration of these parameters. This assumption is supported by results in the section on the influence of seasonal temperature changes on SR performance (6.4.4. below), which show that cell count and TOC concentrations were lower at both the inlet and outlet of C3 SR in cold weather months (January – March). Unfortunately, data for all parameters (including water temperature) other than turbidity and flow and level data is not available between 14.10.19-06.03.20; it is therefore unclear whether this observation is a result of a seasonal effect, which is further exacerbated by the event.

This same observation does not seem to apply to iron and manganese (Figures 6.4.7 and 6.4.8), whose levels on the 06.03.20 are not too different from those on the last available timestamp (14.10.19). However, both metals are also at their lowest during the time-period of 06.03.20-31.03.20, which may again reflect seasonal change, which is enhanced by the change in inlet flow between 11.03.20-17.03.20. This is once again supported by results in section 6.4.4. 'Seasonality: temperature changes' of this chapter, which show that iron and manganese concentrations were lower at both the inlet and outlet of C3 SR in cold weather months.

Post event, on the 18.03.20, inlet flow was restored to its regular pumping cycle of varying intervals between approximately 20 l/s to approximately 56 l/s (Figure 6.4.1). As soon as this happened, both inlet and outlet continuous turbidity values began to return to their expected levels based on previous data and SR performance returned to similar source behaviour of that prior to the event (Figure 4.25). The values for the other measured parameters remained lower (higher for chlorine) in comparison to the other time-periods that they were sampled in. At the next available time-period (05.08.20-24.11.20) these same parameters had re-risen (lowered for free chlorine) (Table 6.4.1). Unfortunately, due to a lack of discrete weekly grab sample data at C3 SR from 31.03.20 onwards, it is unclear how long after the event this took to happen, which also makes it impossible to determine whether there was a continuous effect from the event on the levels of these parameters, or whether this was related to seasonality. Nevertheless, results show that the short-term change in the operation of the fill drain cycle from a pumped flow to a steady filling rate decreased the background concentration of incoming parameters and subsequently led to the improvement in SR performance in relation to the reduction in chlorine decay with travel through the SR.

6.4.2.3. Service reservoir clean

Two project SRs (C3 and D4) underwent an inspection and clean during, or close to the start of, the project. This section presents results from collected water quality data pre and post SR cleans, used to determine whether cleaning had an impact on SR outgoing water quality and asset performance.

C3 SR

C3 SR was inspected and cleaned in June/July 2017 and based on discrete chlorine data collected at the outlet of this SR pre and post clean, it appears that the clean improved SR performance in that chlorine residual was higher at the outlet post clean (see Chapter 6.3 – Figure 6.3.3). This could suggest that cleaning a SR can decrease the amount chlorine decays with travel through it, which could be related to removal of material accumulated within the SR. This suggestion is supported by results from the experiment on chlorine decay rate exerted by resuspended material (section 6.1.3.5.), where it is evident that accumulated material exerts a high chlorine demand, thus the removal of said material could improve disinfection efficacy and longevity. Furthermore, it is known, based on historical inspection reports, that accumulation of material is prevalent in C3 SR (see Chapter 5 – Figure 5.20).

D4 SR

D4 SR was inspected and cleaned during the course of the project, November 2018 to March 2019 for compartment B and in August 2019 for compartment A (Chapter 5: Site Details – Figure 5.25). A variety of water quality parameters were monitored pre, during, and after the clean.

Results from the application of the SR performance metric, which uses continuous turbidity data at the inlet and outlet of D4 SR, show that the SR becomes a sink of material post clean (Chapter 6.3. - Figure 6.3.22), which indicates that its performance was improved, especially as the metric output also shows that the SR was acting as a source of material prior to the clean.

When looking at discrete sampling for metals, results show that iron concentration does not change at the SR outlet pre, during, or after the clean, suggesting that the clean did not affect SR performance with respect to iron levels (Figure 6.4.9). Results for manganese sampling show that pre clean manganese levels were slightly higher at the SR outlet in comparison to the SR inlet and that upon the commencement of the clean, and post clean, manganese levels became lower at the SR outlet in comparison to SR inlet, irrespective of the concentration of incoming manganese (Chapter 6.3 – Figure 6.3.7). These results match those from analysis of accumulated material collected from D4 SR for metals and elements, where manganese was prevalent in the sample and iron was almost negligible (Chapter 6.1. – Figure 6.1.2). This finding could suggest that upon removing material from D4 SR during the clean, manganese was removed with it; hence, the concentration of this metal decreased at the SR outlet post clean, whereas iron levels in the bulk water did not change because there was almost no iron present in the material to remove.

In summary, cleaning D4 SR improved its performance in terms of it acting as a sink, instead of a source, of material, thus removing parameters that are known to cause water quality deterioration from entering the downstream network.

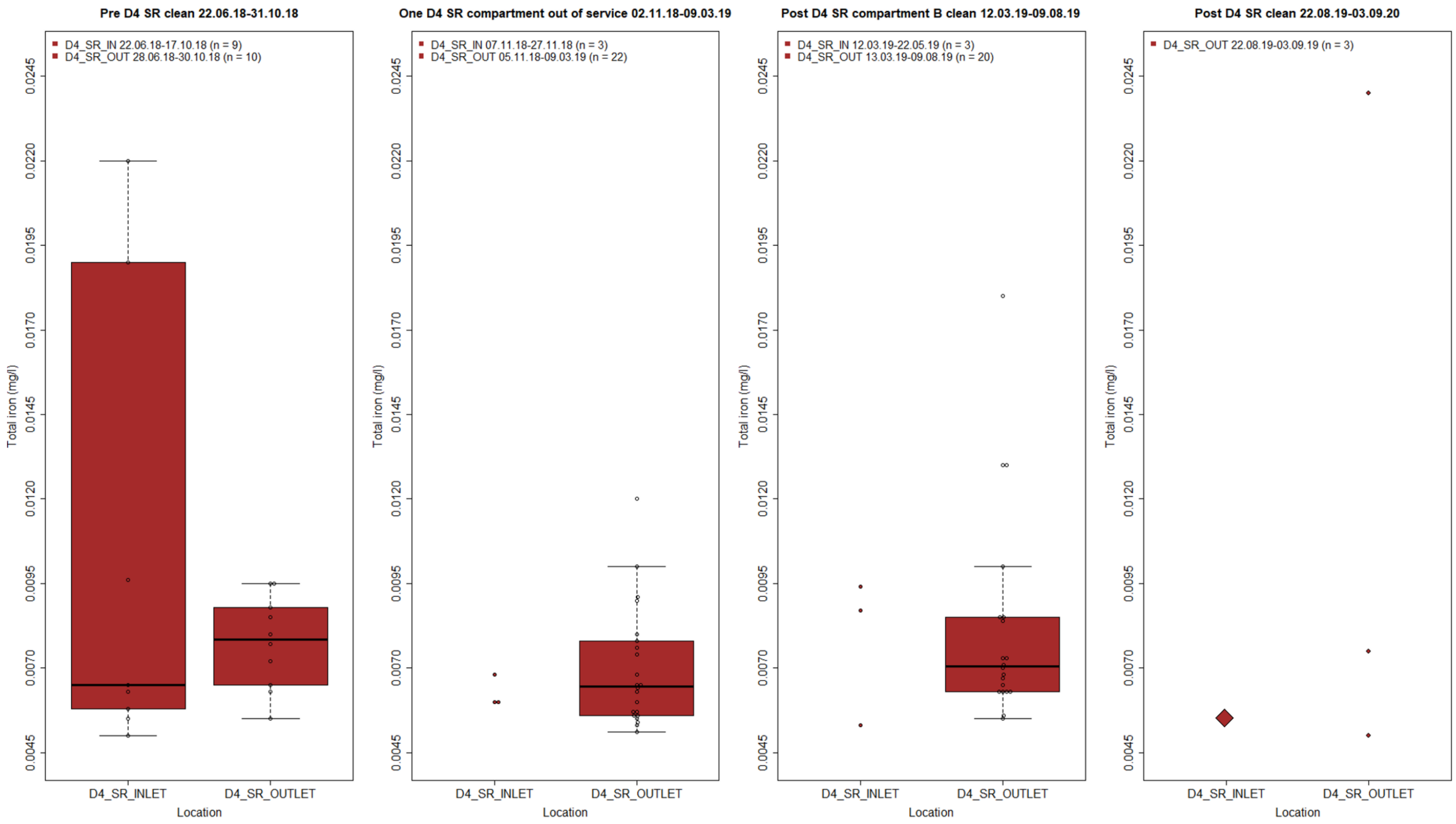


Figure 6.4.9 – Discrete total iron concentrations (mg/l) at the D4 SR across four time periods; pre D4 SR clean, with one compartment out of service, post D4 compartment B clean, and post entire D4 SR clean. In the fourth time period, all SR inlet values were below the minimum detection limit of 0.011 mg/l and are represented here as limit of detection/2 (0.0055 mg/l).

6.4.3. Finished water type

This section presents results from the investigation on how different finished water types could influence SR performance.

Based on the outcome of the performance ranking system described in Chapter 4: Methodology and Methods, presented in Table 6.4.2 below, results suggest that a comprehensive collation of information on finished water type can be useful in adding more detail to the information obtained from the SR performance metric. For instance, why one SR (e.g., A1 SR) is sinking more material than another SR (e.g., C3 SR), which, in this example, is likely related to the condition of the WTW outgoing water quality and material type of supplying trunk mains in the two networks. Using data on finished water type in this way is especially informative in the absence of any other sampling at SRs other than turbidity and regulatory chlorine and bacteriological indicators and could potentially be used to infer upstream network improvements. Information on finished water type is also helpful in comparing the performance of different networks and can potentially be used to help determine the order of network/asset maintenance.

Table 6.4.2 – **Collated information about project sites used to describe finished water quality type and how service reservoirs perform within their respective drinking water distribution systems. Sections in the table are assigned a colour based on a traffic light system that ranks performance of individual categories from best to worst, where the worst performing sites are highlighted in red, then orange, then yellow, then in green for the best.**

				WTW outgoing water quality 2018-2020							
		Supplying trunk main		TOC (mg/l)	Turbidity (NTU)	Al (mg/l)	Fe (mg/l)	Mn (mg/l)	SR inlet turbidity (NTU)	SR performance value	Normalised SR performance
Site	**Source water type**	**Length (km)**	**Material**	Average ± SD	Average ± SD	Average ± SD	Average ± SD	Average ± SD	Average ± SD	(Avg. sink value - NTU)	(/SR inlet turbidity avg.)
A1	Ground (borehole)	10.1	63% PE, 27% PVC, 10% DI	1.12 ± 0.07	0.06 ± 0.02	NA	0.013 ± 0.005	0.0011 ± 0.0002	0.14 ± 0.03	-0.054	-0.386
B2	Surface (river)	7.2	Two mains: ST and concrete lined DI	1.92 ± 0.28	0.11 ± 0.03	0.015 ± 0.010	0.005 ± 0.006	0.0023 ± 0.0025	NA	NA	NA
C3	Surface (reservoir)	50.0	ST for 22 km and unlined CI for 28 km	3.10 ± 2.56	0.31 ± 0.45	0.042 ± 0.018	0.0035*	0.0167 ± 0.0357	0.17 ± 0.21	0.038	0.224
D4	Surface (reservoir)	0.2	Cement lined DI	NA	0.05 ± 0.18	0.022 ± 0.015	NA	NA	0.13 ± 0.03	-0.029	-0.223

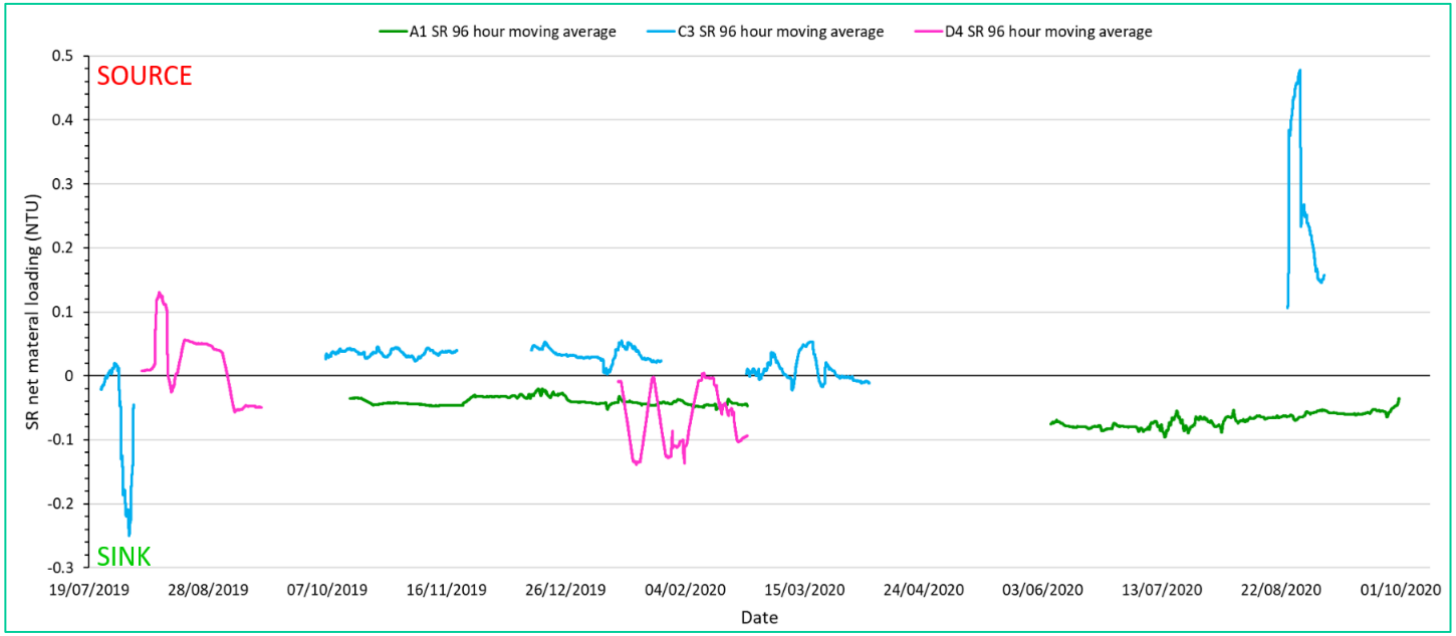


Figure 6.4.10 – **Continuous service reservoir net material loading (NTU) data at three SR sites, A1 (green), C3 (blue), and D4 (pink), from July 2019 to October 2020, plotted as a 96-hour moving average. This plot describes the performance of each SR in terms of it acting as a sink or source of material (NTU).**

6.4.4. Seasonality: temperature changes

This section presents results from the assessment on whether seasonal temperature changes have an influence on SR performance. Tables 6.4.3 and 6.4.4 below show descriptive statistics, percentage differences in water quality parameters sampled at the inlet and outlet of project SRs between cold weather (January to March) and warm weather (July to September) months, and the statistical significance between the data.

