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Understanding the Risk of Underwater Skimming of Slow Sand
Filters

School of Water, Energy and Environment

EngD

Academic Year: 2018 - 2024

Supervisor: Dr Francis Hassard

Associate Supervisor: Professor Bruce Jefferson

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Abstract

This research presents an in-depth examination of underwater skimming (UWS) for cleaning slow sand filters (SSF), as an alternative to the traditional dry skimming (DS). The study explores the risks and advantages of UWS compared to DS methods, particularly in terms of filtration performance, microbial removal effectiveness, and operational efficiencies.

The research includes an evaluation of the current state of SSF technology, including operational practices and associated risks faced by operators within the potable water sector, setting the background for identifying the potential improvements that UWS may offer. The study further analyses the risks of particle penetration, head loss development and water quality in SSFs when employing UWS, supported by data from pilot-scale experiments conducted to compare UWS and DS. These experiments compare the effects of UWS against the conventional methods, focusing on filtrate quality, recovery after skimming, and system resilience. Additionally, the study investigates the effects of UWS on dissolved oxygen consumption within the SSF, using a mass balance model to predict the dynamic changes in oxygen levels that occur due to operational disturbances caused by UWS. This aspect of the research highlights the environmental implications of adopting UWS in water treatment practices.

One of the key findings from this research is that UWS filters exhibited less disruption post-skimming, allowing for quicker recovery to microbial compliance compared to DS filters. They also maintained more stable microbial water quality immediately post-skim, as evidenced by consistent removals of coliform at 1.9 ± 0.2 log, compared to DS where removals dropped to 1.1 ± 0.4 log. While surface agitation in a worst-case scenario UWS system may increase the likelihood of particle penetration and breakthrough, deeper media depth ($>500\text{mm}$) mitigates this, with particle breakthrough reducing from 2229 no/mL at 200 mm to 53 no/mL at 500mm. Maintaining a 'sweetening flow' during UWS could considerably improve DO supply, and reduce the emergence of anoxic conditions, while considerably reducing the recovery time caused by any flow reductions or pauses. For example, recovery can increase from 10.1-10.9 bed

volumes when flow is completely paused, to less than one bed volume with a continuous sweetening flow during skimming.

The study maintains that UWS not only addresses the operational challenges posed by traditional methods but also enhances the efficacy and sustainability of SSFs. Through this comprehensive analysis, the research provides substantial evidence that UWS could be instrumental in advancing SSF operation, solidifying its importance as a vital aspect of future research and application in the field. This research contributes to knowledge by demonstrating that UWS enhances the efficacy and sustainability of slow sand filtration systems, reducing operational downtime and maintaining microbial water quality. The potential impact of this research is significant, as it offers a method to increase production capacity from existing SSF assets, potentially transforming slow sand filtration practices globally.

Keywords: Slow sand filter (SSF), underwater skimming (UWS), dissolved oxygen (DO), microbial removal, water treatment, water quality, operational efficiency.

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– For Tobi.

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List of Abbreviations

AOC	Assimilable organic carbon
BV	Bed volumes
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DS	Dry skimming
EBCT	Empty bed contact time
EPS	Extracellular polymeric substances
ES	Effective size
FCM	Flow cytometry
GAC	Granular activated carbon
HLR	Hydraulic loading rate
HPC	Heterotrophic plate count
NTU	Nephelometric Turbidity Unit
OUR	Oxygen utilisation rate
PVC	Polyvinyl chloride
RGF	Rapid gravity filter
SOUR	Specific oxygen uptake rate
SSF	Slow sand filter
TOC	Total organic carbon
TS	Total solids
TW	Thames Water
UC	Uniformity coefficient
UWS	Underwater skimming
VS	Volatile solids

1 Introduction

Water is an essential and life-sustaining resource, integral to various aspects of human existence. Recognising its fundamental importance, access to clean water has been established as a basic human right (Sereno, 2022) and is a central focus of the United Nations Sustainable Development Goal 6 (United Nations, 2015). The importance of clean water extends far beyond direct consumption; it holds significant implications for human health, socio-economic development, and environmental and ecological well-being. Contaminated water sources foster waterborne diseases, leading to widespread illness and mortality, particularly among vulnerable populations. Studies reveal a direct correlation between the availability of safe drinking water, and a reduction in infant mortality, and enhancement in overall health and well-being (Headey and Palloni, 2019). Beyond its immediate influence on individual health, its role is multifaceted, ranging from hydration and sanitation to agriculture and industrial activities, highlighting its importance as a foundational element of public health and economic advancement. A wide array of technologies such as coagulation-flocculation, rapid gravity filtration, membrane filtration, etc., can be utilised to achieve these aspirations each requiring different chemical and energy inputs as well as the costs for construction and operation. A traditional and long-standing option is slow sand filtration which presents an approach with a very low chemical and energy footprint making it appropriate and desirable in a number of application spaces.

1.1 Slow Sand Filters

A slow sand filter (SSF) is a technology that purifies water by slowly passing it through a bed of small-sized sand grains, utilising a combination of physical and biological mechanisms (Figure 1.1). Although there may be several variations depending on use or function, an SSF consists of supernatant, *Schmutzdecke*, sand bed, underdrainage and flow control (Campos et al., 2002; Visscher, 1990). Housed within a specifically engineered vessel, the bed is equipped with inlet and outflow conduits for hydraulic flow regulation. Additionally, it may contain piping

for draining the filter and recharging (or back filling), which is usually done at the inception of filter operation or if the filter has been drained (Figure 1.1).

In certain applications, SSFs have been enhanced through the incorporation of multiple media, expanding their purification capabilities. An example is the integration of a granular activated carbon (GAC) layer within the filter bed (so-called 'GAC sandwich'), which was originally proposed at Thames Water Utilities Ltd. (Bauer, et al., 1996). The GAC layer serves as a specialised zone within the filter, where its high adsorptive capacity and surface area actively attract and retain organic molecules (Li et al., 2019, 2022; Xu et al., 2021). The GAC layer is widely considered to be a beneficial addition to SSF resilience, providing additional benefits to micropollutant removal, but also reduction of assimilable organic carbon (AOC) which can contribute to poor network biostability. However, the GAC layer is also a net oxygen sink, and thus can contribute to anoxia during periods of low flow or flow interruption (Steele et al., 2006).

The *Schmutzdecke* is a biotically active layer forming on the top part of the sand bed and is a habitat for a myriad of microorganisms, including bacteria, algae, diatoms, protozoans, and various metazoans such as rotifers, nematodes, chironomids, oligochaetes, and copepods, creating a multifaceted and dynamic ecosystem (Tyagi et al., 2009). The *Schmutzdecke* is reported to play a pivotal role in removing organic matter, transforming synthetic compounds, retaining pathogens, and ultimately, producing microbiologically safe and regulatory compliant water (Wotton, 2002). Furthermore, the *Schmutzdecke* is instrumental in the biological extraction of nitrates and a variety of organic contaminants throughout the purification sequence (Aslan and Cakici, 2007). Characterised by a thickness that can be as great as 30 mm (Rachwal et al., 1996), the formation of the *Schmutzdecke* layer is observable after two weeks of filter operation (Bellamy, et al., 1985).

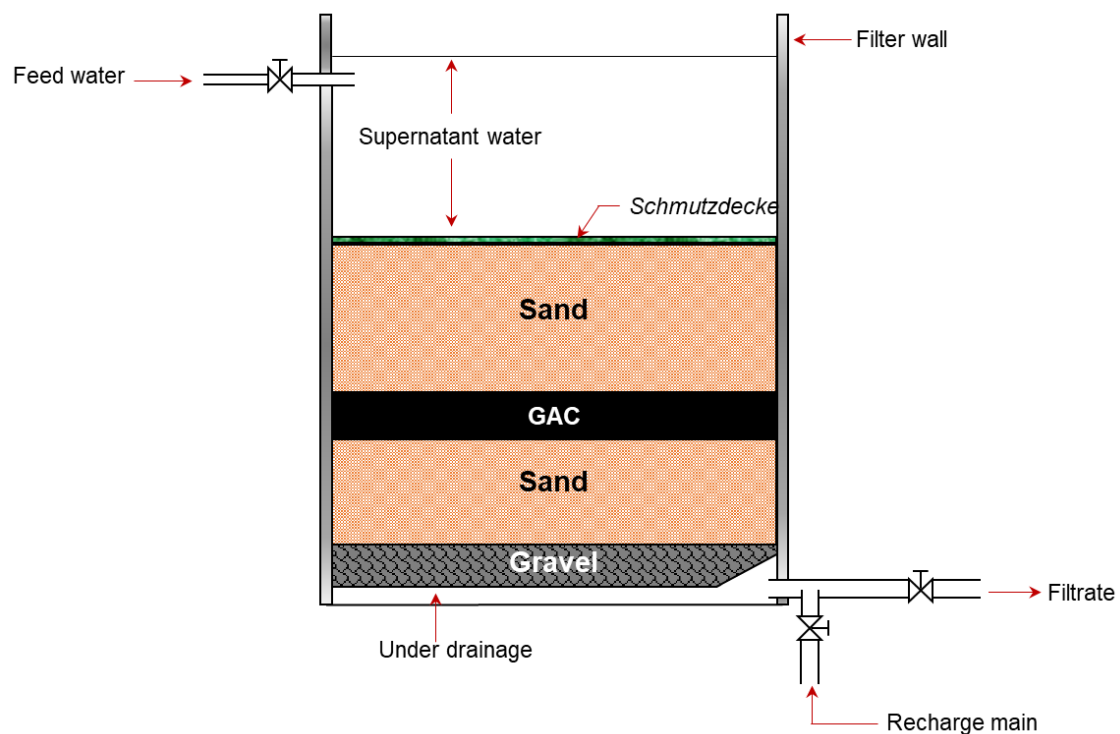


Figure 1.1: A schematic of a municipal slow sand filter design with granular activated carbon (GAC) layer.

GAC layer sandwiched between the sand layer, which is supported by a layer of gravel. Media seats on support layer (made of porous bricks, tiles or concrete) which forms the underdrain.

Slow sand filtration has been employed for centuries as a natural and sustainable method for potable water treatment, predominantly without the reliance on extensive energy or chemical inputs (Ellis, 1985). Its roots are embedded in the practices of ancient civilisations, who depended on this technique to secure clean drinking water for their communities without benefits afforded by modern machinery or electronics. Historical references trace the inception of slow sand filtration to these civilisations, who harnessed layered natural media for water purification (Baker, 1949).

The first documented application of SSF for a municipal water supply was in 1804 in Paisley, Scotland (Huisman and Wood, 1974), which subsequently led to widespread adoption of the technology notably in the UK and Western Europe. For example, today ~80% of London's tap water is still treated via this technology (Hassard et al., 2022). Despite their efficacy, several disadvantages of SSF (such

as large land footprint, sensitivity to temperature and poor water quality (Haig et al., 2014)) led to a decline in the use of SSFs in the early 20th century, with a growing preference for rapid gravity filters (RGF) and chemical treatment options. These alternatives required significantly less land footprint and exhibited less susceptibility to detrimental performance issues associated with poor feed water quality (Haig et al., 2011). However, increasing desire to reduce both chemical and energy use associated with water treatment has led to fresh consideration of the technology with an aim to enhance operational ease and improve the removal of a wider array of contaminants, addressing some of the initially perceived limitations and including contaminants of emerging concern (Castro-Gutierrez et al., 2022).

1.1.1 Process Engineering of SSF

The design and operational paradigms of SSF have remained largely unchanged over the years, reflecting both the robustness of the original design and the conservative nature of the water treatment industry (van Dijk and Oomen, 1978; Logsdon et al., 2002). The efficacy of the bed is influenced by various factors, notably the depth and media type, significantly affecting contaminant removal and final water quality (Kaetzi et al., 2020) and the hydraulic capacity of the bed and its associated frequency of cleaning. Table 1.1 compares design considerations for SSFs from various studies over the years (1974 – 2014). Generally, fine sand is used for SSFs, with effective size (ES) less than 0.5 mm (range from 0.15-0.45 mm shown in Table 1.1) and relatively low uniformity coefficient (UC) of less than three. The hydraulic loading rate (HLR) varies between 0.1 and 0.5 m/h, typically 0.1-0.4 m/h. The depth of supernatant water ranges from 0.4 to 1.5 m, depending on the study. Minimum sand bed depths range from 0.4 to 0.7 m, while maximum depths vary from 0.9 to 2.0 m. In summary, basic design of SSF has remained the same through the years, showing that the trusted design is robust and reliable.

Table 1.1: Comparative design recommendations for slow sand filtration components from various sources over 5 decades.

Consistency in the design considerations for filters over the years illustrates reliability of the system.

Design Consideration	Huisman and Wood (1974)	Bellamy et al. (1985)	Visscher et al. (1990)	Ellis and Aydin (1995)	Logsdon et al. (2002)	Haig et al. (2014)
Effective size (mm)	0.15-0.35	0.15-0.35	0.15-0.30	0.17-0.45	0.15-0.25	0.38
Uniformity coefficient	< 3	< 3	<3	< 3	< 2.5	2.8
Hydraulic loading rate (m/h)	0.1-0.4	0.1-0.4	0.1-0.3	0.1-0.5	0.1-0.3	0.15
Depth of supernatant water (m)	Varies	0.4-0.6	1.0	1.5	0.3-0.6	Varies
Minimum sand bed depth (m)	0.7	0.5	0.5	0.4	0.7	
Maximum sand bed depth (m)	1.5	1.2	0.9	1.2	2.0	1

The filtration rate, which usually varies between 0.1 m/h and 0.5 m/h, needs to be carefully managed to ensure sufficient contact time between the water and the filter media, allowing for effective removal of contaminants. The flow rate is generally controlled by adjusting the water level in the supernatant layer, which in turn affects the hydraulic head and the rate of filtration (Wegelin et al., 1988). The controls need to prevent the tail water (treated water side) from dropping below the sand bed during operation, such as with an effluent weir to prevent the bed from partially draining.

SSF come in a variety of sizes, from household-scale units as small as 0.06 m² (Agrawal, Sharma, and Sharma, 2021) to community-scale filters spanning 5 to 200 m², and even larger-scale municipal systems exceeding 4,000 m² (Visscher et al., 1990) (Figure 1.2). This is one of the reasons SSF is used extensively in remote areas and small communities (Logsdon et al., 2002; Pizzolatti et al., 2014). Larger municipal-scale SSFs are more complex, designed to treat higher

volumes of water to serve urban populations and are part of public water supply systems (Figure 1.2 A). They typically consist of large, open sand beds, often constructed in parallel to handle the significant water throughput required for urban water supply. The depth of the sand layer in these systems is generally greater, around 1 to 2 m, allowing for higher flow rates and more extended filtration cycles. The design of municipal-scale SSFs also includes more complex systems for flow control and transfer between adjacent filters and backfilling to maintain filter effectiveness over time (Logsdon et al., 2002).

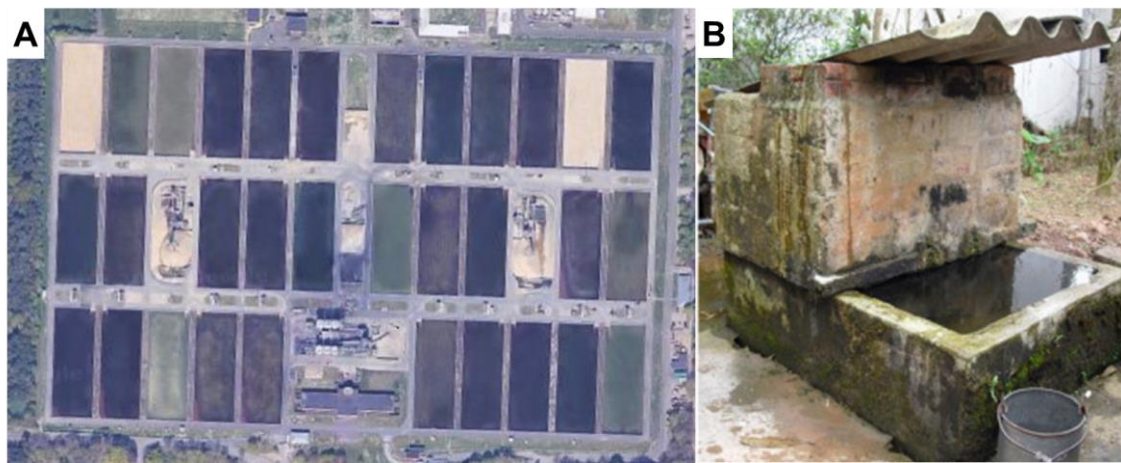


Figure 1.2: Comparison of a large-scale municipal slow sand filter site (A) and a small rural scale SSF (B).

Image A is an aerial photograph of a SSF site in the UK, with each individual filter measuring $>3000 \text{ m}^2$ (Image source: <http://www.earth.google.com> [Accessed 04 October 2024]). Image B shows a rural SSF in Vietnam, measuring about 1 m^2 (Image source: <https://www.sciencedirect.com/science/article/> [Accessed 04 October 2024]).

SSFs fundamentally operate as batch processes. During the initial percolation of water through the sand bed, impurities are captured and accumulate in the upper layers, leading to the formation of the *Schmutzdecke* on the sand bed's surface. This initial phase of operation, characterised by the development and stabilisation of the microbial population within the filter and the formation of the *Schmutzdecke*, is commonly referred to as filter ripening or maturation. It has also been identified as the period of continued improvement in the removal of contaminants (Jegatheesan and Vigneswaran, 2005). Ripening of the filter bed

at start-up or after a cleaning operation is dependent on a variety of factors including raw water quality, temperature (Pyper, 1985) and HLR (Bellamy et al., 1985). There is no clear consensus on parameters for determining when a bed has reached 'maturity' nor is there an explicit description. Different researchers use different indicators to determine this point. For example, Bauer et al. (2011) used the removal of phages as an indicator for bed maturation. Other microbial indicators such as total coliform (Barrett et al., 1991) and viruses (Poynter and Slade, 1977) have been used. In many instances, turbidity removal is used to determine bed maturity (Selecky et al., 2003). Irrespective, the state of maturity is always associated with filtrate water quality. The time it takes a bed to ripen or reach maturity varies and can range from anywhere between 6 hours (Cullen and Letterman, 1985a) to 100 days (Pyper, 1985).

1.1.2 Cost and Energy

SSF is principally a chemical-free treatment option unless there is poor inlet water quality or requirement to increase the hydraulic loading rates, in which case pre-treatment steps such as coagulation may be introduced (Freitas et al., 2021; Holmes et al., 2023). Furthermore, the process operates under the influence of gravity, thereby eliminating the need for energy input, except for essential energy-related requirements associated with auxiliary operations such as pumping, monitoring instruments, or cleaning. Accordingly, the technology can be considered as a low carbon process aligned to the delivery of *net zero* targets.

A notable benefit of slow sand filtration lies in its straightforward operability and reduced maintenance costs compared to other treatment options (Kaetzel et al., 2020). To illustrate, the total operational and maintenance expenditure of an SSF plant was estimated to be 30% lower than an RGF plant producing the same water volume (Barrett et al., 1991). With regards to energy, Bukhary, et al. (2019) estimated that a small drinking water treatment plant using conventional treatment (coagulation + pressure filters + disinfection) will require 3.1 Wh/m³ (excluding distribution pumping costs). An equivalent capacity plant replaced with SSF (i.e., replacing the pressure filters with SSF) would on the other hand only require 0.8 Wh/m³ with its associated carbon saving. To demonstrate the

significance of the difference, based on the UK's electricity generation profile (DENSZ, 2023), producing 1 million litres of water via SSF would result in an annual 0.2 tonnes carbon dioxide equivalent (CO₂e) savings over a pressure filtration system. Once chemical dosing is put into consideration (~0.08 kg/m³, Biswas and Yek, 2016), this can rise to as much as 29 tonnes CO₂e savings, solidifying the argument of SSF being more environmentally friendly.

1.1.3 Treatment Performance

SSFs demonstrate a high degree of efficacy in the removal of a diverse range of contaminants typically present in water sources, including biological (e.g., organic matter, microorganisms, invertebrates, and metazoans), physical (e.g., particulate matter, inorganic substances) and chemical (e.g., heavy metals, micropollutants, pesticides) contaminants. The removal process involves both physical straining and biological actions within the *Schmutzdecke*, a biofilm layer on top of the sand layer and the whole depth of the filter. Enteric bacteria with a typical size of 1-10 µm are effectively removed by 2 log or more (>99%) (Langenbach et al., 2010). Viruses, though smaller in size than bacteria (typically ranging from 0.02-0.3 µm), are also removed by SSF through mechanisms like physical straining and adsorption. Reported removal efficiencies range from as low as 0.2 log to over 4 logs (Anderson et al., 2009; Dizer et al., 2015). Protozoa and invertebrates, which are larger than both bacteria and viruses, ranging from 2-50 µm and 50-2000 µm respectively, are removed by up to 5 log (Hijnen et al., 2004, 2007).

Suspended particles, including sediments and colloids are removed by up to 99% (Mahaffy et al., 2015) through a wide range of mechanisms from sedimentation for heavier particles to diffusion and electrostatic attraction for colloids. Furthermore, SSF systems are adept at removing a wide range of organic matter. This category includes natural organic matter, such as humic substances, and various anthropogenic contaminants, whose size and molecular structure can vary widely. The removal of organic matter in SSF is achieved through a combination of adsorption onto the biofilms that form around sand grains and biodegradation by the microbial communities in the filter. Because of its ability to

breakdown organic compounds to smaller molecules, SSFs have also more recently been considered for the removal of chemicals of emerging concern such as personal care products, pharmaceutically active compounds and household chemicals, endocrine disruptors pharmaceuticals. For instance, D'Alessio et al. (2015) found that SSFs were able to completely remove caffeine and partially removed estradiol and estrone. Furthermore, after testing various filtration rates, Li et al. (2018) found that incorporating a GAC layer within the middle of the filter bed (at depths between 5 and 20 cm) resulted in a significantly higher average removal of pharmaceuticals, achieving 96.2% to 97.7% removal, compared to 51.9% removal with a sand-only filter.

1.1.4 Operational Considerations

One of the primary operational challenges faced in SSF is the clogging of the sand bed and the *Schmutzdecke* layer. Clogging can be exacerbated by high levels of turbidity or algae (algal blooms) in the raw water, which may also cause odour and necessitate more frequent cleaning and can impact the overall operational efficiency of SSF (Logsdon et al., 2002). This underlines the importance of pre-treatment in certain cases (Wegelin, 1988), as well as the even more important activity of source management, for instance reservoir mixing to eliminate stratification to control algal blooms (Rachwal, et al., 1988). As such, head loss development within the filter is a crucial aspect of SSF operation, where excessive head loss can result in diminished flow rates, signalling the need for maintenance interventions. Additionally, the run length, or the duration between maintenance intervals, can vary based on multiple factors, including water quality which may impact the concentration of contaminants being fed to the bed, as well as climatic conditions and seasonality which impacts the rate of growth of biota, thus influencing the operational efficiency and predictability of SSFs.

1.2 Cleaning SSF

The traditional cleaning of SSF, known as dry skimming, is a batch process that includes draining, skimming, refilling, running to waste, and returning to operation. The *Schmutzdecke*, along with 10-100 mm of sand, is removed with each skim. This process continues until the sand reaches the minimum

permissible depth for effective filtration, which can range between 0.4-0.7 m (Table 1.1). Once this minimum level is reached, the remaining sand is removed and cleaned, along with any stored sand, before being returned to the filter to restore its original bed depth (Huisman and Wood, 1974). The frequency of cleaning and replacement of sand varies based on site specific standards but is mostly entrenched in water quality criteria.

Historically, the cleaning of SSF has transitioned from using simple hand tools to modern day mechanised cleaning, using heavy machinery (Figure 1.3). Classical scraping technique is considered labour-intensive. To illustrate, a study of six plants in central New York found that filter scraping requires approximately 5.4 h per 100 m² of filter surface, while the re-sanding operation requires about 50 h of labour for the same area (Letterman and Cullen, 1985). This compares to more modern machinery which are more efficient and are estimated to use about 0.2 h per 100 m² of bed (Kem, 1996).

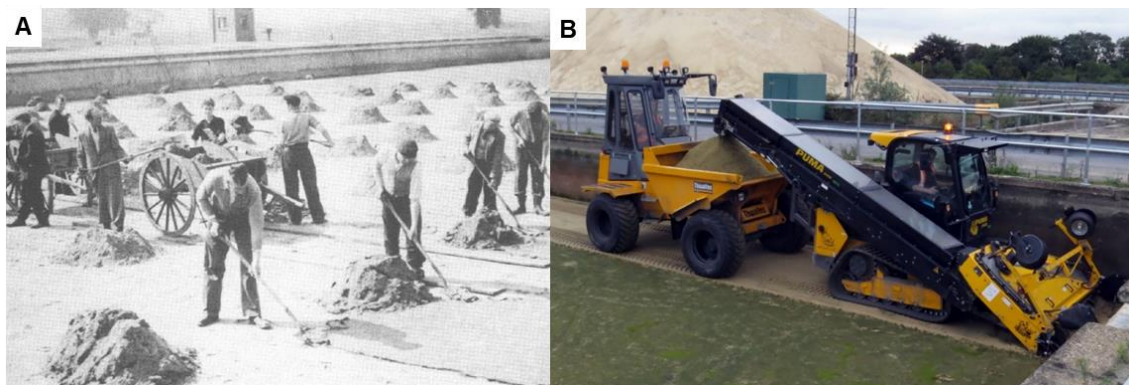


Figure 1.3: (A) Vintage image of SSF cleaning with hand tools (Source: Collins et al., 1991) and (B) more recent image of scraping with machine (©Thames Water Utilities).

Draining the bed for dry skimming can be achieved through either complete or partial draining, which involves emptying the entire filter tank, necessitating the shutdown of influent flow. While it ensures comprehensive cleaning, it comes at the cost of longer downtime and increased water replacement during restarting operations. In contrast, partial draining is less disruptive, allowing for quicker cleaning and a faster return to normal filter operation.

Several approaches have been developed to enable partial or no drainage including wet harrowing, *in-situ* sand washing and backwashing (Table 1.2). *Wet harrowing* originated in USA and utilised a rubber-tired tractor, equipped with a comb-tooth harrow that racks the sand media while the filter surface sumps remain open, allowing a steady discharge of overlaying water (Collins et al., 1991). To ensure the continuous removal of suspended materials during wet raking, the process begins by partially draining the SSF while maintaining the water level between 5-30 cm above the sand layer. A harrow or rake is then driven or dragged over the surface, creating a cross flow of 3.6 to 9 m/h and an upward flow of 0.02 m/h, which is insufficient to fluidise the media, but enough to remove deposited particles. This method effectively washes away debris and particles lifted by the harrow, thus preventing deep particle penetration into the filter media. After this, the bed is drained below the surface and harrowed with a larger tooth comb to break any deeper crusts. The bed is then backfilled, and the filter is returned to service, potentially including a period of ripening (Kem, 1996). This approach has been reported to reduce cleaning time and enhance the removal of organic compounds (Collins et al., 1991; Kem, 1996). However, it has also been found to modestly decrease the removal efficiency of bacteria and turbidity up to 7 days after cleaning (Jenkins et al., 2011).

In-situ washing of SSFs, an innovation trialled by the Metropolitan Water Board (now Thames Water Utilities Limited) in the late 1950s, represents a significant advancement in filter maintenance technology. This process, like the wet harrowing, involves cleaning the filter media without removing it from the bed, however with the ambitious aim of eliminating the need to replace the media altogether (Burman and Lewin, 1961). The cleaning was achieved by a bespoke washing plant that spanned the width of the test filter (~34 m), that consisted of a movable built-in caisson or cofferdam with clean water connections for washing and drainage for the dirty water. Prior to washing, a rake was used to remove aquatic weeds from the filter if necessary. The washing process began by lowering the caisson to a predetermined depth in the sand. Radially disposed lances lowered into the sand supplied the clean wash water while dirty water was drained through a pipe. After washing, the lances were lifted, the caisson

withdrawn from the sand, and the plant moved forward to continue the operation until the entire filter length was cleaned (Lewin, 1961). This method was reported to offer several advantages including reducing filter downtime and enabling quicker recovery in satisfying bacteriological criteria compared to traditional cleaning. However, there were some notable challenges associated with this method. One of the primary issues with this system was the observation of shorter filter run lengths, lasting only a few days compared to weeks when using dry skimming. It was found that washing did not sufficiently remove algae, leading to quick bed recolonisation and hence more frequent cleaning requirements. This problem was somewhat alleviated with seasonal changes and drops in temperature, which were less conducive to algal growth. Another operational challenge was the hydraulic grading of sand particles caused by fluidisation during the washing process. This grading resulted in smaller grains rising to the top of the filter, reducing porosity at the top and accelerating clogging (Burman and Lewin, 1961).

Backwashing of SSFs have also been reported on a few occasions (de Souza, et al., 2021a). In different cases, the backwashed filters have been shown to have similar performance to the conventional cleaning methods. Backwashing has also been shown to speed up the cleaning process, with time saving benefits, backwashing being almost six times quicker than conventional cleaning (Pizzolatti et al., 2014). Also, there is no need for re-sanding with backwashing, the filter depth can be maintained. However, backwashing requires bed expansion of between 10% (Pizzolatti et al., 2014) and 25% (de Souza et al., 2021b), which might be a constraint if planning to retrofit existing assets. While backwashing is successful in small SSFs, it becomes impractical for bigger surface area filters. For one, uniform backwash becomes very difficult when surface area $>93 \text{ m}^2$ (Pizzolatti et al., 2014). Also, the volume of water required for backwashing will become restrictive. For example, the volume of water required to backwash a 1 m^2 by 1 m SSF operating at 0.3 m/h hydraulic loading rate will be equivalent to more than 6 hours' production volume.