Table 6.4.3 – **Differences in the concentration of various water quality parameters at the inlet of project SRs between cold weather (January to March) and warm weather (July to September) months across 2018 to 2020. Values in blue indicate a negative percentage change and values in red indicate a positive percentage change.**

SERVICE RESERVOIR INLET																
		Cold weather (Jan-Mar)					Warm weather (Jul-Sep)									
Parameter	SR	n	Mean	Median	SD	RNG	n	Mean	Median	SD	RNG	% difference between the means	Test (T/W)	p-value	Statistically significant? (Y/N)
Chlorine (total) (mg/l)	B2	24	**1.06**	1.07	0.07	0.26	14	**0.95**	1.00	0.20	0.81	**-11.6%**	W	0.012	**Y**
	D4	11	**1.15**	1.18	0.12	0.41	6	**0.85**	0.96	0.35	0.84	**-35.3%**	T	0.099	**N**
Chlorine (free) (mg/l)	B2	24	**0.96**	0.98	0.11	0.51	14	**0.82**	0.89	0.21	0.76	**-17.1%**	W	0.001	**Y**
	D4	11	**1.10**	1.13	0.11	0.35	6	**0.78**	0.85	0.38	0.90	**-41.0%**	T	0.094	**N**
Flow cytometry (TCC) (cells per ml)	B2	22	**1839**	1409	1714	5980	10	**855**	823	329	1129	**-115.1%**	W	0.143	**N**
	C3	3	**12400**	9600	11264	22000	9	**207151**	201480	33321	107800	**94.0%**	T	<2.2^e-16	**Y**
Flow cytometry (ICC) (cells per ml)	B2	22	**274**	126	587	2768	10	**300**	295	91	329	**8.7%**	W	0.003	**Y**
	C3	3	**11133**	9200	10830	21400	9	**165422**	161480	20981	64680	**93.3%**	T	3.06^e-07	**Y**
Iron (total) (mg/l)	B2	5	**0.004**	0.004	0.002	0.004	3	**0.006**	0.003	0.005	0.008	**33.3%**	W	1.000	**N**
	C3	29	**0.079**	0.083	0.022	0.089	33	**0.206**	0.199	0.052	0.248	**61.7%**	W	1.78^e-11	**Y**
Manganese (total) (mg/l)	B2	23	**0.002**	0.002	0.001	0.004	14	**0.004**	0.004	0.003	0.009	**50.0%**	T	0.012	**Y**
	C3	27	**0.003**	0.003	0.001	0.003	33	**0.010**	0.009	0.005	0.026	**70.0%**	W	5.62^e-11	**Y**
	D4	8	**0.004**	0.003	0.002	0.005	6	**0.014**	0.012	0.010	0.027	**71.4%**	W	0.112	**N**
Organic carbon (total) (mg/l)	C3	5	**0.70**	0.70	0.10	0.20	9.00	**1.30**	1.30	0.10	0.20	**46.2%**	T	7.66^e-07	**Y**
Temperature (°C)	B2	24	**5.9**	5.9	0.9	3.1	14	**17.1**	17.6	1.3	3.7	**65.5%**	W	3.96^e-07	**Y**

Table 6.4.4 – Differences in the concentration of various water quality parameters at the outlet of project SRs between cold weather (January to March) and warm weather (July to September) months across 2018 to 2020. Values in blue indicate a negative percentage change and values in red indicate a positive percentage change.

SERVICE RESERVOIR OUTLET															
		Cold weather (Jan-Mar)					Warm weather (Jul-Sep)								
Parameter	SR	n	Mean	Median	SD	RNG	n	Mean	Median	SD	RNG	% difference between the means	Test (T/W)	p-value	Statistically significant? (Y/N)
Chlorine (total) (mg/l)	B2	34	**0.87**	0.88	0.15	0.78	36	**0.80**	0.80	0.15	0.88	**-8.7%**	W	0.015	**Y**
	D4	245	**1.02**	1.02	0.11	1.22	187	**0.85**	0.83	0.10	0.61	**-20.0%**	W	2.20^e-16	**Y**
Chlorine (free) (mg/l)	B2	34	**0.78**	0.78	0.14	0.75	36	**0.69**	0.69	0.50	0.88	**-13.0%**	W	0.0004	**Y**
	D4	245	**0.99**	0.98	0.11	1.19	187	**0.80**	0.79	0.10	0.66	**-23.8%**	W	2.20^e-16	**Y**
Flow cytometry (TCC) (cells per ml)	B2	17	**420**	222	412	1480	32	**1417**	638	1705	6695	**70.4%**	W	0.001	**Y**
	C3	3	**12000**	8800	11150	21600	10	**10464**	6700	8275	22960	**-14.7%**	W	0.937	**N**
Flow cytometry (ICC) (cells per ml)	B2	17	**107**	40	175	700	32	**516**	263	1004	5583	**79.3%**	W	2.77^e-05	**Y**
	C3	3	**1467**	1600	231	400	10	**3784**	368	1165	4480	**61.2%**	W	0.034	**Y**
Iron (total) (mg/l)	B2	7	**0.004**	0.002	0.007	0.018	13	**0.007**	0.005	0.007	0.020	**42.9%**	W	0.057	**N**
	C3	10	**0.109**	0.095	0.061	0.229	33	**0.186**	0.187	0.027	0.138	**41.4%**	W	0.0002	**Y**
	D4	20	**0.008**	0.007	0.004	0.019	12	**0.011**	0.009	0.005	0.019	**27.3%**	W	0.047	**N**
Manganese (total) (mg/l)	B2	18	**0.002**	0.002	0.001	0.002	22	**0.007**	0.003	0.018	0.085	**71.4%**	W	0.006	**Y**
	C3	10	**0.005**	0.004	0.004	0.014	33	**0.008**	0.007	0.003	0.014	**37.5%**	W	0.0001	**Y**
	D4	32	**0.003**	0.002	0.002	0.010	25	**0.005**	0.005	0.003	0.010	**40.0%**	W	0.001	**Y**
Organic carbon (total (mg/l)	C3	5	**0.70**	0.70	0.10	0.20	10.00	**1.30**	1.30	0.10	0.40	**46.2%**	W	0.002	**Y**
Organic carbon (dissolved) (mg/l)	D4	12	**0.70**	0.70	0.10	0.40	11.00	**1.40**	1.40	0.30	1.20	**50.0%**	W	0.0003	**Y**
Temperature (°C)	A1	24	**8.5**	8.6	0.6	2.6	40	**13.4**	13.4	0.5	2.2	**36.6%**	T	<2.2^e-16	**Y**
	B2	28	**6.1**	6.2	1.2	5.7	35	**17.4**	17.5	1.8	8.1	**64.9%**	T	<2.2^e-16	**Y**
	D4	246	**7.6**	7.6	1.4	14.1	187	**17.7**	17.2	1.9	8.5	**57.1%**	W	<2.2^e-16	**Y**

Results from discrete water quality samples above show that, on average, in warm weather:

- As expected, **chlorine residual decreased** at the inlet and outlet of B2 and D4 SRs, with a bigger change seen at D4 SR.
- Total cell count either decreased or increased at the inlet and outlet of B2 and C3 SRs, but the only statistically significant change is seen during an increase.
- **Intact cell count increased** at the inlet and outlet of B2 and C3 SRs.
- **Iron** and **manganese increased** at the inlet and outlet of all SRs, although changes in manganese were more likely to be statistically significant than iron, especially at SR outlets.
- Total and dissolved **organic carbon increased** at the inlet and outlet of C3 and D4 SRs.
- The lowest increase in temperature was at A1 SR, then D4 SR, and highest at B2 SR, which happens to be proportional to their capacities; 0.9 ML, 9.1 ML, and 90 ML respectively (Chapter 5: Site Details, Table 5.1).

Discrete turbidity data was not included in the above tables as no consistent pattern was observed in concentration change between cold and warm weather for this parameter. However, continuous turbidity data showed that A1 SR becomes more of a sink in warm weather, which can be seen as an improvement in its performance (See Chapter 6.3. – Figure 6.3.21). It is also important to acknowledge that there is a limitation in using discrete data for this type of assessment as sample numbers will always be low, with a maximum of 12 samples per season in a calendar year if data is collected on a weekly basis.

6.4.5. Summary

Results presented in this chapter have shown that SR performance can be affected by a number of factors, including the operation and performance of upstream assets, changes in hydraulic regimes, cleaning programmes, and seasonal changes in temperature. Results also highlighted that these factors are often confounding and that for clearer understanding of network and SR performance each factor and SR should be considered individually.

Chapter 7: Discussion

7.1. Service reservoir effect on water quality

7.1.1. Value of inlet monitoring at service reservoirs

A key aim of this research was to investigate how SRs affect drinking water quality. A big limitation of current practices and assessment of SRs is that water utilities are only regulated to sample water quality at SR outlets and only for disinfectant residual and bacteriological indicators. This does not provide much information about asset performance, aside from alerting to events that could pose a risk to water safety. Furthermore, the lack of sampling between WTW outlet and SR outlet makes it difficult to establish the origin of deterioration, which often leads to wrongly attributing the cause of water quality issues and failures to SRs. In this project, analysis of historical data collected at different stages of studied DWDSs revealed that even when other additional, non-regulated parameters are sampled for at SR outlets, data can only show that water quality changes between WTW and SR outlets, but this observed change cannot be attributed directly to SRs without inlet monitoring (Chapter 6.2.1.).

One of the most impactful and novel aspects of this research was the planned investigation involving the inclusion of inlet monitoring alongside outlet monitoring across multiple SRs for a variety of water quality parameters. This allowed for the first time the ability to differentiate between SR and upstream network performance and their individual effect on water quality, which fundamentally challenges where the location of water quality issues actually is. For example, in the B2 DWDS, the supplying trunk mains were identified as the likely source of increased iron (Figure 6.3.4) and WTW as the source of manganese (Figure 6.3.7). In the D4 DWDS, it was established that the supplying WTW is contributing excess material (lime) into the network, negatively impacting downstream water quality (section 6.3.1.3.3.). With the inclusion of inlet monitoring, it was also possible to observe that the SR in the D4 DWDS was actually acting as a beneficial treatment stage, removing the excess lime out of supply (Figure 6.3.22).

7.1.2. Monitoring flow and level at service reservoirs

The collection of flow and level data alongside water quality parameters at C3 SR showed that changing the operation of the fill drain cycle of a SR can potentially improve outgoing water quality (Chapter 6.4.2.2.). In this instance, changing from a pumped regime to a steady filling rate reduced concentrations of various incoming water quality parameters and subsequently resulted in the reduction of chlorine decay with travel through the SR. This observation demonstrates that the hydraulic operation of SRs can be managed in a way that results in the reduction of water quality deterioration with travel through these assets.

7.1.3. Analysis of service reservoir accumulated material

Characterisation of the inorganic and organic composition of SR accumulated material can be useful in identifying the origin of particulate matter and unexplored network issues, which is important in improving its management. For example, in this research, aluminium concentrations were higher than other metals in accumulated material collected from D4 SR (Figures 6.1.1 and 6.1.2), which could be an indication of excess carry-over of aluminium coagulant dosed at the supplying WTW, located only 0.2 km away (Figure 5.23). Material can also come from corrosion by-products and assessing its composition can help specify the source of corrosion. For example, in material collected from C9 SR, manganese concentrations were highest in the sample collected under the access ladder (Figure 6.1.5), which could suggest that the interaction of the corroded ladder with the surrounding bulk water is leading to the precipitation of manganese into the water supply as loose deposits (Cerrato et al., 2006). This knowledge could justify replacing the corroded ladder, which would be a proactive way of managing material deposits in this SR.

Observations above demonstrate that although accumulation of material is prevalent in SRs, the origin of this material and, therefore, the source of water quality deterioration does not necessarily stem from the SR itself. Most of the existing research on SR accumulated material is focused on its microbiological composition (e.g., Liu et al., 2014; Qin et al., 2017), and not on its inorganic and organic make-up. Where organic and inorganic composition of SR accumulated material has been characterised (e.g., Gauthier et al., 1996; Qin et al., 2017), findings are rarely linked to other stages of the DWDS.

7.1.4. Duration of time service reservoirs have been in service vs the likelihood of bacteriological failure occurrence

In this project, the association between older SRs and the increased likelihood of them experiencing a bacteriological failure was assessed. Analysis showed that there was no correlation between the duration of time an operational SR has been in service and the occurrence of bacteriological failures (Figure 6.2.6). Analysis also revealed instances where new SRs, no older than 20 years old, had experienced one or more bacteriological failures. A similar observation was made in a 2016 assessment of bacteriological failure rates in Severn Trent SRs, which uncovered that average failure rates occur at SRs an average 28 years after construction (Hope, 2016). This observation could potentially be related to poor construction of new SRs, resulting in structural issues, which could have led to bacteriological contamination through ingress. Alternatively, the root cause of the identified failures could have been upstream of the newer SRs but could not be identified due to lack of upstream sampling.

A limitation in the project data used was that some operational SRs that had experienced a bacteriological failure did not have a known construction age, inclusion of which could have altered some of the results. Nevertheless, results indicating that SR age does not correlate with bacteriological failure occurrence were unanimous across data from all water utilities in this project and this finding is supported in recent research, such as that by UKWIR (2019) who state that SR age does not always correlate with structural issues and failures.

In industry, the ingrained association of older SRs with ingress and risk of bacteriological contamination could be a consequence of most bacteriological failures being detected at SR outlets. For example, in 2020, there were 112 bacteriological failures at SR outlets, in comparison to 77 at WTW outlets and 15 at customer taps in England (DWI, 2020). At present, SR outlets are a convenient sampling point for bacteriological indicators in the DWDS, but just because a failure is identified there does not necessarily mean that the root cause of the issue is the SR itself as opposed to somewhere else in the upstream network.

7.1.5. Summary

With the current lack of understanding of SR performance and its effect on drinking water quality, the perception that SRs negatively affect water quality lacks supportive evidence. This work has shown that monitoring at both the inlet and outlet of SRs for a variety of water quality parameters and characterising the composition of SR accumulated material enables the assessment of SR performance and provides a great deal of valuable information concerning operations, treatment, and distribution, challenging the assumption that SRs always deteriorate water quality.

7.2. Service reservoir performance

7.2.1. Application of the sink or source model to service reservoir performance

Describing system performance in terms of sink or source behaviour has been shown to be valuable in other disciplines. In this research, exploring and expanding on the application of the sink or source model to SRs provided an effective way to assess and quantify SR performance, which has not been done before in this way. The definition of sink or source behaviour of material in SRs (Figure 4.22) coincided with that in other disciplines, where sink behaviour is generally considered good (e.g., carbon sequestration) and source behaviour bad (e.g., nutrient input into rivers) (Oechel et al., 1993; Ma et al., 2021), and this definition works in practice.

Applying the model to discrete sampling across different project sites has been beneficial in providing information on SR and upstream network performance with respect to mass balance of various parameters, whereby different parameters (regulatory and non-regulatory) provided a different insight. For instance, temperature data showed that bulk water heats up with travel through all project SRs (Figure 6.3.18). Although observed temperature increases are not as drastic as they might be in SRs located in areas of extreme weather, results challenge the assumption in the UK industry that buried SRs are not affected by changes in air temperature and are therefore not at risk from water quality issues associated with higher temperatures. Results also raise a potential need for awareness of temperature fluctuations in SRs, especially when considering the implications of climate change.

Discrete inlet and outlet sampling for turbidity and metals was valuable in determining SR performance in terms of sink or source of material. For example, turbidity sampling in the A1 DWDS showed that the SR is improving outgoing water quality by sinking suspended material (Figure 6.3.10). Conversely, manganese and iron data in the B2 DWDS showed that the SR is acting as a source, contributing both metals into the downstream network (Figures 6.3.4 and 6.3.7). Discrete iron sampling also highlighted water quality risk in C3 DWDS, where monitoring revealed that iron concentrations increased between WTW and SR outlet, regularly breaching PCV (Figures 6.3.5 and 6.3.6). High iron levels pose a risk to the aesthetic quality of the water supply and as iron is not a regulated parameter at SRs, it would not normally be possible to capture this risk (Husband and Boxall 2011). The trunk main supplying C3 SR has been identified as the source of excess iron and since this information alongside other water quality data was shared with Company C, a plan for the proactive management of this system has been put in place. This will be in the form of conditioning the supplying trunk main, which will likely reduce future discolouration risk and water quality failures in the C3 network, increasing public trust in the water supply and reducing penalty costs incurred by the utility from customer complaints.

Mass balance analysis of discrete data was effective in assessing SR performance at any given point in time, but it was not possible to use this data to monitor changes in performance over time. To achieve this, a metric that uses continuous inlet and outlet turbidity monitoring was developed for the assessment of SR performance in real-time by quantifying sink or source behaviour in terms of material loading. The application of this metric to project SRs has uncovered varying sink or source behaviours and has been able to provide actionable information on asset and network performance. At A1 SR, the metric revealed a temperature effect, whereby the SR is acting more of a sink in warmer months (Figure 6.3.20). At C3 SR, the metric showed that, from the start of project sampling, the SR gradually becomes more and more of a source of material over time (Figure 6.3.21). The metric also picked up regular fluctuations in D4 SR performance during the last three months of data collection (Figure 6.3.22), which, upon further investigation revealed that the supplying WTW is regularly overdosing lime, resulting in excess material entering the SR (section 6.3.1.3.3). Because D4 SR is acting as a sink of this incoming material, preventing it from reaching the outlet, it is not possible to see excess turbidity at the outlet, which means that it would not have been possible to capture the negative effect of lime overdosing without SR inlet monitoring or the performance metric. Additionally, with each increase in incoming excess material, it appears that the SR is acting as less and less of a sink and is gradually moving towards becoming a source. This change in sink to source behaviour suggests that the operation of the supplying WTW is having a direct, negative, effect on SR performance as the SR will likely become a source sooner than it would have without additional spikes in incoming material negating the positive effects of a recent SR clean. Furthermore, in this system, water quality data sampled at the outlet of D4 SR is taken as the final WTW data. Using the metric has exposed a reliability issue in using SR outlet as an indicator of final treated water as the SR has an influence (beneficial in this instance) on water quality. In addition, inlet turbidity monitoring also raises a potential problem with disinfection efficacy at this site. Incoming water is UV filtered at the inlet of D4 SR (Figure 5.24), but water containing a high number of suspended particles can hinder the effectiveness of UV disinfection (Chang et al., 1985).