Table 1.2: Comparison of cleaning methodologies

Factor	Traditional cleaning (scraping/dry skimming) ¹	Wet harrowing ²	<i>In-situ</i> sand washing ³	Backwashing ⁴	Underwater skimming (proposed) ⁵
Labor intensity	Very labour-intensive	Less labour-intensive	Moderate labour intensity	Varies with system setup	Moderate labour intensity
Efficacy	Effective but impacts filtration initially	Effective; maintains higher bacterial count	Effective with some efficacy concerns post-cleaning	Similar to conventional methods	Potentially very effective
Time requirement	Time-consuming	Relatively quick	Quick	Very quick	Quick
Operational downtime	Approximately 5 days*	Significantly reduced; hours, not days	Reduced	Significantly reduced	Minimal
Impact on filter microbiology	High impact: requires time for <i>Schmutzdecke</i> to re-establish	Lower impact; faster recovery	Variable; quicker recovery but issues with algae	Minimal initial impact	Minimal impact on microbiology
Frequency of cleaning	Less frequent	More frequent due to shorter run lengths	More frequent due to algal recolonisation	Varies; can be frequent in large filters	Frequency depends on technology effectiveness
Resource usage	High manual resource requirement	Less manual resource; more mechanical	High water usage for backwashing	High water usage; no re-sanding	Moderate resource usage
Operational flexibility	Limited	More flexible; can operate in various conditions	Flexible; remote control capabilities	Highly flexible	Highly flexible
Safety concerns	Moderate (manual scraping risks)	Reduced (mostly mechanical)	Lower (automated process)	Low (automated process)	Low (remote-controlled, underwater)
Impact on bed uniformity	Can cause unevenness due to manual scraping	More uniform due to mechanised process	Can cause unevenness due to fluidisation	Even, due to controlled backwash	Uniform due to precision technology
1. Huisman and Wood, 1974 2. Collins et al., 1991; Kem, 1996; Jenkins et al., 2011 3. Burman and Lewin, 1961; Lewin 1961 4. Pizzolatti et al., 2014; de Souza et al., 2021a, b 5. These are proposed benefits of the current UWS					

Different methodologies have been investigated to reduce filter ripening duration after cleaning including using additives (Calixto et al., 2020; Weber-Shirk, 2002) and seeding from a mature bed (Weber-Shirk and Dick, 1999). Another approach was the use of non-woven fabric to improve performance and speed up filter cleaning (Graham and Mbvette, 1991; Mondal, et al., 2007). However, eliminating filter draining in the cleaning regimen has been identified as an

effective method for achieving shorter ripening times (Huisman and Wood, 1974), as it is believed that filter will remain in a 'mature state'.

1.3 Development in Underwater Skimming

Eliminating the draining means modification to the traditional cleaning approach and development of equipment and methodology to clean the bed while fully submerged. Some innovations have sought to achieve this, including *in-situ* sand washing (Burman and Lewin, 1961; Lewin, 1961), backwashing (de Souza et al., 2021a; de Souza, et al., 2021b), and other surface manipulations (Singer, et al., 2017). Some of these changes had associated risks as the performance of filter bed became compromised, leading to shorter filter runtimes, quicker head loss development (Burman and Lewin, 1961; Lewin, 1961) and poor filtrate quality (Singer, et al., 2017). However, despite extensive filtrate monitoring in these studies, there were no clear-cut reasons as to why the filters behaved in the way they did. Therefore, it is posited here that the introduction of *in-situ* underwater skimming (UWS) can substantially help to offset the challenge of downtime, with its associated loss of production, enabling the technology to operate more efficiently and remain a pertinent and advantageous process option within modern water treatment facilities (Hassard et al., 2022).

Underwater skimming (UWS) is a cleaning innovation in which the filter remains undrained while the *Schmutzdecke* and top sand layers are removed using a shrouded blade to simultaneously skim *Schmutzdecke* and capture particles, sand, and biofilm prior to *ex-situ* separation and washing of the recovered sand (Figure 1.4). The skimming system is mounted on a free-floating (e.g., vessel) or bed-mounted (e.g., vehicle) platform, "crawling" along the media surface with a pipe to facilitate transport of *Schmutzdecke*-sand-water slurry to the surface. Through UWS, improvement to the cleaning processes of SSF could accrue from (i) reduced time spent draining and refilling the filter and scraping media; (ii) reduced ripening time expanding the window for safe operation; and therefore (iii) result in less pre-treated water lost to supply and indirectly, cost, and energy benefits.

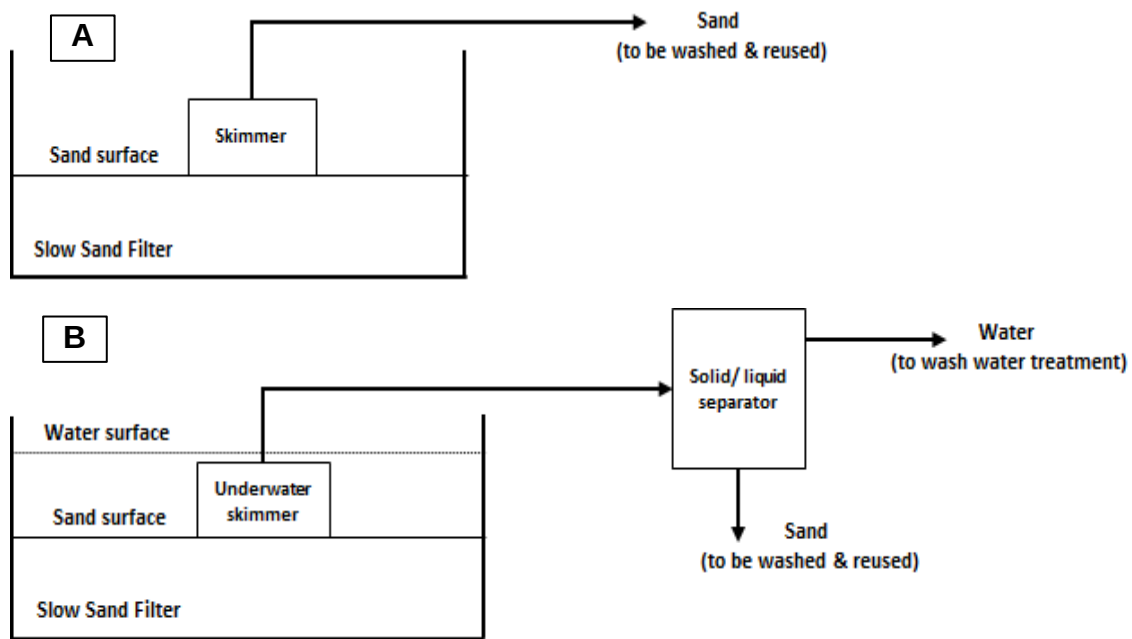


Figure 1.4: Comparing the traditional dry skimming where the filter is drained (A) to underwater skimming where filter is not drained (B).

It is important to ensure that SSFs retain their core treatment function: the production of high-quality filtrate water. There are several uncertainties to the widespread use of UWS. For example, during long-term operation, the UWS SSFs may exhibit reduced filter porosity because the beds are neither backfilled nor desiccated and are thus less disturbed. The drain down and refilling of filter bed processes are thought to remove particles and clean biofilm. Consequently, this implies that head loss development will be more rapid in the UWS bed when compared with an equivalent conventionally cleaned SSF, leading to shorter filter run lengths in UWS beds. Therefore, a more frequent cleaning regimen will be necessary, potentially impacting anticipated net production volume gains. Finally, during continuous operation, particle penetration in newly skimmed sand areas may cause short-circuiting of the *Schmutzdecke* in the non-skimmed areas. This issue could be mitigated by employing a closed loop recycling process, which involves returning the filtrate to the start of the treatment works or adjacent filters where feasible. Alternatively, the filtrate can be run-to-waste during cleaning. A summary of the uncertainties around UWS can be found in Table 1.3.

Table 1.3: Summary of some uncertainties of underwater skimming and their potential consequences.

Risk	Consequences
Deep penetration of particle within the filter bed	- More rapid head loss development and shorter filter run lengths, - More frequent skimming (and media replacement) required.
Anoxic/ anaerobic conditions within filter	- Production of deleterious anaerobic byproducts (including ammonia, undesirable taste and colour compounds, etc.), - Reduction in biological removal mechanisms and subsequent deterioration of filtrate water quality, - Increased disinfection (chlorine) demand of effluent.
Disruption of filter treatment performance	- Deterioration of physical and biological removal mechanisms and subsequent deterioration in water quality. - Modifications to the media, for instance from stratification, leading to more rapid head loss development.

1.4 Aim and Objectives

The aim of this thesis is to establish an evidence base to understand the risks associated with using UWS for the cleaning of SSFs. It is hypothesised that utilising UWS will not negatively affect treated water quality or disrupt filter operations. Additionally, keeping the bed in an undrained state is expected to preserve a mature microbiome, thus reducing the filter's ripening time.

To assess the validity of these anticipated benefits and to uncover any further implications of UWS, a series of objectives have been structured to address the perceived risks:

- I. To review prevailing “best-in-class” practices in slow sand filtration. This involves reviewing literature, consulting experts on effective

methodologies, and establishing a baseline to compare the efficiency of the new underwater skimming regime.

- II. To determine how UWS-induced agitation affects particle breakthrough and retention, with a focus on the role of sand depth.
- III. To assess the utilisation of dissolved oxygen under varying flow interruption durations and temperatures, and to estimate the requirements for dissolved oxygen management.
- IV. To compare the performance, filtrate quality, and head loss development in pilot filters using underwater skimming with those using traditional cleaning method (dry skimming).

A conceptual diagram of the how the work fits together to assess the risks associated with UWS with objectives highlighted is presented in Figure 1.5.

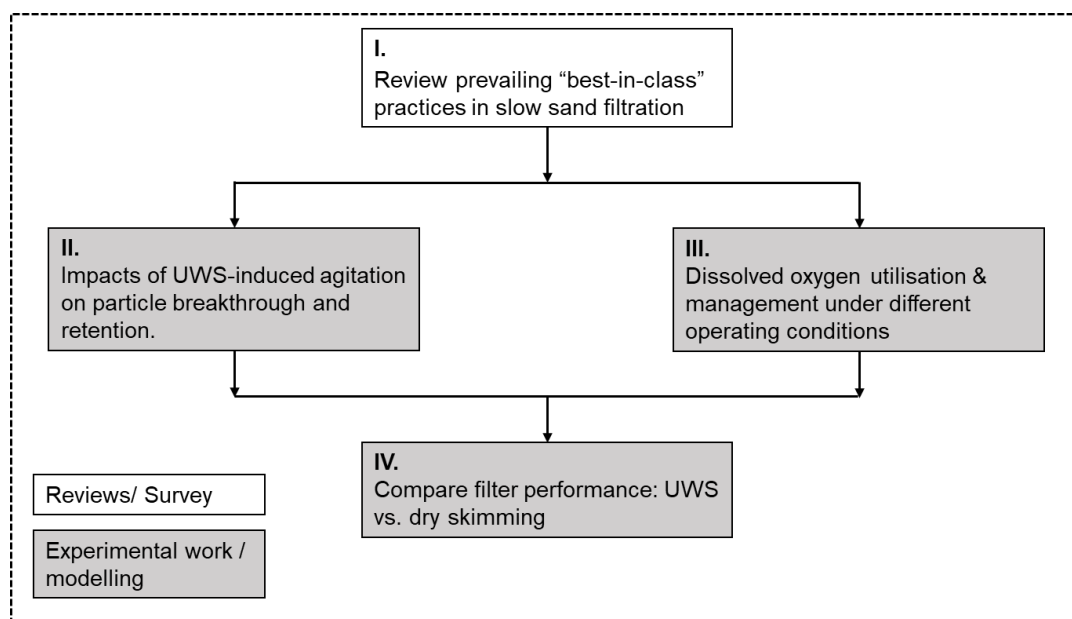


Figure 1.5: Summary of the objectives in the thesis

1.5 Thesis Plan

The research presented in this thesis was conducted as part of the STREAM Industrial Doctorate Centre (IDC) in conjunction with the sponsoring partners Thames Water and Northumbrian Water Group. Ethics approval for the project was obtained from Cranfield University via the Cranfield University Research Ethics System, under the reference CURES/22831/2024 (Appendix A.1).

The thesis is presented as a series of chapters formatted as journal papers. All papers were written by the primary author and edited by Professor Bruce Jefferson and Dr Francis Hassard.

All experiments were designed, coordinated, and completed by the author at Thames Water, with contributions from Thames Water staff, apprentices, and the Thames Water Central laboratory. Additional support was provided by PhD candidate Sophie Bretagne and laboratory technician Hannah Charlotte at Cranfield University. Contributions are summarised as follows:

- Dr Michael Chipps, Dr Jenny O'Reilly, and Ian Doggett (Thames Water) assisted with experiment planning and methodology, pilot plant construction, refurbishment, modifications, and the procurement of filter media and instruments.
- Routine operation, sampling, and skimming for four of the ten filter runs described in Chapter 5 were conducted with the assistance of Michael Bradford (Thames Water).
- Microbial analysis of indicator organisms (coliforms and heterotrophic plate counts) reported in Chapter 5 was performed by the Thames Water Central Laboratory.
- Genomic DNA extraction was carried out by Sophie Bretagne and Hannah Charlotte (Cranfield University).
- The extracted DNA was commercially amplified and sequenced by Novogene (Cambridge, UK).
- The rRNA amplicon sequence data was analysed in collaboration with Sophie Bretagne (Cranfield University).

Initially, a survey of current practices was completed to understand the range and variety of operational practices, evaluate the similarities and differences and outline what is considered as 'best practice' among practitioners and an outlook for the future of the technology. This is presented in *Chapter 2* (Paper 1 – in preparation: Elemo, T., Chipps, M., Graham, N.J.D., Turner, A., Bretagne, S., Jefferson, B. and Hassard, F. Current status of slow sand filter technology: A best practice guide and future considerations. H₂Open Journal).

One of the main concerns with the UWS is the risk of increased clogging in the filter. *Chapter 3* (Paper 2 – submitted: Elemo, T., Chipps, M., Graham, N.J.D., Turner, A., Jefferson, B. and Hassard, F. Understanding the risk of enhanced particle penetration into slow sand filter beds when using underwater skimming techniques. Environmental Technology) explores the particle breakthrough and penetration following filter agitation in biologically immature filters. It also considers the impact of media depth and HLR on particle retention.

Dissolved oxygen (DO) utilisation in SSF has been identified as one of the key parameters ensuring effectiveness of biological removal mechanisms, which are predominantly aerobic. In *Chapter 4* (Paper 3 : Elemo, T., Chipps, M., Graham, N.J.D., Turner, A., Jefferson, B. and Hassard, F. Impact of underwater skimming on dissolved oxygen consumption in slow sand filters for potable water treatment. Water Research), a mathematical model is developed to predict DO utilisation after flow perturbation associated with UWS, and the impacts of sweetening flows on the availability of DO within SSF.

The main crux of the work involves an exploration of the performance and application UWS in the cleaning of SSFs compared to traditional DS method is explored in *Chapter 5* (Paper 4 – submitted: Elemo, T., Chipps, M., Graham, N.J.D., Turner, A., Bretagne, S., Jefferson, B. and Hassard, F. Understanding the impact of underwater skimming on slow sand filter performance and operation, Water Research). Results from a long-term pilot scale filters are presented, with exploration of water quality, head loss development and microbiome of SSFs.

Chapter 6 presents an overall discussion highlighting the implications of the findings of this study. This chapter addresses the potential risks associated with

UWS of SSFs and how the findings of this study address these risks. Furthermore, it highlights the efficacy of the lower media depths of the SSF in the absence of the *Schmutzdecke* in an UWS filter. This chapter also provides some operational benefits of UWS to water production and resource management in treatment works.

Finally, *Chapter 7* recaps the key conclusions and recommendations while *Chapter 8* provides areas for additional areas for future development and research on the understanding and implementation of UWS for SSFs

Table 1.4 summarises the thesis plan and the status of submissions made to journals.

Table 1.4: Summary of the Thesis plan

Chapter	Paper	Objective	Title	Journal	Paper Status
2	1	I	Current Status of Slow Sand Filter Technology	H ₂ Open Journal	In preparation
3	2	II	Understanding The Risk of Enhanced Particle Penetration into Slow Sand Filter Beds When Using Underwater Skimming Techniques	Journal of Water Process Engineering	Submitted
4	3	III	Impact of Underwater Skimming on Dissolved Oxygen Consumption in Slow Sand Filters for Potable Water Treatment	Science of the Total Environment	In press
5	4	IV	Understanding the Impact of Underwater Skimming on Slow Sand Filter Performance and Operation	Water Research	Submitted
6	--	I – IV	Implications of the Underwater Skimmer and Overall Discussion	--	--
7	--	I – IV	Conclusions, Future Direction and Further Research	--	--

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2 Current status of Slow Sand Filter Technology

Abstract

This chapter evaluates the current status of slow sand filter (SSF) technology, focusing on design, operational practices, maintenance routines, and the challenges faced by practitioners in the potable water sector. Through a survey of nine companies operating substantial SSF assets in the UK, Sweden, and the Netherlands, the research identifies commonalities and variations in design and operational standards, as well as ongoing and emerging challenges. The findings indicate that SSFs are predominantly employed either as a main treatment step with minimal upstream pre-treatment or as a final polishing step, which influences filter run length. Design parameters closely align with established literature, ensuring optimal performance, while operational practices are consistent, driven by similar regulatory frameworks, with turbidity and microbial indicators routinely monitored. Although dry skimming remains the predominant cleaning method, alternative approaches are being explored. Significant challenges identified include water quality issues such as algal blooms and hygiene-related concerns like pest control, with time management for cleaning emerging as a critical area needing innovative solutions. This study provides new insights into the practical aspects of SSF operation and identifies areas for improvement and innovation, offering a detailed comparison of design and operational standards and highlighting both common and unique challenges faced by the industry.

Keywords: Operational practices; survey data; potable water sector; emerging challenges; cleaning innovations.

2.1 Introduction

A slow sand filter (SSF) consists of filtration media (typically sand) contained in a vessel, which can range from plastic in household scale (Elliott et al., 2006) to concrete structures (Riesenberg et al., 1995). The key components of an SSF include the supernatant (headwater), sand bed and *Schmutzdecke*, underdrainage system, and flow control mechanisms (Figure 1.1). The supernatant layer is the top layer of water that provides a consistent flow through the sand bed, ensuring stable filtration (Haig et al., 2011). The sand bed is the core component where most of the filtration occurs, but also provides a support matrix for the biological components, both at the surface of the bed and at depth. The *Schmutzdecke* that forms on the surface of the sand, comprises abiotic and biotic particles strained by the filter, along with a diverse community of microorganisms and is significantly contributing to SSF efficacy (Weber-Shirk and Dick, 1997). The underdrainage system collects and distributes filtered water, while flow control maintains the optimal filtration rate (Ellis, 1985; Huisman and Wood, 1974).

The operation of SSFs involves allowing water to slowly percolate via gravity through the sand bed at controlled hydraulic loading rates (HLR), typically ranging from 0.1-0.5 m/h (Table 1.1). As particles accumulate in the filter – predominantly in the *Schmutzdecke* and top sand layers (Campos et al., 2002) - head loss builds up until it is restrictive to flow. Effective cleaning, traditionally achieved by draining the filter and removing the top 10-100 mm of sand—either manually or with mechanised assistance (Lewin, 1961)—is essential to restore functionality and maintain filtration effectiveness. After cleaning, water is gradually reintroduced into the filter by backfilling, and then the filter is allowed to ripen until desired water quality is reached and then returned to service. Removed sand is usually washed and stored hygienically for reuse in the future.

Differences in the language and terminology used to define slow sand filtration have created barriers to effective knowledge exchange and sharing. For example, the term '*Schmutzdecke*' has sparked debates about its definition and

constitution (Campos et al., 2002; Dizer et al., 2004; Huisman and Wood, 1974; Weber-Shirk and Dick, 1997), with some even questioning the word's use entirely. Additionally, the term 'slow sand filter' itself has brought a level of misunderstanding among some practitioners, leading some authors to adopt alternative names like 'slow rate biosand filters' or 'biological sand filters', emphasising the biological activity involved in the filtration process (O'Connell et al., 2017). Others use 'ecological filters' to highlight the filtration mechanism's ecological aspects, reflecting the natural treatment process within the filter bed (Pompei et al., 2022). This diversity in terminology can complicate communication and hinder the sharing of best practices and innovations in the field.

SSF are generally perceived as a robust process with the ability to operate with minimal input. They are primarily used in drinking water treatment as the main treatment process or as a polishing step. However, they are also used in wastewater treatment as a tertiary treatment step (Langenbach et al., 2009; Pfannes et al., 2015), in agriculture for irrigation water treatment (Calvo-Bado et al., 2003; King-Nyamador et al., 2020) and for treating swimming pool water (Lu and Amburgey, 2016). Filters are effective in removing a wide range of contaminants, including suspended solids, microorganisms, and some dissolved organic matter (Table 2.1). In urban settings, SSFs are often used to treat surface water sourced from lakes, rivers, and reservoirs. These sources typically contain high levels of turbidity, algae, and microbial contaminants, effectively removed by SSFs (Ellis, 1985). Conversely, in rural areas, SSFs are employed to treat groundwater or surface water sources that are less contaminated, which generally has fewer contaminants but may still require significant purification to meet drinking water standards (Haarhoff and Cleasby, 1991).

Table 2.1: Summary of treatment performance of SSF in literature

Parameter	Filter type	Source water	Treatment performance	Reference
Turbidity	Full-scale	Surface water	68%	(Erba et al., 2014)
	Pilot	Not specified	47-96%	(Fitriani et al., 2023)
	Household	River	75.9±31.1 %	(Lamon et al., 2021)
True colour	Full-scale	Surface water	48%	(Erba et al., 2014)
	Lab	Surface water	83-95%	(Muhammad et al., 1996)
	Household	River	57.5±46.8 %	(Lamon et al., 2021)
Total organic carbon	Bench-scale	Groundwater	~100%	(Vu and Wu, 2022)
	Bench-scale	Artificially contaminated water	68.3-90.3%	(Li, Zhou and Campos, 2018)
<i>E. coli</i>	Pilot	Secondary effluent	1.9-2.6 log	(Langenbach et al., 2009)
	Household	River	2.2±1 log	(Lamon et al., 2021)
Total coliform	Lab	Surface water	96.4-99.7%	(Muhammad et al., 1996)
	Full-scale	wastewater	66.7-100%	(King-Nyamador et al., 2020)
	Household	River	1.6±0.04 log	(Lamon et al., 2021)
<i>Cryptosporidium</i> oocysts	Full-scale	Pre-treated surface water	>5 log	(Hijnen et al., 2004)
	Pilot	Pre-treated surface water		(Hijnen et al., 2004)
Giardia cysts	Full-scale	Surface water	2-4 log	(Collins et al., 1991)
	Pilot	Surface water	Up to 100%	(Heller et al., 2007)
Virus	Full-scale	Pre-treated surface water	2-3 log	(Hijnen et al., 2004)
	Pilot	Secondary effluent wastewater	0.3-0.6 log	(Aronino et al., 2009)
	Household	Reservoir stored water	1-2.5 log	(Elliott et al., 2008)

SSF design and operation, as documented in literature, have remained relatively unchanged over the years (see Table 1.1). However, there is a need to evaluate and understand how these systems are designed and operated in real-world conditions. Comprehensive data on the operational practices and standards of SSF systems across different regions and organisations is lacking. The variations in design and operational standards among practitioners are not well-documented, and new and recurring problems in SSF operation have not been systematically addressed.

The aim of this work is to evaluate the operational practices of SSF systems within the potable water sector by conducting a survey of practitioners. This survey seeks to identify similarities and differences in design and operational standards, as well as to uncover recurring and emerging issues. Data from operators of full-scale SSFs in municipal cities is presented, highlighting current practices and what is considered good practice in the 21st century. The novelty of this work lies in its systematic approach to evaluating SSF operational practices through a practitioner survey. This study provides a detailed comparison of design and operational standards, highlighting both common and unique challenges faced by the industry. By doing so, it offers new insights into the practical aspects of SSF operation and identifies areas for improvement and innovation.

2.2 Materials and Methods

A survey was conducted among practitioners of SSF in the UK, Sweden, and the Netherlands to understand the design and operational standards from currently active sites.

2.2.1 Sample Justification

The rationale behind the selection of these European countries was based on their use of SSF systems, similar regulatory frameworks, and environmental conditions. European regulations on water quality and treatment practices are often harmonised which allows for a cohesive analysis of operational standards and challenges. For instance, the Drinking Water Directive (Directive 98/83/EC),

sets stringent quality standards for drinking water across the European Union (EU) forming the baseline for water quality regulations in the region.

The USA was excluded to maintain an emphasis on European practices, thereby ensuring the availability of data that is more directly comparable. Additionally, the significant amount of existing USA-based SSF research makes a European focus more contributory to knowledge (Ellis, 1985; Huisman and Wood, 1974; Logsdon et al., 2002; Fox, 1984). Discrepancies in regulatory frameworks and environmental circumstances could have complicated the process of comparative analysis.

2.2.2 Questionnaire Development

The content of the survey was determined based on a literature review of SSF operational practices, combined with consultations with researchers and other experts in the field. Key considerations included relevance to critical aspects of SSF operation, clarity to avoid ambiguity, and comprehensiveness to cover a wide range of topics.

The required information was collected by compiling a comprehensive list of key aspects of SSF operation and management into an Excel sheet. Participants were asked to provide detailed responses directly into this sheet, ensuring that all the relevant data points were covered systematically and consistently. The list included aspects such as company details, site location, number and size of filters, volume of water treated, source water, pre-treatment, post-treatment, filter structure and design, media properties, operating parameters, cleaning practices, and maintenance routines.

2.2.3 Data Collection and Analysis

The questionnaire was distributed electronically via email in an Excel sheet format to the target companies. This format was chosen for its ease of use and familiarity among the respondents. The respondents were requested to fill details directly into the spreadsheet and return the completed forms via email. This approach ensured that the data was collected in a structured and standardised

manner, facilitating easier analysis. A copy of the questionnaire can be found in Appendix B.2, Table A.1.

Prior to disseminating the questionnaires, ethics approval was obtained from Cranfield University via the Cranfield University Research Ethics System, under the reference CURES/9349/2019 (Appendix A.2). Key stakeholders, managers or operators of SSF treatment works were identified and contacted to complete the questionnaire. Participants from a total of nine companies were contacted. Each questionnaire took approximately 45 min to complete (excluding wait time if participant needed confirmation of information for other parties within their company). Each participant provided one questionnaire with information about their company spanning all their available SSF treatment works.

Each company provided data for multiple sites, allowing for a detailed analysis of SSF operations across different locations. Upon receipt of the completed questionnaires, the data was extracted, anonymised, and coded. The coding of the answers was based on predefined categories derived from the key sections of the questionnaire. Quantitative data such as the number of filters, size/area of filters, volume of water treated, hydraulic loading rates, and water quality parameters were analysed using summary statistics. Qualitative data such as descriptions of major operational challenges, maintenance activities, and parameters monitored were reviewed to identify common themes and unique practices.

The survey results were analysed to identify similarities and differences among practices in these countries. Additionally, the analyses revealed recurring and emerging problems within SSF operations. From these insights, the best operational practices were identified. The study also provided a 21st-century outlook on SSF operations and projected the future of SSF and similar biological filtration processes.

2.3 Results and Discussion

The survey involved nine participant companies from the UK (5), Sweden (2), and the Netherlands (2). The companies collectively manage 401 SSFs across 27 treatment works (Table 2.2). Majority of sites use SSF as the main secondary treatment step in the treatment train (20 sites) while the other 7 sites use SSF as the final treatment step in the treatment train, i.e., as a final polishing step (Table 2.2).

Table 2.2: Summary of the number of treatment works and slow sand filters per company surveyed and the treatment application used by each company.

Company	Number of treatment works	Number of filters	Main treatment step or polishing step
A	2	15	Main
B	3	13	Main
C	5	114	Main
D	5	70	Main
E	3	47	Polishing
F	2	33	Main
G	2	54	Main
H	4	37	Polishing
I	1	18	Main

The feed water to the SSFs predominantly came from surface water sources from rivers and lakes, with only one treatment works reported to be treating from a groundwater source. Following abstraction, 63% of the treatment works included pre-treatment storage or reservoir before the head of the works (Figure 2.1). Pre-treatment storage not only ensures a consistent flow rate to the works but also offers treatment benefits by balancing the feed and mitigating concentration peaks in solids that could adversely affect the SSFs (Huisman and Wood, 1974; Logsdon et al., 2002). This also facilitates better source management.

To make the water suitable for feeding the filters, various pre-treatments are required, including coagulation, rapid sand filtration, ozone dosing, pellet softening, biological activated carbon filtration, micro-sieving, flocculation,

sedimentation, and roughing filters (Table 2.3). Pre-treatments like roughing filters are specifically introduced to improve feed water quality, thereby preserving turbidity removal efficiency of the filters and extending their operational lifespan (Wegelin, 1988). Depending on the quality of the source water, additional pre-treatment steps might be necessary. For example, pre-ozonation is used where dissolved organic carbon (DOC) poses a significant challenge, as it increases the bioavailability of the DOC for better treatment outcomes (Graham, 1999). Although the SSFs in this survey were all 'chemical-free', meaning no chemicals were dosed directly into the filters, some respondents did indicate the use of coagulation upstream of a roughing filter.