A limitation of the metric is that it directly compares values at the inlet and outlet at the same point in time and although the applied moving average is used to smooth out influences of SR retention time, a more accurate representation of SR performance would be to shift the outlet values in accordance with retention time. Comparing inlet and outlet values at the same point in time can potentially result in the recorded sink/source behaviour to not be entirely accurate. For instance, when there was a hydraulic event at C3 SR, the concentration of incoming turbidity values dropped, and the metric recorded an increase in source behaviour of the SR during this time to a magnitude that was probably not entirely correct as there was a time lag between turbidity values dropping at the inlet and then the outlet (section 6.4.2.2.). However, a key reason for not shifting the outlet values by the retention time of project SRs is that accurate retention times are very difficult to obtain, requiring methods such as tracer studies and/or CFD modelling, which were not in the scope of being conducted in this project. Even if accurate retention times were obtained, retention is not a static value and is likely to change in a dynamic system like a DWDS. Additionally, the intended usage of the metric was to provide a general trend in SR performance over time, unaffected by changes in normal operation, but sensitive enough to alert to events that may otherwise go unnoticed by picking up a shift in SR performance in response to such events, which was achieved at each studied SR.

7.2.1.1. Turbidity as a surrogate measure for other water quality parameters

Results from discrete and continuous sampling above highlight the benefit of monitoring turbidity at SRs and using this parameter as a measure of asset and network performance. Since turbidity was of such value in this research, it was explored whether turbidity could potentially be a surrogate for other parameters. In literature, turbidity is considered to correlate strongly with iron and manganese (Seth et al., 2004; Douterelo et al., 2014). However, this relationship has not been studied in SRs. The sampling programme in this project made it possible to carry out correlational analysis between turbidity and metals. Results showed that the material of the supplying trunk main could be a key factor in influencing whether turbidity can be used as a surrogate measure for iron and manganese at SRs, whereby the relationship was present in systems with iron/steel trunk mains and absent in systems with plastic/cement lined mains (Table 6.3.2). The significance of the relationship seemed to depend on the length of the supplying trunk main or distance from the WTW. It was therefore concluded that the extent to which turbidity can be used as a surrogate for metals at SRs is influenced by both the material and the length of the supplying main. Therefore, care should be taken when associating turbidity with either iron or manganese at SRs, as the relationship is likely to be specific to each given SR, a finding that is supported by similar work on trunk mains by Seth et al. (2004) and Boxall and Husband (2010).

7.2.2. Monitoring flow and level at service reservoirs

The collection of flow and level data alongside water quality parameters at C3 SR made it possible to capture the influence of an operational event on water quality. A sudden change in inlet flow regime at the SR resulted in a decrease in concentrations of several key water quality parameters at the inlet, and subsequently the outlet of the SR, resulting in improved outgoing water quality (Chapter 6.4.2.2.). This finding demonstrated a clear link between flow and water quality, which is in line with the premise of the University of Sheffield's PODDS (Prediction of Discolouration in Distribution Systems) model, often applied in distribution networks to improve discolouration management through flow conditioning. This finding also supports a suggestion made in the literature that adjusting SR operating levels can improve water quality (Brand et al., 2004; AWWA, 2012), and that monitoring flow and level data at SRs can provide a more comprehensive assessment of asset performance (Grayman and Kirmeyer, 2000; UKWIR, 2019).

7.2.3. Benefits/limitations of different types of monitoring at service reservoirs

In this project, water quality monitoring was able to provide a comparison between the benefits and limitations of discrete and continuous sampling. Discrete sample data was useful in providing a snapshot of water quality at the time of collection and in understanding long-term SR behaviour, especially when there was a good variation of sampled parameters. However, discrete sampling is limited in that it is not possible to use this type of data for tracking real-time changes and developing events, making it difficult to alert, identify, or validate causes for water quality issues or changes in SR and network performance (Doronina et al., 2020). It is, however, possible to use continuous monitoring to capture and analyse water quality variation in real-time. Unlike discrete sampling, online monitoring is also able to capture changes in water quality across various demand patterns. The application of the performance metric to continuous turbidity data also meant that the effect of SR retention time was taken into account, something that is almost impossible to do with discrete sampling. These observations support suggestions in the literature that monitoring real-time changes in water quality at SRs would provide an enhanced operational insight into SR performance (Kirmeyer et al., 1999; ATi, 2021).

In terms of data collection, discrete sampling is done manually and is therefore more labour intensive than samples collected using online monitors. However, mirroring current discrete regulatory SR outlet monitoring at the inlet would not require a lot of additional time, as it would simply involve water utilities taking one extra sample from their SRs, although it would add to the expenditure on analysis (Doronina et al., 2020). Online continuous sampling produces immediate results, whereas discrete sampling requires a wait time for the sample to undergo analysis in the laboratory. However, the limitations of continuous sampling come with the cost of purchasing, installing, and maintaining equipment. Data can also take time to download and analyse. In addition, most online monitoring equipment relies on a constant power supply, which is rarely available at SRs. Although, in this research, many online turbidity monitors were deployed that did not require a power supply, and data showed that just several weeks of continuous turbidity data collected every few months provided more detailed information on changes in SR and network performance than discrete data did across years of sampling (Chapter 6.3.2.).

In this project, automatic sampling was employed as an innovative way to monitor water quality at SRs, providing the opportunity to collect discrete samples on a more continuous basis. Automatic samplers can also be used to collect discrete sample data out of working hours and allow for a snapshot analysis of water quality for parameters that would not usually be sampled for on a regular or regulatory basis. However, this method of sampling cannot be installed on a permanent basis as the volume of water automatic samplers can collect and battery life is limited. Automatic samplers are also difficult to set up on site without appropriate connections. Additionally, samples need to be collected from the automatic samplers manually and be sent to the lab for processing, which can be laborious and costly.

7.2.4. Analysis of service reservoir accumulated material

The sink or source model applied to SR performance in this project demonstrates that as long as a SR is acting as a sink of material (accumulating it) this improves downstream water quality. This finding challenges the assumption in the literature that SRs affect water quality negatively because accumulation of material is a prevalent process in these assets (Grayman and Kirmeyer, 2000). SR accumulated material is also rarely collected or analysed, which creates a missed opportunity to obtain valuable information on SR and network performance. For instance, the collection and analysis of SR accumulated material in this project provided an insight into the potential risks posed to the safety of the water supply if material was to remobilise; results from an experiment looking at the effect of material resuspension on chlorine decay rate showed that material exerted a high chlorine demand (Figures 6.1.10 to 6.1.12). This outcome was surprising considering collected material should have had previous and regular exposure to disinfectant, which would typically lead to the oxidation and reduced reactivity of any inorganic or organic matter. However, because samples were collected from the bottom of SRs, it is likely that bulk water disinfectant did not reach or penetrate the accumulated material. Remobilised material samples also frequently breached PCV for turbidity, even after 30 hours of settling time (Figure 6.1.9). These observed risks to water quality highlight the importance of tracking SR performance using the sink or source model, paying close attention to when the asset starts to become a source, as this is likely to be evidence of material resuspension.

7.2.5. Iron and manganese behaviour in service reservoirs

In this research, it was interesting to observe that the main metals identified in all collected SR material samples were aluminium, present in 100% of the samples, followed by manganese in 90%, copper in 74%, and zinc in 42% of the samples, whereas iron was only present in 13% of the samples (Figures 6.1.1 to 6.1.5). This finding contradicts current literature, which states that iron is the more predominant metal in the DWDS, both in bulk water and in accumulated material (e.g., Gauthier et al., 1996; Seth et al., 2004; Lytle et al., 2012). There are other examples in this project where a lower proportion of iron appears to settle and remobilise as loose deposits in SRs in comparison to manganese. For instance, cleaning D4 SR made no difference to outlet iron levels but did manganese, which aligns with the results from the analysis of the collected material sample from this SR, which contained almost no loose iron deposits but did manganese (Chapter 6.4.2.3). Higher manganese levels at SR outlets were observed during the pandemic, when water utilities started using SR outlets as alternative sampling points to customer taps for regulatory monitoring for metals (DWI, 2020). They found that they had less sample failures for iron, but a lot more sample failures for manganese. This suggests that iron potentially settles and remobilises more in pipes than SRs, and manganese settles and remobilises more in SRs than pipes. A similar observation highlighting different environments and consumption rates between pipes and SRs was made by Pick et al. (2021), who found that the concentration of assimilable organic carbon decayed through pipes but increased slightly with travel through SRs. In pipes, both manganese and iron accumulate in cohesive layers on pipe walls, assimilated into biofilms (Husband and Boxall, 2010). Potentially, the same thing is happening to iron in SRs, where it could be accumulating in biofilms on SR walls and internal structures, but not as loose deposits. There is reason to speculate about this based on the metals and elements composition in the outlier material sample (C7 MID. COMP. 2) that was likely exposed to biofilm-sloughing biocide, where not only was iron present, but concentrations also breached PCV (Figure 6.1.5). Aside from iron, manganese and aluminium concentrations were also high enough to breach PCV, and this was the only sample that contained arsenic, uranium, and lead. Biofilms are known to act as sinks for metals and elements, and perhaps certain metals and elements accumulate in biofilms on SR surfaces instead of settling out in their loose particulate forms. Concrete material, often used to construct SRs, or any coated SR surfaces, may accelerate biofilm growth, and it is reasonable to assume that these surfaces have similar adsorptive properties to those of pipes. The difference in surface type (material and area) and residence time of water between SRs and pipes may also influence pH, which can subsequently affect the speciation of metals at these stages of the DWDS. For instance, SRs tend to have longer residence times than pipes, which may allow for slower reactions to take place, like the oxidation of metals to their insoluble forms. In addition, concrete SRs can leach lime, which can increase the surrounding pH (a limiting factor in the oxidation of metals). Conversely, shorter residence times in pipes and often lower pH at pipe surfaces may result in the release of metals predominantly in their soluble, instead of insoluble, forms. Furthermore, pipes are often made from iron, which increases the likelihood of iron release and accumulation in this part of the DWDS. Although there is not enough evidence in this project to confirm these assumptions, there is a novelty and potential impact in the discovery of the difference in behaviour between manganese and iron in SRs in comparison to the rest of the DWDS and is worth exploring this thread further in future research.

7.2.6. Assessment of service reservoir performance as a gateway to proactive operational management

7.2.6.1. Informing the need for maintenance and proactive management

In this research, the information obtained on SR performance using both continuous and discrete monitoring made it possible to predict and prevent potential future issues, inform the need for maintenance, and lead to proactive management of both SRs and the upstream network. For example, at C3 SR, the application of the performance metric revealed that the SR was acting as a sink of material at the start of project sampling, but gradually became more and more of a source of material over time (Figure 6.3.21). Having been cleaned only a year prior to the commencement of project data collection, it was unanticipated that the accumulative capacity of C3 SR would exceed so quickly after the clean. C3 SR is not scheduled to be cleaned again until 2023, and with it already acting as a source of material, outgoing water quality is likely to only get worse over the years, putting the acceptance and the safety of the supply at risk. This information led to proactive measures being taken to improve upstream network performance through trunk main (identified source of water quality deterioration) conditioning and subsequent SR clean, thus likely improving SR performance (potentially promoting sink behaviour) and downstream water quality. At D4 SR, the application of the performance metric enabled the prediction of potential future issues by identifying deterioration in D4 SR performance over time in terms of its behaviour getting closer to the threshold of becoming a source of material before it had actually done so (Figure 6.3.22). At B2 SR, discrete water quality monitoring showed that the SR is acting as a source, contributing both manganese and iron into the downstream network (Figures 6.3.4 and 6.3.7). Such information about the performance of both D4 and B2 SRs could be used to justify the need for maintenance, either in the form of a SR clean, maintenance of the upstream network, or both, resulting in the proactive operational management of these assets and prevention of future issues.

Aside from assessing the structural condition of a SR during a physical inspection and identifying issues that could cause potential future water quality failures (e.g., broken access hatch), there is currently no method suggested in the literature of assessing SR performance in a way that would help to predict and prevent potential future issues in these assets. There are also limitations in relying on physical inspections to assess SR performance, which include the need to take SRs out of supply to conduct such inspections and the subjective nature of condition assessments. Whereas, using intentional and proactive continuous water quality monitoring at SRs provides a reliable indication of SR and network performance without the need to take the asset out of supply. However, there is benefit in taking a SR out of supply for inspection as information can be gained about the condition and performance of the asset that cannot be obtained from monitoring alone. For example, one of the SR accumulated material samples collected in this project contained zoological creatures (Figure 4.8), which are an indication of ingress. The SR in which they were found did go on to fail its flood test and the source of ingress was identified. However, flood tests are not always successful in identifying ingress. Therefore, the presence of flora and/or fauna in sampled material could serve as an indication of ingress, which, if not identified by a flood test, could be investigated further in other ways.

Irrespective of approach, moving towards a more proactive paradigm of assessing SR performance would improve operational management, reducing the occurrence of water quality failures, and decreasing costs in the long term. For instance, the whole SR cleaning procedure can cost water utilities up to £100,000 (Hope, 2016) and having the ability to detect and measure changes in SR condition and performance over time can inform appropriate maintenance frequencies, thus reducing costs on unnecessary cleans or reactive investigations (Ellis et al., 2018; Speight et al., 2019). Furthermore, additional costs in terms of effort and time can also be saved by managing the network proactively. The argument for allocating appropriate and site-specific SR cleaning frequencies is supported by UKWIR research (2019), who state that the current standard 'one-size-fits-all' approach to SR inspections is not practical.

7.2.6.2. Assessing the effectiveness of service reservoir maintenance

In this research, monitoring SR performance pre and post clean made it possible to measure and evaluate the effectiveness of SR maintenance. For example, at D4 SR, turbidity, manganese, and iron were monitored throughout the duration of its clean. Results showed that although the clean did not affect outgoing iron levels (Figure 6.4.9), D4 SR switched from contributing turbidity (Figure 6.3.22) and manganese (Figure 6.3.9) into the downstream network pre clean to retaining it post clean, suggesting that the clean improved performance by potentially restoring the capacity of D4 SR to accumulate material. At C3 SR, discrete sampling for chlorine residual pre and post clean showed that SR outlet chlorine residual increased after the clean, which could suggest that cleaning the SR decreased the rate of chlorine decay with travel through it, potentially in relation to the removal of material accumulated within (Figure 6.3.3). Currently, there is no literature that has looked at or outlined a method for measuring the effectiveness of a SR clean.

7.3. Summary

In summary, this research has made significant and novel contributions to knowledge on SR performance and its effect on water quality. Monitoring water quality at the inlet and outlet of SRs has led to the identification of sink or source behaviour in these assets and subsequently the development of a method to assess SR performance in terms of the quantification of sink or source behaviour where sink behaviour is considered beneficial and source behaviour detrimental to water quality. Work has also shown that there is great benefit in sampling for non-regulated parameters at SRs because these were able to provide information on SR and network performance that regulated parameters could not. The inclusion of inlet monitoring has also enabled the ability to differentiate between SR and upstream network performance, helping to identify the true location of water quality changes. Finally, research has shown that by monitoring and managing SRs properly and proactively, so that they do not turn into a source of material, SRs can act as beneficial treatment stages in the DWDS, protecting and improving downstream water quality.

A synthesis of key outputs from the various components of this work can be seen in Figure 7.1 below. The figure is set up as a flow diagram, which summarises information and practical values that can be obtained on SR and network performance when conducting different types of monitoring for various water quality parameters at SRs. The figure distinguishes between current practice and the novel approaches taken in this project, demonstrating the contribution to knowledge on SRs and the wider field of drinking water research.