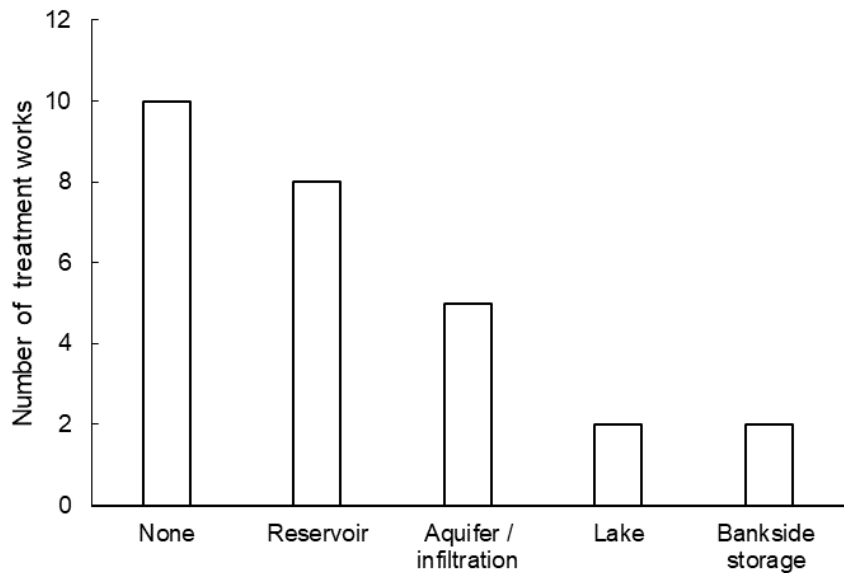


Figure 2.1. Water storage options in SSF treatment works

Table 2.3: Summary of pre-treatment options

Company	Works	Source water	Major contaminants	Sedimentation (via storage)	Micro straining or screening	Coagulation + Flocculation	Secondary Sedimentation or Clarifier	Rapid gravity filtration	Membrane filtration	Activated carbon filtration	Ozonation
A	1	Surface		Y				Y			Y
	2	Surface		Y				Y			Y
B	1	Groundwater	Algae Manganese			Y		Y	Y		
	2	Surface	Algae		Y			Y			
	3	Surface	Algae Arsenic		Y			Y			Y
C	1	Surface	Algae Turbidity	Y				Y			Y
	2	Surface	Algae	Y				Y			Y
	3	Surface	Algae	Y				Y			Y
	4	Surface	Algae	Y				Y			Y
	5	Surface	Turbidity			Y	Y				Y
D	1	Surface	Algae	Y				Y			Y
	2	Surface	Algae	Y				Y			Y
	3	Surface	Algae	Y				Y			
	4	Surface	Algae	Y							
	5	Surface	Algae								
E	1	Surface	Algae	Y	Y			Y		Y	
	2	Surface	Algae	Y	Y			Y		Y	
	3	Surface	Algae	Y	Y			Y		Y	
F	1	Surface	NOM/ DOC Algae	Y				Y			
	2	Surface	NOM/ DOC Algae					Y			
G	1	Surface	Wastewater effluent		Y	Y	Y	Y			
	2	Surface	Wastewater effluent		Y	Y	Y	Y			
H	1	Surface	DOC	Y		Y		Y		Y	Y
	2	Surface	DOC	Y		Y		Y		Y	Y
	3	Surface	DOC	Y		Y		Y		Y	Y
	4	Surface	DOC	Y		Y		Y		Y	Y
I	1	Surface	NOM			Y		Y			

2.3.1 SSF Filtrate

In treatment works where SSF serves as the final treatment step, a more complex treatment process is implemented upstream. Here, the SSF primarily functions as a disinfection step whilst also improving the biostability of the filtrate by reducing assimilable organic carbon, thus diminishing microbial regrowth within the distribution network (van der Kooij et al., 2017). In such cases, although no chemical disinfection is included, the capacity for chlorine disinfection remains available for emergency situations. Conversely, in facilities where the SSF is the main treatment step, there is more extensive disinfection post-SSF, which may include chlorination/chloramination, UV disinfection, or a combination of both, with a requirement for a disinfection residual. This is to prevent regrowth in the distribution network.

In England and Wales, operators follow the Drinking Water Inspectorate's requirement for a residual chlorine concentration of 2 mg/L at the customer's tap (DWI, 2023), which is significantly higher than the World Health Organization's 0.2-0.5 mg/L recommendation (WHO, 2022).

While regulations typically stipulate water quality either leaving the treatment works or at the customer's tap, there are no specifics for water quality at the outlet of individual treatment steps, and as such, no specifications for filtrate from SSFs. Instead, individual companies establish quality standards and criteria based on the treatment steps downstream of the SSF (Table 2.4). The parameters monitored are also dictated by persistent contaminants in the area; for example, Company B, which identified arsenic as a major contaminant at one of its sites, routinely monitors arsenic along with other heavy metals at the outlet of its SSFs. However, one consistent criterion across all treatment works is turbidity; all maintain very low turbidity levels at the SSF outlet, with turbidity consistently ≤ 0.3 NTU (Table 2.5). This low turbidity is maintained to ensure effective disinfection, with regulatory guidelines recommending a turbidity level of less than 1 NTU prior to disinfection.

Table 2.4: Parameters monitored on the outlet of SSF

Company	Works	Turbidity	Dissolved oxygen	Methyl-Isoborneol (MIB) & geosmin	Colour	UV ₂₅₄	Total organic carbon	Ammonia & Nitrates	Heavy metals	Flow cytometry	Clostridia	Coliform	E. coli	Enterococci	Cryptosporidium	Heterotrophic plate count
A	1	Y														
	2	Y														
B	1	Y		Y					Y							
	2	Y		Y		Y	Y		Y	Y		Y	Y	Y		Y
	3	Y		Y	Y	Y	Y		Y	Y	Y	Y	Y			Y
C	1	Y	Y					Y			Y	Y	Y	Y	Y	
	2	Y	Y					Y			Y	Y	Y	Y	Y	
	3	Y	Y					Y			Y	Y	Y	Y	Y	
	4	Y	Y					Y			Y	Y	Y	Y	Y	
	5	Y	Y					Y			Y	Y	Y	Y	Y	
D	1	Y	Y					Y				Y	Y		Y	
	2	Y	Y					Y				Y	Y		Y	
	3	Y	Y					Y				Y	Y		Y	
	4	Y	Y					Y				Y	Y		Y	
	5	Y	Y					Y				Y	Y		Y	
E	1	Y	Y									Y	Y	Y		
	2	Y	Y									Y	Y	Y		
	3	Y	Y									Y	Y	Y		
F	1	Y										Y	Y			
	2	Y										Y	Y			
G	1	Y				Y	Y	Y	Y							
	2	Y				Y	Y	Y	Y							
H	1	Y									Y	Y		Y		
	2	Y									Y	Y		Y		
	3	Y									Y	Y		Y		
	4	Y									Y	Y		Y		
I	1	Y								Y		Y	Y			Y

Table 2.5: Working and maximum allowable turbidity for SSF

Company	Working Turbidity (NTU)	Maximum turbidity (NTU)
A	<0.3	0.30
B	0.10	0.50
C	<0.1	0.30
D	<0.3	0.30
E	<0.1	
F	<0.1	0.15
G	0.06	0.10
H	<0.03	0.03
I	0.01-0.05	0.25

An emerging monitoring trend in SSFs is the adoption of flow cytometry (FCM), which complements traditional microbial indicators. This technique is used to assess the biofilm maturity and microbial removal performance of the filters (Chan et al., 2018). However, only two companies, representing 11% of the treatment works surveyed, reported using FCM for monitoring. Although FCM provides a time-efficient tool for microbial analysis (van Nevel et al., 2017), it has not yet been included in regulatory frameworks. Therefore, from both public health and compliance perspectives, traditional microbial indicators, such as faecal bacteria like *E. coli*, continue to be preferred.

2.3.2 Design

The survey revealed remarkably consistent design specifications across the SSFs, particularly in terms of media size and depth. The effective size (ES) of sand used in nearly all filters ranged from 0.1 to 0.4 mm, except for one site where the range was 0.13 to 0.6 mm (Table 2.6). This is in line with the commonly recommended size of 0.15 to 0.4 mm found in the literature (Table 1.1). The uniformity coefficient (UC) was reported to be between 1.4 and 3.5, with the majority of respondents noting values below 2.5, which aligns with the ranges recommended in the literature (Table 2.6). Sand depth varied from 0.3 to 1.3 m, fitting well within the literature's recommended range of 0.3 m minimum (Ellis,

1985) to 1.5 m maximum (Huisman and Wood, 1974). However, it was noted that in systems where the SSF served as the final polishing step, the operational minimum acceptable sand depth was typically between 0.8 and 0.9 m. This adjustment is understood as removal efficiencies, particularly for microbial contaminants such as bacteria and viruses, tend to improve with increased media depth (Bellamy et al., 1985).

Normal operation of all the filters surveyed was at HLRs ranging from 0.1-0.4 m/h (Table 2.6), which is within the reported HLRs of 0.04-0.5 m/h found in the literature (Ellis and Aydin, 1995; Letterman and Cullen, 1985). Some respondents also reported having a maximum allowable HLR, typically within the normal range, but a few works reported maximum rates of 0.5-0.7 m/h. These higher rates were generally associated with facilities where the SSF served as the final polishing step and could operate at higher rates due to low influent contaminant loads. One respondent noted that this higher rate was only utilised during periods of increased water demand. Literature suggests that while a mature filter can handle increased HLRs, this may compromise removal efficiencies (Bellamy et al., 1985b) and lead to increased filter clogging and more frequent cleaning needs (Ellis and Aydin, 1995).

Table 2.6: Summary of the filter design specifications used by the different companies surveyed.

	Suggested from literature	Companies surveyed								
		A	B	C	D	E	F	G	H	I
Effective size (mm)	0.15-0.40 ^{a-d}	0.27-0.37	0.35	0.3	0.3	0.3	Unknown	0.4	0.13-0.6	0.35
Uniformity coefficient	1.5-5 ^{a, c, d}		1.5-3.5	1.7-2.3	1.7		Unknown	<2.5	1.4	<2.5
Sand depth (m)	0.8-1.5 ^{a-d}	0.75-0.90	1	1.2	1.2	1.2	0.9-1.0	1.2	1.2-1.3	1.1
Min. sand depth (m)	0.3-0.9 ^{a, c, d}	0.5	0.6	0.5	0.3	0.9	0.3-0.5	0.30-0.65	0.8	0.7
Supernatant water (m)	1.0-3.0 ^{a-d}			1.2	1.0-1.2	0.8-1.0	1.0-1.5	0.5-1.5	1.7-2.25	1.1-2.65
Support layer (m)	0.3-0.5 ^c		0.15	0.1	0.3	0.15	Variable	0.2	0.5	0.3-0.45
Hydraulic loading rate (m/h)	0.04-0.5 ^{a-f}	0.1-0.3	0.2	0.2-0.35	0.05-0.25	0.2-0.45	0.11-0.3	0.25-0.35	0.25-0.4	0.22-0.4

a - Huisman & Wood (1974); b - Ellis (1985); c - Visscher (1990); d - Barrett et al. (1991); e - Letterman & Cullen (1985); f - Ellis & Aydin (1995)

2.3.3 Cleaning

Ideally, filters should only be cleaned when maximum head loss is reached to optimise output from a filter run. However, in practice, this is often unfeasible due to time and resource constraints. Therefore, most treatment works with multiple filters schedule cleaning based on available labour, typically within normal weekday working hours (i.e., 9 AM-5 PM). A fixed filter run length is common, especially in facilities using SSF as the main secondary treatment, with run lengths varying from 40-180 days (sites A-D, F-G, and I). Conversely, sites using SSF as a polishing step (sites E and H) may have more varied run lengths, from 1-7 years (Figure 2.2). For instance, Thames Water adheres to statutory filter run lengths of 40 days in summer and 70 days in winter. Additional operational criteria for cleaning might include preferential cleaning of filter beds experiencing elevated head loss regardless of run length or decommissioning filters starting with head losses greater than 80% of the maximum allowed (Toms, 1996). Water quality compliance failures can also necessitate filter cleaning or re-cleaning if issues arise shortly after a cleaning event and the standard maturation period has passed without improvement in water quality.

All companies surveyed reported using traditional dry skimming for cleaning their filters. This method involves draining the filter, removing the top sand layers, and gradually backfilling the SSF before putting it into forward flow to allow a period of ripening prior to return to service. The associated downtime for this cleaning method was reported to range from 2 to 30 days (Figure 2.2). Variations in cleaning downtime are influenced by factors such as the execution of the cleaning process, including the speed and number of skimming machines used. Respondents also reported that the time for filters to 'ripen' or reach 'maturity' varied from two days to two months. Literature indicates that maturation can take anywhere from two to three weeks (Nimatuzahroh et al., 2022). However, the discrepancies in the definition of terminology makes this difficult to ascertain. Bauer et al. (2011) noted that while constant performance might be achieved in ten days, reaching full maturity could take up to 40 days.

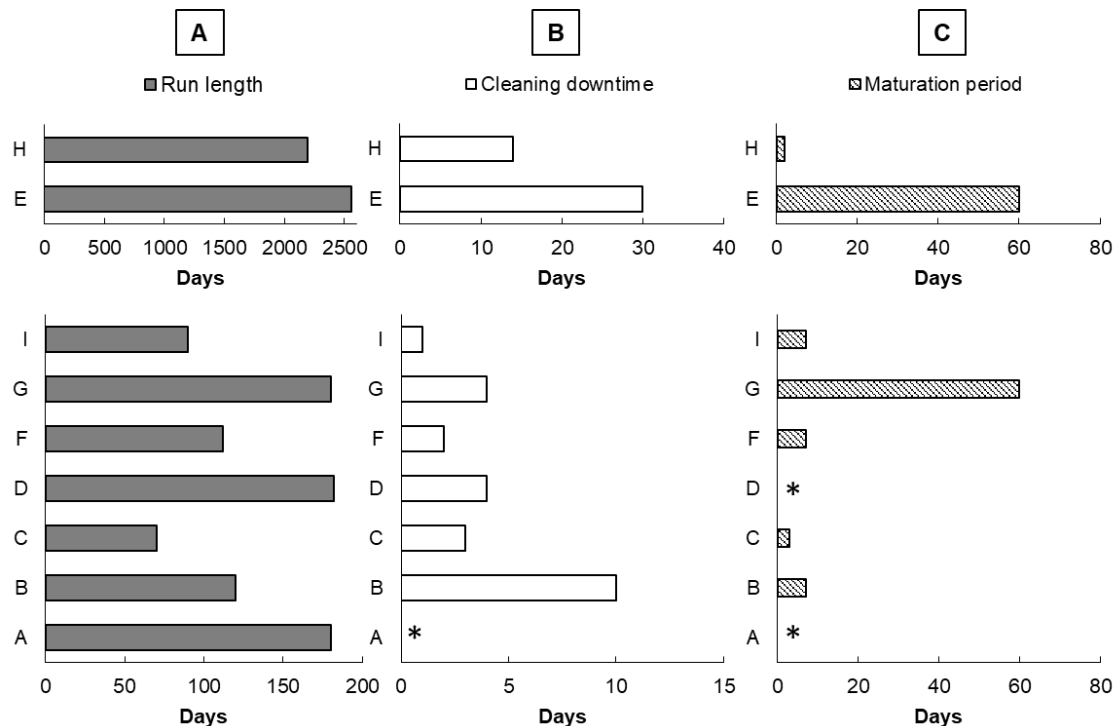


Figure 2.2. Filter run length (A), cleaning downtime (B), and filter ripening period (C) for surveyed companies.

*** no data provided by respondent**

The depth of sand removed during cleaning is determined by the extent of clogging in the sand bed, necessary to recover head loss and ensure adequate flow for the next filter run. Typically, a predetermined depth of media, ranging from 25 to 100 mm, is removed each time filters are cleaned, consistent with literature specifications of 10-100 mm (Letterman and Cullen, 1985). However, one company performs a ‘dirt test’ to assess how deeply particles have penetrated, thereby determining the precise depth of sand to be removed.

Normal operational practice involves multiple skims until reaching a minimum allowable depth of sand, after which the sand is either topped off or replaced. Historically, operators used trenching—a process where the sand at the bottom of the filter was swapped with the top—as standard practice (Lewin, 1961). Currently, none of the respondents follow this method; instead, they replace the sand media based on fixed time intervals or quality criteria. Replacement intervals reported by the companies vary from 6-15 years when SSF serves as the main

treatment method and can extend to several decades when used as a polishing step. However, two respondents indicated that their sand media is never replaced. Others noted replacing the sand with either used, washed sand or as mentioned by one respondent, with virgin sand.

Operators typically avoid cleaning filters during winter (the colder months) due to multiple reasons. This period often sees a longer run length, attributed to reduced microbial activity at lower temperatures, which slows clogging and extends the time needed for filters to ripen. Additionally, surface water quality tends to be better in the colder months, particularly with fewer algal problems.

2.3.4 Operational Challenges

Algal blooms were identified as the predominant issue, with about 60% of respondents reporting problems related to such occurrences (Figure 2.3). Some studies suggest that algae can benefit SSF by contributing to the development of the *Schmutzdecke* and enhancing treatment efficiency (Unger et al., 2008; Wakelin et al., 2010, 2011). Nonetheless, when algal populations peak during spring and autumn, they pose significant challenges. The specific problems vary depending on the species of algae present. For instance, small pennate diatoms can be problematic as they may pass through the SSF and reach the filtrate due to their size and shape (Kelkar et al., 2009). Cyanobacteria (blue-green algae) are particularly challenging in SSFs due to their potential to produce taste and odour compounds in the water. The combination of higher temperatures and low HLRs fosters algal growth, particularly in the supernatant (Toms and Bayley, 1988). Once algal blooms become problematic, either by causing clogging or reducing water quality, the only remedies are more frequent cleaning and maintenance. Therefore, the best preventive measures include source control, such as reservoir mixing, or a more comprehensive pre-treatment approach.

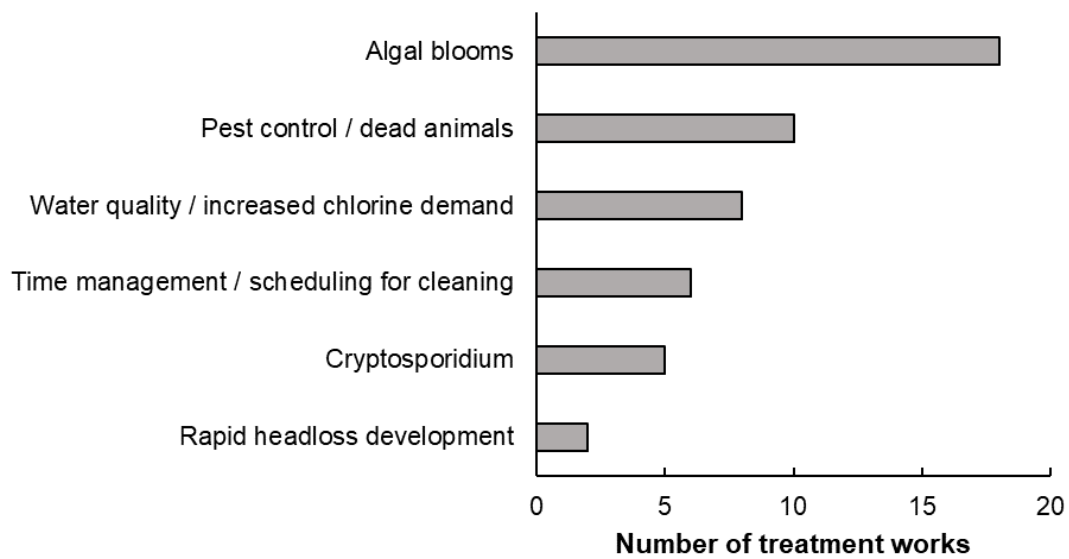


Figure 2.3. Common operational problems identified.

The second most common issue reported was related to animal and pest control. This problem is particularly acute for treatment facilities where the filters are either uncovered or not housed within a building. Steele (2004) noted that the presence of various bird species could lead to a deterioration in the bacteriological quality of the filtrate and recommended that filters be covered. However, covering filters is not always feasible, especially for older SSF assets, as retrofitting covers may compromise their structural integrity and will be very expensive. While Voogt (2013) demonstrated success with retrofitting covers on SSFs smaller than 100 m², experiences with larger filters have not been as favourable. Consequently, alternative measures are necessary to manage birds and other pests, with an emphasis on maintaining site cleanliness and hygiene. Six companies outlined their pest and animal control strategies, which commonly included good housekeeping practices and visual checks, with some implementing a structured daily inspection routine. Additionally, other pest deterrents used include fences, netting, inventive bird deterrents, and outsourcing to external companies specialising in pest management.

Most of the common operational problems encountered are directly linked to water quality issues, either due to seasonal effects on influent water, such as

algal blooms, or negative impacts on water quality from the presence of pests and pathogens like *Cryptosporidium*. However, time management and scheduling for cleaning also stood out as critical for the smooth operation of treatment works, involving more human management than process control. Underwater cleaning methods, as noted by Huisman and Wood (1974) for being significantly faster than methods that require draining, allow labour hours to be freed up for other activities.

2.3.5 Recommended Practice

Based on the information provided in the survey as well as the information from literature, the following recommended practice can be summarised:

Filter Design

Design parameters for SSFs including media properties like effective size, uniformity coefficient, and depth as summarised in Table 2.6, have been demonstrated to be ideal and effective. HLR in the range of 0.1-0.4 m/h have also proven effective. Nevertheless, there is potential to increase throughput from SSFs, and operators may cautiously explore higher HLRs. Although some practitioners have tested rates as high as 0.7 m/h, any increase in HLR should be implemented gradually and during periods with minimal contaminant risks in the influent water, such as in colder winter months.

Filter Operation

Operating filters until they reach maximum head loss before initiating cleaning can enhance production. This strategy may be more suitable for SSFs used as a final polishing step but presents challenges for SSFs with shorter run lengths that require more frequent cleaning. Thus, a combination of time-based and head loss-based cleaning strategies is optimal, as practiced by many operators. Monitoring and sampling should be conducted as needed. Regular monitoring of parameters that are neither regulated nor present in the feed water lacks financial justification. Instead, prioritising site-specific and regulatory requirements is crucial.

With the challenges posed by climate change and deteriorating water quality, ensuring consistent feed water quality for SSFs is becoming increasingly difficult. Practitioners should prioritise source control as the first step. When direct management of incoming water quality is not feasible, implementing upstream pre-treatment solutions is essential to maintain SSF effectiveness and ensure adequate filter run lengths.

Filter Cleaning

Minimising filter downtime is crucial, especially when filters are left dry. To prevent desiccation and loss of biological capability within the filter bed, filters should be kept in service at a reduced HLR when immediate cleaning is not feasible. While innovative cleaning approaches can offer time-saving benefits and potentially reduce costs, a thorough cost-benefit analysis is essential. If the costs of new methods outweigh the benefits, alternative approaches should be considered.

It is essential that the entire media in an SSF be periodically replaced with either washed or virgin sand. This occurs because, after prolonged use, particles accumulate throughout the depth of the filter, clogging the pores and resulting in elevated initial head loss and shorter filter run lengths. Although a fixed timeframe facilitates planning, an evidence-based approach is more advantageous for managing costs and time. Conducting silt tests and shake tests on the lower layers of sand during routine cleaning can provide valuable insights into the remaining operational lifespan of the filter bed, thereby informing decisions on the timing of complete sand replacement. Neglecting to replace the sand can compromise the filter's effectiveness and longevity.

Maintenance and Housekeeping

The most effective method to deter pests and animals from SSFs is through the use of physical barriers and covers. It is recommended that all new SSF installations include a covering. For existing systems, structured covers should be considered where feasible. However, if adding a cover might compromise the structural integrity of the asset due to additional weight, alternative pest and

animal deterrents should be implemented. It is also advisable to seek external assistance and advice to ensure that pests are humanely deterred, and any protected species are appropriately managed and relocated.

2.4 Conclusions

There were many similarities in the design of the SSFs from the survey, with design specifications generally aligning with those prescribed in key SSF literature. This included sand media properties such as effective size ranging 0.13-0.6 mm, uniformity coefficient 1.5-3.5 and operational sand depth ranging from a minimum of 0.3 m to a maximum of 1.3 m. A significant difference was noted in the implementation of SSFs as either a main treatment step with minimal pre-treatment or as a final polishing and disinfection step. This difference directly influenced the filter run length, as filters handle varying contaminant loads. Operation and maintenance also showed many similarities across surveyed countries, which share similar regulatory requirements. Sampling and water quality monitoring always include turbidity (<1 NTU) and some microbial indicator, usually of faecal origin. However, other monitoring efforts are site-specific and depend on local contaminants of concern. All treatment works surveyed use dry skimming as the primary cleaning approach, although a few are exploring alternative methods (currently on trial).

Most operational challenges are related to water quality and contaminants. Algal blooms present a significant challenge at the majority of the works, with the most effective solution being to manage the problem upstream of the SSF to prevent excessive filter clogging and poor water quality. In instances where filters cannot be roofed or housed, implementing good housekeeping and pest deterrents is necessary to manage the prevalence of pests and deceased animals in and around filters. Time management and scheduling associated with cleaning were also identified as major issues, and operators would benefit from cleaning approaches that minimise downtime, such as methods that eliminate the need to drain and refill filters.

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3 Understanding the Risk of Enhanced Particle Penetration into Slow Sand Filter Beds When Using Underwater Skimming Techniques

Abstract

Biologically immature slow sand filters' (SSF) performance was simulated to understand the risk of particle penetration posed by underwater skimming (UWS) operations, focusing on clogging, rapid head loss, and particle breakthrough. Pilot scale filters were challenged with dispersed kaolin particles to simulate particle accumulation on the filter surface and skimmed without draining. Agitating the filter surface during UWS reduced particle capture efficacy; however, increasing the depth of the filter media lessened this effect, and at depths beyond 500mm, the impact became negligible. At deeper levels of the filter, there was limited evidence of clogging as 90% of the head loss occurred in the upper layers. Increasing the hydraulic loading rate from 0.3 m/h to 0.5 m/h decreased particle retention by 0.72 log, yet the system achieved >2 log particle capture. Small particles (2-10 μm) were removed by 2 logs, suggesting pathogens would be sufficiently retained within the bed. Good particle capture of particle size 2-125 μm indicates that filters retain turbidity, implying minimal risk to water quality and public health during UWS use. This study represents a worst-case scenario for biologically vulnerable SSFs, excluding biological activity's impact. Thus, with effective skimming under normal conditions, SSFs reliably prevent particle breakthrough suggesting no risk associated with particle penetration from using UWS.

Keywords: Slow sand filter (SSF); particle penetration; pilot scale filters; media depth; surface agitation; head loss.

3.1 Introduction

Slow sand filtration combines particle capture and biological activity leading to the development of head loss over time, necessitating regular maintenance to prevent flow reduction (Abdiyev et al., 2023). Typically, this maintenance involves dry skimming (DS), where the top 10-50 mm of media is removed after draining the bed (Ellis and Aydin, 1993). To reduce the associated down time and thereby increase water production, an innovative approach is being developed based on skimming whilst the bed is still submerged, underwater skimming (UWS) (Hassard et al., 2022). A potential challenge to this approach, is that UWS could potentially dislodge particles into the water or fail to remove disturbed particles, risking filter clogging and reduced effectiveness by expediting head loss (Singer, et al., 2017). Additionally, UWS could impact media compaction of the top layers with corresponding impacts on particle removal and head loss development. Understanding the risks of enhanced particle penetration within the filter beds associated with UWS procedures will help maintain filtrate quality and control particle breakthrough, ensuring the effectiveness of subsequent water treatment processes i.e., disinfection (Singer et al., 2017).

SSFs differ compared to rapid gravity filters (RGF) in terms of the media size used (0.2-0.3 mm versus 0.5-1.2 mm), the hydraulic loading rates (HLR) (0.1-0.3 m/h versus 5-15 m/h) and the cleaning procedures (skimming versus backwashing) (Crittenden et al., 2012). In addition, the process of skimming reduces the bed depth through removal of the top section. This continues until a limiting point when the cleaned sand is added to the bed and the height returned to its initial value (Maiyo, et al., 2023). The overall change can be between 0.3 and 1.2 m with lower limits on bed depth of 0.3-0.5 m associated with effective removal of turbidity and bacteria (Ellis, 1985). In addition, a minimum bed depth of 0.6 m is required to maintain virus log reduction credits (Poynter and Slade, 1977). Importantly, these recommendations are based on DS, highlighting a gap in understanding particle behaviour during UWS.

Particle removal mechanisms in SSFs mirror those of RGF and can be modelled with a single collector efficiency model incorporating collision and attachment mechanisms. Classical theory identifies three core mechanisms that impact collision: diffusion, interception and sedimentation and these can be described relative to the size of the particle and media as well as the temperature, water velocity and particle density (Meng et al., 2024). Previous work has also shown that reduced HLR, and hence water velocity, enhanced transport of particles and improved filtration, with removal of suspended solids increasing from an average of 66% to 87% when HLR was halved (Verma, et al., 2017). As such, standard practice, post skimming, is to gradually increase the HLR from a low base to the target rate, over 48 h, coinciding with time required for bacteriological testing (Steele, 2004). In contrast, quickly restoring the operational HLR after cleaning helps filter maturation and minimises downtime but could contribute to deeper particle penetration (Steele, 2004). The influence of filter media depth and HLR on particle removal, especially post-UWS, remains uncertain. UWS involves the cleaning of SSF by removing the *Schmutzdecke* and top sand layers while the bed is still fully submerged (i.e., eliminating the draining down of the filter bed). This presents a risk of increased particle penetration and breakthrough, especially as disturbing the filter surface can reduce compaction, increase hydraulic conductivity, and consequently lead to greater particle infiltration.

This research addresses key uncertainties in implementing UWS for SSF maintenance, including how surface agitation from UWS, particularly under worst-case malfunctions, impacts particle penetration and breakthrough. The required sand/media depth for effective filtration during agitation and the influence of different HLRs on particle penetration remain unclear. Operational risks, such as increased particle penetration and deep bed clogging, are also poorly documented. This study investigates how UWS-induced surface agitation affects particle dynamics in SSFs, particularly when the filter surface is disturbed without skimming. It aims to examine particle breakthrough, determine the minimum sand depth required for effective filtration, and evaluate the effects of different HLRs on particle penetration post-agitation. The novelty of this research

lies in its focus on UWS-induced surface agitation, addressing these critical gaps to provide insights into UWS risks and benefits. This work supports the development of more efficient SSF maintenance strategies, enhancing water production and quality.

3.2 Materials and Methods

3.2.1 Pilot Filtration Setup

The experimental pilot filters consisted of 150 mm diameter PVC columns with an area of $\sim 0.018\text{m}^2$ and featured a PWT™ K-floor nozzle base. The columns were filled with sand (effective size (ES) 0.3 mm, uniformity coefficient (UC) 1.75) above a 100 mm layer of 10 mm pea shingle gravel, with clear plastic piezometers for head loss monitoring. The SSF experiments were biologically immature to represent the highest risk of particle penetration. Accelerated head loss was induced using a kaolin dispersion, chosen for its minimal biological reactivity, to model rapid solids loading. The kaolin solution was made up from 100 g of kaolin dispersed into 10 L of SSF feed water (outlet from a pilot roughing filter) and this generated a size distribution of predominately $<2\text{ }\mu\text{m}$ and $2\text{-}10\text{ }\mu\text{m}$ particles which made up to 94% of the particle size distribution (Appendix C.1). The remaining particles were in the 10-15 and 25-75 μm bands. Turbidity in the supernatant following the addition of kaolin was estimated to range from 1,400-2,300 NTU (Table A.2). Kaolin was allowed to settle overnight ($\sim 20\text{ h}$) before experiments were commenced (see Appendix C.2, Table A.2).

To undertake a UWS, a custom 2.5 m stirrer with a wooden paddle, was powered by a battery drill, to mimic the UWS auger's action, agitating the top $40 \pm 10\text{ mm}$ of sand at 100 rpm for two seconds, based on extrapolations from tests of full-scale UWS.

The experiments were divided into two phases. Phase 1 determined the minimum sand depth needed to minimise particle breakthrough post-agitation, testing sand depths from 200 to 900 mm at a constant HLR of 0.3 m/h with a 100 g kaolin challenge. The control filter was the same but without agitation (Figure 3.1).

Phase 2 explored particle penetration across a filter's depth under different ramp-up speeds and HLRs, aiming to find the depth at which surface-settled particles infiltrate the sand when the flow rate increases rapidly. This involved measuring head loss at 50 mm intervals in a fixed depth of SSF under varying HLRs, with a control gradually increasing HLR over three days to reach 0.3 m/h (Figure 3.2). Breakthrough was monitored using turbidity and particle counts, with a Hach TU5200 (Hach Co., Loveland, Colorado, USA) turbidimeter for turbidity and a Liquilaz® E20 (Spectris plc, UK) for particle counts spanning 2-125 μm .

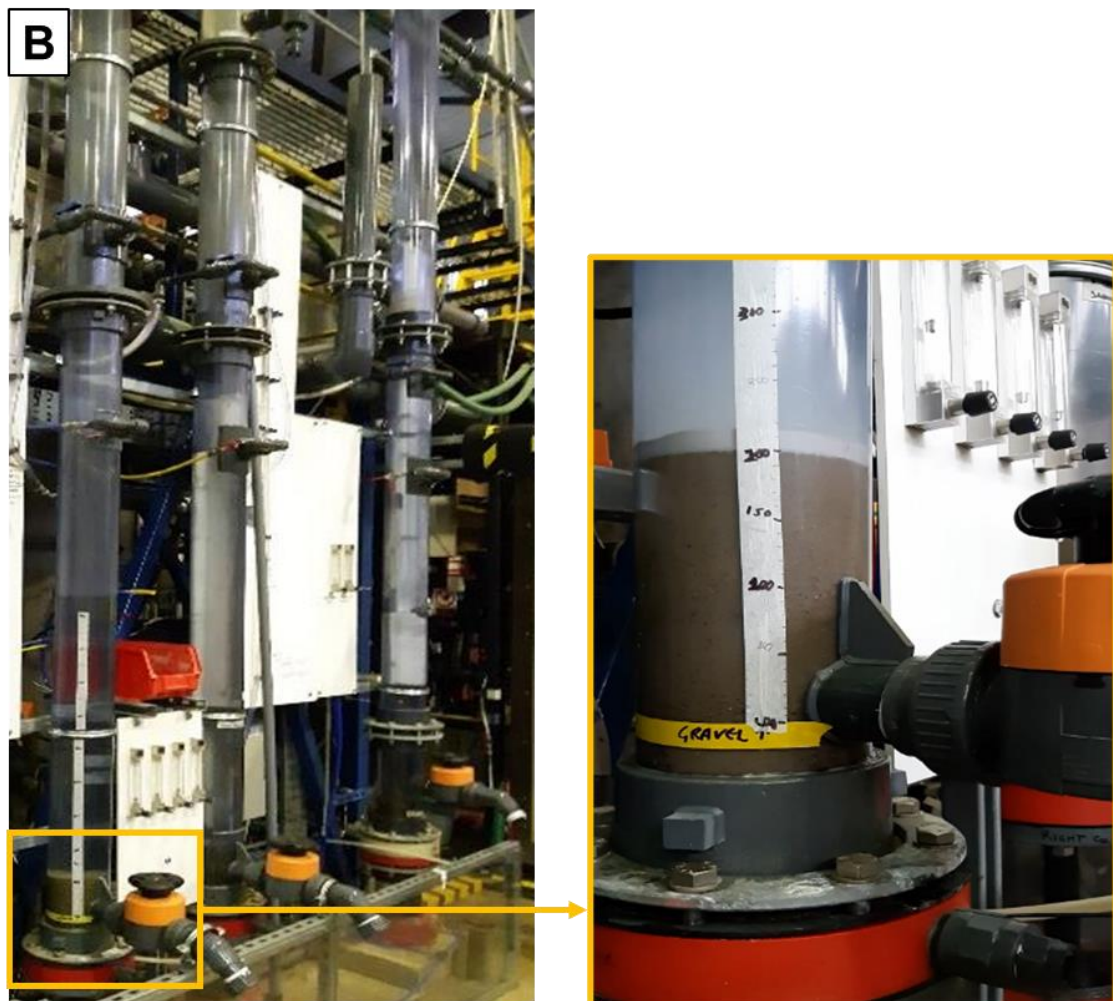
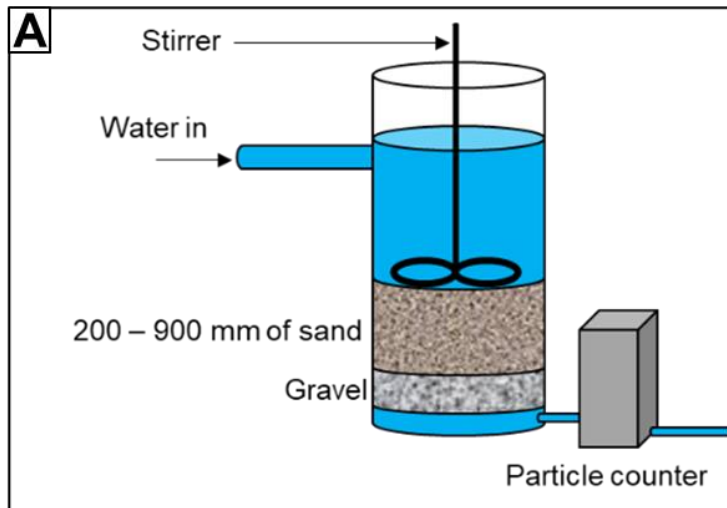


Figure 3.1: Experimental set-up to monitor the effect of filter surface agitation and media depth on filtrate particle count.

- (A) Schematic of the experimental set-up showing the particle counter position;
 (B) Image of the columns.

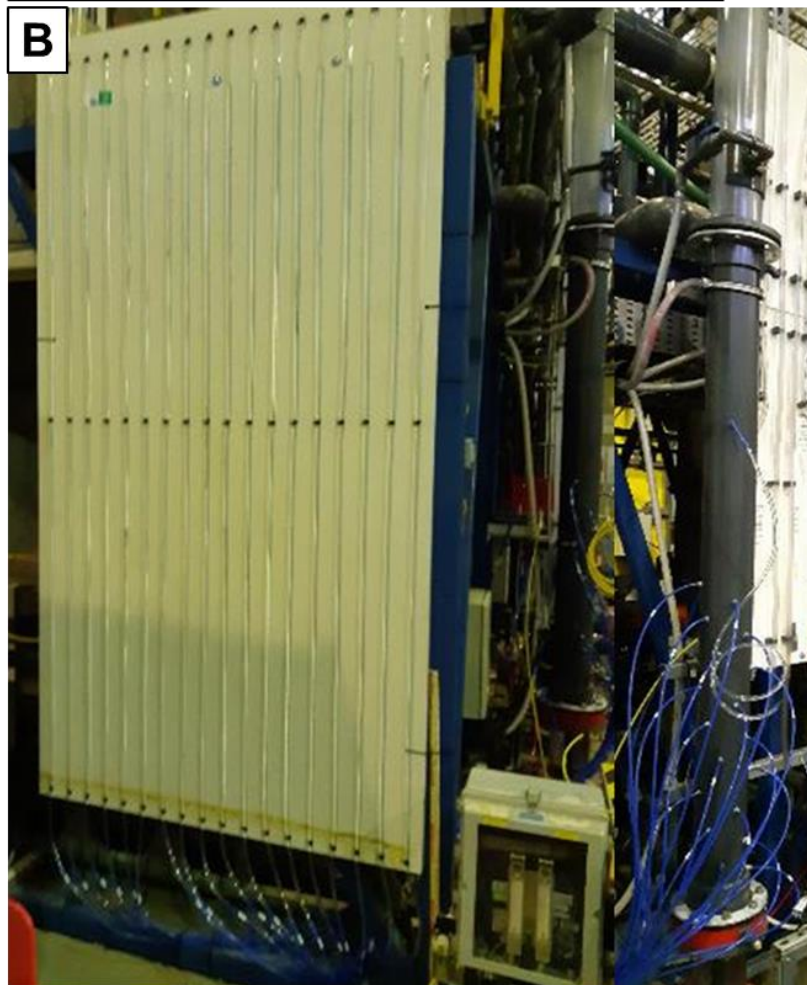
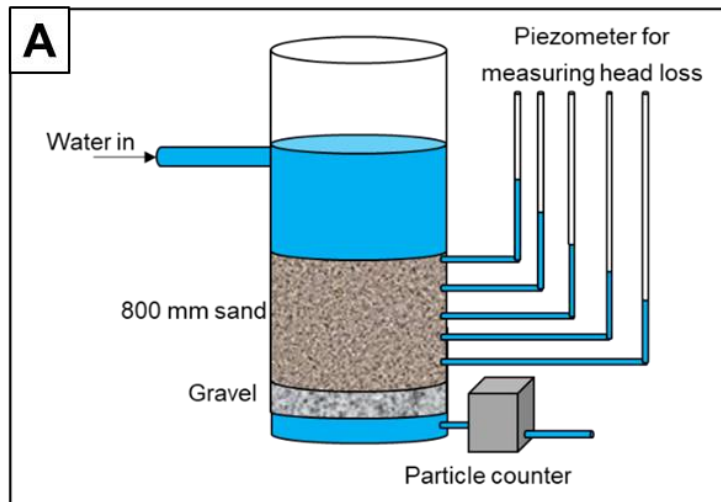


Figure 3.2: Experimental set-up to monitor the effect of filter surface agitation on particle penetration and impacts of increased filtration rates.

(A) Schematic of the experimental set-up showing the particle counter position (not all piezometer ports shown); (B) Image of the columns showing the 50 mm interval piezometer tubes.

3.2.2 Particle Retention Models

The performance of the filters was modelled based on the single collector efficiency correlation equation developed by Tufenkji and Elimelech (2004). The model assumes that the overall single collector efficiency (η_{total}) can be calculated as the sum of the individual transport mechanisms of diffusion (η_D), gravity sedimentation (η_G), and interception (η_I)

$$\eta_{total} = \eta_I + \eta_G + \eta_D \quad (3.1)$$

The terms are then converted to nondimensional equivalents such that the single collector collision efficiency can be described by four dimensionless terms:

$$\eta_{total} = \eta_{total}(N_R, N_{Pe}, N_V, N_G) \quad (3.2)$$

Where N_R is the aspect ratio (interception term), N_{Pe} is the Peclet number, N_V is the van der Waals number and N_G is the gravitational number with corresponding equations:

$$N_R = \frac{d_p}{d} \quad (3.3)$$

$$Pe = \frac{3\pi\mu d_p u}{k_B T} \quad (3.4)$$

$$N_V = \frac{H}{k_B T} \quad (3.5)$$

$$N_G = \frac{(\rho_p - \rho)gd_p^2}{18\mu u} \quad (3.6)$$

Where k_B is the Boltzman constant ($\text{kg.m}^2/\text{s}^2/\text{K}$), ρ_p is particle density (kg/m^3), ρ is water density (kg/m^3), u is filtration velocity (m/s), H is the Hamaker constant ($\text{kg.m}^2/\text{s}^2$), L is media depth (m), d is media size (m), C is the particle concentration (no/mL) with subscripts C_0 and C_L representing the initial and filtrate concentrations, T is temperature (Kelvin, K) and μ is the water viscosity ($\text{kg}/\text{m.s}$). The equations then need to be integrated into a flow field model with

the most commonly used being the Happel flow field with the associated porosity dependent parameter A_s :

$$A_s = \frac{2(1 - \gamma^5)}{2 - 3\gamma + 3\gamma^5 - 2\gamma^6} \quad (3.7)$$

with γ is based on the porosity of the bed:

$$\gamma = (1 - \varepsilon)^{\frac{1}{3}} \quad (3.8)$$

The resultant correlation for the single collector efficiency is then:

$$\begin{aligned} \eta_{total} = & 2.4A_s^{\frac{1}{3}}N_R^{-0.08}Pe^{-0.72}N_V^{0.05} + 0.55A_sN_R^{1.55}Pe^{-0.13}N_V^{0.13} \\ & + 0.22N_G^{1.11}N_R^{-0.24}N_V^{0.05} \end{aligned} \quad (3.9)$$

To estimate the removal efficiency of the SSF, an estimate of the number of particles added to the supernatant before each trial (i.e., 100 g of kaolin) was determined empirically. 10 litres of 0.1 w/v% of kaolin suspension was prepared using the feed water to the SSF columns. This suspension was then measured separately using the particle counter, to determine the total number of particles and particle size distribution. Log removal of particles was thus measured as:

$$\text{Log reduction} = \log_{10} \frac{A}{B} \quad (3.10)$$

Where A is the estimated total number of particles added to column and B is the cumulative number of particles measured in the filtrate.

Removal efficiency was calculated as:

$$\text{Removal efficiency} = 1 - \left(\frac{A}{B} \right) \quad (3.11)$$

One bed volume (BV) was estimated as the retention time in the effective filter volume, i.e., volume occupied by the filter media. This was estimated as:

$$BV \text{ (min)} = \frac{\text{effective volume (m}^3\text{)}}{\text{flow rate (m}^3\text{/min)}} \quad (3.12)$$

Where effective volume is the product of the media volume and the media porosity. As such, the BV for the varying media depths used in this study, one BV was 24 min, 48 min, 60 min, 84 min, and 108 min at media depth of 200 mm, 400 mm, 500 mm, 700 mm, and 900 mm respectively.

3.3 Results and Discussion

3.3.1 Impact of Media Depth on Particle Removal Following Surface Agitation

A comparison between the agitated trial filters and the control at depths <500 mm revealed deteriorated filtrate in the former (Figure 3.3. A). To illustrate, for the 200 mm depth agitated filter, average outlet particle concentration was 2229 no/mL, compared to 63 no/mL in the non-agitated control of the same depth. At 400 mm, outlet particle counts in the agitated filter decreased to 240 no/mL, while at depths greater than 500 mm, there was no significant difference between the test and control filters (6-11 no/mL difference between trial and control). This improved performance with greater filter media depth is consistent with theory and literature (Darby and Lawler, 1990), which explains why the impact of agitation was observed in the upper layers with more removal occurring further down into the filter depth. This reflects the plug flow nature of depth filtration processes whereby the filter can be viewed as a series of connected filter layers (Bai and Tien, 1997). In addition, there was observed improved removal of particles across the different size bands measured with increased depth (Figure 3.3 B). Further, no difference was observed when using deeper filter depths for each of the size bands from 500 mm and beyond.

Time based turbidity profiles aligned to the particle count data, showing a peak in the turbidity signal to a maximum value of 4.2 ± 1.6 NTU across the 200 mm filter, which lasted for 45 min before stabilising at 0.7 NTU (Figure 3.3 C). A similar but more moderate profile was observed for the 400 mm trial, with a peak turbidity of 0.7 ± 0.1 NTU. Beyond 400 mm, agitation had negligible impact on turbidity, aligning with particle count trends (Figure 3.3 A and B) and suggests a minimum safe depth of 500 mm. This is beyond that previously recommended for achieving

good water quality (Ellis, 1985). Post the initial peak, stable turbidity values were observed at the outlet of each layer of 0.7 ± 0.05 NTU, 0.5 ± 0.03 NTU, 0.5 ± 0.03 NTU, 0.4 ± 0.01 NTU, and 0.4 ± 0.02 NTU for depths of 200 mm, 400 mm, 500 mm, 700 mm, and 900 mm respectively. These correspond to turbidity removal of 99.96%, 99.97%, 99.97%, 99.98%, and 99.98% with an overall removal efficiency of greater than 99%. This reflects that the top of the bed was delivering most of the removal and that the lower layers were operating redundantly over the time period of the trial. This is consistent with theory and practice aligned to the plug flow nature of depth filtration such that the lower levels start to remove more only once the upper layers are fully loaded (Bai and Tien, 1997). The current work confirms previously reported turbidity removal associated with SSFs even with shallow beds such as >76% at 220 mm depth (Verma et al., 2019) and an increase from 87% to 92% when depth ranged from 55 mm to 135 mm (Farooq and Al-Yousef, 1993). The significance of these findings imply that greater media depth provides assurance that surface disruptions in the filter will not adversely affect the filtrate quality.

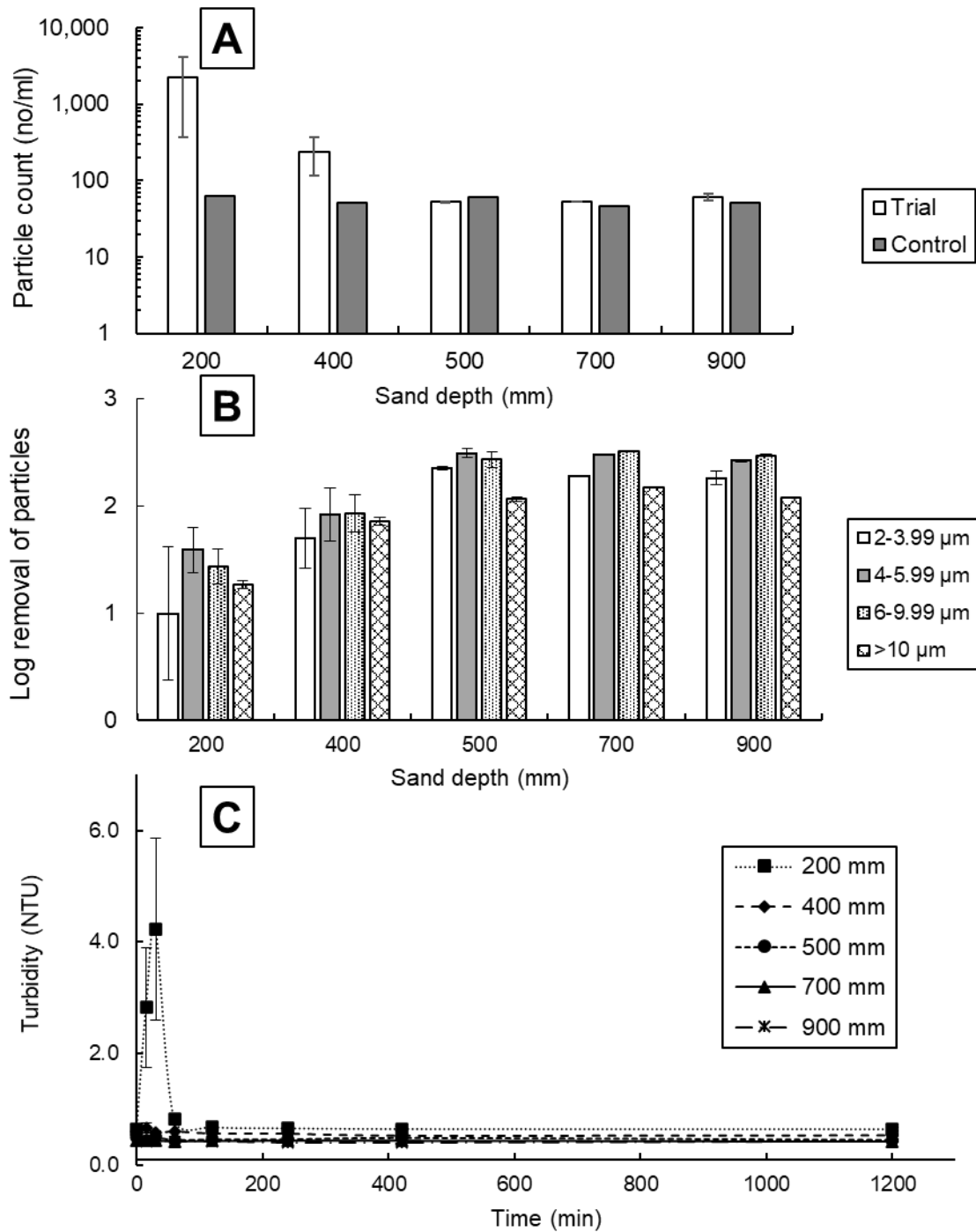


Figure 3.3: A- Filtrate particle count at different media depths following filter surface agitation (2-125 μm). B- Log removal of particles in different size bands. C- Filtrate turbidity at different media depths following filter surface agitation. Based on grab samples collected at different times throughout experiment period. Control is a filter without surface agitation. Error bar is the range of duplicate trial runs. Time 0 min is immediately after the agitation (C).

3.3.2 Impact of Varying HLR on Head Loss and Particle Removal

Differential head loss was mainly observed within the top 100 mm of the filter with minimal head loss at greater depths (Figure 3.4). The top 50 mm, accounted for 86 mm (48%), 61 mm (42%), 77 mm (57%), and 61 mm (55%) of the total head loss in the control, 0.3 m/h, 0.4 m/h, and 0.5 m/h filters respectively. This increased to 94 mm (53%), 64 mm (48%), 80 mm (60%) and 64 mm (60%), by 100 mm media depth. Within the lower layers, difference in head loss between the 50 mm intervals ranged between 1-10 mm. This concentration of head loss within the top layers of sand is similar to previously reported trials where over 80% of the head loss occurred across the top 50 mm of the sand, showing minimal variation between 50-400 mm depths (Campos et al., 2006). This is related to the reduced porosity that occurs in these layers due to particle retention and biofilm growth (Ojha and Graham, 1994). Presence of biofilm and biological activity in the above examples explains the greater percentage of head loss at the top due to the contribution of *Schmutzdecke* at the top and biofilms at lower layers. This is in contrast to this study where head loss was mainly due to deposition of particles on top of the sand bed, as 54% of the kaolin particle were greater than 2 μm . It should be noted that the variation between the measured head loss values in the different trials were relatively small and not statistically significant (Kruskal Wallis: $H(3) = 0.7$, $p = 0.863$).

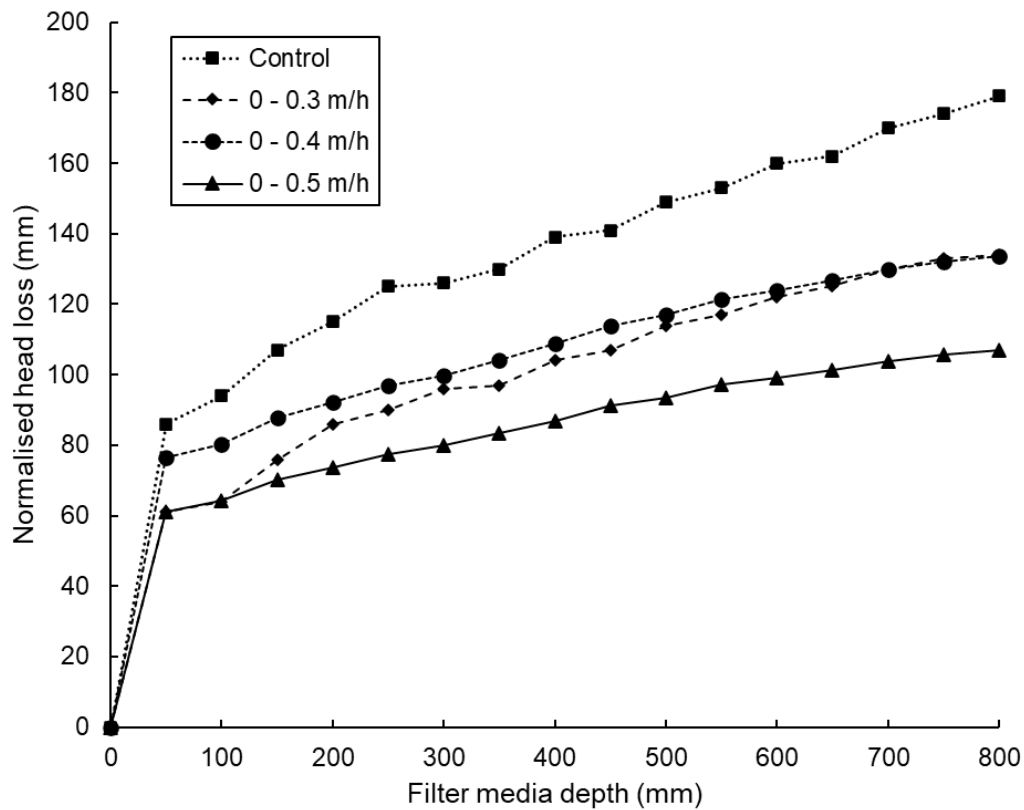


Figure 3.4: Normalised head loss (mm) between piezometer tubes placed at 50 mm intervals along the depth of filter, measured at different HLR following filter surface agitation.

Increased particle breakthrough was observed when operating at higher HLR, especially under surface agitation (Figure 3.5 A). To illustrate, outlet particle counts were 36 no/mL at 0.3 m/h raising to 49 no/mL at 0.4 m/h, and 115 no/mL at 0.5 m/h. Correspondingly, log removal decreased as HLR increased, with a 0.25 log drop from 0.3 m/h to 0.4 m/h, and a 0.72 log drop to 0.5 m/h. Overall log removal remained over 2 across all size ranges and HLR (Figure 3.5 B). Schijven et al. (2013) noted a slight reduction in pathogen log removals with increased HLR, where a decrease in the HLR of full-scale SSFs by 0.8-0.15 m/h resulted in a small improvement of the predicted log removals of pathogens (bacteriophage and *E. coli*) by 0.06-0.27 log. Conversely, van der Hoek et al. (1996) found that filtration rate changes did not significantly affect particle removal, aligning with this study's findings where increased HLR did not markedly alter the filter's particle removal efficiency.

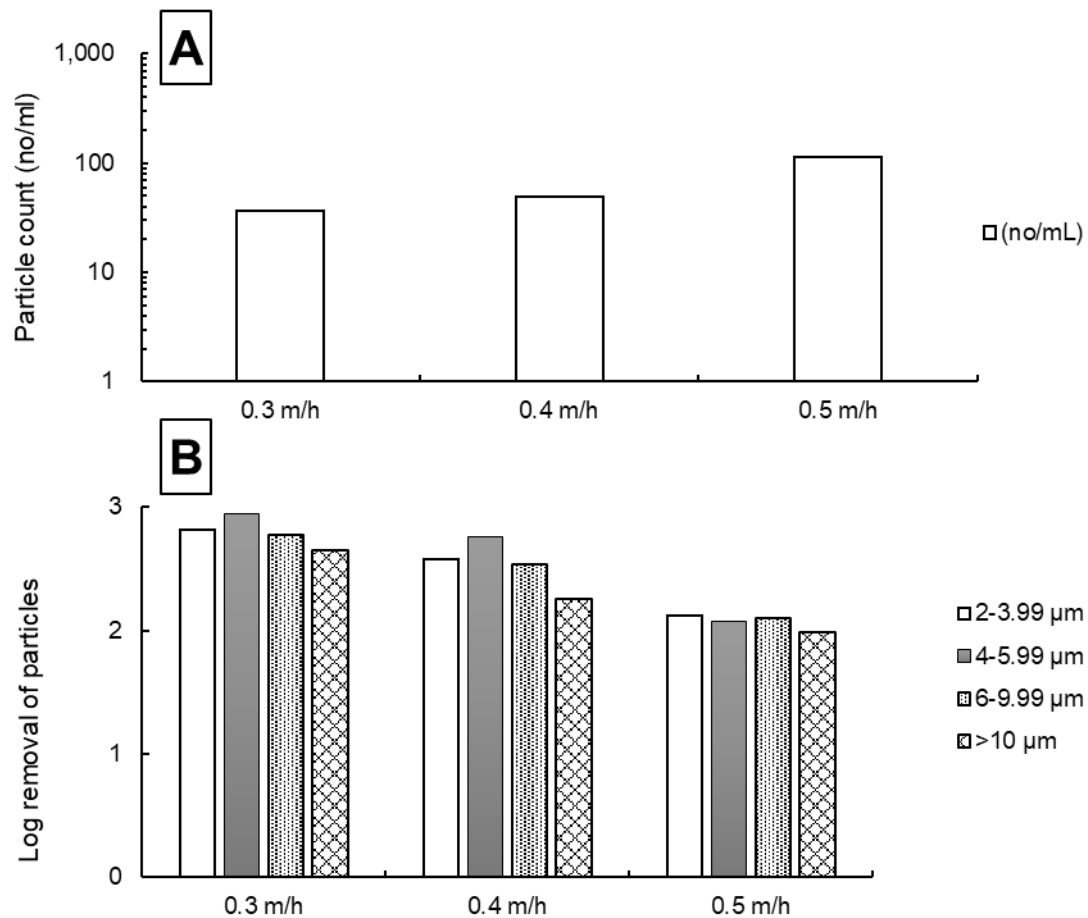


Figure 3.5: A. Filtrate particle count at the different HLR, and B. Log removal of particles in different size bands. Media depth = 800 mm.

Further analysis was conducted to better understand the impact of filtration rate by running a filter model at different flow rates for the treatment of 2 μm particles (Figure 3.6). The single collector contact efficiency for 2 μm particles when using a collector diameter of 0.3 mm and a porosity of 0.4, decreased from 0.0295 at 0.3 m/h to 0.0223 at 0.4 m/h and 0.0181 at 0.5 m/h. At this particle size, the predominant transport mechanism is sedimentation, i.e., the third term in Equation (3.9) is the largest, compared to diffusion (first term) and interception (second term). The reduction was thus associated with the sedimentation mechanism which dominated transport and represented 81% of the collision efficiency at 0.3 m/h down to 75% at 0.5 m/h. At higher HLR, the interception

mechanism increasingly contributed to particle transport, rising from 9% at 0.3 m/h to 14% at 0.5 m/h, as particles moved more rapidly. The impact of the change was demonstrated in terms of removal efficiency as a function of media depth (Figure 3.6 B). At all filtration rates, the removal efficiency of 2 μm particles increased from between 32% and 47% at a bed depth of 100 mm to between 86% and 96% at a bed depth of 500 mm. The impact of increasing filtration rate was thus more pronounced for bed depths less than 500 mm.