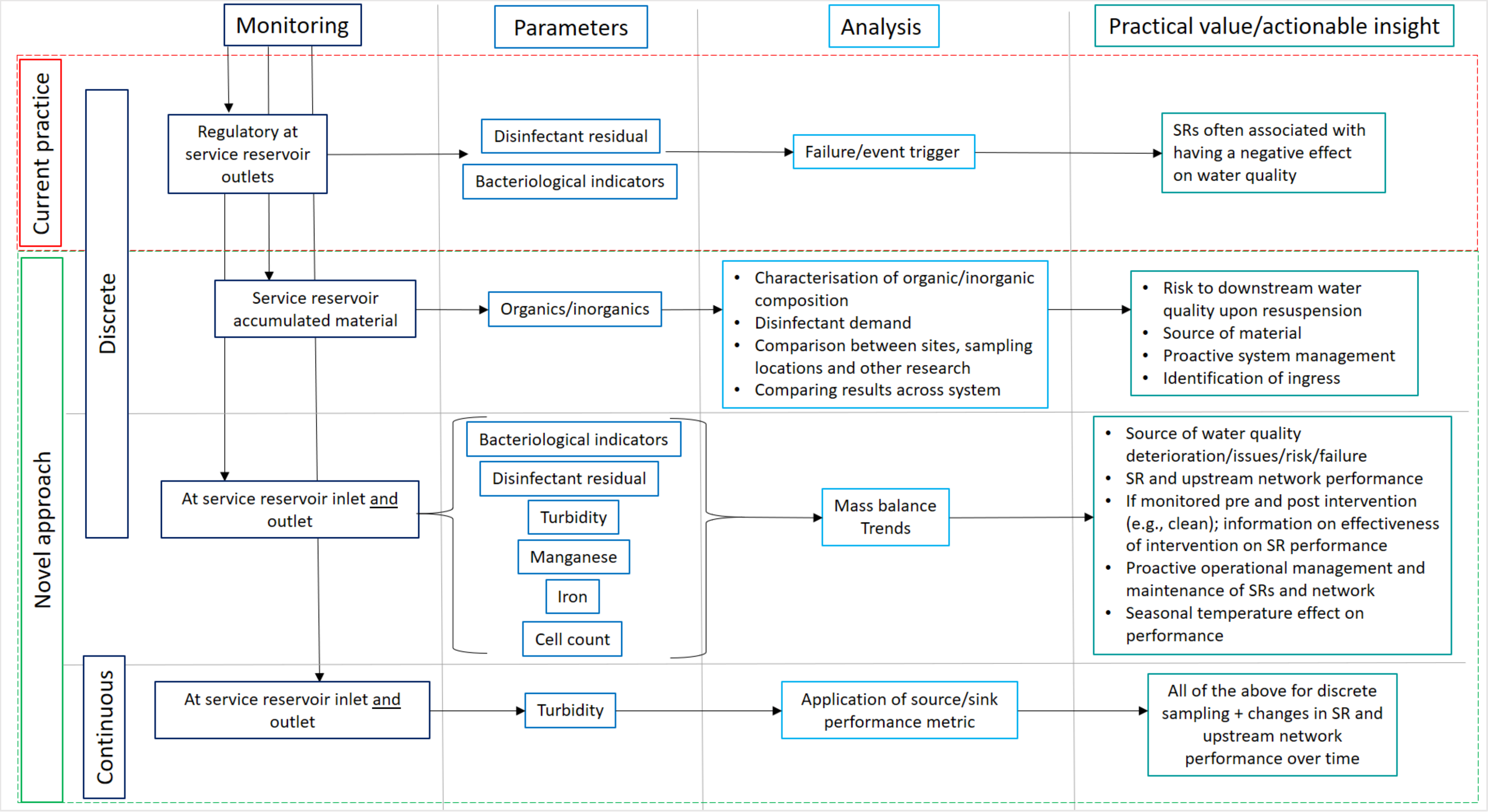


Figure 7.1 - A synthesis of practical values and insights that can be obtained on SR and network performance using different types of monitoring and analysis at service reservoirs.

7.4. Future research

Several future research questions and needs stem from the main findings in this project.

Continuous turbidity monitoring proved to be one of the most informative ways to measure SR and network performance. To expand this understanding further, it would be of value for future studies to investigate the possibility and value in assessing SR performance using monitoring for other continuous water quality parameters. For instance, continuous monitoring for disinfectant residual can allow for the assessment of disinfection loss between WTW and SR, with travel through the SR, and how the rate of this loss varies with SR turnover/mixing and pipeline flows, which can help inform water utilities on how to manage residual levels proactively in the DWDS. Another form of continuous monitoring worth exploring is FCM. In this project, FCM proved to be a more informative method of measuring SR performance in comparison to traditional methods, like HPC (Chapter 6.3.1.3.4.). Monitoring FCM continuously could capture trends in cell count over time and be used as a tool for proactive management of SRs and in identifying high-risk sites (DWI, 2018).

A more precise collection and assessment of SR accumulated material would enhance the knowledge obtained on the subject in this project. To do this, future research could involve the use of ROVs for sample collection, which would enable material to be collected without needing to take the SR out of service. ROVs are also able to collect water quality samples, which could be informative in mapping out water quality conditions, such as areas of stagnation within SRs, helping to identify potential water quality risks (Prest et al., 2013). In terms of the application of ROVs in industry, using this equipment has the potential to move the current SR cleaning approach from a standard frequency to a proactive one with frequency determined based on monitoring data. For instance, using an ROV for a quick clean of the SR could be done when performance indicates that this is a good option when SR cannot come out of service easily.

The difference in behaviour between manganese and iron in SRs in comparison to the rest of the DWDS identified in this research is worth exploring further in future research as more accurate findings could fundamentally change the understanding of how the water quality risks posed by these two metals (e.g., discolouration) manifests in SRs. This information could then be used to help inform a targeted approach specific to SRs for proactive management of those risks. It is proposed that the first step in this research would be to sample and characterise the composition of inorganic and organic constituents in SR biofilms and SR accumulated loose deposits and compare the results to identify whether there is a significant difference in composition.

Chapter 8: Conclusions

Research overview:

This research has made significant contributions to the limited knowledge on SR performance and its effect on water quality through the means of a carefully planned, extensive monitoring programme at the inlet and outlet of four project SRs. A key novel contribution from the work is the development and successful application of the 'sink or source' concept to the process of material loading in SRs, and the creation of an effective metric to quantify such sink or source behaviour using continuous turbidity data, providing a practical way to assess and quantify SR performance with changes over time. Applying the metric, in combination with comprehensive water quality monitoring, enabled, for the first time, the ability to evidence the effectiveness of asset maintenance in improving SR performance and demonstrated that SRs often act as beneficial treatment stages, depending on how they are managed. With the ability to assess SR performance over time and identify sources of deterioration, it is now possible for water utilities to make proactive, justifiable, and targeted decisions on the location and frequency of network maintenance and management, ensuring that interventions address water quality issues at their origin, preventing future reactive investigations and maintaining safety of supply.

Main conclusions:

1. It was proven that the development and application of the sink or source concept to SRs works in describing SR performance in terms of material loading, where sink behaviour is an indication of good asset performance and a switch to source behaviour is an indication of deterioration in asset performance.
2. An innovative metric was developed to assess and quantify sink or source behaviour in SRs using continuous turbidity data, providing a practical and effective way to assess a general trend in SR performance over time.
3. Applying the metric revealed how SR performance can deteriorate and, in combination with comprehensive water quality monitoring, enabled, for the first time, the ability to evidence the effectiveness of asset maintenance in improving SR performance.
4. It was established that inlet monitoring at SRs is essential for the assessment of, and differentiation between, SR and upstream network performance, and has been used to identify the location of water quality deterioration.

5. Monitoring water quality parameters that are not currently regulated at SRs (in this project Fe, Mn, NTU, and cell counts) is essential to the understanding of SR and network performance in terms of sink or source behaviour.
6. Information obtained on SR performance challenges the assumption in literature that SRs always deteriorate water quality and shows that more often than not SRs improve water quality, mitigating and highlighting previously unseen upstream network issues.
7. Contrary to popular belief, detailed analysis showed that the duration of time a SR has been in service does not increase the likelihood of bacteriological failure occurrence at the outlet.
8. SR accumulated material analysed in this project was shown to be low in organic content, yet exerted a high chlorine demand upon remobilisation, which supports the definition of source behaviour in SRs as being detrimental to water quality.
9. Discrete iron and manganese sampling and analysis of SR accumulated material undertaken in this project has indicated that manganese accumulates as loose deposits within SRs, creating a risk of higher concentrations if remobilised, whereas iron appears not to settle.
10. A flow diagram was created that can be used as a systematic guide on how to obtain desired information about SR and network performance when conducting different types of monitoring for various water quality parameters at SRs. This diagram also provides a comparison between the benefits and limitations of conducting different types of monitoring at SRs, contributing to the limited knowledge on the subject.

Epilogue

"Anyway, you are a lot more confident and charming than me, you will smash it…"

Dr Grigorios Kyritsakas

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Appendix 1

Service Reservoir Material Sampling Protocol

Equipment:

- Personal Protective Equipment (PPE):
    - PPE wellies
    - PPE boots
    - Hardhat
    - Goggles
    - Gloves
    - Coveralls
    - High visibility vest/top/jacket
    - Gas monitor
    - Ear protectors
- National Hygiene Card
- Sampling equipment:
    - 1L HDPE plastic bottle – sterile (food grade) – per sample
    - Sterile scoop – 100ml min – sterile (food grade) – per sample
    - Cooler box
    - Freezer packs for cooler box

Training:

- Essential: National hygiene course.
- Essential: Confined space training.
- Recommended: Outdoor first aid training.

Protocol:

Before:

- Complete a site-specific risk assessment.
- Freeze the freezer packs prior to setting off and put these inside the cooler box.

- Upon arrival on site:
  - Put on the following PPE: boots, high visibility vest/top/jacket, hardhat, and goggles.
  - Familiarise yourself with the configuration of the service reservoir.
  - Discuss plan of action for the inspection/clean with the contractors/team leader on site.
- Prepare the necessary sampling equipment on the designated work area.
- Prior to entry into the service reservoir put on the following PPE: wellies, hardhat, gloves, coverall, goggles, and gas monitor. Ear protectors may also be necessary – see risk assessment.
- For entry into the service reservoir, follow specified hygienic practice guidance, which should be prepared by the party responsible for carrying out the SR cleaning operation. Figure a provides an example of what the SR entry set up should look like.

Figure a – An example of what a hygienic SR set up should look like.

During:

- Read this section fully before proceeding.
- Once safely in the service reservoir, lower the required sampling equipment (bottles and scoops).
- Assess the amount of material available for collection and the locations of the inlet, outlet, and overflow of the tank. Make physical notes on the location, amount, and type of material accumulation (if any) in the tank, when feasible. The condition of the structural components

of the tank should be recorded in the inspection report issued by the party responsible for the service reservoir clean.

- If the tank is rectangular or square:
    - Collect a sample from each corner, the middle, and the floor around the outlet of the tank (if possible/appropriate).
- If the tank is circular/donut in shape:
    - Envision a triangle in the tank; collect a sample at each point of the triangle along the outside wall. Reverse the triangle and collect a sample at each point of the triangle in the middle of the tank. Collect a sample from the floor under the outlet (if possible/appropriate).
- If the tank is semi-circular in shape (one compartment of a two-compartment circular tank):
    - Envision a triangle in the tank; collect a sample at each point of the triangle along the outside wall. Collect a sample around the inlet and a sample around the outlet (if possible/appropriate) and a sample from the middle of the tank.
- Figure b provides an example of what the above scenarios might look like.
- Rinse scoop using subject SR water between each sample bottle or, ideally, use a different scoop each time.
- Record where each sample was collected by labelling the bottles with a permanent marker.

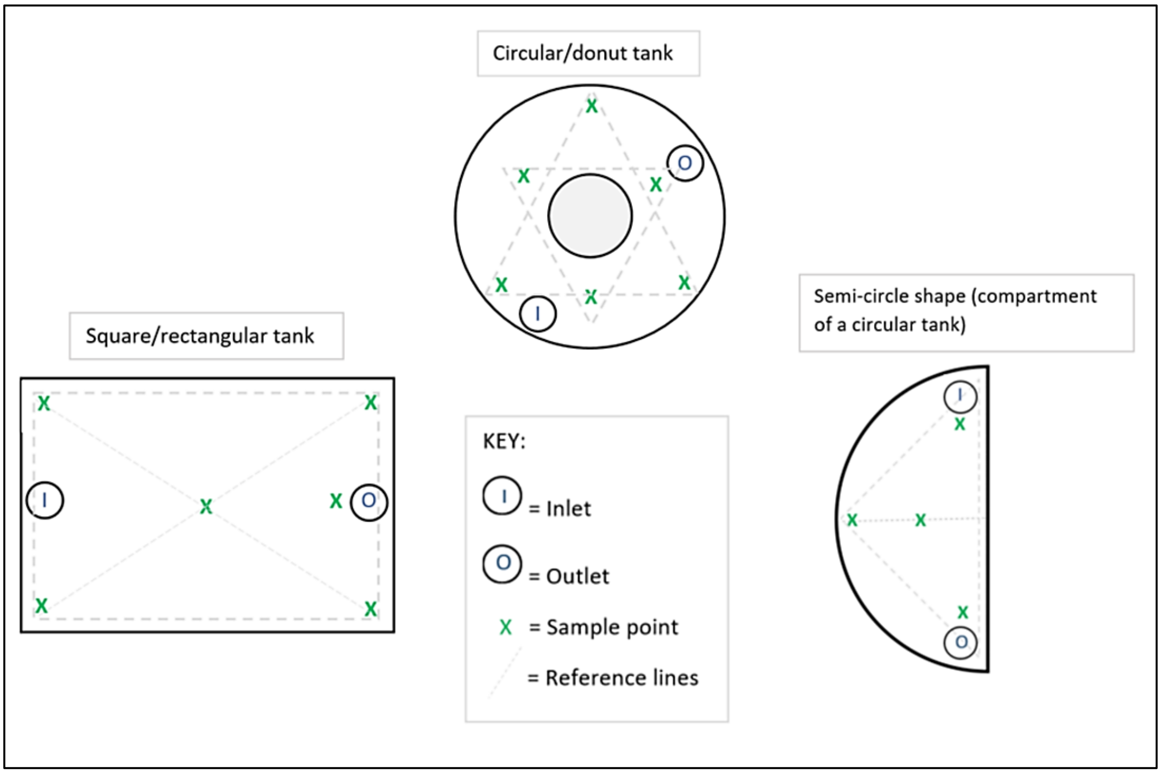

Figure b – A diagram showing potential sampling locations in a rectangular/square/circular/donut service reservoir tank.

- Amount of material to collect:
    - Ideal scenario: minimum 250g (1/4) maximum 500g (1/2) per litre bottle, with the rest of the bottle filled with service reservoir water.
    - If material is limited, collect as much as possible per bottle, and fill the rest with service reservoir water.
    - If no water remains in the service reservoir upon sampling, collect the material without.
- Once the desired material is collected, ensure that the lids on all sample bottles are securely shut and raise these, along with the used/unused sampling scoops, out of the service reservoir.
- Safely exit the service reservoir.

After:

- Immediately put all of the collected sample bottles into the prepared cooler box and shut securely. Samples must be kept at low temperatures, ideally below 10 °C.
- Safely discard any used sampling scoops, disposable latex gloves, disposable coveralls, and damaged sampling bottles (if any).
- Change back into the original PPE if remaining on site.
- When leaving site transport the samples to a fridge as soon as possible and keep below 10 °C until required for analysis, (samples should be analysed as soon as possible).

NB: In practice, shaking/mixing of the sample contents has not been found to influence the results of analysis for organic carbon, UV/absorbance, and metals. Nevertheless, care should still be taken to keep bottles upright.

Appendix 2

Table a – Dates, locations, and sample numbers for historical, supporting background, and discrete/continuous project water quality data collected in the A1 DWDS. Grey shading indicated areas with no available data.

Site: A1

Parameter	Historical data[7]			Supporting background data[8]			Discrete/continuous data at SR[9]		
	Date	Location	Number	Date	Location	Number	Date	Location	Number
Aluminium							07.19 – 11.19 09.19 – 12.19	SR INLET SR OUTLET	5 7
Chlorine (free)	01.12 – 12.17	WTW	581	01.18 – 12.19 01.18 – 02.20	WTW WQZ	106 55	06.19 – 12.19 04.18 – 12.20	SR INLET SR OUTLET	29 165
Chlorine (MetriNet) (free)							11.19 – 09.20 11.19 – 09.20	SR INLET SR OUTLET	347282 348870
Chorine (total)	01.12 – 12.17	WTW	581	01.18 – 12.19 01.18 – 12.19	WTW WQZ	106 55	06.19 – 12.19 04.18 – 12.20	SR INLET SR OUTLET	29 165
Chlorine (MetriNet) (total)							11.19 – 09.20 11.19 – 09.20	SR INLET SR OUTLET	347282 348870
Conductivity	01.12 – 12.17 01.12 – 12.17	RAW WTW	94 70	04.18 – 05.20 02.18 – 12.19	RAW WTW	27 24	06.19 – 12.19 04.18 – 10.20	SR INLET SR OUTLET	29 31
Conductivity (MetriNet)							10.19 – 09.20 10.19 – 09.20	SR INLET SR OUTLET	367448 368398
Flow cytometry (ICC)							01.20 – 02.20	SR OUTLET	6
Flow cytometry (TCC)							01.20 – 02.20	SR OUTLET	6

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[7] Pre January 2018 company-wide and site-specific data that does not include SR inlet samples.

[8] January 2018 onwards site-specific data that does not include SR inlet or outlet samples.

[9] January 2018 onwards site-specific SR inlet and outlet samples only.

Iron	01.12 – 12.17	RAW	371	11.19 – 07.20 02.18 – 12.19 01.18 – 02.20	RAW WTW WQZ	39 25 53	06.19 – 12.19 06.19 – 10.20	SR INLET SR OUTLET	29 30
Manganese	01.12 – 12.17	RAW	371	04.18 – 07.20 09.19 – 12.19 01.18 – 02.20	RAW WTW WQZ	183 4 53	06.19 – 11.19 06.19 – 09.19	SR INLET SR OUTLET	3 3
Organic carbon (total)	06.12 – 10.17	RAW	9	09.18 – 08.19 08.19 – 12.19	RAW WTW	3 8			
pH	01.12 – 10.17	RAW	20	01.18 – 05.20 08.19 – 12.19 02.18 – 02.20	RAW WTW WQZ	15 21 25	06.19 – 12.19 04.18 – 10.20	SR INLET SR OUTLET	29 31
Temperature (water)	01.12 – 12.17 01.12 – 12.17 01.12 – 12.17	RAW WTW SR OUTLET	213 578 310	01.18 – 07.20 01.18-12.19 01.18 - 02.20	RAW WTW WQZ	113 104 57	06.19 – 12.19 04.18 – 12.20	SR INLET SR OUTLET	29 147
Temperature (MetriNet)							09.19 – 09.20 09.19 – 09.20	SR INLET SR OUTLET	398359 399952
Turbidity	01.12 – 12.17 01.12 – 12.17	RAW WTW	375 242	01.18 – 07.20 01.18 – 12.19 01.18 – 02.20	RAW WTW WQZ	187 92 55	06.19 – 12.19 04.18 – 11.19	SR INLET SR OUTLET	26 27
Turbidity (MetriNet)							10.19 – 09.20 10.19 – 09.20	SR INLET SR OUTLET	378036 378900

Table b – Dates, locations, and sample numbers for historical, supporting background, and discrete/continuous project water quality data collected in the B2 DWDS. Grey shading indicated areas with no available data.

Site: B2

Parameter	Historical data7			Supporting background data8			Discrete/continuous data at SR9		
	Date	Location	Number	Date	Location	Number	Date	Location	Number
Aluminium	06.17 – 12.17 01.11 – 12.17 01.07 – 12.17	RAW WTW SR OUTLET	12 842 121	05.18 – 04.20 01.18 – 08.20 01.18 – 12.19	RAW WTW WQZ	24 265 22	10.18 – 07.20 05.19 – 06.20	SR INLET SR OUTLET	30 27

	01.04 – 12.17	WQZ	311						
Chlorine (free)	01.07 – 12.17	WTW	2943	01.18 – 09.20	WTW	1010	10.18 – 08.20	SR INLET	95
	01.07 – 12.17	SR OUTLET	635	01.18 – 10.19	WQZ	114	01.18 – 09.20	SR OUTLET	133
	01.04 – 12.17	WQZ	623						
Chorine (total)	01.07 – 12.17	WTW	2943	01.18 – 09.20	WTW	1010	10.18 – 08.20	SR INLET	95
	01.07 – 12.17	SR OUTLET	638	01.18 – 01.20	WQZ	115	01.18 – 09.20	SR OUTLET	134
	01.04 – 12.17	WQZ	623						
Conductivity	07.08 – 07.17	SR OUTLET	22	08.18 – 04.20	RAW	19	10.18 – 08.20	SR INLET	95
	01.04 – 12.17	WQZ	311	01.18 – 09.20	WTW	164	01.20 – 08.20	SR OUTLET	34
				01.18 – 12.19	WQZ	71			
Flow cytometry (ICC)	05.16 – 12.17	SR OUTLET	15	01.18 – 09.20	WTW	399	10.18 – 08.20	SR INLET	63
							01.18 – 08.20	SR OUTLET	97
Flow cytometry (TCC)	05.16 – 12.17	SR OUTLET	15	01.18 – 09.20	WTW	399	10.18 – 08.20	SR INLET	63
							01.18 – 08.20	SR OUTLET	97
Iron	06.17 – 12.17	RAW	12	02.18 – 04.20	RAW	28	10.18 – 07.20	SR INLET	32
	01.07 – 12.17			01.18 – 08.20	WTW	243	01.18 – 08.20	SR OUTLET	48
	01.07 – 12.17	WTW	1589	01.18 – 12.19	WQZ	22			
	01.04 – 12.17	SR OUTLET	121						
		WQZ	311						
Manganese	06.17 – 12.17	RAW	12	02.18 – 04.20	RAW	28	10.18 – 08.20	SR INLET	94
	01.07 – 12.17	WTW	1920	01.18 – 09.20	WTW	444	01.18 – 08.20	SR OUTLET	80
	01.07 – 12.17	SR OUTLET	126	01.18 – 12.19	WQZ	22			
	01.04 – 12.17	WQZ	311						
Organic carbon (total)	01.15 – 12.17	WTW	119	06.18 – 04.20	RAW	80			
				01.18 – 09.20	WTW	117			
pH	07.08 – 07.17	SR OUTLET	47	05.18 – 04.20	RAW	21	10.18 – 08.20	SR INLET	95
	01.04 – 12.17	WQZ	311	01.18 – 09.20	WTW	454	01.20 – 08.20	SR OUTLET	34
				01.18 – 12.19	WQZ	82			
Temperature (water)	01.07 – 12.17	SR OUTLET	155	08.18 – 04.20	RAW	18	10.18 – 08.20	SR INLET	95
				01.18 – 09.20	WTW	139	01.18 – 09.20	SR OUTLET	127
Turbidity	01.07 – 09.17	WTW	2742	05.18 – 04.20	RAW	21	10.18 – 02.20	SR INLET	24
	01.07 – 07.17	SR OUTLET	105	01.18 – 06.20	WTW	662	08.18 – 08.20	SR OUTLET	30
	01.04 – 12.17	WQZ	311	01.18 – 01.20	WQZ	84			

Turbidity (SWAN)							09.18 – 08.20	SR INLET	4655

Table c – Dates, locations, and sample numbers for historical, supporting background, and discrete/continuous project water quality data collected in the C3 DWDS. Grey shading indicated areas with no available data.

Site: C3

Parameter	Historical data[7]			Supporting background data8			Discrete/continuous data at SR9		
	Date	Location	Number	Date	Location	Number	Date	Location	Number
Aluminium	01.08 - 12.12 01.08 – 12.17 01.08 – 12.17	RAW WTW WQZ	310 292 236	01.18 - 06.20 01.18 - 06.20 01.18 – 06.20	RAW WTW WQZ	132 107 74	07.19 & 02.20 07.19 & 02.20	SR INLET SR OUTLET	47 28
Chlorine (free)	01.08 – 12.17 01.08 – 12.17 01.08 – 12.17	WTW SR OUTLET WQZ	5013 485 649	01.18 - 06.20 01.18 – 06.20	WTW WQZ	898 198	07.19 – 11.20 01.18 – 11.20	SR INLET SR OUTLET	6 146
Chlorine (total)	01.08 – 12.17 01.08 – 12.17 01.08 – 12.17	WTW SR OUTLET WQZ	5012 484 649	01.18 - 06.20 01.18 – 06.20	WTW WQZ	898 198	09.19 – 11.20 01.18 – 11.20	SR INLET SR OUTLET	22 150
Conductivity	02.08 – 09.13 05.09 – 09.14 02.08 – 12.17	RAW WTW WQZ	21 8 209	08.18 – 07.19 11.18 – 05.20 02.18 – 06.20	RAW WTW WQZ	14 10 61	09.19 – 11.20 09.19 – 11.20	SR INLET SR OUTLET	73 55
Flow cytometry (ICC)							09.19 – 11.20 09.19 – 11.20	SR INLET SR OUTLET	23 24
Flow cytometry (TCC)							09.19 – 11.20 09.19 – 11.20	SR INLET SR OUTLET	23 24
Flow cytometry (TCC) (BactoSense)							04.20 – 11.20	SR OUTLET	969
Iron	01.08 - 12.17 07.08 – 10.17 01.08 – 12.17	RAW WTW WQZ	432 31 128	01.18 – 06.20 10.18 – 10.20 01.18 – 12.20	RAW WTW WQZ	121 19 39	09.19 – 11.20 09.19 – 11.20	SR INLET SR OUTLET	73 57

Manganese	01.08 – 12.17	RAW	453	01.18 – 06.20	RAW	121	09.19 – 11.20	SR INLET	73
	01.08 - 12.17	WTW	284	01.18 – 06.20	WTW	108	09.19 – 11.20	SR OUTLET	57
	01.08 – 12.17	WQZ	236	01.18 – 06.20	WQZ	74			
Organic carbon (total)	03.12 – 12.17	RAW	229	01.18 – 06.20	RAW	235	09.19 – 11.20	SR INLET	26
	03.12 – 12.17	WTW	102	01.18 – 06.20	WTW	68	09.19 – 11.20	SR OUTLET	27
	03.10 – 11.17	WQZ	30	02.18 – 06.20	WQZ	7			
pH	01.08 - 12.17	RAW	318	01.18 – 06.20	RAW	120	09.19 – 11.20	SR INLET	73
	01.08 - 12.17	WTW	285	01.18 – 06.20	WTW	109	09.19 – 11.20	SR OUTLET	53
	02.08 – 12.17	WQZ	209	02.18 – 06.20	WQZ	61			
Temperature (water)							09.19 – 03.20	SR INLET	6
							09.19 – 03.20	SR OUTLET	7
Turbidity	01.08 – 12.17	RAW	306	01.18 – 03.20	RAW	116	09.19 – 03.20	SR INLET	59
	01.08 - 12.17	WTW	3245	01.18 – 06.20	WTW	782	09.19 – 03.20	SR OUTLET	41
	02.08 – 12.17	WQZ	209	02.18 – 06.20	WQZ	61			
Turbidity (NephNet)							07.19 – 09.20	SR INLET	252900
							07.19 – 09.20	SR OUTLET	259407

Table d – Dates, locations, and sample numbers for historical, supporting background, and discrete/continuous project water quality data collected in the D4 DWDS. Grey shading indicated areas with no available data.

Site: D4

Parameter	Historical data7			Supporting background data8			Discrete/continuous data at SR9		
	Date	Location	Number	Date	Location	Number	Date	Location	Number
Aluminium	01.17 – 12.17	WTW	35024	01.18 – 02.20	WTW	73472	06.18 – 01.20	SR INLET	134
	01.08 – 12.17	SR OUTLET	537	10.18 – 01.20	WQZ	59	01.18 – 01.20	SR OUTLET	148
Chlorine (free)	01.08 – 12.17	SR OUTLET	1935	10.18 – 02.20	WQZ	155	06.18 – 01.20	SR INLET	137
							01.18 – 02.20	SR OUTLET	1095
Chorine (total)	01.08 – 12.17	SR OUTLET	1935	10.18 – 02.20	WQZ	155	06.18 – 01.20	SR INLET	137
							01.18 – 02.20	SR OUTLET	1095

Conductivity	01.17 - 12.17	RAW	35022	01.18 – 02.20 01.18 – 02.20 10.18 – 02.20	RAW WTW WQZ	48594 73465 50	06.18 – 01.20 02.18 – 01.20	SR INLET SR OUTLET	136 35
Flow cytometry (ICC)							10.19 – 01.20 04.19 – 02.20	SR INLET SR OUTLET	22 127
Flow cytometry (TCC)							10.19 – 01.20 04.19 – 02.20	SR INLET SR OUTLET	23 133
Iron	01.08 – 12.17	SR OUTLET	277	10.18 – 01.20	WQZ	56	06.18 – 05.19 01.18 – 09.19	SR INLET SR OUTLET	15 64
Manganese	01.08 – 12.17	SR OUTLET	535	10.18 – 01.20	WQZ	57	06.18 – 01.20 01.18 – 01.20	SR INLET SR OUTLET	134 147
Organic carbon (dissolved)	04.08 – 12.17	SR OUTLET	45				 01.18 – 01.20	SR INLET SR OUTLET	 45
pH	01.17 – 12.17 01.17 – 12.17 01.08 – 12.17	RAW WTW SR OUTLET	35022 35022 281	01.18 – 02.20 01.18 – 02.20	RAW WTW	48594 73464	06.18 – 01.20 01.18 – 01.20	SR INLET SR OUTLET	90 89
Temperature (water)	01.08 – 12.17	SR OUTLET	1926	10.18 – 02.20	WQZ	152	10.18 – 06.19 01.18 – 02.20	SR INLET SR OUTLET	93 1017
Turbidity	01.17 – 12.17 01.17 – 12.17 01.08 – 12.17	RAW WTW SR OUTLET	35022 35022 1975	01.18 – 02.20 01.18 – 02.20 10.18 – 01.20	RAW WTW WQZ	48594 73465 51	06.18 – 01.20 02.18 – 01.20	SR INLET SR OUTLET	36 144
Turbidity (NephNet)							08.19 – 02.20 08.19 – 02.20	SR INLET SR OUTLET	136004 134903

Appendix 3

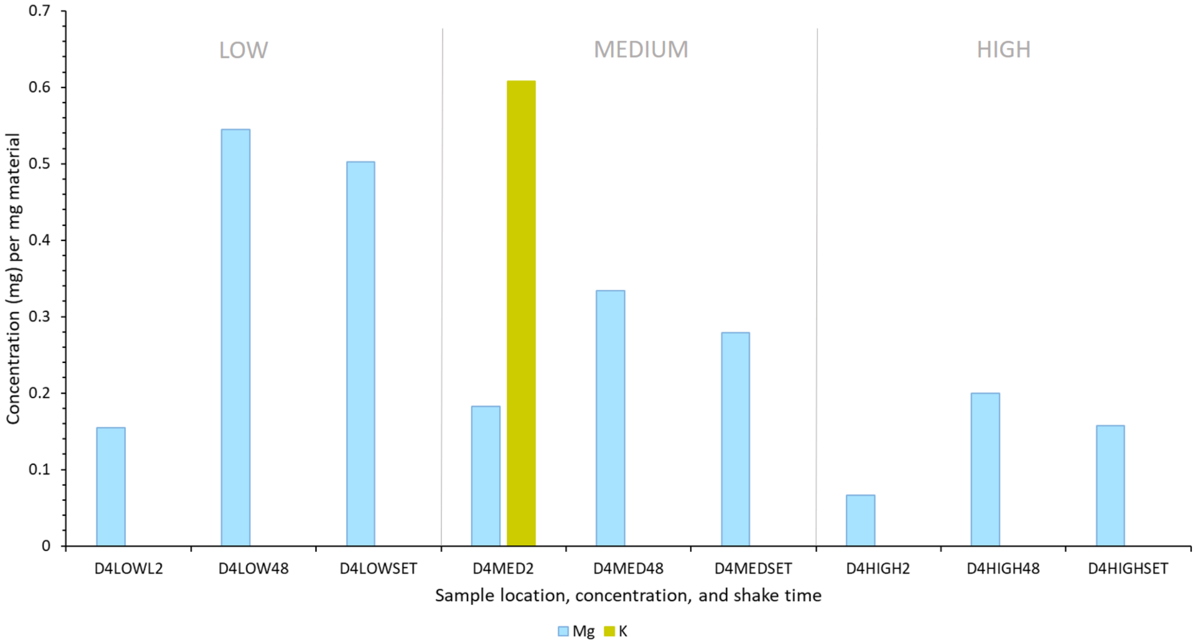

Figure a – **Magnesium and potassium concentrations (mg) per mg of varying concentrations of material collected from D4 SR.**