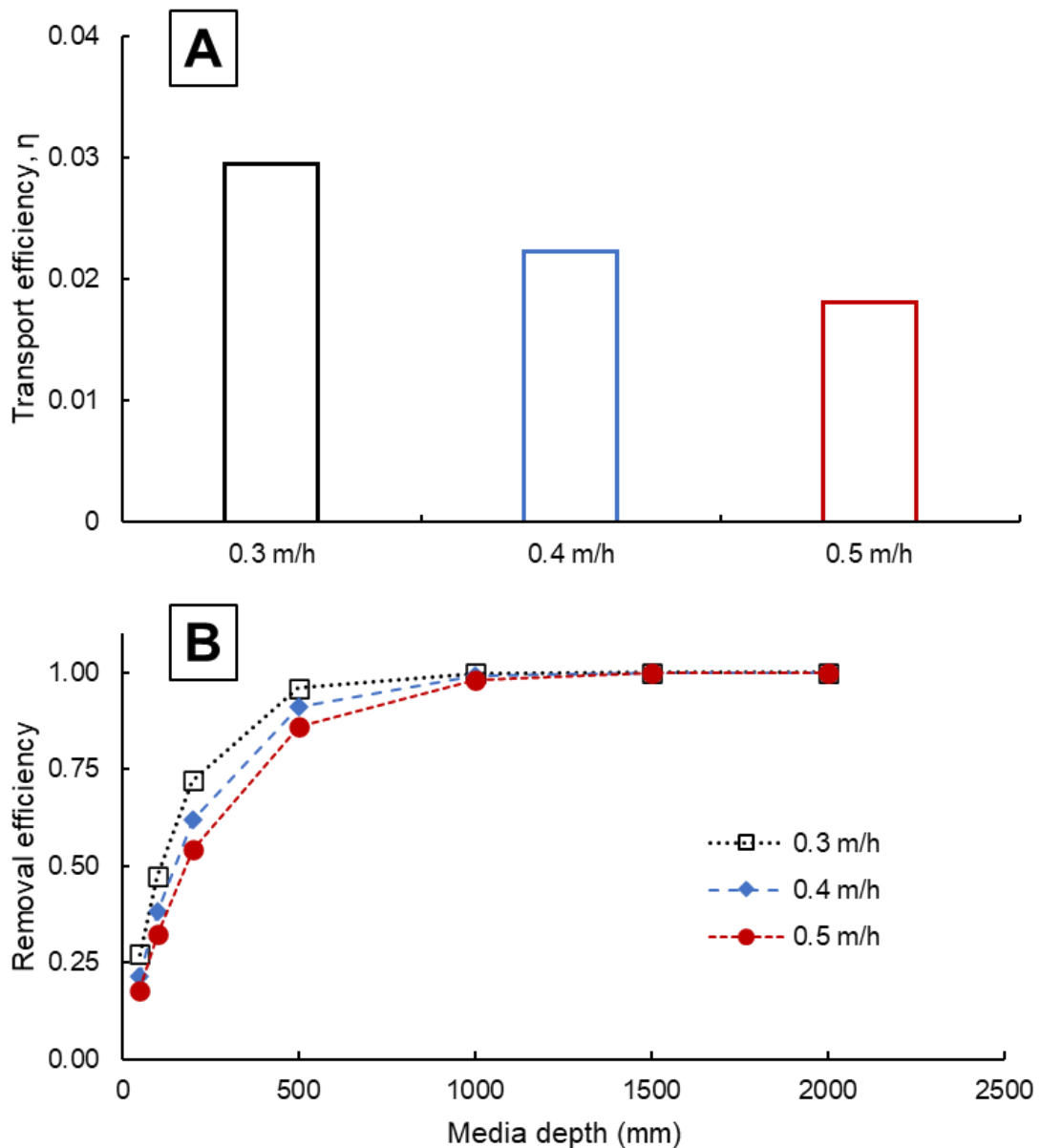


Figure 3.6: Impact of different HLR on: (a) Single-collector contact efficiency, η and (b) removal efficiency of a 2 μm sized particle at different filter depths.

3.3.3 Removal of Different Particle Sizes

The 4-6 μm range is notable as it corresponds to the size of *Cryptosporidium* oocysts (which are of concern in SSF treatment, especially for surface water sources with high animal waste contamination). This size band (measured as 4-5.99 μm in this study) showed particle log removal levels ranging from 1.4 to 2.2 log reductions for filters with depths <500 mm, while at greater than 500 mm, log

reductions were more consistent between 2.4 to 2.5 log reductions. This compares to literature value that are highly variable, ranging from 0.28 log reduction (Fogel et al., 1993) to >5 log reduction (Hijnen et al., 2004) highlighting inconsistent retention of smaller particles associated with pathogens. This wide variability in removal efficiencies could be a function of many different variables including the feed water quality, but it is mostly driven by differences in operational parameters and environmental conditions. For instance, in the two examples referenced above, there were differences in the filter size, media depth, operational HLR and location of the filters. In addition, Fogel et al. (1993) conducted their study with a covered full-scale filter, while Hijnen et al. (2004) used controlled column filters.

The impact of bed depth was further investigated for two size bands where the greatest change was observed: 2-3.99 μm and 4-5.99 μm (Figure 3.7). Removal efficiency was calculated using Equation (3.11). In the case of the 4-5.99 μm particles, a bed depth of 500 mm was required before stable removal was observed. To illustrate, removals were 86.9%, 95.8%, and 99.4% at bed depths of 200 mm, 400 mm and 500 mm respectively. After six bed volumes the removal levels had increased to 98.2%, 99.3%, and 99.9% respectively. A similar pattern was observed for the 2-3.99 μm particles but the removal levels were generally lower. For instance, at a bed depth of 200 mm the removal was 55.1% after one bed volume and 69.4% after six bed volumes. Comparison to the collision efficiency model revealed that it over predicted after one bed volume but accurately predicted the removal after six bed volumes. Previous work shows a similar pattern when removing 2 μm particles, noting 71% removal at 55 mm depth versus 14% at 10 mm after one hour (Darby and Lawler, 1990).

No specific size band was disproportionately affected by surface agitation, similar to observations in RGF where flow disturbances did not selectively impact particle sizes (Glasgow and Wheatley, 2001).

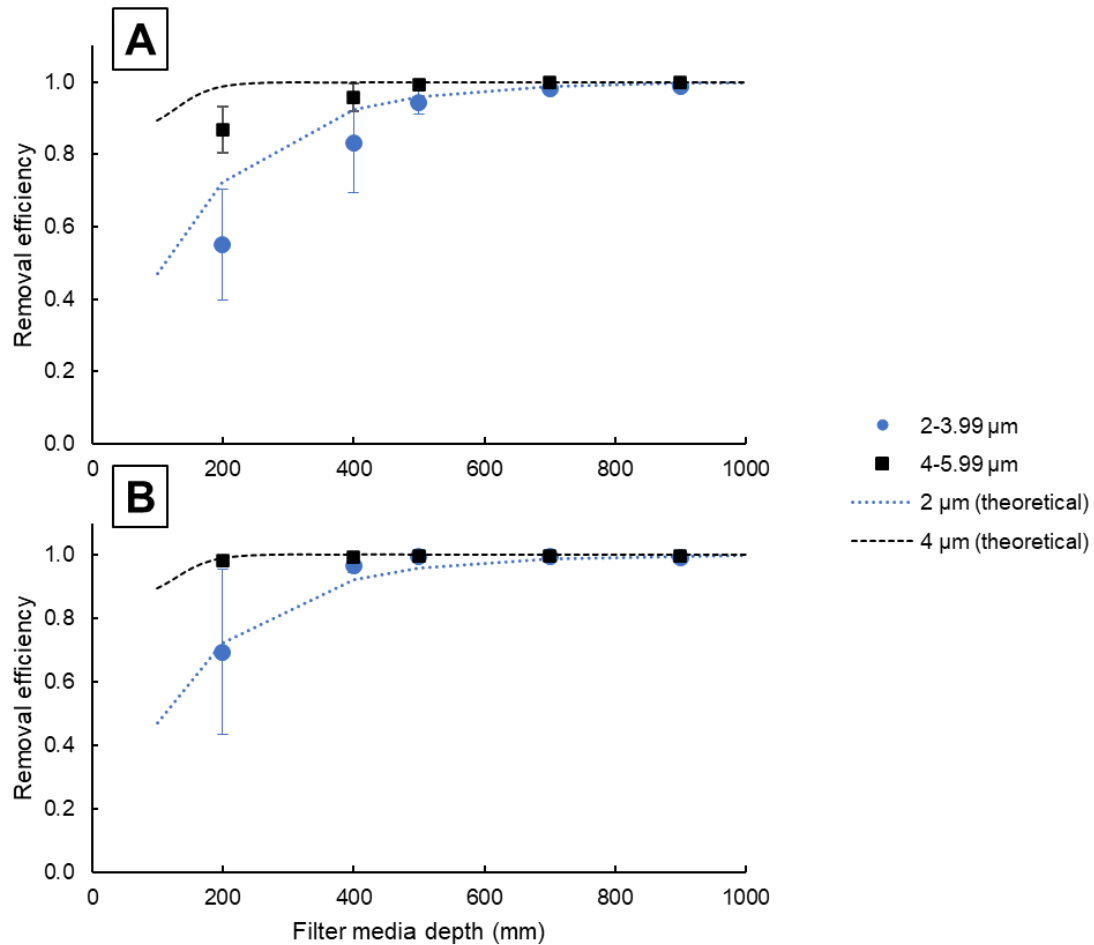


Figure 3.7: Filter removal efficiency following surface agitation at various media depths

(A) After one bed volume, and (B) after six bed volumes of treated flow, for particle size ranges 2-3.99 µm and 4-5.99 µm. Theoretical values calculated from the model developed by Tufenkji and Elimelech, (2004).

3.3.4 Conclusions

This study examined biologically immature pilot-scale SSFs, lacking biological maturity and a *Schmutzdecke*, under conditions simulating enhanced risk periods for UWS. The focus was on evaluating the potential for clogging, rapid head loss, and particle breakthrough, using kaolin to represent particle accumulation and a stirrer paddle to simulate skimmer movement. Findings indicated that surface agitation reduced removal efficiency, but deeper media (>500mm) mitigated this effect. Reduced media depths showed increased particle breakthroughs and

turbidity after agitation. Particle breakthrough reduced from 2229 no/mL at 200 mm to 240 no/mL at 400 mm and 53 no/mL at 500mm. Similar observations with improvement in turbidity with depth. In addition, there was no discernible disproportionate clogging or significant head loss beyond the top 100 mm. Increasing HLR from 0.3 to 0.5 m/h raised particle breakthrough during agitation, yet filters maintained over 2 log particle removal, suggesting effective filtration.

Particle removal for sizes 2-10 μm , covering range of sizes for bacteria and *Cryptosporidium* oocysts, exceeded 2 log reduction, indicating robust pathogen removal during reduced filter efficacy. The results reflect a worst-case scenario, emphasising the negative impacts when UWS malfunctions, without representing the full range of biodegradable materials in natural feed water. However, under standard operation with functional UWS, there is limited risk of particle breakthrough or filter compromise.

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4 Impact of Underwater Skimming on Dissolved Oxygen Consumption in Slow Sand Filters for Potable Water Treatment

Abstract

In a well-functioning slow sand filter (SSF), dissolved oxygen (DO) is crucial for enabling aerobic processes and microbiota growth. Given that DO supply is predominantly via the feed water, flow pauses (e.g., during cleaning) may trigger anoxic/anaerobic conditions in the stagnant filter bed. This study investigates the impact of Underwater Skimming (UWS) on the risk of depleting DO below the operational limit during periods of flow pause. UWS is an advanced cleaning technique that employs a skimmer with a shrouded blade, mounted on a mobile platform, to remove the fouling layer composed of sand and particles, thereby improving the efficiency of slow sand filtration. A mathematical model was developed to predict DO utilisation after a flow perturbation associated with UWS operation, based on depth-resolved measurements of specific oxygen utilisation derived from a full-scale SSF. Pilot plant experiments monitored DO in the feed and filtrate of SSFs cleaned using both underwater and conventional dry skimming techniques. The highest oxygen utilisation was observed in the *Schmutzdecke* layer, with rates of 6.74 ± 0.44 gO₂/g dry solids/h, and additional demand imposed by the presence of a granular activated carbon (GAC) sandwich layer, with rates of 0.52 ± 0.01 gO₂/g dry solids/h. The study found that pseudo-steady state conditions occurred following filter ripening, where DO utilisation, driven by biological activity, remained relatively constant. For flow pauses between three and 24 hours, the significance of the pause duration reduced, and the hydraulic loading rate (and hence DO supply) became more critical for filter DO recovery. Introducing a 'sweetening flow' during UWS ensured a continuous DO supply, facilitating quicker DO replenishment post-cleaning. As such, UWS can be confidently applied to clean SSFs, with careful modifications made to the methodology to prevent any detrimental effects to DO management within the filter. Nevertheless, further research is needed to enhance the model's predictive capability and extend its application to other types of filters or water treatment

processes. This research enhances understanding of UWS effects on DO dynamics in SSFs by integrating empirical data with a new model, offering a predictive tool for improved operational strategies and microbial risk management.

Keywords: Slow sand filter (SSF); underwater skimming (UWS); flow pauses; empirical SSF model; sweetening flow.

4.1 Introduction

Slow sand filtration is economical, requires minimal energy, and chemical input, and delivers contaminant removal through both physical and biological mechanisms (Maiyo et al., 2023). Slow sand filters (SSFs) are predominantly positioned after primary roughing filtration, or other pre-treatment processes such as ozonation to improve treatment (Abdiyev et al., 2023). In certain instances, such as within the Dutch water sector, SSFs are utilised as a concluding treatment step to enhance the biostability of drinking water (van der Kooij et al., 2017). In all cases, it is believed that the critical functional component of an SSF is the *Schmutzdecke*, a microbial biofilm layer formed by turbidity-causing materials, biodegradable organic matter, and algae on, and within, the sand bed surface. Consequently, the contaminant removal capacity is principally concentrated in the top layers (< 50 mm) of the SSF bed where there is heightened activity (Trikanad et al., 2023).

The biological processes within an SSF predominantly function in an aerobic environment and hence ensuring sufficient dissolved oxygen (DO) within the bed is crucial. Temperature and seasonal shifts can modulate DO utilisation, with warmer waters leading to intensification of microbial metabolism and organic matter decomposition (M. E. J. Steele et al., 2006). The primary DO source is the feed water, with a supplementary contribution diurnally from daylight photosynthesis by algae (Ellis, 1985). Furthermore, perturbations in filtration rates or flow can hinder the continuous DO supply. This induces anaerobic or anoxic conditions leading to a reduced treatment and a decline in grazer organisms and consequently, pathogen removal (Elliott et al., 2011).

Regular cleaning of the filter is necessary to address head loss caused by the accumulation of particles, algae, and biofilm growth, ensuring the system operates at its intended flow rate. This maintenance usually entails removing the top layer of sand, which is typically between 10 to 50 mm deep using mechanised techniques including robotic dry skimming devices (Cullen and Letterman, 1985b). Conventional cleaning methods like dry skimming require the filter to be

drained before cleaning, resulting in substantial operational downtime accounting for up to 90% of the total downtime associated with SSFs (1-3 days). The removed sand is then cleaned, ready for reuse.

An alternative technique, Underwater Skimming (UWS), has been considered to address this inefficiency by cleaning the bed whilst still submerged of which a number of variants exist including a shielded blade, a vacuum system, or a floating dredging device (Hassard et al., 2022). In such cases, microbial oxygen utilisation persists and as such if sufficient flow is not maintained, the DO within the beds can be reduced below an agreed operational limit of 3 mg/L and heightened risk of anaerobic or anoxic conditions within the bed (Burman, 1978). This has previously been reported in intermittently operated SSFs where anoxic zones have formed during periods of submersion lasting 24 h or more (Young-Rojanschi and Madramootoo, 2014).

Many SSFs employ an in-bed layer of GAC to assist in micropollutant elimination, a process that amplifies the demand for DO due to both abiotic sorption and biotic consumption (M. E. J. Steele et al., 2006). The GAC layer is infrequently replaced (for example >70,000 bed volumes (BV) or 3 years' operation), thereby encouraging microbial growth and biodegradation as the primary pollutant removal mechanism (Velten et al., 2011). As such, in an acclimated GAC layer, DO utilisation may be largely attributed to biological activities (Eighmy et al., 1993). The overall DO utilisation within SSFs raises concerns around the risk associated with underwater skimming leading to periods of operation below the 3 mg/L DO set point. To date, there is a paucity of information concerning declining DO patterns and no model currently exists to effectively predict DO as a function of operational parameters.

Accordingly, the aim of this study was to investigate the impact of UWS operation on the risk of depleting the DO below the operational limit during periods of flow pause. The research aimed to elucidate how variables such as filter media depth, stagnation durations, water temperature, feed DO concentrations and 'sweetening flow' during skimming might affect SSF performance during these

periods. 'Sweetening flow' in this study refers to the flow maintained through an SSF (i.e., full or reduced operational flow rate) while skimming underwater. To achieve this, specific oxygen consumption data collected from a full-scale SSF were used to develop a model of DO utilisation. This model was subsequently tested and validated through a series of filtration experiments conducted with real water from an operational treatment works, involving four different filter runs and three skimming events, thereby enabling direct observation of DO utilisation in pilot SSFs.

This study addresses several research gaps, including the lack of information on declining DO patterns in SSFs during UWS or alternative cleaning operations and the absence of an effective model to predict DO as a function of operational parameters. The novelty of this work lies in its investigation of 'sweetening flow' during UWS to maintain DO levels, the development of a predictive model for DO utilisation, and the new insights provided into the operational parameters influencing DO levels. These contributions are significant advancements in the field, offering potential optimisations for SSF performance and reducing the risk of anaerobic or anoxic conditions.

4.2 Materials and Methods

4.2.1 Pilot Filtration Setup

Pilot experiments were carried out at the Thames Water Research, Development and Innovation Centre, located in Kempton Park AWTW, Hanworth, UK, from March 2021 to June 2022. The pilot plant encompassed ten identical, individual filters, each with a surface area of approximately 0.54 m². The composition of each filter bed included a layer of sand (0.2-0.5 m in depth, effective size = 0.3 mm, uniformity coefficient = 1.8), a layer of GAC (0.1 m in depth, effective size = 0.6 mm, uniformity coefficient = 1.9), followed by a 0.2 m fixed sand layer, and a 0.1 m gravel support layer stacked vertically above each other in the order top to bottom (Figure 4.1). The pilot plant received its feed water from a storage reservoir directly connected to the river Thames (a surface water source) which has a retention time of approximately 30 days (see Figure 5.2). The operational

flow rate was a target value of 0.3 m/h, which required twice daily checking and was adjusted as head loss developed. Over the 15-month operational trial, the DO concentration of the feed water averaged 10.5 ± 2.3 mg/l, total organic carbon (TOC) was 3.6 ± 0.2 mg/l, turbidity was 0.6 ± 0.4 NTU, and pH was 8.1 ± 0.2 . Filters were operated at ambient air temperature (-6 to 22 °C) with water temperature ranging from 3-16 °C.

All filters underwent similar operation procedures except for the cleaning methodology, which served as the primary distinguishing factor. Cleaning methodologies implemented encompassed UWS at varying flow percentages of sweetening flows (100%, 33%, and 0% of full flow rate and traditional dry skimming, which served as the control (Table 4.1). Sweetening flows lasted for the duration of the cleaning. Dry skimming was carried out with a custom-made scraper and shovel (both cleaned and disinfected with 70% isopropanol between uses). UWS was executed with a vacuum cleaner modified through addition of a custom-designed scraper for sand and water removal during periods of submergence. Attachments and hoses were cleaned between use, with clean water and the parts in contact with the filter and supernatant further disinfected with 70% isopropanol (see Figure 5.3). The depth skimmed was monitored using graduated lines within the filter (Figure 5.4) and using an underwater camera as a guide and to confirm accuracy of skim.

Post-skimming, filters were adjusted to the operational HLR using the 24-hour 0.1 m/h increment method. For instance, the UWS-100 did not necessitate any increments as skimming was executed at operational HLR, whereas both UWS-33 and UWS-0 required two increments each.

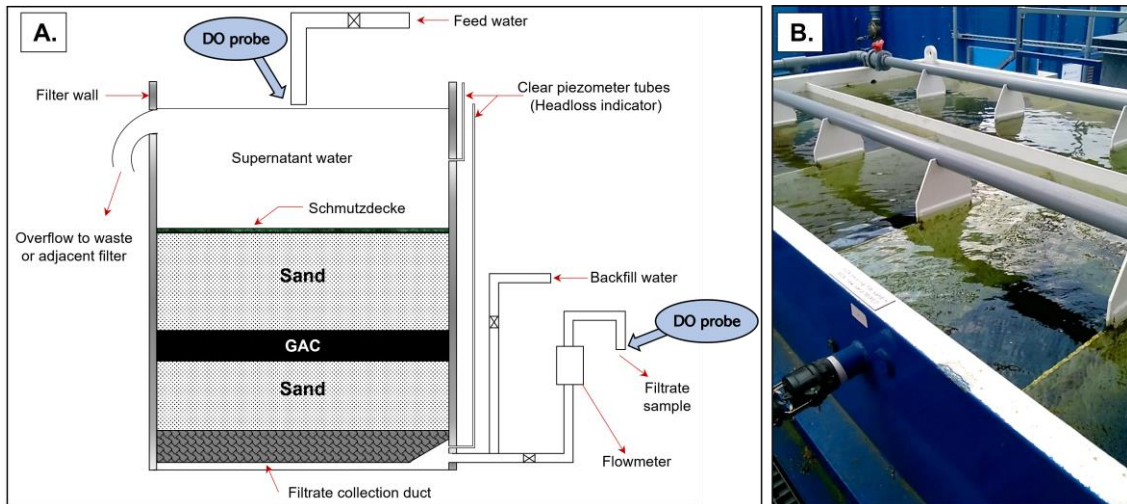


Figure 4.1: (A) Schematic illustrating a cross-sectional representation of each test filter. (B) Photographic image displaying the 10 individual cells of the pilot SSF facility, illustrating its physical structure and design.

Table 4.1: Description of the different skimming treatments performed in the SSF pilot facility, with corresponding measured rates of DO consumption.

Skimming (UWS ¹ / Dry)	Sweetening flow ²	Total time left dry (h) ³	ID ⁴
UWS	100%	0	UWS-100
UWS	33%	0	UWS-33
UWS	0%	0	UWS-0
Dry	n/a	14	DS

1 UWS refers to Underwater skimmed beds
2 Sweetening flow is the percentage of the operational filtration rate (0.3 m/h) permitted during skimming
3 Total time left dry is the duration where a filter was left completely dry before, during and after skimming.
4 ID is the identity of each treatment in the graphs and discussion.

DO was measured via luminescence probes (Hach Co., Loveland, Colorado, USA) calibrated weekly using manufacturer instructions and sampled every 15 min. The filters were scraped after operational setpoints of head loss or time were reached, whichever limit was reached first. The longest time for operation was 70 days, which aligns with the local water utility operational guideline. While in most

cases head loss was the operational trigger to clean the SSF, the exception was after filter 're-sand' events when time was the factor as the head loss did not meet the setpoint after 70 days. Three individual filter runs were captured for this DO study, with run lengths of 71, 41 and 43 days for runs I, II and III respectively. Detailed DO levels in the feed and filtrate of five beds were captured for these runs. DO was measured in 15-min intervals via the luminescent method using a Hach 40d meter with LDO101 probe (Hach Co., Loveland, Colorado, USA). Each filter run was split into *pseudo*-steady state operation, (i.e., 14 days into the filter run, as further described in Section 4.2.3) and dynamic state operation (i.e., during skimming and flow pause). A total of nine unique data sets were recorded during dynamic states (3 each for UWS-100, UWS-33, and UWS-0 for the 3 filter runs).

Additionally, nitrate concentration in both the feed and filtrate was monitored as an indicator of anaerobic activity within the filter, i.e., the use of an alternative electron acceptor aside from oxygen. Nitrate as Nitrogen ($\text{NO}_3\text{-N}$) was monitored weekly with grab samples and analysed using the Thermo Scientific Aquakem 600 Photometric Analyzer (Thermo Fisher Scientific Inc., Waltham, Massachusetts, US). The methodology used was modified from Oxidised Nitrogen in Waters 1981 - Methods for the Examination of Waters and Associated Materials.

4.2.2 Specific Oxygen Uptake Rate (SOUR) of Biologically Active Media

The SOUR for the SSF media at various depths, which encompassed the biofilm in both the sand and GAC layers, was assessed by modifying the method outlined in Method 1683 (U.S. EPA, 2001). The samples used for the SOUR measurement were taken from a full-scale SSF bed with a surface area of 3087 m^2 . This bed was mature and had been operational for 56 days since its last cleaning. The total volume of water treated by the GAC within this SSF was roughly 68,000 BV. The full-scale SSF was selected for sampling because it offered a more accurate representation of the microbial state of an actively functioning process, compared

to pilot SSF. The sampling process was conducted at the conclusion of an operational cycle, with three randomly chosen locations which had fully formed *Schmutzdecke* on the layer. Samples were collected in early spring (April 2021). At each of these sites, a hole measuring 0.25m by 0.25m was created, from which horizontal core samples were extracted at varying depths using a large spatula and a meter rule to guide depth. 50 g of media was collected at each depth and the spatula was wiped cleaned and disinfected with 70% isopropanol between samples.

The depth ranges measured were: 0-25 mm (Sch), 25-50 mm (S1), 50-100 mm (S2), 100-200 mm (S3), 100 mm-above GAC (S4), within the GAC (GAC), and below the GAC layer (S5). The three samples collected from each depth from the different locations sampled were carefully combined to form a composite sample. Each sample was placed into a 300-mL flask, previously cleaned with a 10% HCl solution and heat sterilised at 150°C. Each flask, containing a magnetic stirrer, was then filled to achieve a total solid concentration of 20 g/L using sterile 0.01 M phosphate-buffered saline (PBS) solution with a pH of 7.4. DO probes (Hach Co. LDO101, using Luminescent method) were used to measure DO readings over a 15-minute period. The measurements were taken at 15-second intervals for the first two minutes and 1-minute intervals for the remainder of the experiment. Prior to the experiment, DO probes were calibrated according to manufacturer instructions. Temperature control throughout the process was maintained at ± 0.2 °C using a heated water bath. Lastly, the total solids (TS) and volatile solids (VS) content of the media/biomass was measured according to Method 1684 (U.S. EPA, 2001). The SOUR was calculated as:

$$SOUR_T = \frac{OUR}{TS} \times \frac{60 \text{ mins}}{h} \times \frac{1}{VS} \quad (4.1)$$

Where:

$SOUR_T$ = specific oxygen uptake rate in the sample at analysis temperature, T (mgO₂/gVS)/h

OUR = oxygen uptake rate in the sample (mgO₂/L)/min. This is the slope of a plot of observed readings (DO, mg/L) versus time (min)

TS	=	total solids in the analysis sample (g/L)
T	=	temperature of the sample during analysis, °C
VS	=	volatile solids of media aliquot (gVS/g)

Values were corrected for temperature using:

$$SOUR_{20} = SOUR_T \times \theta^{(20-T)} \quad (4.2)$$

Where:

$SOUR_{20}$	=	specific oxygen uptake rate at 20°C (mgO ₂ /gVS)/h
θ	=	temperature correction factor 1.05 above 20°C, 1.07 below 20°C

4.2.3 Modelling DO Utilisation

A mass balance model was developed to study the potential impact of UWS operations on the profile of DO in an SSF. The SSF bed was modelled as an assembly of layers comprised of the *Schmutzdecke* layer (defined as the top 25 mm), sand layers, and GAC layers. The gravel support layer was excluded from the model since our empirical data suggested negligible oxygen consumption in this layer (Appendix D, Figure A.3).

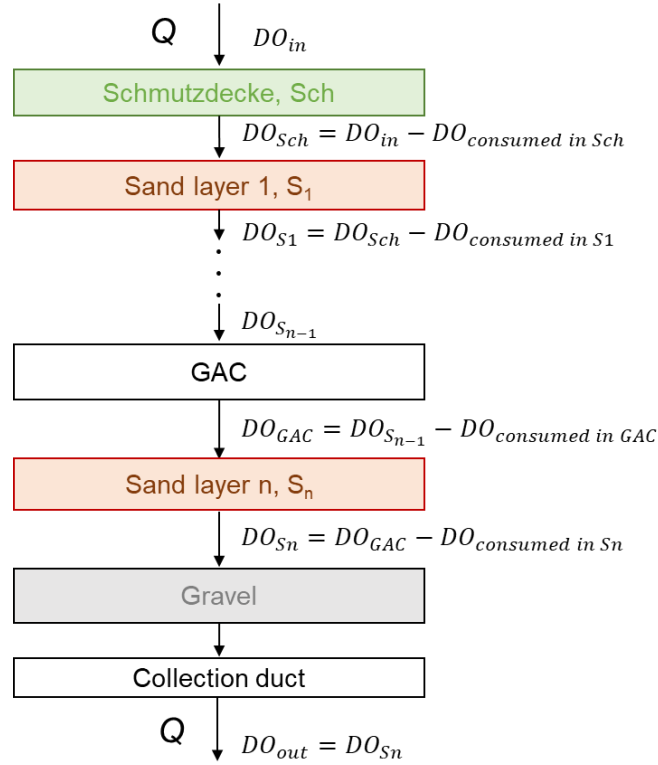


Figure 4.2. Conceptual representation of the mathematical model in terms of the flow of DO through a biologically mature SSF that features a GAC layer.

The amount of DO utilisation was estimated using a mass balance approach, under the following assumptions:

1. Negligible mass transfer from the gas phase to the bulk liquid.
2. DO adsorption onto media grains (sand and GAC) was deemed negligible compared to biological utilisation.
3. The biofilm was homogeneous on individual media grains or within layers in terms of both its mass and activity.
4. Excluding the *Schmutzdecke*, the biofilm is considered to be in a pseudo-steady state, implying that the biofilm mass and activity remain relatively constant over time.
5. The activity within the *Schmutzdecke* maintains a steady state, even though the mass of the *Schmutzdecke* continues to grow.
6. The generation of DO within the filter can be considered as negligible, and any accumulation was also assumed to be zero.