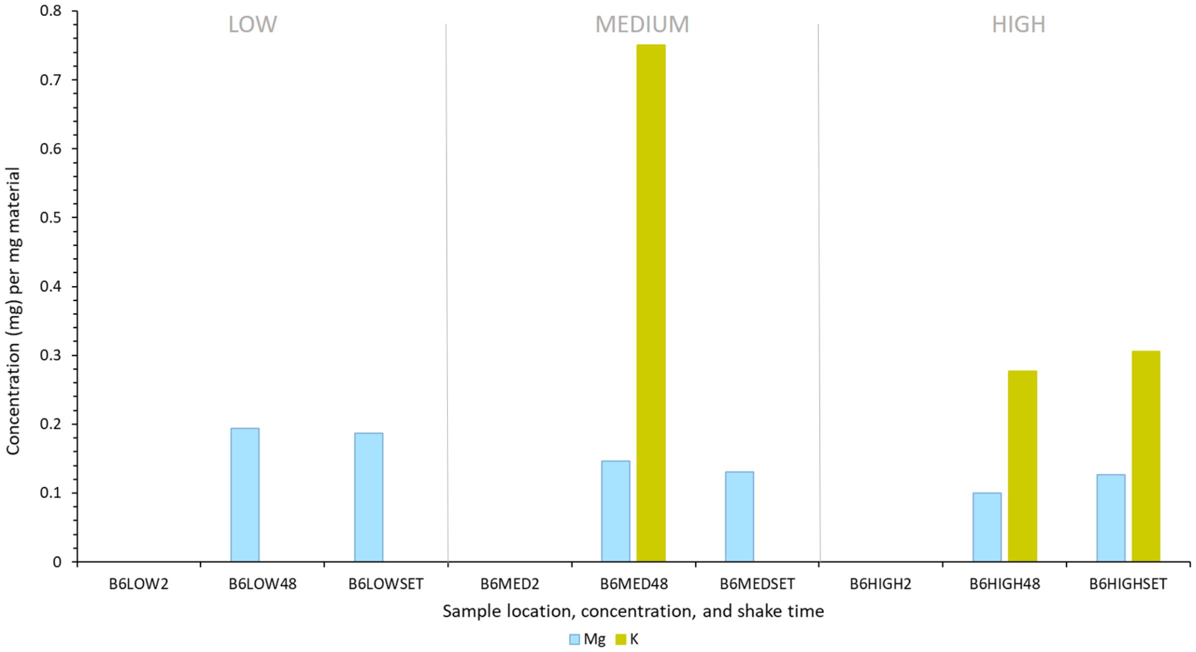

Figure b – **Magnesium and potassium concentrations (mg) per mg of varying concentrations of material collected from B6 SR.**

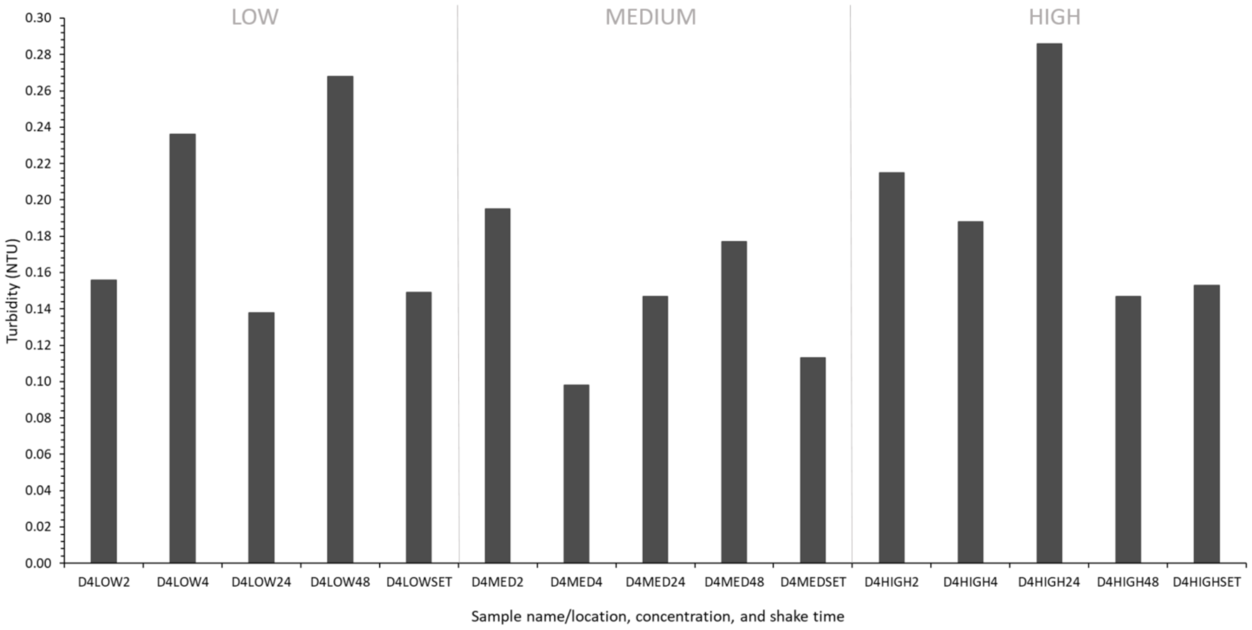

Figure c – **Turbidity (NTU) in varied concentrations of material collected from D4 SR (low = 60 mg/l, medium = 120 mg/l, and high = 240 mg/l), which was shaken continuously in 250 ml of deionised water for 2 hours, 4 hours, 24 hours, 48 hours, and, for settled samples, shaken for 24 hours and left to settle for 24 hours.**

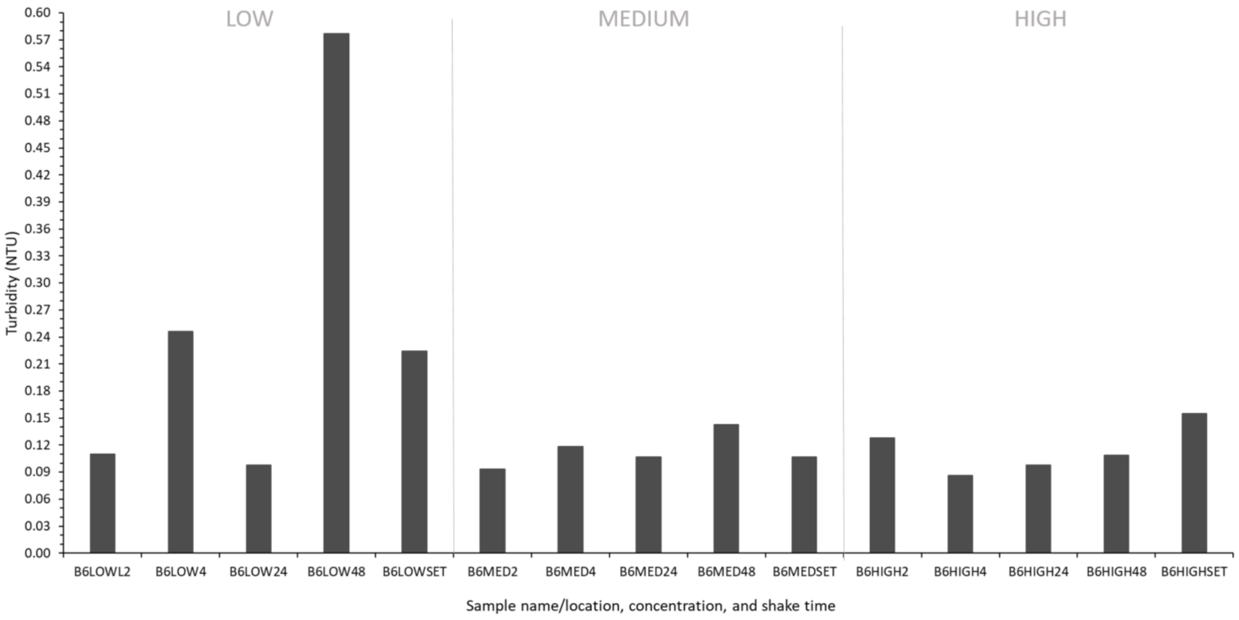

Figure d – **Turbidity (NTU) in varied concentrations of material collected from B6 SR (low = 60 mg/l, medium = 120 mg/l, and high = 240 mg/l), which was shaken continuously in 250 ml of deionised water for 2 hours, 4 hours, 24 hours, 48 hours, and, for settled samples, shaken for 24 hours and left to settle for 24 hours.**

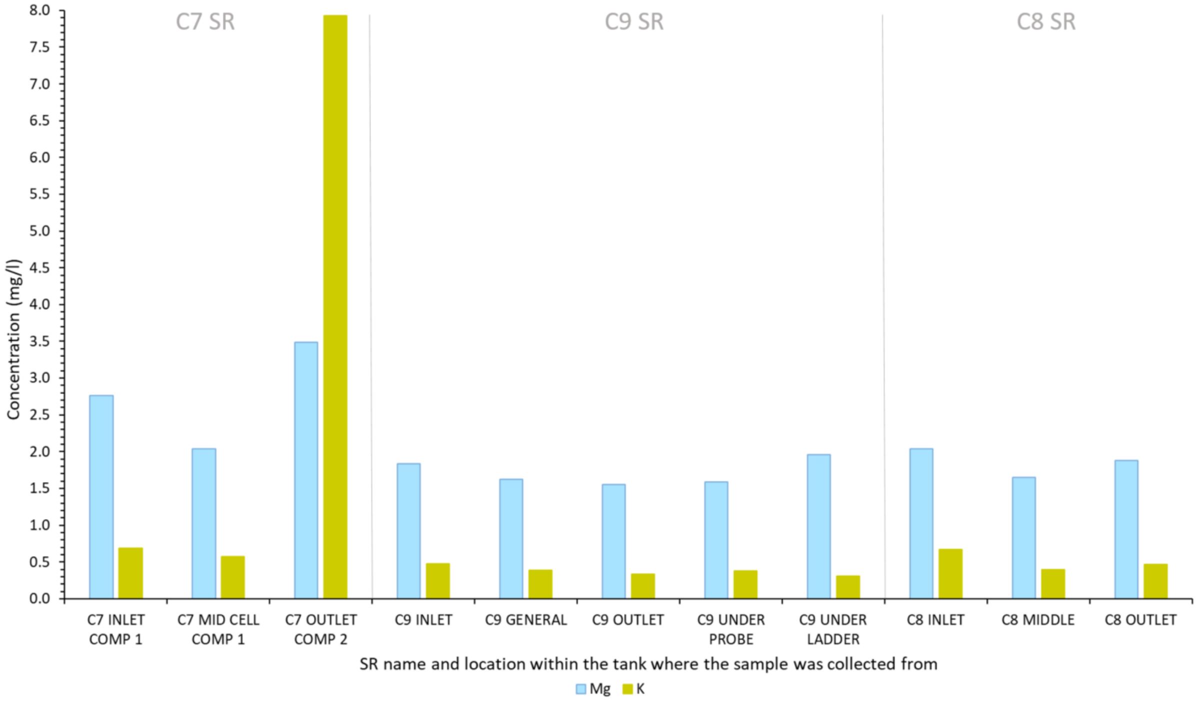

Figure e – **Magnesium and potassium concentrations (mg/l) in material samples collected from different locations within C7, C8, and C9 SRs.**

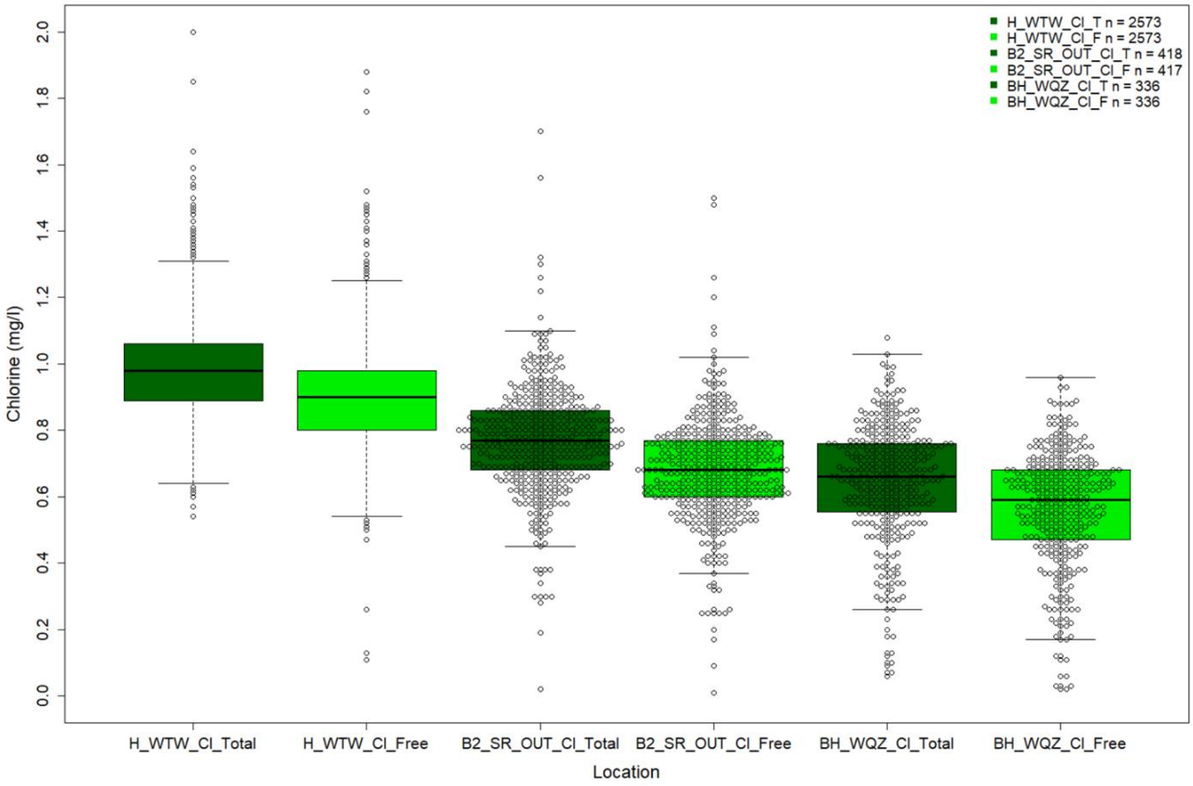

Figure f – **Total and free chlorine (mg/l) at different stages of the B2 DWDS across 2007 to 2011, 2015, and 2017.**

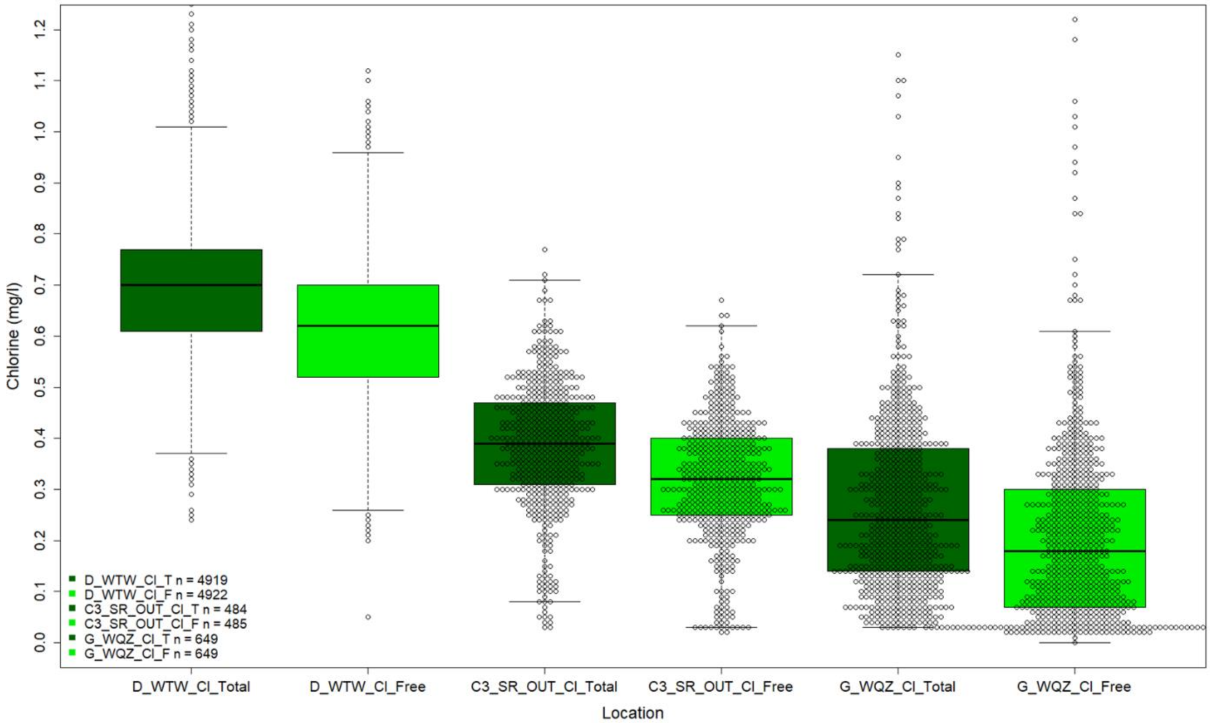

Figure g – **Total and free chlorine (mg/l) at different stages of the C3 DWDS across 2008 to 2017. There is secondary chlorine dosing at the inlet of C3 SR, which is important to take into account when looking at chlorine values at the C3 SR outlet and in the WQZ.**