Pseudo Steady State Operation

At steady state, the general mass balance equation can be presented as follows:

$$Output = Input - Consumption \quad (4.3)$$

An SSF is considered to be in a steady state once the *Schmutzdecke* layer is fully developed - a stage referred to as a 'ripened SSF'. In the context of this study, this state was assumed to occur after 14 days of operation, which was supported by observations of total coliform removal (assessed via most probable number (MPN) method via Colilert 24, Idexx, UK) and filtrate turbidity obtained from both pilot and full-scale studies in the water utility. The consumption of DO is a function of the SOUR within individual layers. Thus, the DO consumption in each individual layer can be expressed as follows:

$$r_i = SOUR_i \times VS_i \times \tau_i \quad (4.4)$$

where r_i is the DO consumption within an individual layer, i (mg/ g dry solid), and τ_i is the residence time within the individual layer (h), calculated as:

$$\tau_i = \frac{V_i}{Q} \quad (4.5)$$

Where V_i is the volume of individual layer (L) and Q is the operational flow rate (L/h). The mass of DO consumed in each layer, M_i (mg) is thus a product of the consumption and the mass of media in the layer, w_i (g).

$$M_i = r_i \times w_i$$

The modified mass balance for DO in the filter can be re-written as:

$$DO_{out} = DO_{in} - \sum_{i=1}^N r_i \cdot w_i \quad (4.6)$$

In this equation, N represents the total number of layers. For the sand layers above the GAC, the value of N decreases with each filter run due to the removal of the *Schmutzdecke* and underlying sand layer.

DO Utilisation During Skimming and Flow Pauses

The UWS occurs when the filter is completely submerged in water, with a continuous flow (of some proportion of normal flow). However, in a situation where there is no flow — meaning there is no incoming or outgoing water — the individual layers in the filter behave similarly to a batch reactor in terms of DO consumption. At the starting point ($t = 0$), a definite volume of water is present within each layer, providing a mass of DO, denoted as m_i (mg).

$$m_{i,0} = DO_{i,0} \times V_i \cdot \epsilon_i \quad (4.7)$$

Where ϵ_i is the effective porosity of the media (dimensionless).

The amount of DO within each distinct layer is progressively depleted during the pause in flow. Following the removal of the *Schmutzdecke* layer, the rate of DO consumption within the remaining layers is hypothesised to remain consistent with the rate observed just prior to the pause. Consequently, the amount of DO consumed during this period of paused flow (R_i) can be represented as:

$$R_i = (r_i \cdot w_i) \times t \quad (4.8)$$

Where t is the duration for which the flow was paused (h).

The mass of DO left in the filter at the end of the pause (and the start of a new filter run) is:

$$m_{i,t} = m_{i,0} - R_i \quad (4.9)$$

The DO concentration in the individual layers is thus:

$$DO_{i,t} = \frac{m_{i,t}}{V_i} \quad (4.10)$$

Upon re-establishing flow, the filter takes on characteristics akin to a plug flow reactor. This implies that there is no interlayer mixing, but perfect intralayer mixing. The consideration is applied to the volume of water within each layer separately. The DO input for each successive layer is the reduced DO content from the preceding layer, for instance $DO_{i+1,t} = DO_{i,t}$.

In the majority of SSFs, a collection duct at the bottom of the filter exists. It is assumed that there is no further DO consumption within this collection duct, and complete mixing occurs, leading to a consistent DO concentration at any given moment. When the flow is interrupted, $DO_{duct} = DO_{N,t}$. Once flow is resumed, the DO in the duct becomes:

$$DO_{out} = DO_{duct} = DO_{N,t} - \frac{V_{N,t+x}}{V_{duct}} (DO_{N,t} - DO_{N,t+x}) \quad (4.11)$$

Where $V_{N,t+x}$ is the volume treated in the time x after flow is resumed.

During periods of ‘sweetening flow’ the filtration rate is partially reduced, and a continuous movement of water persists through the filter which results in a consistent DO supply. As a result, the filter operates similarly to a plug flow reactor, with DO consumption happening as the water passes through the distinct layers.

4.2.3.1 Model Validation, Sensitivity and Limitations

Run I was used to develop the model while Runs II and III were used to validate.

To evaluate the accuracy of the developed model in predicting DO consumption, the root mean square error (RMSE) was computed, comparing the predicted and observed DO concentrations in the filtrate. Additionally, the dataset underwent Bland-Altman analysis — a statistical method employed to assess agreement between two quantitative measurements. A Bland-Altman plot juxtaposes two measurements by plotting the difference against the average. The average difference reflects the estimated bias, while the standard deviation accounts for random variations. If differences between measured and estimated values fall within the mean ± 1.96 SD (which represents 95% of data in a normal distribution),

then the difference between the two methods are deemed insignificant, and the methods can be interchangeably used. These boundaries signify the limits of agreement (Altman and Bland, 1983; Bland and Altman, 1999).

Local sensitivity analysis was performed to assess the model's responsiveness to changes in operational conditions and skimming scenarios. This was achieved by changing one parameter at a time while keeping the others constant. The parameters that were varied included:

1. Flow pause duration:

Different flow pause durations were selected to reflect different lengths of time that the filter bed is left fully submerged while carrying out UWS with no sweetening flow. The durations selected were 0.5h, 1h, 3h, 6h and 24h.

2. Flow re-introduction regimes.

Due to hydraulic constraints, as well as historical plant operational practices, it is common for SSFs to be gradually ramped up post skim. However, some studies have shown that this is unnecessary (Steele et al., 2006). Nevertheless, it is still common practice and three flow re-introduction regimes were considered: slow (2.5% of the operational rate per hour), gradual (10% of the operational rate per hour) and instantaneous.

3. Temperature fluctuations.

Temperature ranges from 5-22°C were used as it reflected the range of temperatures observed during the pilot plant operation as well as what is commonly applicable in water treatment works in the UK.

The model parameters used in this study are presented in Table 4.2 while details of the filter runs are shown in Table 4.3.

Table 4.2: Model parameters used in this study

Description	Symbol	Unit
Depth of GAC layer	L_{GAC}	m
Depth of sand layer 1	L_{S1}	m
Depth of sand layer 2	L_{S2}	m
Depth of sand layer 3	L_{S3}	m
Depth of sand layer 4	L_{S4}	m
Depth of sand layer 5	L_{S5}	m
Depth of <i>Schmutzdecke</i> layer	L_{sch}	m
Dissolved oxygen concentration	DO	mg/L
Dissolved oxygen consumption within individual layers	r_i	mg/g
Effective porosity of media	ϵ_i	dimensionless
Flow pause duration	t	h
Flow rate	Q	L/h
Hydraulic loading rate	HLR	m/h
Mass of dissolved oxygen consumed within individual layer	M_i	mg
Mass of dissolved oxygen within layers during flow pause	m_i	mg
Mass of DO consumed during pause	R_i	mg
Mass of media in individual layer	w_i	g
Residence time within individual layers	T_i	h
Specific oxygen uptake rate	SOUR	mg/h/gVS
Temperature correction factor	θ	dimensionless
Total depth of filter bed	L	m
Volatile solid	VS	gVS/g
Volume of collection duct	V_{duct}	L
Volume of individual layers	V_i	L

Table 4.3: Details of the filter runs used in model

Filter run	Run length (days)	Media depth (m)
I	71	0.80
II	41	0.76
III	43	0.72

4.3 Results

4.3.1 DO Utilisation with Filter Depth

The *Schmutzdecke* layer exhibited the highest oxygen utilisation rate per unit mass of media at 6.74 ± 0.44 gO₂/g dry solids/h (Figure 4.3:). The oxygen utilisation rate consistently diminished with depth down to a rate of 0.43 ± 0.01 gO₂/g dry solids/h for S4 until the GAC layer, where it increased by over fivefold compared to the sub-sand layers to a rate of 0.52 ± 0.01 gO₂/g dry solids/h. This finding is consistent with previous observations, such as those by Steele et al. (2006), which showed that DO drop was greatest within the GAC sandwich layer (between 6 to 12 mg/L) compared to the sub-sand layers (between 0.5 to 2.5 mg/L). The enhanced demand in the GAC layer can be linked to the large surface area it provides to support microbial growth (Wang et al, 1995). Though SOUR is not a direct measure of biological activity, it serves as a valuable indicator for assessing biological degradation (van der Aa et al., 2011).

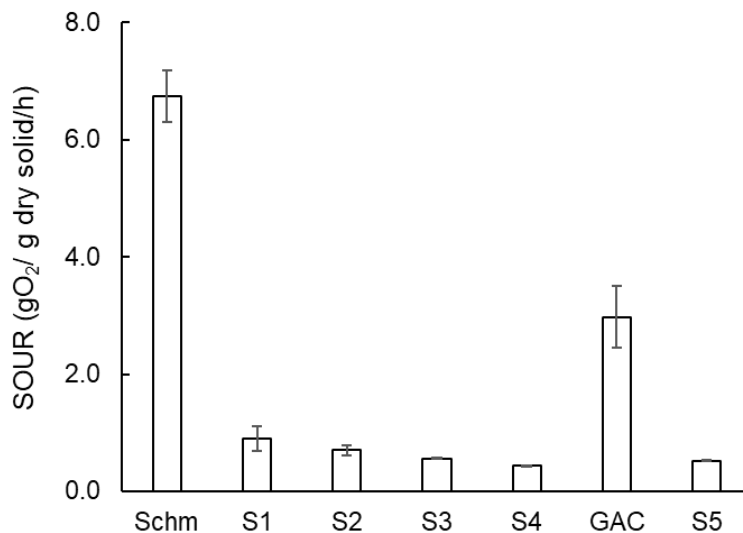


Figure 4.3: Profile of SOUR with bed depth

***Schmutzdecke* (Schm); S1: 25-50 mm; S2: 50-100 mm; S3: 100-200 mm; S4: 200-top of GAC layer; S5: below GAC layer. Composite samples collected from 3 different spatial locations within a mature full-scale SSF. Error bars represent average $\pm$ standard deviation (n=3). SOUR values were adjusted to a standard temperature of 20°C using the Arrhenius equation for comparison across different experimental conditions.**

Filtrate water quality parameters were similar between filters for all the filter runs. There was no significant difference between the different treatments for pH and turbidity (Table 4.4).

Table 4.4: Average feed and filtrate water parameters for the three filter runs (I, II and III) used.

Parameter	Run	Feed	UWS-100	UWS-33	UWS-0	DS	Statistics ²
Water temperature (°C) ¹	I	9±2.4 (n=20,492)					
	II	5.6±1.6 (n=11,809)					
	III	7.5±1.8 (n=12,384)					
DO (mg/L)	I	10.0±0.9 (n=4247)	6.5±1.1 (n=3913)	7.0±1.0 (n=4004)	6.7±1.2 (n=3844)	6.7±1.0 (n=3642)	
	II	13.1±0.4 (n=2627)	9.3±0.4 (n=2457)	10.2±0.4 (n=2113)	9.9±0.4 (n=1858)	10.6±0.4 (n=2326)	
	III	13.2±0.4 (n=2757)	9.0±0.5 (n=2577)	10.0±0.6 (n=2606)	9.5±1.0 (n=2158)	10.3±0.7 (n=2621)	
pH	I	7.8±0.3 (n=64)	7.7±0.2 (n=64)	7.7±0.2 (n=64)	7.7±0.1 (n=64)	7.8±0.1 (n=64)	H (3) = 6.7, p = 0.084
	II	8±0.2 (n=40)	7.9±0.1 (n=39)	7.9±0.1 (n=39)	7.9±0.1 (n=39)	7.9±0.1 (n=37)	H (3) = 1.6, p = 0.662
	III	8.2±0.1 (n=43)	8±0.1 (n=43)	8±0.1 (n=43)	8±0.1 (n=41)	8±0.1 (n=41)	H (3) = 2.4, p = 0.493
Turbidity (NTU)	I	0.4±0.2 (n=64)	0.1±0.03 (n=64)	0.1±0.03 (n=64)	0.1±0.02 (n=64)	0.1±0.03 (n=64)	H (3) = 5.8, p = 0.123
	II	1.1±0.3 (n=38)	0.1±0.05 (n=37)	0.1±0.02 (n=37)	0.1±0.03 (n=37)	0.1±0.03 (n=35)	H (3) = 5.2, p = 0.159
	III	1.2±0.3 (n=43)	0.1±0.03 (n=43)	0.1±0.02 (n=43)	0.1±0.03 (n=41)	0.1±0.03 (n=41)	H (3) = 5.3, p = 0.962
Nitrate (mg-NO ₃ /L)	I	6.1±0.5 (n=15)	6.2±0.5 (n=15)	6.2±0.5 (n=15)	6.3±0.5 (n=15)	6.3±0.5 (n=15)	H (3) =0.1, p = 0.989
	II	6.7±0.2 (n=10)	6.8±0.3 (n=10)	6.9±0.2 (n=10)	6.9±0.2 (n=10)	6.7±0.3 (n=9)	H (3) =1.5, p = 0.694
	III	7.1±0.2 (n=11)	7.2±0.2 (n=11)	7.2±0.2 (n=11)	7.3±0.3 (n=10)	7.2±0.2 (n=10)	H (3) =0.8, p = 0.838
1. Water temperature as measured in the feed. 2. Statistical test used is Kruskal Walis at 0.05 significance. Degree of freedom = 3. No statistical difference between treatments for the water quality for all the filter runs.							

In every scenario studied, filtrate DO levels consistently remained above 0 mg/L, with no anoxic or anaerobic conditions observed. This study did not explore how

such conditions might affect the SOUR and subsequent oxygen usage. Nitrate monitoring during pilot experiments, however, indicated no usage of this alternative electron acceptor, evidenced by the absence of net nitrate removal (Table 4.4).

4.3.2 DO Utilisation Under Steady State and Dynamic Operation.

Throughout the pseudo-steady state periods of the trials, the DO consumption (difference between feed and filtrate DO) was between 2.0-5.0 mg/L. This occurred as the DO increased in both the feed and effluent (Figure 4.4). To illustrate in the case of a UWS operated with a 100% sweetening flow, the DO of the feed increased from 8.3-12.3 mg/L over the 60 days of the run with the effluent DO changing from 4.2-8.7 mg/L over the same time period. Importantly this trend persisted for all monitored filters, indicating that the different skimming arrangements did not influence biological activity. Throughout the period of operation, the DO level in the filtrate did not go below an operational minimum of 3.0 mg/L DO suggesting that UWS poses minimal risk in terms of maintaining suitable DO levels.

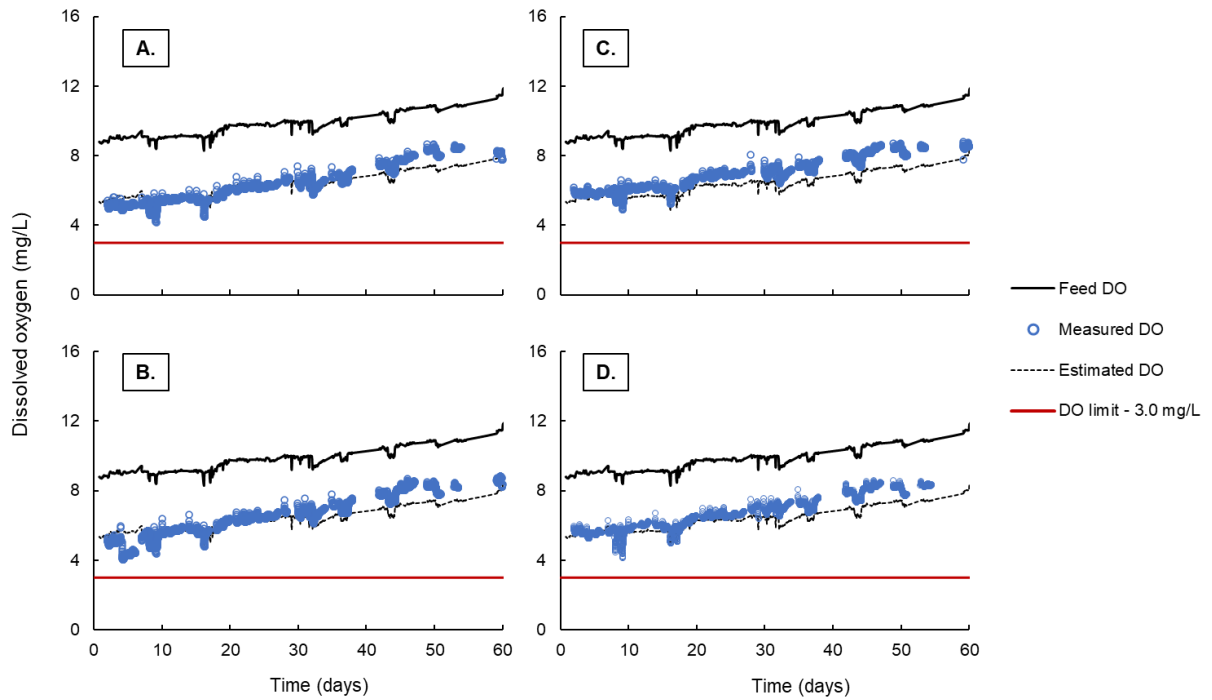


Figure 4.4: Observed and model-estimated DO concentrations in the feed and filtrate of the pilot SSFs during one of the filter runs (Run I).

The figures show filters that were cleaned using different USW methodologies: (A) UWS with 100% operational flow (UWS-100); (B) UWS with 30% flow (UWS-33); (C) UWS without operational flow (UWS-0); (D) Dry skimming (DS) as a control.

Under dynamic conditions, defined here as during and immediately after skimming, particularly during UWS without a sweetening flow (UWS-0), the rate of oxygen consumption during skimming was consistent at 2.7 mgO₂/kg media per hour, with less than a 5% difference between the skimming treatments (2.6-2.7 mgO₂/kg media per hour) and with good reproducibility between runs I- III (Figure 4.5, A - I). When the flow was interrupted as part of the skimming cycle (i.e., either reduced or stopped), the DO present within the water in the filter decreased during skimming. This decrease resulted from the continued consumption of DO within the filter bed and the reduced or absent supply of additional DO due to the reduced or lack of influent water. To illustrate, the effluent DO reached a minimum level of 2.7, 1.4 and 1.7 mg/L for runs I, II and III for the scenario with no flow during skimming. Partial flow during skimming

ameliorated the decrease leading to a minimum DO in the effluent of 5.6, 6.0 and 3.8 mg/L for runs I, II and III with a 30% flow (Figure 4.5). When the flow was resumed, the water with depleted DO levels within the filter bed was replaced with water with greater DO concentration, leading to a return to the pseudo-steady state levels (Figure 4.5). The stepwise increase displayed in the figure arises from the SSF operation where the flow rate was progressively increased (by increments of 0.1 m/h). The impact of UWS whilst maintaining a sweetening flow was demonstrated by the time taken to return to the steady state conditions (Figure 4.5). The recovery duration was 0.1 BV for UWS-100 but extended to between 9.7 and 10.1 BV for UWS-33. This was close to the no flow case of UWS-0 which resulted in recovery times of between 10.1 and 10.9 BV. Consequently, the results indicate that reduced flow sweetening has marginal benefit and that to see the maximum benefit higher sweetening flows will be required.

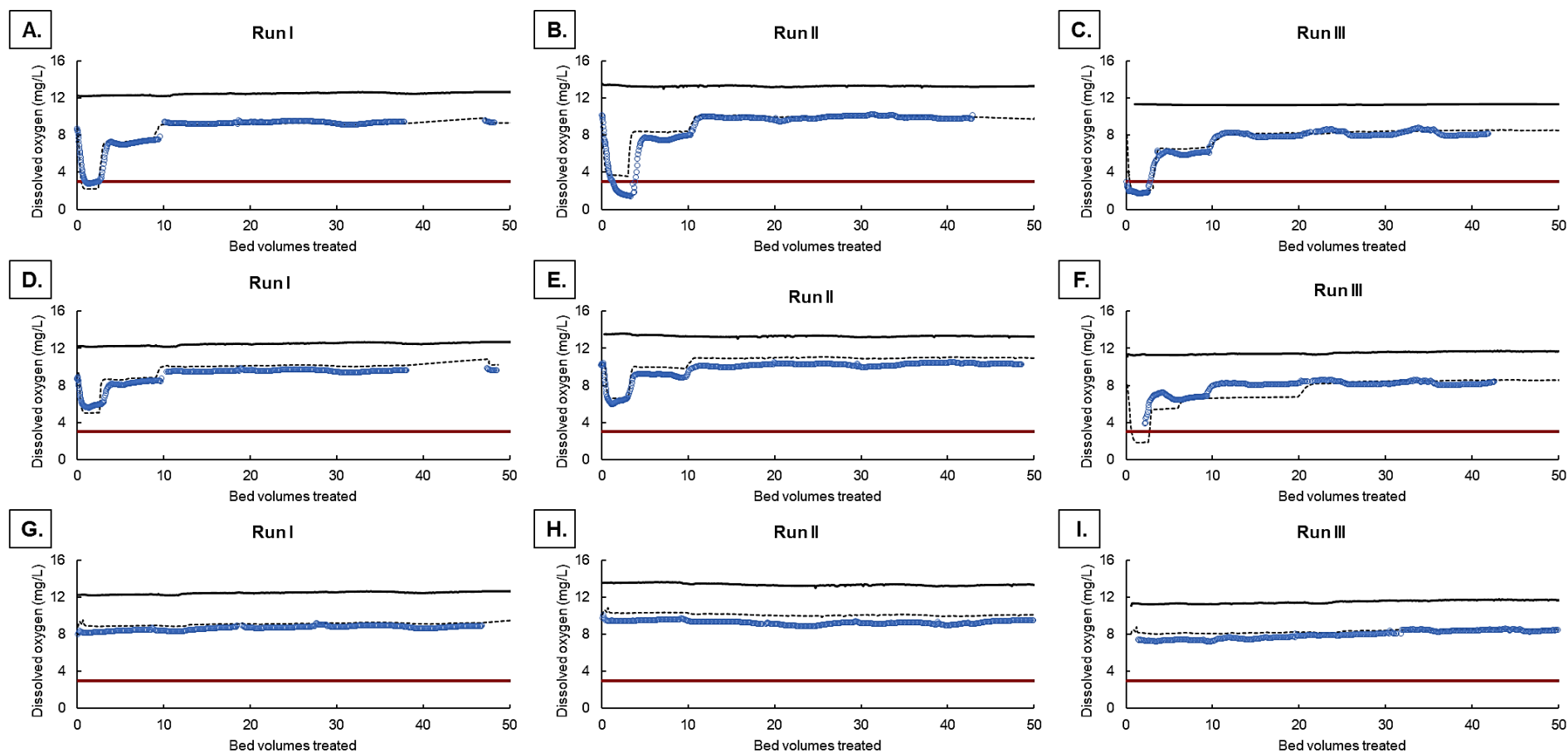


Figure 4.5: DO concentrations in the feed and filtrate (observed and estimated from model) in pilot SSFs for different filter runs immediately after skimming.

UWS-0 (A - C); UWS-33 (D - F); UWS-100 (G - I). BV = 0, is the start of a new filter run.

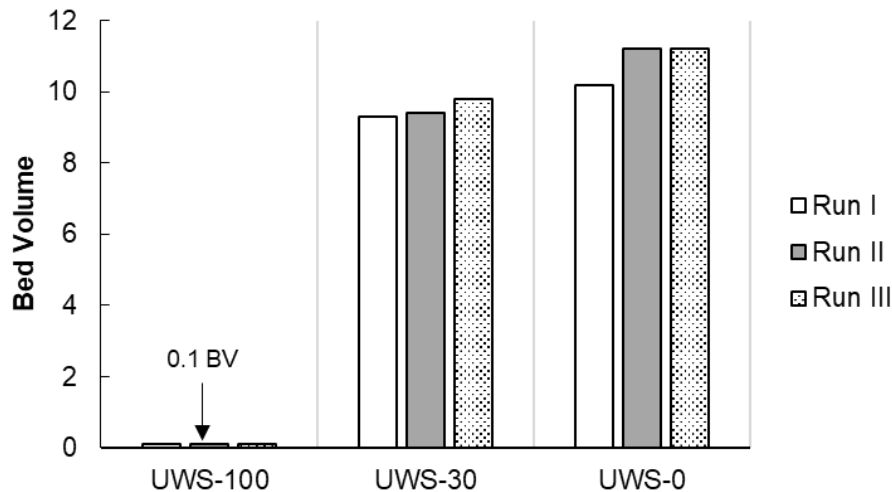


Figure 4.6: The impact of sweetening flow on the recovery duration in terms of BV in the pilot SSF post-skimming.

Run I (January 2022), Run II (February 2022), and Run III (March 2022).

For the validation of the model, the deviations were found to be minimal, with a root mean square error value of 0.6 mg/L. This suggests a high degree of reliability in the model, with the predicted filtrate DO exhibiting an accuracy of less than ± 0.6 mg/L. To further examine the significance of this finding, a Bland-Altman analysis was conducted (Figure 4.7). The observed and estimated values were found to be in strong agreement as about 96% of the values were within the limits of agreement (i.e., mean ± 1.96 standard deviation). The 4% outside the limit may be attributed to random variation, suggesting that there is minimal bias in the estimated values. The results imply a strong agreement between the measured and modelled values and provided confidence pertaining to the model's robustness.

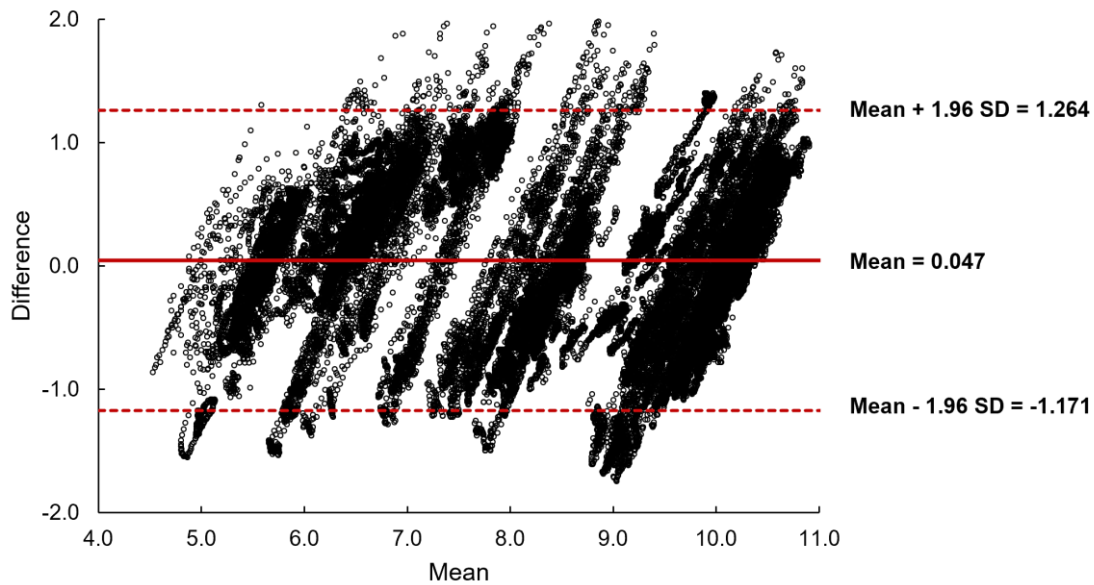


Figure 4.7: Bland-Altman plot demonstrating the agreement between observed and estimated filtrate DO under pseudo-steady state conditions.

The plot illustrates the difference (observed - estimated) against the mean [(observed + estimated)/2]. The graph includes results from three distinct filter runs, encompassing a total of 45,170 data points obtained from 5 pilot SSFs. Data points within limit = 43,363 or 96%).

4.3.3 Model Simulations of How Flow Rate and Its Pause Duration Impact DO Utilisation

The model was used to investigate the impact of operational variations on the effluent DO and the time to return to steady state conditions (Figure 4.8 - Figure 4.10). The duration of flow pause significantly influenced both the extent of DO concentration drop within the filter and the recovery time required for the filter to return to pseudo-steady-state conditions. For instance, increasing the pause duration from 30 min to 3h led to a more pronounced reduction in DO levels of 94% for a 30 min pause to 99% after a 3h pause, and a lengthier recovery period from 2h to 3h respectively (Figure 4.8). In the scenario of a 24-hour flow pause, upon resumption of flow, the DO level fell to below detectable limits (i.e., <0.1 mg/L), denoting complete DO consumption and anoxic conditions within the filter during this extended pause. This happened irrespective of the method of flow resumption (whether incrementally in 0.1 m/h steps or not). However, when the flow was reintroduced swiftly and at a higher rate, the bed's

recovery was three times as fast, within only two BV required to return to operational DO levels. For the case where the pause exceeds three hours, the filter risks becoming anoxic. These findings highlight that the HLR post-skimming has a more profound effect on recovery than the flow pause duration during skimming.

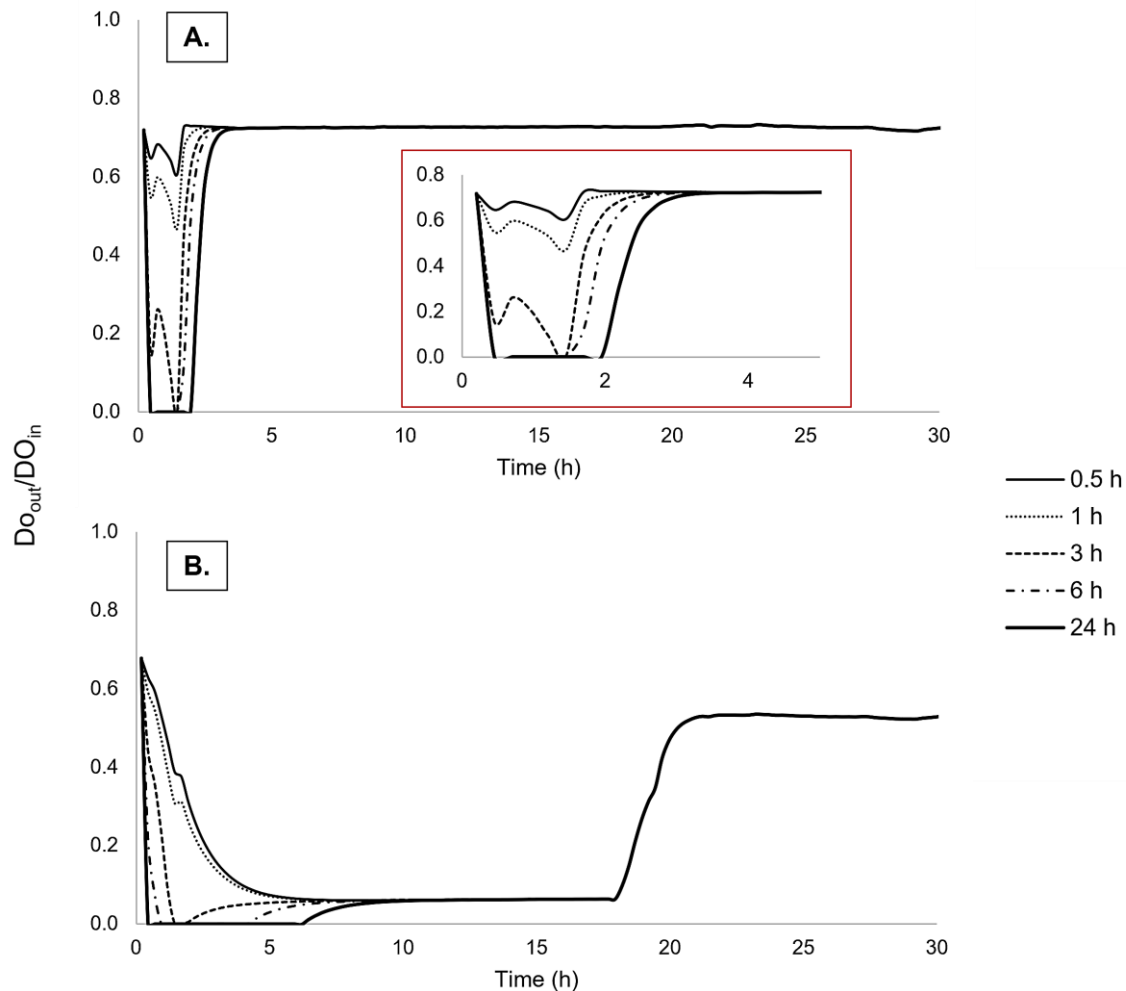


Figure 4.8: Impact of pause duration on DO concentrations in the feed and recovery duration after a flow pause and skimming event (UWS-0).

The depicted scenarios were: (A) immediate resumption of flow at full rate post-pause; (B) gradual stepwise resumption flow increments post-pause. Media depth = 0.8 m, average feed DO concentration = 12.3 mg/L.

When the HLR was reintroduced at a rate of 2.5% per hour, the recovery took about 3.5 times longer (72.3 h) than when it increased by 10% per hour (20.7 h). Conversely, an immediate reintroduction of the flow at the operational rate expedited the recovery process, with the filter reverting to a pseudo-steady state DO consumption rate within

two hours of operation. However, operational decisions regarding the flow reintroduction rate post-skimming should consider the limitations of operational systems. For example, it may not be feasible to physically restore the flow to the operational HLR rapidly due to pipe work limitations or site-specific hydraulics. As such, re-introduction flow rates should be increased as quickly as is practically possible.

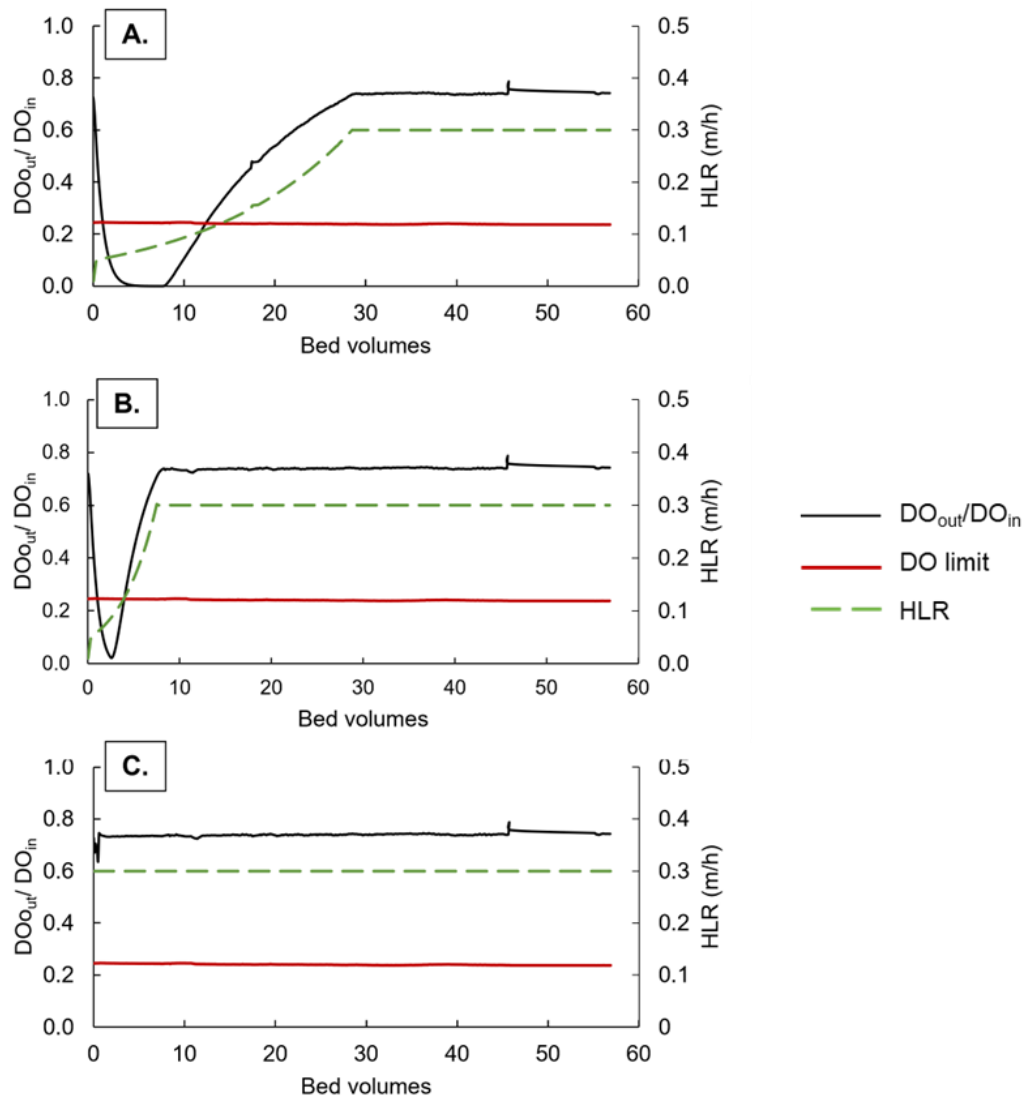


Figure 4.9: The predicted influence of HLR on DO supply and consumption in a standard full-scale SSF immediately post-skimming.

Scenarios include: (A) Slow HLR reintroduction at 2.5% of the operational rate per hour; (B) Gradual HLR reintroduction at 10% of the operational rate per hour; (C) Instantaneous return of HLR to the operational rate. BV equals 0 represents the commencement of a new filter run. Media depth = 0.8m, filter surface area = 3087 m², average feed DO = 12.3 mg/L.

4.3.4 The Impact of Temperature Variations on DO Utilisation in SSF

Predicted forecasts of DO usage at various temperatures when operating a UWS with no sweetening flow showed an increase in DO consumption with rising temperatures from 1.0 mgO₂/kg media per hour at 5°C, to 2.7 mgO₂/kg media per hour at 20°C, for a fixed inlet feed DO concentration of 12.3 mg/L (Figure 4.10). The consequence was that at and above temperatures of 15°C, the DO dropped below the operational limit once flow had been restored. Notably, at 20°C, the DO concentration was unacceptably low, approaching anaerobic conditions (filtrate DO <0.3 mg/L), and extended the recovery time to achieve levels above the threshold, taking over 1.5 times longer than at 15°C. Steady state DO levels were reached after 8 BVs for all temperatures with the actual DO level commensurate with the temperature dependent saturation level. The work shows the combined impact of reduced DO solubility and increased consumption associated with enhance biological/microbial activities.

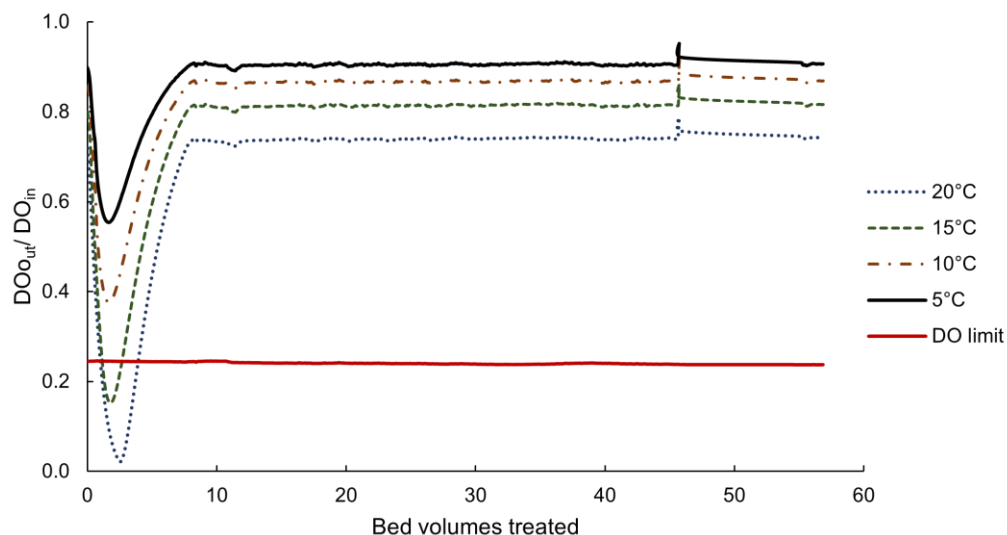


Figure 4.10: Illustration of the influence of temperature on the supply and consumption of DO in a full-scale SSF post-UWS-0 skimming.

Media depth = 0.8m, filter surface area = 3082m², GAC layer = 0.1m, average feed DO = 12.3 mg/L. BV=0 is start of new filter run, with 1 BV increments. UWS-0 selected as worst-case scenario.

4.4 Discussion

Overall, the work has shown that UWS can be applied with minimal risk to the biological function of SSFs (Figure 4.4). Reduction in filtrate DO can be expected in cases of flow pause or reduced HLR during the cleaning process where consumption outstrips supply. The impact is shown to have a temperature dependency due to the combination of reduced solubility and increased microbial activity as temperatures increase (Figure 4.10), requiring specific consideration at temperatures above 15°C. Consequently, minimum acceptable sweetening flow rates should be adjusted for temperature to ensure DO supply consistently meets demand, especially during the highest temperatures. Importantly, during pilot trials where DO decreased below the operational limit of 3 mg/L, no significant nitrate removal was observed (Table 4.4), indicating that the low DO levels were insufficient to trigger the onset of anoxic or anaerobic activity (Young-Rojanschi and Madramootoo, 2014). In addition, the work has shown the importance of the rate of flow reintroduction post skimming in terms of the recovery time required to return the SSF back to its steady state condition which needs to be delivered at the maximum rate that is practically possible.

Accordingly, the work posits that operational SSFs will have a combination of sweetening flow and the rate of reintroduction that will negate any risk of UWS on maintaining the desired DO conditions within the bed. Once validated to a specific site, the model offers predictive capabilities to establish the combination of conditions needed. The current model compliments existing SSF models and fills an important gap not currently covered by those models. For instance, this model integrates with models designed for pathogen removal (like those suggested by Schijven et al., 2013 and Langenbach et al., 2010), and for forecasting head loss and filter run durations (such as the one presented by (Campos et al., 2006)). This integration would assist in microbial risk assessment, operational planning and resource management for SSFs across various operating conditions and across multiple filter cycles. This research enhances understanding of UWS effects on DO dynamics in SSFs by integrating empirical data with a new model, offering a predictive tool for improved operational strategies and microbial risk management.

4.5 Conclusions

A mass balance model has been developed utilising empirical derived DO consumption rate data to predict the impact of UWS under various sweetening flows. Overall, the work has demonstrated that UWS offers no increase in risk to operation of SSFs compared to traditional skimming methods. This research suggests that the inclusion of a 'sweetening flow' during UWS could considerably improve DO supply, reduce the emergence of anoxic conditions, and expedite filter recovery time. Maintaining a sweetening flow during UWS reduced recovery times, with UWS-100 achieving 0.1 BV compared to 10.1-10.9 BV for UWS-0.

Implementation of the findings translates to setting the level of flow pause and the rate of introduction as a function of temperature. Importantly, the work shows that higher temperatures pose the most challenge due to the combined impact of reduced solubility and increased activity. Predicted DO usage at various temperatures showed an increase from 1.0 mgO₂/kg media per hour at 5°C to 2.7 mgO₂/kg media per hour at 20°C, for a fixed inlet feed DO concentration of 12.3 mg/L. Accordingly, agreed practice should be based on summer conditions.

Also, flow pause duration was critical, as an increase from 30 minutes to 3 hours led to a more pronounced DO reduction (94% to 99%) and longer recovery periods (2 to 3 hours). Reintroducing the HLR at 2.5% per hour extended recovery to 72.3 hours, compared to 20.7 hours at 10% per hour. Immediate reintroduction expedited recovery to within two hours.

The study also identifies the *Schmutzdecke* and GAC layers as the highest DO consumers, with rates of 6.74 ± 0.44 gO₂/g dry solids/h and 0.52±0.01 gO₂/g dry solids/h, respectively, and suggest that they remain stable once the bed matures. Further research is needed to understand the range of DO utilisation rates in these layers across different SSFs, which will aid in calibrating the model for use at other sites and determining the applicability of standard values.

Other unexplored impacts of varying sweetening flows on the performance SSFs cleaned with UWS are presented in Chapter 5, including the impacts on water quality and filter operational performance.

4.6 References

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5 Understanding the Impact of Underwater Skimming on Slow Sand Filter Performance and Operation

Abstract

Traditional cleaning of slow sand filters (SSF) requires the beds to be drained before a layer of media and the *Schmutzdecke* are removed, called dry skimming, which can result in significant downtime. An alternative is proposed whereby the filter is skimmed whilst still submerged, called underwater skimming (UWS). Previous attempts to avoid draining the bed, have led to concerns about the risks head loss development, particle penetration, and microbial water quality. In this study, pilot scale SSFs, cleaned by either DS or UWS, were operated concurrently, to compare and assess the potential risk of UWS in terms of filtrate quality, microbial removal, and recovery following skimming. While all filters exhibited effective turbidity removal (0.04-0.9 NTU), UWS filters had improved performance immediately after cleaning compared to DS in terms of recovery of filtrate microbial water quality. Specifically, total coliforms in the UWS filters, in the first seven days post-skim ranged from 1 to 109 most probable number (MPN)/100 mL, compared to 1 to 1414 MPN/100 mL for DS filters. Both methods yielded satisfactory head loss recovery, indicative of limited particle penetration at depth, and effective cleaning. Exploring different sweetening flows during UWS revealed no observable differences between them. *Schmutzdecke* microbial assembly was similar irrespective of cleaning method and was governed instead by seasonal changes, and the ripening process. Notably, UWS filters exhibited less disruption post-skimming, allowing for quicker recovery to microbial compliance, with lower coliform levels (2 MPN/100 mL) compared to DS filters (25 MPN/100 mL). The improved microbial removal afforded by UWS immediately after skimming provides a means of improving water production volume and enabling options for much better utilisation of SSFs.

Keywords: Slow sand filter (SSF); filter cleaning; underwater skimming (UWS); dry skimming (DS); *Schmutzdecke*; sweetening flow

5.1 Introduction

Slow sand filtration is a low energy and chemical free treatment that removes a wide range of contaminants including inorganic particles, dissolved and particulate organics, algae, and pathogens from influent water through physical, chemical, and biological processes (Chan et al., 2018). An important part of SSF treatment occurs within top biofilm layers (*Schmutzdecke*), which provides a primary site for biological activity (Hijnen et al., 2007). The *Schmutzdecke* is reported to be essential for eliminating microbial contaminants, including coliforms (Burman and Lewin, 1961), other bacteria (Hijnen et al., 2004), viruses (Poynter and Slade, 1977), phages (H. Wang et al., 2014), and *Giardia* spp./*Cryptosporidium* spp. (Bellamy, Silverman, and Hendricks, 1985). The unavoidable consequence of the function of the *Schmutzdecke* is an increasing head loss as particles accumulate and biofilm assembles, eventually clogging the filter (Graham and Collins, 2014). The subsurface filter bed supports further filtration and biofilm, enhancing the overall efficiency, especially of the capture of difficult-to-filter small particles, such as viruses (Trikanad et al., 2023).

The rate and extent of SSF clogging depends on the source water quality and cleaning frequency. Traditional amelioration involves dry skimming (DS), where the filter is initially drained before the top 10-50 mm of the bed are removed. Once complete, the bed is refilled with water and the flow restarted, with the treated water run to waste until the required water quality is achieved. Cleaning typically occurs every 1-3 months, so that over a year the filter will be operation around 80-90% of the time (Hassard et al., 2022). Further, DS is reported to create environmental stress within the biofilms, changing nutrient availability, and disrupting the SSF microbial assembly by removing microbes at varying rates, analogous to sludge wasting in sequencing batch wastewater reactors (Ellis, 1985). Accordingly, minimising drainage time, and cleaning disruption is crucial to maintain the stability of the SSF ecosystem.

To address such concerns, underwater skimming has been proposed (Hassard et al., 2022) which involves removing the *Schmutzdecke* and top sand layers, just

like with the DS, except with the filter fully submerged. UWS employs a skimmer, fitted with a shrouded blade moving along the surface of the bed which concurrently removes sand and *Schmutzdecke* and captures it to be pumped out of the filter as a slurry. The UWS process may involve either a complete pause of flow or a continuous 'Sweetening' flow regimen, facilitating the steady provision of oxygen and nutrients to the filter during cleaning. 'Sweetening flow' in this study refers to the flow maintained through an SSF (i.e., full or reduced operational flow rate) while skimming underwater (also see Section 5.2.3). UWS eliminates SSF drainage, minimising 'stop-start' cycles and hence offers a less disruptive cleaning method, potentially increasing water production through semi- or fully continuous filter operation (Lloyd, 1996). In addition, UWS is hypothesised to preserve the microbial ecosystems leading to enhanced resilience (Hassard et al., 2022).

The potential disadvantages of UWS and similar cleaning methods where the bed is left fully submerged, have been reported to be a reduction in filtrate quality and increased problems post-cleaning (Singer et al., 2017), faster head loss development (Burman and Lewin, 1961), and deeper particle penetration (Huisman and Wood, 1974). For instance, a full-scale *in-situ* sand washing test indicated reduced filter run times, over months, attributed to rapid biofilm/algae growth and suboptimal cleaning, underscoring the need for further refinements in UWS applications for SSF (Burman and Lewin, 1961). One such refinement is the *ex-situ* washing of the sand slurry produced from cleaning (as opposed to *in-situ* in the examples above).

In this study, an investigation into the impacts of UWS on water quality, filter performance and microbiome are presented with a real time side-by-side comparison with DS. Furthermore, a novel investigation of the previously unexplored impacts of varying sweetening flows on the performance of UWS is provided, offering new insights that could significantly enhance filter efficiency with regards to maintaining production through SSFs during and after cleaning.

Accordingly, this study assesses the potential risks associated with UWS in terms of impacts on filtrate quality, hydraulic performance and any associated shift in the microbiome population or diversity using ten 0.54 m² pilot SSFs in a real-world WTW setting for 15 months. It contrasts UWS with traditional DS comparing head loss development, recovery time to achieve microbial compliance, and performance over multiple UWS cycles. The underpinning hypothesis is that UWS minimises SSF ecosystem disruption, quickens ripening, and lessens quality impacts, enhancing performance during the post-skim period through reduced breakthrough. In addition, it is suggested that the proposed benefits will occur without an associated increase in clogging in the lower layers of the SSF. This will be tested by comparing the post-skim head loss of UWS to DS. Furthermore, introduction of a sweetening flow through the filter while UWS promotes the improved benefits of UWS.

The novelty of this research lies in its comprehensive, real-time side-by-side comparison of UWS and DS within SSF systems, conducted in a real-world water treatment works setting. This study uniquely explores the previously unexamined impacts of varying sweetening flows on UWS performance, providing new insights that could significantly enhance SSF efficiency. It further builds on learnings in Chapter 4, where sweetening flows have been seen to improve DO supply to UWS filters and hasten recovery post-skim. Additionally, it offers a holistic assessment by not only evaluating hydraulic and water quality impacts but also examining the microbiology via traditional microbial indicators, flow cytometry and rapid rRNA monitoring, thereby contributing to a deeper understanding of the implications of UWS on SSF systems.

5.2 Materials and Methods

5.2.1 Description and Operation of Pilot SSFs

The SSF pilot plant assembly included 10 No. ~0.54 m² filters, containing from the top downwards: a layer of sand (0.2-0.5 m, effective size, ES=0.3 mm, uniformity coefficient, UC=1.8), (of which the top 0.3 m was subject to successive skims), GAC (0.1 m, ES=0.6 mm, UC=1.9), sand (0.2 m), and gravel (0.1 m),

resting on a metal plate containing 24 spaced nozzles, with 36 no. 0.2 mm width slots acting as a filter false floor. These gravity-fed filters were manually controlled via outlet valves and monitored with flow meters. Sampling from the inlet and filtrate occurred approximately five days a week, with parameters measured daily during startup and immediately after skimming, and consequently measured weekly. Treatment was assigned to filters, allowing duplicate filters for each treatment. Beds were not assigned at random due to the hydraulic constraints of the pilot plant, making it easier to have the dry skimmed filters at one end (see Figure 5.2 and Appendix E.2).

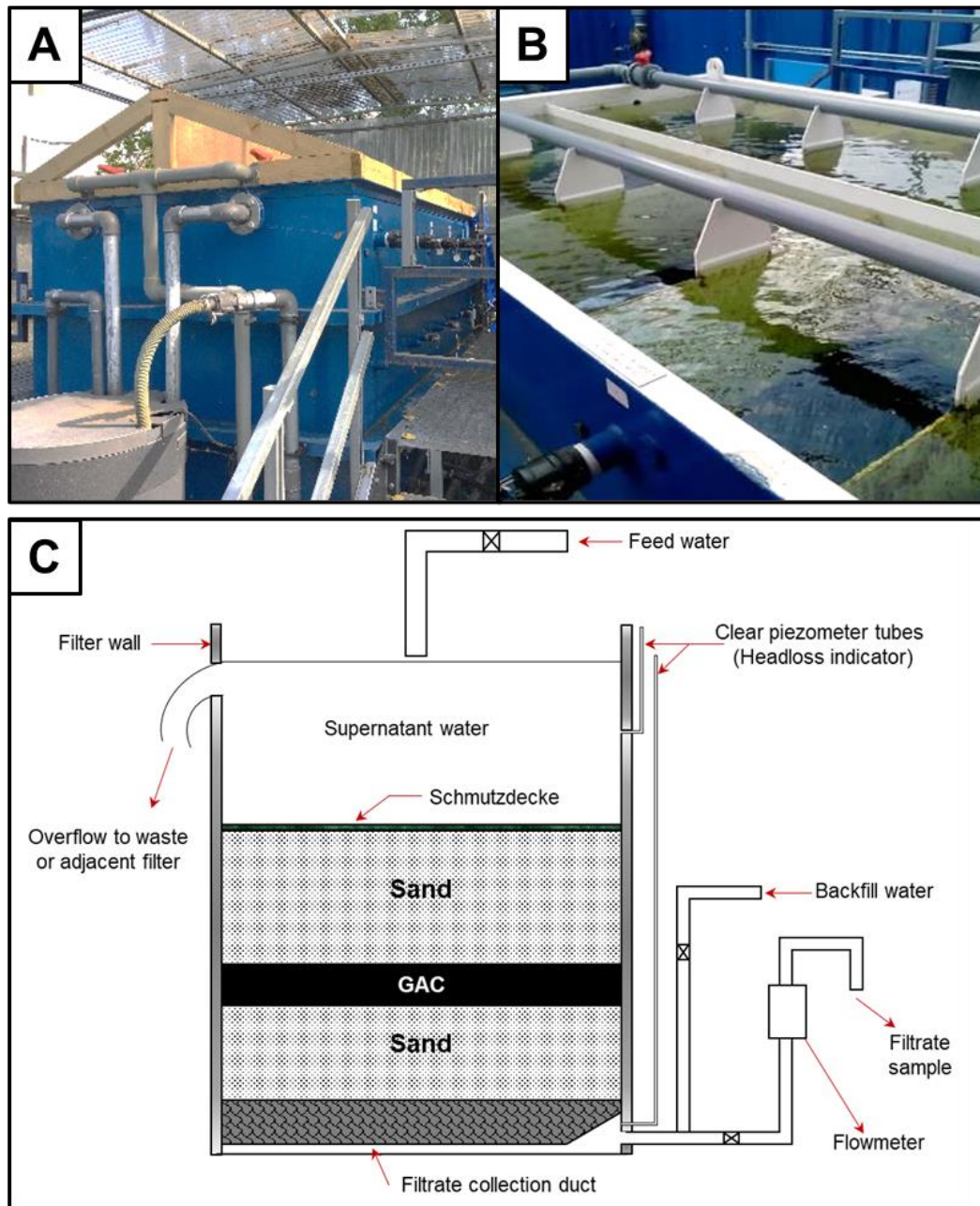


Figure 5.1: SSF pilot plant assembly:

(A) an anterior view of feed pipes overflows and transparent roof of the filtration tank and access platform; (B) 10 individual cells and central dividing wall, individual submerged filter dividing walls and parallel common feed pipes; (C) a schematic of an individual filter.

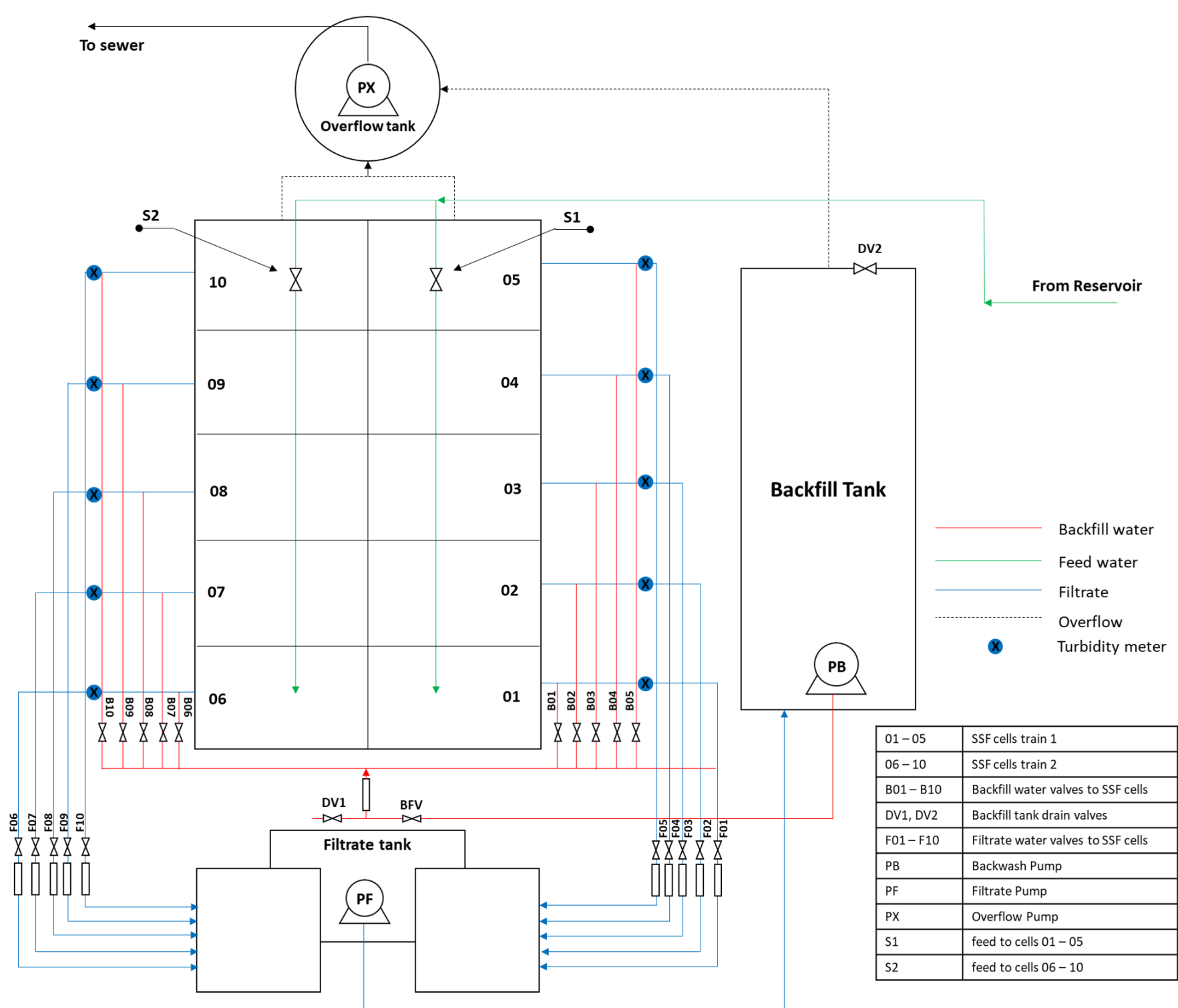


Figure 5.2: Schematic of the plan view of the SSF pilot set-up.
Showing the direction of water flow, valves, flowmeters and online turbidity meter locations.

5.2.2 Feed Water Characteristics and Filter Operation

The pilot plant influent came from a raw water reservoir, with a 30-day retention, fed from the river Thames. Average feed water quality included a total organic carbon (TOC) of 3.6 ± 0.2 mg/L, turbidity at 0.6 ± 0.4 NTU, and pH at 8.1 ± 0.2 (Appendix E.1, Table A.3). The filters operated in air temperatures of -6 to 22°C, and water temperatures from 3-16°C (Appendix E.1, Figure A.4). Initially backfilled with filtrate, filtration started at a hydraulic loading rate (HLR) of 0.1 m/h, increasing by 0.1 m/h daily until reaching an operational rate of 0.3 m/h HLR. Typical SSF pre-treatment by roughing filtration was omitted for the duration of the experiment due to the low feed water turbidity which averaged 0.6 ± 0.4 NTU.

5.2.3 Head Loss Measurement and Skimming Procedures

Head loss was measured using piezometers attached to each SSF, calculated as the difference between the supernatant surface and the bed depth at the distal end, with a maximum measurable head loss of 1350 mm. Before each measurement, the flow rate was set to the operational rate, and values were temperature-normalised to account for viscosity changes:

$$h_N = h_m \cdot \frac{\mu_N}{\mu_m} \quad (5.1)$$

Where:

- h_N Normalised head loss (mm)
- h_m Measured head loss (mm) at time, t
- μ_N Dynamic viscosity (Pa.s) at normalising temperature of 20°C
- μ_m Dynamic viscosity (Pa.s) at measured temperature at time, t

Skimming started when the maximum head loss was reached, for one or more of the filters, or at seasonally adjusted intervals (40 days in summer due to biological growth, 70 days in winter), whichever came first, which is standard practise for the water utility. The decision to skim all filters within days of each other (whether or not max head loss was reached for some), was to allow, for all filter runs to commence at similar times and under similar conditions.