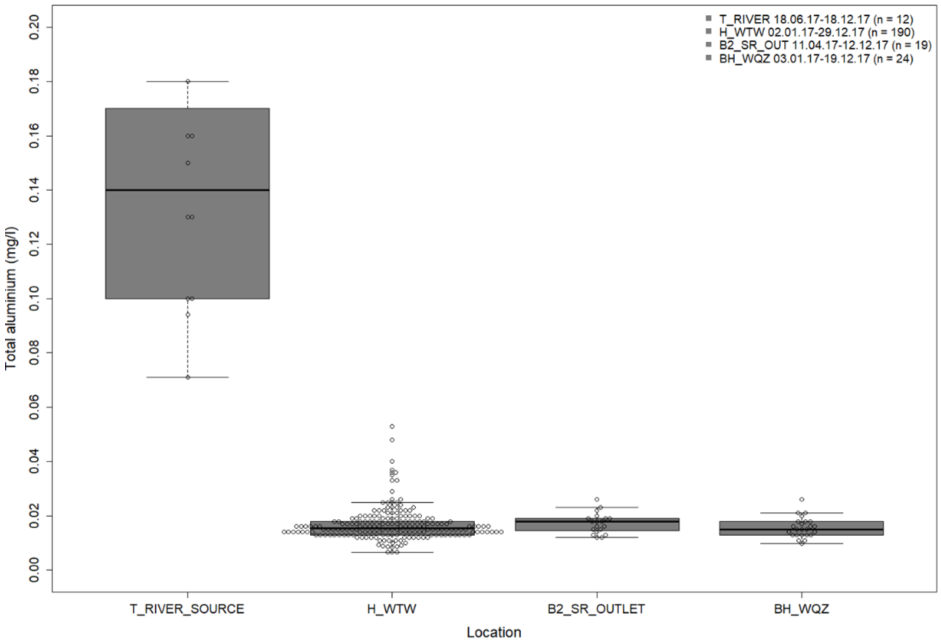

Figure h – **Total aluminium (mg/l) at different stages of the B2 DWDS across 2017. Averages: source water 0.156 mg/l, WTW 0.017 mg/l, SR outlet 0.017 mg/l, and WQZ 0.016 mg/l.**

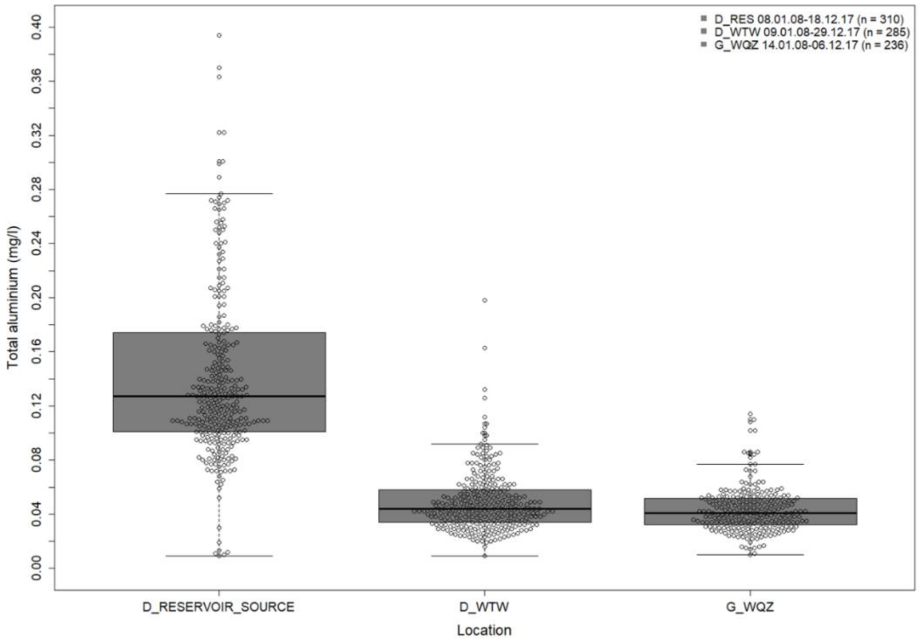

Figure i – Total aluminium (mg/l) at different stages of the C3 DWDS across 2008 to 2017. Averages: source water 0.166 mg/l, WTW 0.049 mg/l and WQZ 0.045 mg/l.

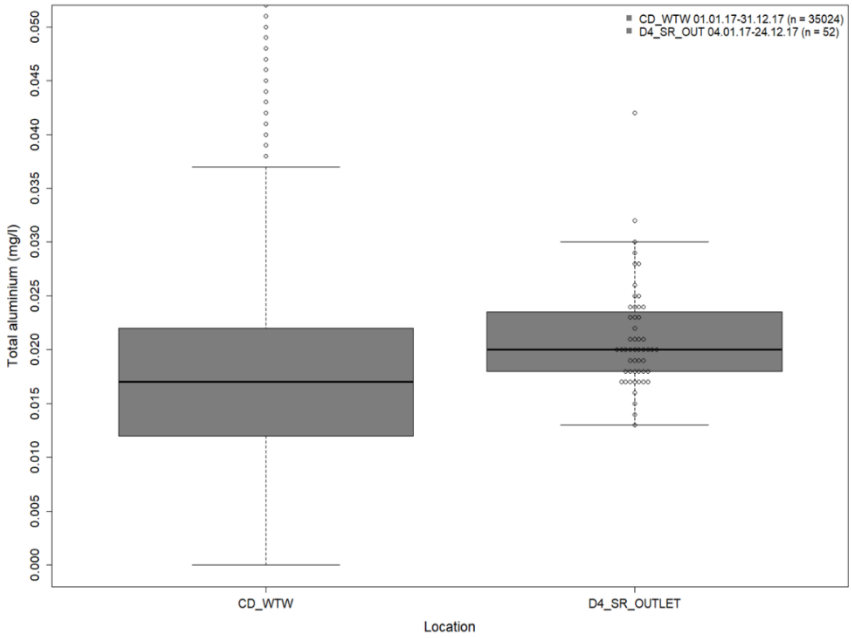

Figure j – Total aluminium (mg/l) at the WTW and SR outlet of the D4 DWDS across 2017. Averages: WTW 0.019 mg/l and SR outlet 0.021 mg/l.

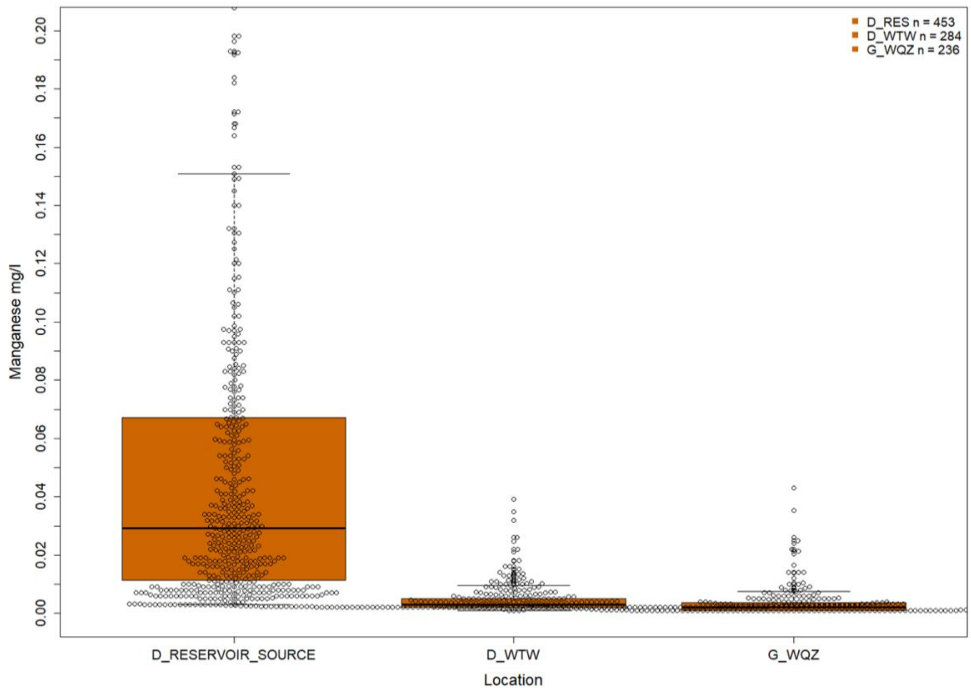

Figure k – **Total manganese (mg/l) at different stages of the C3 DWDS across 2008 to 2017. Averages: source water 0.067 mg/l, WTW 0.005 mg/l, WQZ 0.004 mg/l.**

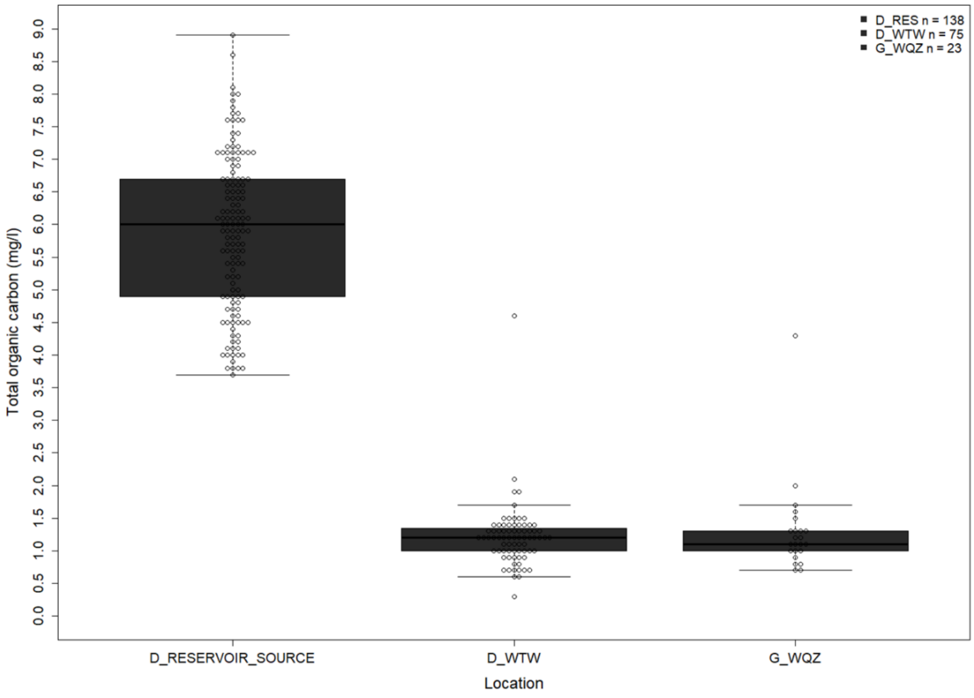

Figure l – **Total organic carbon (mg/l) at different stages of the C3 DWDS across 2012 to 2017. Averages: source water 5.6 mg/l, WTW 1.2 mg/l, and WQZ 1.3 mg/l.**

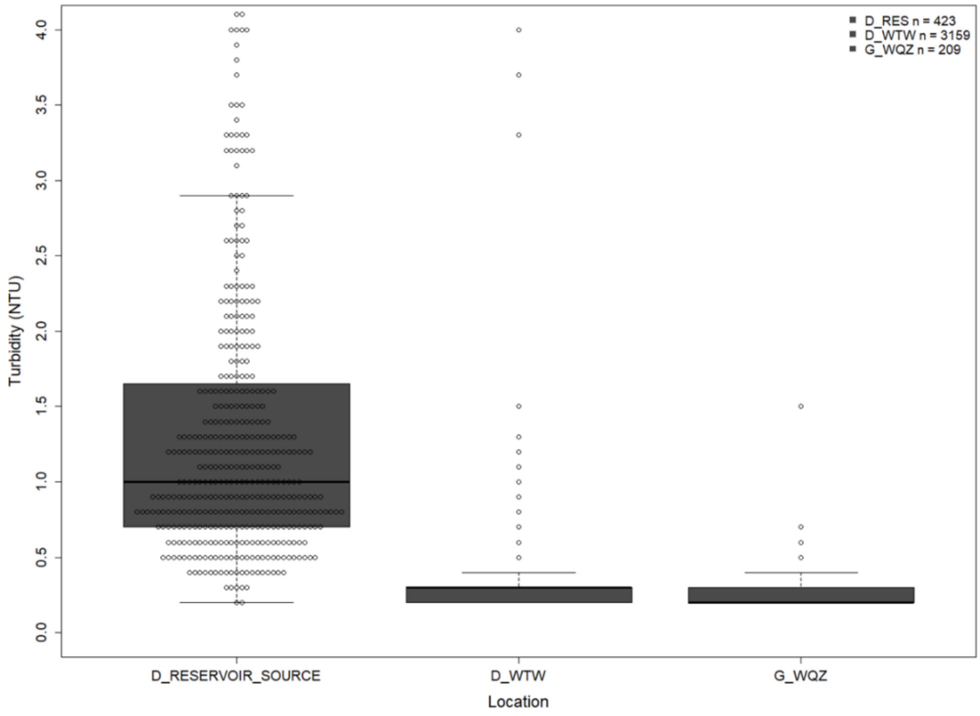

Figure m – Turbidity (NTU) at different stages of the C3 DWDS across 2008 to 2017. Averages: source water 1.6 NTU, WTW 0.3 NTU, and WQZ 0.3 NTU.

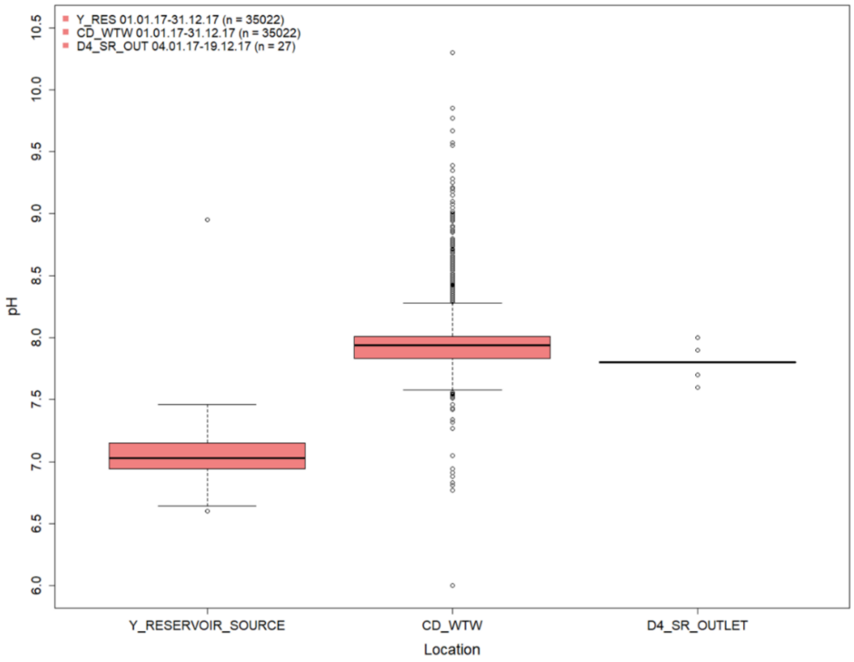

Figure n – pH at different stages of the D4 DWDS across 2017. Averages: source water 7.0, WTW 7.9, and WQZ 7.8.

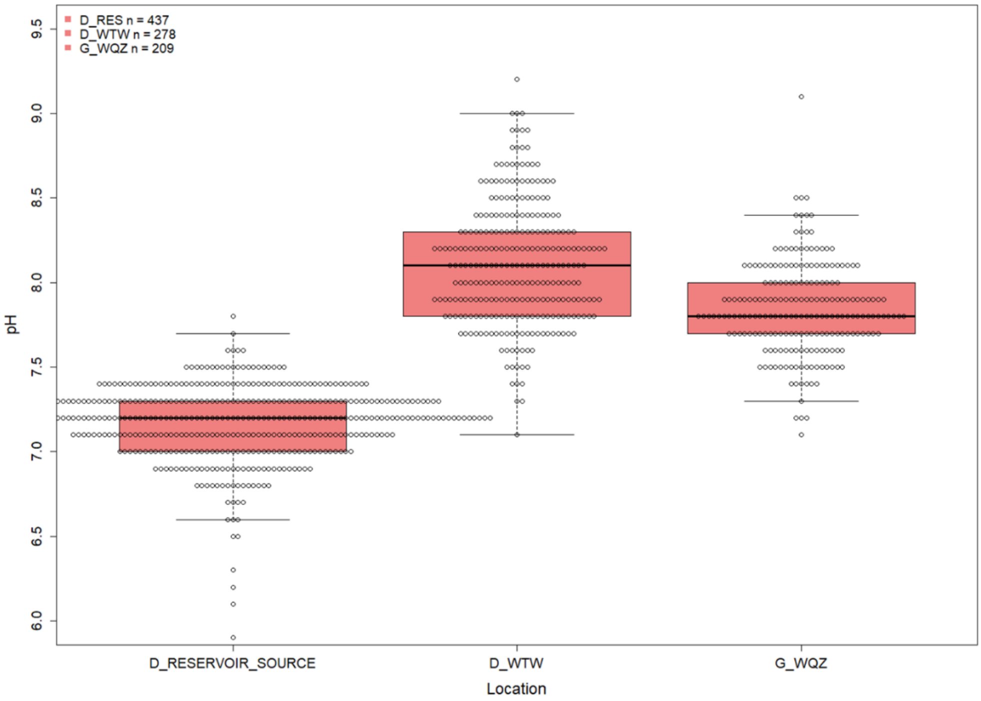

Figure o – **pH at different stages of the C3 DWDS across 2008 to 2017. Averages: source water 7.1, WTW 8.1, and WQZ 7.8.**

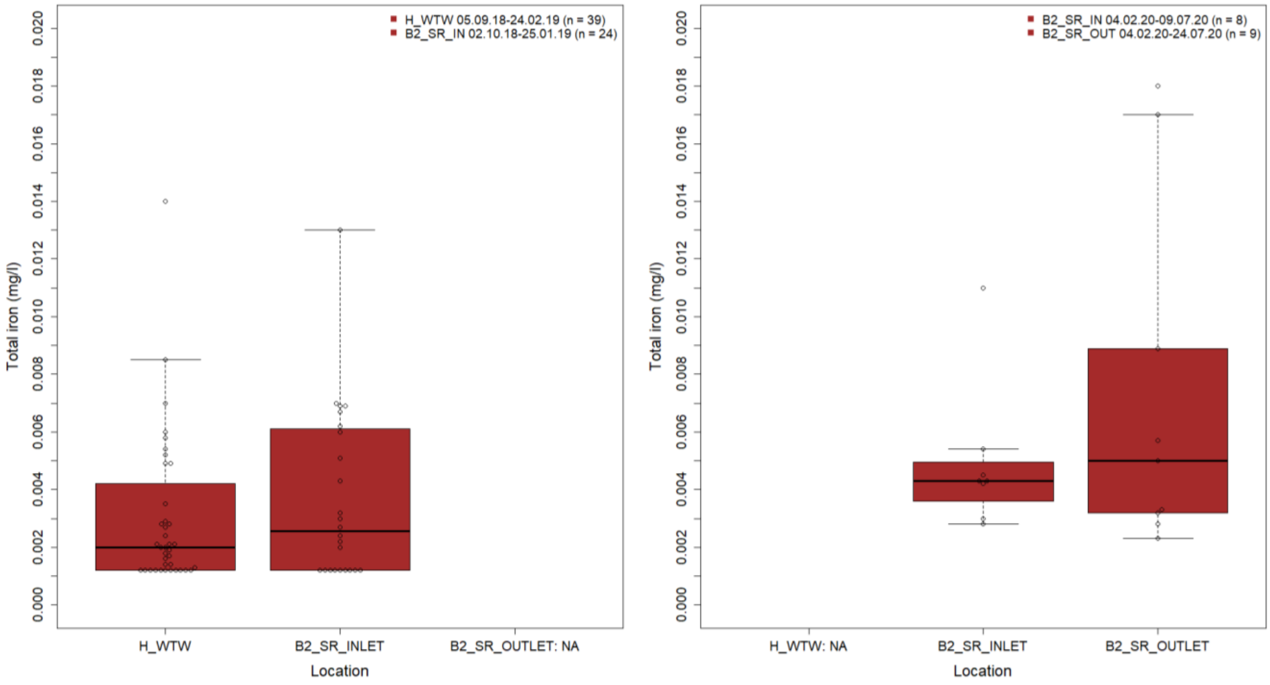

Figure p – **Discrete total iron (mg/l) at different stages of the B2 DWDS across two time periods, 05.09.18 to 24.02.19 and 04.02.20 to 24.07.20.**

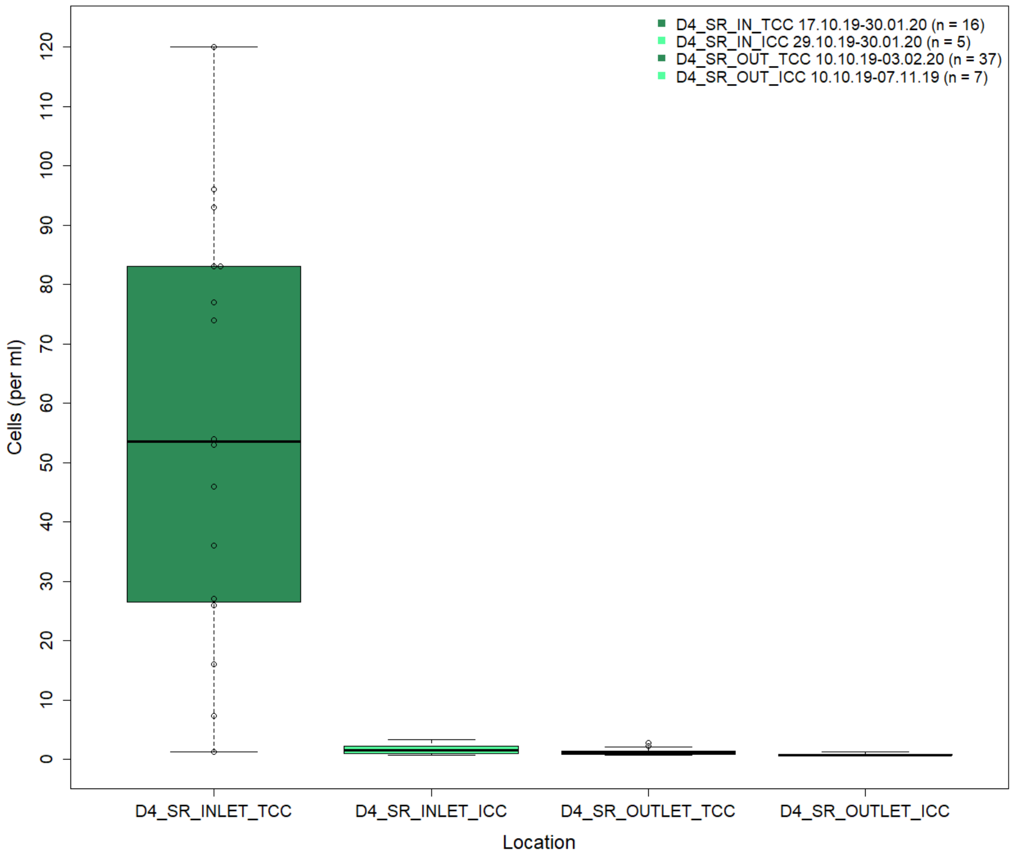

Figure q – **Total and intact cell count (ml) at the inlet and outlet of D4 SR 10.10.19 to 03.02.20.**

Table e – Descriptive statistics for data used in correlation analyses between turbidity and other parameters (iron, manganese, and cell count) at the inlet and outlet of project SRs (A1, B2, C3, and D4).

	SR INLET											
	Turbidity for metals (NTU)				Mn (mg/l)				Fe (mg/l)			
Site name	n	median	mean	stdev	n	median	mean	stdev	n	median	mean	stdev
A1	25	0.08	0.09	0.05	NA	NA	NA	NA	25	0.013	0.010	0.004
B2	23	0.14	0.18	0.15	23	0.0007	0.0007	0.0005	23	0.003	0.003	0.002
C3	61	0.37	0.38	0.10	61	0.0063	0.0070	0.0052	61	0.121	0.150	0.073
D4	9 (Fe)/35 (Mn)	0.16 (Fe)/0.07 (Mn)	0.47 (Fe)/0.17 (Mn)	0.92 (Fe)/0.48 (Mn)	35	0.0052	0.0070	0.0054	9	0.007	0.013	0.012

	SR OUTLET											
	Turbidity for metals (NTU)				Mn (mg/l)				Fe (mg/l)			
Site name	n	median	mean	stdev	n	median	mean	stdev	n	median	mean	stdev
A1	25	0.07	0.08	0.06	NA	NA	NA	NA	25	0.012	0.014	0.008
B2	23 (Fe)/15 (Mn)	0.13 (Fe)/0.28 (Mn)	0.24 (Fe)/0.30 (Mn)	0.25 (Fe)/0.30 (Mn)	15	0.0031	0.0100	0.0214	23	0.004	0.020	0.066
C3	45	0.35	0.35	0.07	45	0.0065	0.0070	0.0036	45	0.184	0.168	0.047
D4	14 (Fe)/33 (Mn)	0.08 (Fe)/0.07 (Mn)	0.10 (Fe)/0.08 (Mn)	0.04 (Fe)/0.03 (Mn)	33	0.0058	0.0060	0.0033	14	0.007	0.010	0.006

	SR INLET										
	Turbidity for cells (NTU)			TCC (ml-1)				ICC (ml-1)			
Site name	n	median	mean	n	median	mean	stdev	n	median	mean	stdev
A1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B2	23	0.14	0.18	23	1021	1194	631	23	266	321	180
C3	14	0.35	0.36	14	201240	176525	72987	14	161060	141971	54967
D4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

	SR OUTLET										
	Turbidity for cells (NTU)			TCC (ml-1)				ICC (ml-1)			
Site name	n	median	mean	n	median	mean	stdev	n	median	mean	stdev
A1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B2	27	0.11	0.20	27	768	1155	1313	27	180	500	1080
C3	17 (dis.)/163 (cont.)	0.30 (dis.)/0.50 (cont.)	0.32 (dis.)/0.61 (cont.)	17 (dis.)/163 (cont.)	8800 (dis.)/31122 (cont.)	10658 (dis.)/31512 (cont.)	7693 (dis.)/10383 (cont.)	17	1600	3292	1516
D4	13 (TCC)/6 (ICC)	0.07 (TCC)/0.06 (ICC)	0.08 (TCC)/0.06 (ICC)	13	1.15	1.23	0.57	6	0.80	0.89	0.25

Appendix 4

Table f - **Health-based prescribed concentrations and values for parameters monitored and analysed in this project.**

Parameter	Prescribed concentration or value (PCV)	Units of measurement	Point of compliance
Aluminium	0.2	mg/l	Consumers' taps
Arsenic	0.01	mg/l	Consumers' taps
Copper	2	mg/l	Consumers' taps
Hydrogen ion	9.5	pH	Consumers' taps
Iron	0.2	mg/l	Consumers' taps
Lead	0.01	mg/l	Consumers' taps
Manganese	0.05	mg/l	Consumers' taps
Residual disinfectant (chloramine)	3	mg/l	Consumers' taps
Residual disinfectant (chlorine)	5	mg/l	Consumers' taps
Total and dissolved organic carbon	No abnormal change	mg/l	Supply point
Uranium	0.03	mg/l	Consumers' taps
Conductivity	2500	µS/cm at 20°C	Supply point**Error! Bookmark not defined.**
Turbidity	4 1	NTU NTU	Consumers' taps WTW's

Appendix 5

Table g - **Descriptive statistics for aluminium (total), conductivity, pH, and temperature sampled between 2018 to 2020 across studied DWDSs (A1, B2, C3, and D4).**

A1 DWDS																				
Parameter	Source Water					WTW					SR Inlet					SR outlet				
	n	Mean	Median	SD	RNG	n	Mean	Median	SD	RNG	n	Mean	Median	SD	RNG	n	Mean	Median	SD	RNG
Aluminium (total) (mg/l)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	5	0.0148	0.0144	0.0007	0.0015	6	0.0149	0.0147	0.0005	0.0013
Conductivity (µS/cm at 20°C)	8	563	538	45	112	12	576	573	13	48	29	581	581	14	52	29	581	581	13	50
Conductivity (MetriNet) (µS/cm at 20°C)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	367448	527	524	14	599	368398	513	509	14	541
pH	3	7.60	7.54	0.15	0.29	21	7.70	7.70	0.04	0.14	29	7.73	7.71	0.07	0.27	29	7.82	7.81	0.06	0.22
Temperature (°C)	26	10.7	10.7	0.5	1.6	40	11.1	11.2	0.6	2.1	29	11.7	12.1	1.6	5.2	29	11.8	12.4	1.9	5.9
Temperature (MetriNet)(°C)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	398359	10.9	10.9	3.2	13.3	399952	10.7	11.0	2.8	10.5
B2 DWDS																				
Aluminium (total) (mg/l)	6	0.2633	0.2250	0.1961	0.5400	57	0.0180	0.0160	0.0092	0.0493	30	0.0173	0.0160	0.0061	0.0242	5	0.0182	0.0180	0.0018	0.0040
Conductivity (µS/cm at 20°C)	8	194	195	41	140	67	304	290	43	250	95	303	300	36	160	32	307	300	38	150
pH	8	7.80	7.80	0.15	0.50	170	7.62	7.70	0.20	1.00	95	7.64	7.70	0.18	0.80	32	7.60	7.60	0.22	0.80
Temperature (°C)	8	9.3	8.5	2.5	6.8	51	9.3	7.1	4.9	17.9	95	10.4	9.5	4.6	15.3	52	10.3	9.1	4.3	14.9
C3 DWDS																				
Aluminium (total) (mg/l)	103	0.1836	0.1570	0.1053	0.8380	119	0.0416	0.0380	0.0177	0.1060	47	0.0339	0.0342	0.0046	0.0193	28	0.0360	0.0370	0.0026	0.0120
Conductivity (µS/cm at 20°C)	23	35	34	3	12	12	73	74	8	20	73	79	79	6	28	55	76	74	6	24
pH	10	6.99	6.95	0.16	0.40	5	7.92	7.90	0.15	0.40	71	7.90	7.90	0.21	1.00	54	7.82	7.80	0.17	1.00
Temperature (°C)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	9	8.8	6.4	3.4	7.9	10.0	9.1	9.2	3.9	8.8
D4 DWDS																				
Aluminium (total) (mg/l)	NA	NA	NA	NA	NA	56535	0.0215	0.0170	0.0164	0.2000	79	0.0262	0.0210	0.0175	0.1000	90	0.0270	0.0190	0.0271	0.2180
Conductivity (µS/cm at 20°C)	48594	47	40	16	95	54801	70	68	20	495	81	82	79	9	42	29	87	84	13	40
pH	30028	6.96	6.94	0.24	5.88	54800	7.82	7.80	0.19	7.63	81	7.76	7.60	0.36	2.10	79	7.66	7.60	0.15	1.20
Temperature (°C)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	46	9.5	9.5	1.9	8.3	890	11.6	10.7	4.2	18.8