Two cleaning methods, UWS and DS were compared. DS used a disinfected scraper and shovel, cleaned with 70% isopropanol and then WTW water, to manually remove a 40 mm surface layer from drained filters, confirmed by a laser measurement tool. UWS involved a specialised HDPE wet vacuum blade for submerged sand removal, operating at varying 'sweetening flows' (100, 67, 33, 0% of operation flow), with DS as the control (see Table A.4 for breakdown of skimming procedure). Attachments and hoses for the UWS were cleaned between use, with clean water and the parts in contact with the filter and supernatant further disinfected with 70% isopropanol (Figure 5.3). The depth skimmed was monitored using graduated lines painted at 20 mm intervals within the filter (Figure 5.4), and an underwater camera was used as a guide to confirm the accuracy of the skim.

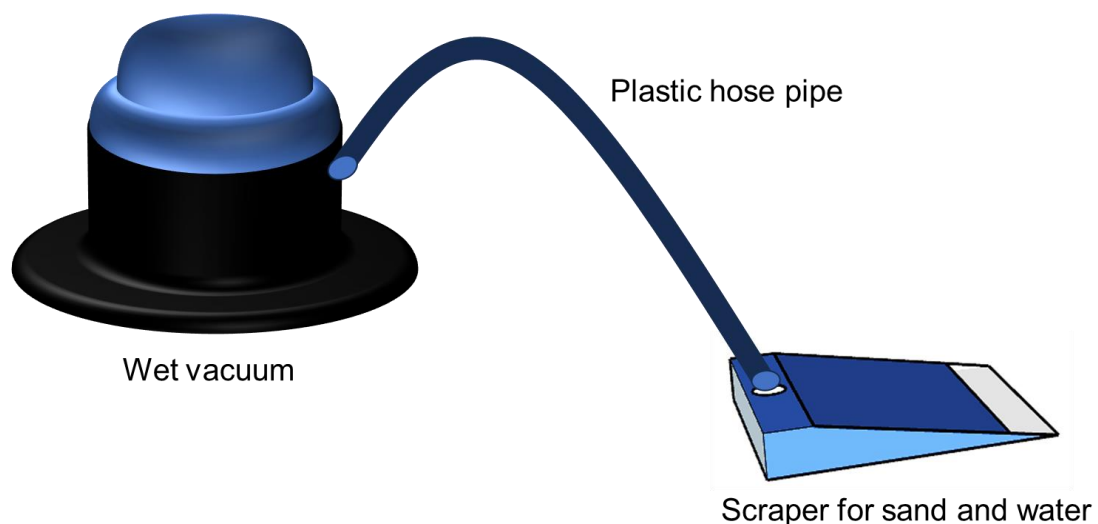


Figure 5.3: Schematic of the underwater skimmer used in the pilot, showing the wet vacuum and a custom scraper.



Figure 5.4: Image of one of the filters before operation, showing the 20 mm graduated lines used to guide skimming depth.

An underwater camera was used as a guide to confirm the accuracy of the skim during underwater skimming.

'Sweetening flow' refers to a continuous and steady flow of water through the SSF that is maintained during UWS. In this study, this ranged 100% of the operational HLR (UWS-100) to 33% of the HLR (UWS-33). Post-skimming, SSFs returned to the operational HLR with 0.1 m/h increments every 24hrs. UWS-100 needed no increments, UWS-67 one increment, and UWS-33 and UWS-0 two each. DS filters were restarted in the same manner as the initial setup, with backfilling and gradual filtration resumption using the daily 0.1 m/h increments.

Consistent with full-scale SSF practice, sand was not replaced during skimming. After five filter runs (Phase 1), all filters were drained (including the UWS filters), and sand levels were increased via a "re-sand event", where used washed sand was used to replenish the filters, akin to full-scale SSF practices, to maintain >500 mm minimum media depth (200 mm sand above 100 mm GAC above 200 mm

sand). At this point, an additional DS methodology was included (Phase 2) that further increased the downtime from approximately 14 h to about 28 h) to better replicate conditions that are observed in field SSFs. Consequently, the UWS-67 experiment was discontinued and an additional set of DS filters (labelled as DS-Ext) were introduced (Table A.4).

5.2.4 Water Sampling and Analysis and Biofilm Analysis

Water samples (feed and filtrate) were aseptically obtained from the inlet to the filters (feed) and from the outlet of individual filters (filtrate) for microbial analysis. These samples were collected daily during the first week after start-up or following a skimming process, and weekly thereafter.

Total coliforms and *E. coli* were quantified via the most probable number (MPN) method, using Colilert and Quanti-Tray, per standard protocols (Standing Committee of Analysts, 2009). Heterotrophic plate count (HPC) involved culturing on yeast extract agar with a 68-hour incubation at 22°C (Standing Committee of Analysts, 2007).

Automated inline flow cytometry (FCM) was undertaken using a BactoSense instrument (bNovate, Ecublens, Switzerland), measuring total cell count every 30 min. This instrument features a built-in laser operating at a wavelength of 488 nm, a side scatter (SSC) detector, and two fluorescence detectors equipped with bandpass filters for green-light (FL1, 525/45 nm band pass) and red-light (FL2, 715 nm long pass) emissions (Appendix E.4).

Turbidity was determined daily with a TU5200 instrument (Hach Co., Loveland, Colorado, USA), and water temperature was measured automatically on an hourly basis using Metrinet M-node (Analytical Technology Inc., Saddleworth, UK). Conductivity and pH were measured weekly with Hach HQ440d Multi-Parameter Meter (Hach Co., Loveland, Colorado, USA) using the intellical CDC401 and PHC101 probes respectively. TOC was measured weekly using O.I. Analytical Carbon Analyser, Model 1030 (Xylem Inc., Washington, D.C., USA)

and true colour was measured by spectrophotometry using Cecil CE 2021 Spectrophotometer (Cecil Instrumentation Services Ltd., Cambridge, UK).

During the first year of operation (March 2021-March 2022), weekly samples of the top 25 mm of the individual beds were collected (n=460). Samples were collected while the beds were in operation. Sample collection entailed extracting 'cores' using sterilised, modified syringes, with their nozzle and shoulder removed. This was then stored at -20°C in sterile centrifuge tubes until ready for DNA extraction. Extracted DNA was analysed by Novogene (Cambridge, UK) for amplification of the 16S rRNA gene via the NovaSeq PE250 platform (Illumina Inc.). The raw sequence data obtained from the Illumina sequencing were processed via QIIME2 (version 2018.11) and its associated plugins (Bolyen et al., 2019). The sequence data was analysed using PRIMER v7/PERMANOVA+ software (Primer-e, UK). Detailed description of the extraction, sequencing, and data analysis are provided in Appendix E.5.

5.3 Results and Discussion

5.3.1 Treatment Performance

In this study, the maturation period was defined by filtrate coliform levels <50 MPN/100 mL. During the initial startup (Run 1), before any skimming had been done, this period ranged from 1-17 days. Following re-sanding (Run 6), maturation period was between 1-14 days, consistent with the performance of full-scale SSFs.

Comparison of the performance of the SSFs with regards to the physicochemical properties monitored such as pH and conductivity (Table A.5), as well as TOC and true colour (Figure A.6) revealed no difference in treatment efficacy between the DS and UWS treatments. This consistent performance held true for the entire duration of the experiments. Accordingly, the use of UWS offers no risk of treatment deterioration during the steady state phase of operation irrespective of the rate of sweetening flow consistent with observations when using backwashing (de Souza et al., 2021a), and *in-situ* sand washing (Burman and Lewin, 1961),

which found that filter performance remains consistent once filters have matured, regardless of the cleaning method employed.

For the turbidity monitoring (Figure 5.5), the feed water values ranged between 0.4 NTU (March-December 2021) and 1.1 NTU (January-April 2022), representing low values compared to previous studies of higher inlet turbidity values (e.g., >30 NTU (Aydin, 1996)). All SSFs exhibited good turbidity removal, with filtrate turbidity values ranging from 0.04-0.7 NTU (UWS-100), 0.04-0.4 NTU (UWS-67), 0.04-0.4 NTU (UWS-33) for the UWS filters and 0.04-0.9 NTU for the DS filters. There was no statistical difference between the UWS and DS filters across all the filter runs (Kruskal Wallis: $H(1) = 0.1$, $p = 0.751$).

Turbidity levels exceeding the UK 0.3 NTU standard were very infrequent in filter skimming treatments, only occurring during the initial run at the start of the experiment (Run 1), and on three other separate occasions throughout the experiment (0.39 NTU for UWS-0 Run 5, 0.33 NTU for DS-Ext Run 7 and 0.34 NTU for UWS-33 Run 8). These three separate occurrences of filtrate turbidity measurement >0.3 NTU did not suggest any pattern favouring DS over UWS. In addition, the level of sweetening flow did not affect filtrate turbidity, as values remained below the set limit (0.3 NTU). Furthermore, when comparing the DS filters, there was no significant difference in the treatments with the extended downtimes (Kruskal Wallis: $H(1) = 0.5$, $p = 0.471$).

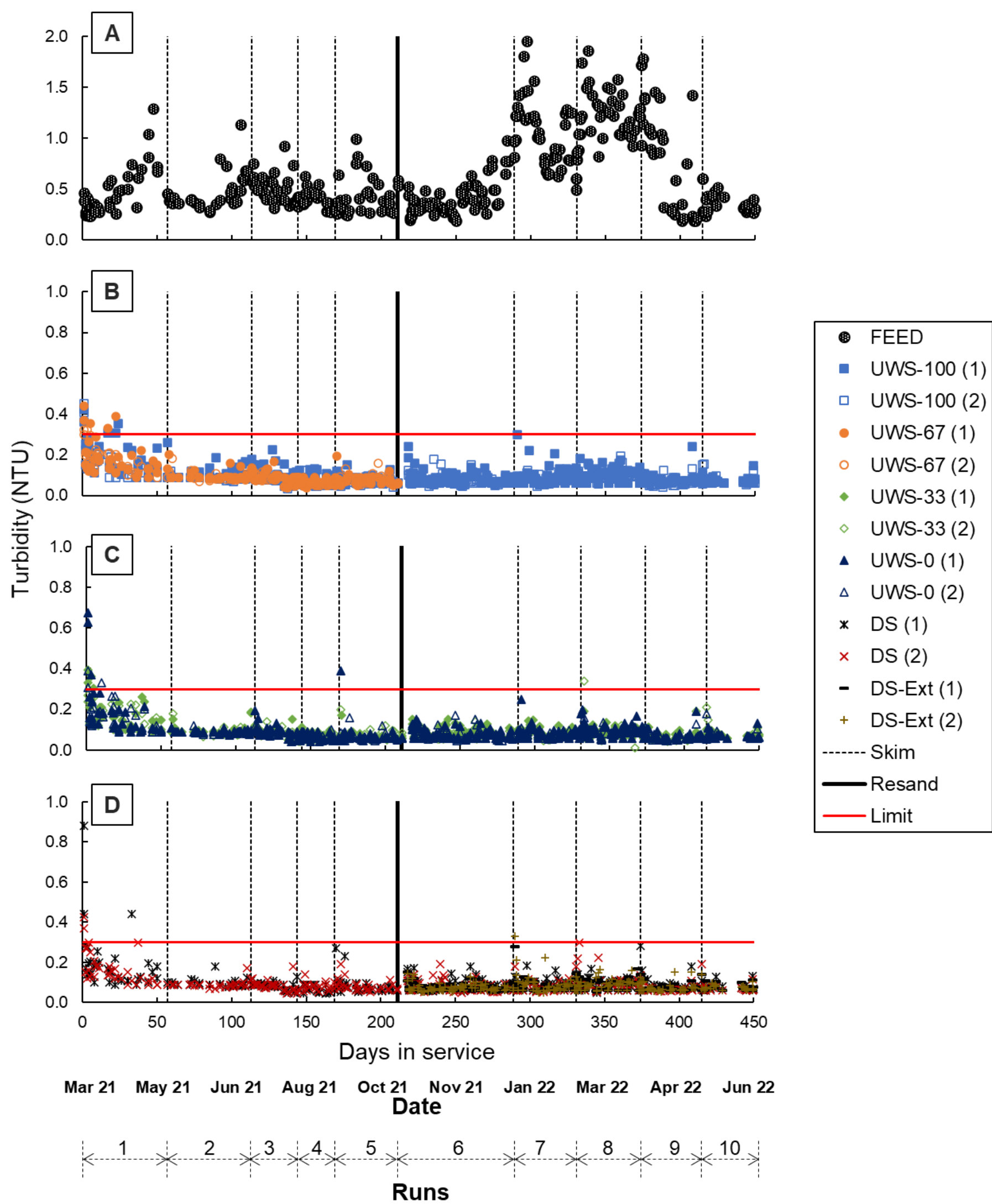


Figure 5.5: Turbidity in feed and filtrate, indicating skimming/re-sanding events.

(A) feed water turbidity (n=367); (B), (C) detail UWS turbidity at operational loadings: UWS-100 (1/2) (n= 353 / 352); UWS-67(1/2) (n=149 / 149), UWS-33(1/2) (n= 353 / 353), UWS-0(1/2) (n=351 / 350); (D) DS treatments: DS(1/2) (n= 340 / 340), DS-Ext(1/2) (n= 194 / 194). Operational limit is 0.3 NTU

Head loss development was characterised by three distinct phases: an initial gradual increase (slow rate), an intermediary phase with more rapid incline, followed by a sharp ascent (fast rate), marking the transition from depth filtration to surface filtration and subsequent clogging (Figure 5.6). These phases were determined based on the slope of the individual sections of the head loss development curves, where the slow rate was based on segments of the curves where the slope was less than 10 mm/d and the fast rate based on segments of the curves where the slope was greater than 15 mm/d (further details Appendix E.6). The difference in head loss development between runs was greater than that observed between different skimming options within individual runs. To illustrate, in the case of run two, the initial slow rates of head loss development were 1.7 mm/day for the DS and 1.5, 1.3, 1.4, and 1.4 mm/day for the UWS-100, UWS-67, UWS-33, and UWS-0 respectively. Whereas, by Run 5 no initial linear phase existed and all filters showed rapid increase only.

The head loss profiles were different again after the re-sand for all filters compared to before the re-sand but the head loss development was more rapid for the UWS compared to the DS filters. Statistical analysis of the rate of head loss development in mm/day showed that for all the filter treatments and across all filter runs (excluding runs 1 and 6), the slow rate of head loss development at the start of each run was similar (Kruskal-Wallis: $H(80)=10.6$, $p=0.385$) (Figure 5.7). Runs 1 and 6 were excluded from the analysis as they did not have the different skimming methods preceding them, for run 1 this was the start of the experiment and run 6 was after a re-sand event. For the fast rate, on the other hand, there were statistical differences between DS and UWS filters (Kruskal-Wallis: $H(80)=8.4$, $p=0.004$), with the DS having average fast rates ranging from 6.2 to 40.1 mm/d, while UWS had rates between 23.3 and 72.5 mm/d (Figure 5.7). To further illustrate, in run 9, once the fast rate was reached, head loss in UWS filters was developing up to three times faster (19.6 ± 6.1 mm/d) than the DS filters (6.2 ± 1.6 mm/d).

The more rapid ripening observed with UWS has interesting implications for SSFs applied as a pre-distribution polishing treatment step (i.e., Netherlands) where ripening periods are extended. No statistical difference was seen as a function of sweetening flow within individual runs (Kruskal-Wallis: $H(56)=6.8$, $p=0.341$). Also, an extended period of downtime associated with the DS (DS-EXT) showed no statistical difference compared to DS with regards to head loss development (Kruskal-Wallis: $H(24)=5.0$, $p=0.174$).

Both skimming methods recovered up to 90% head loss post cleaning, but higher initial head loss was observed as the runs continued, and this was similar for both DS and UWS filters. To illustrate, the normalised starting head loss for the DS beds were 25 ± 1 , 52 ± 3 , 59 ± 2 , 30 ± 2 , 52 ± 5 , 71 ± 7 , 88 ± 7 , 109 ± 13 , 124 ± 18 and 103 ± 10 mm for runs 1 to 10 respectively. In comparison, the equivalent normalised starting head loss for the UWS-100 were 27 ± 3 , 56 ± 12 , 52 ± 7 , 46 ± 13 , 46 ± 7 , 81 ± 10 , 97 ± 9 , 90 ± 6 , 125 ± 9 and 132 ± 15 mm. Analysis of variance showed that there was no significant difference between the UWS and DS starting head loss (ANOVA: $F(1, 18)=0.063$, $p=0.804$) as well as between the different sweetening flows (ANOVA: $F(3, 31)=0.787$, $p=0.510$). This increasing starting head loss with subsequent runs was not considered to be unusual or exceptional, as Mauclair et al. (2004), noted that extracellular polymeric substance occupied up to 7% of top layer pore volume, and 3% sub-surface, thus preventing return to clean bed conditions, underscoring the requirement to replace sand after prolonged treatment. Also, simulations by Campos et al. (2000) found that initial head loss in the sand increases after successive filter cleanings, which may, in turn, influence the behaviour of subsequent filter runs.

This increasing starting head loss did not raise concerns about disproportionate deep penetration of particles and accumulation at specific depths due to UWS, as the head recovery after skimming allowed the filters to operate at normal HLR and sustained their performance for the entire duration of the subsequent filter run. It is also noteworthy that the starting head loss continued to increase even after the re-sanding activity. This is because, although the top sand layers (0-0.2 m) were replaced, the hydraulic conductivity of the entire bed (estimated using

Darcy's law) was not restored to its initial conditions. For instance, during run 1, the hydraulic conductivity of the filters was 9.2 ± 0.7 m/h ($L=0.8$ m). By the start of the second run, this had dropped, to 4.4 m/h ($L=0.76$ m), and after re-sanding in run 6, it was 3.2 ± 0.4 m/h ($L=0.8$ m). At this point, the lower part of the filter bed (0.2-0.8 m) was operating with reduced hydraulic conductivity, as such, a marginal increase in starting head loss is acceptable. In full-scale operations, this phenomenon is accepted as normal observation, and there is often a set limit on maximum starting head loss allowable. At Thames Water Utilities, increase in starting head loss between filter runs is acceptable up to 200 mm (Thames Internal document). Overall, the results indicate that UWS provides a less disruptive cleaning process and does not pose additional risks compared to DS. Furthermore, the introduction of sweetening flow did not exacerbate head loss development beyond that observed with DS.

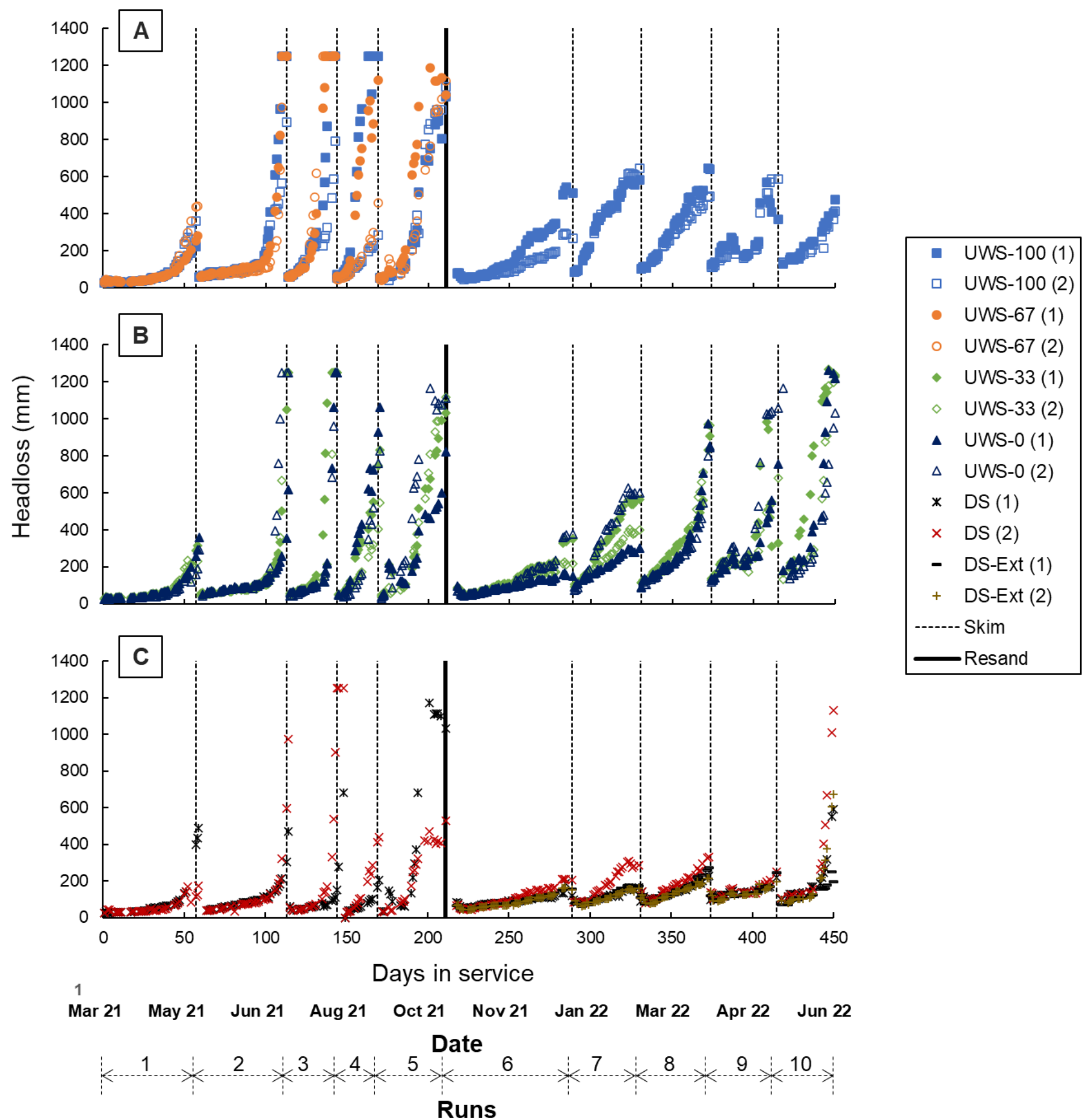


Figure 5.6: Normalised head loss during pilot plant operation indicating skimming/re-sanding events.

(A) UWS-100(1), UWS-100(2), UWS-67(1), UWS-67(2); (B) UWS-33(1), UWS-33(2), UWS-0(1), UWS-0(2); (C) DS(1), DS(2), DS-Ext(1), DS-Ext(2).

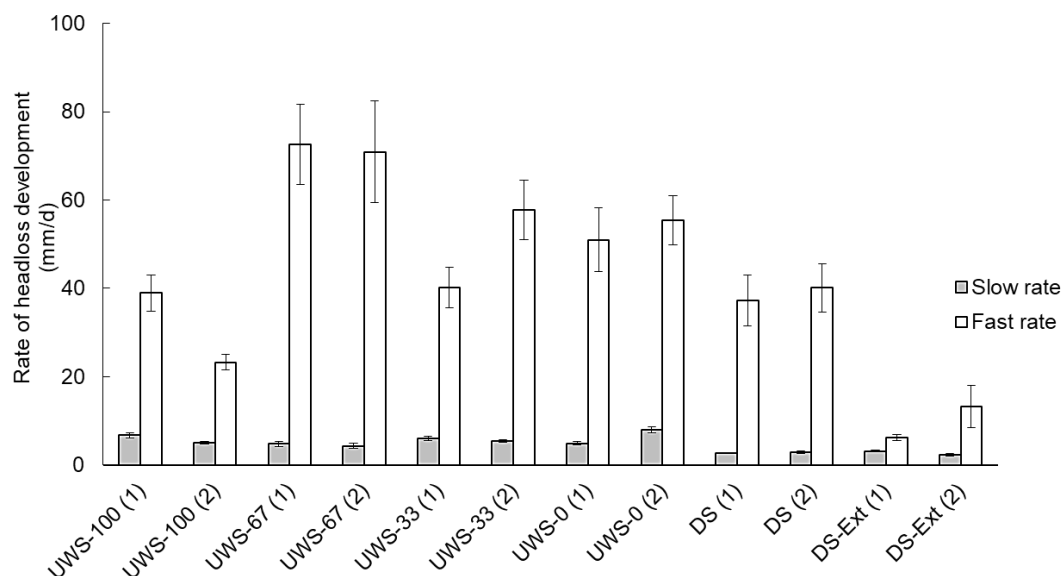


Figure 5.7: Head loss development showing the slow rate and fast rate.

Values are averages of all runs (excluding runs 1 and 6); error bars are the standard deviation.

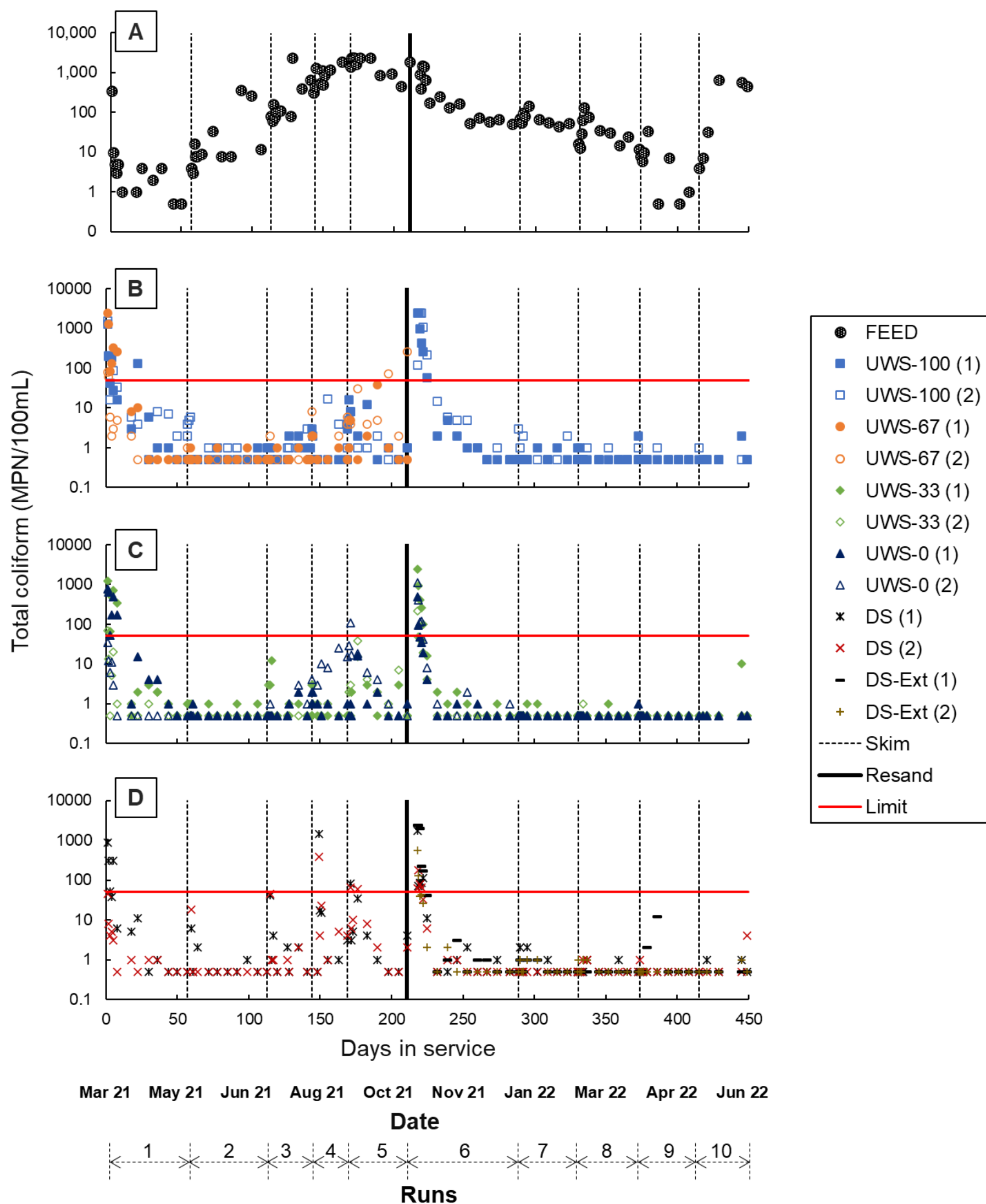
5.3.2 Impact of skimming on Filtrate Microbial Quality

Barring the maturation period at the initial start of the experiments (run 1) and after re-sanding (run 6), all UWS SSFs reduced the total coliform count to under 50 MPN/100 mL, below operational limits, with the exception of UWS-0 at the start of run 5 and UWS-67 at the end of run 5 (Figure 5.8 B - C). These two exceedances were not of concern, as one occurred at the end of the filter run while the other was an outlier which was not replicated in the duplicate filter. For the DS filters on the other hand, there were a few more occurrences of exceedances (see runs 4 and 5 in Figure 5.8 D) and these were mirrored in the replicates. After re-sanding there was more consistency and less coliform variability attributed to the combination of new sand being placed on top of seven-month mature sand. In general, DS SSF showed a greater frequency for high coliform (Figure 5.8) and HPC (Figure 5.9) levels immediately post-skimming compared to UWS.

Closer inspection of the coliform removal was conducted with a focus on the skimming window, i.e., one day before a skim and the first 7 days post-skim (Figure 5.10). DS filters showed reduced log removal immediately post-skim, with

log removals of coliform dropping from an average of 1.6 ± 0.2 log before skim to 1.1 ± 0.4 log on day 1 post-skim (Figure 5.10 C). On the other hand, the UWS filters performed better, achieving consistent microbial removals, and producing safer quality of water from as quickly as 3 hours after skimming, with coliform removals maintained at an average of 1.9 ± 0.2 log (Figure 5.10 A & B). In addition, not only did the UWS filters have better performance on Day 1, on consequent days there was a greater average log removal (Day 3: 1.9 ± 0.2 log and Day 7: 2.2 ± 0.1 log) compared to the DS filters (Day 3: 1.7 ± 0.1 and Day 7: 1.9 ± 0.1 log). This suggests a very rapidly maturing filter or a filter that consistently remains in a mature state. Analysis of the filtrate coliform in the 7 days following a skimming event showed that there was a significant difference between the UWS and DS treatments (Kruskal-Wallis for coliform: $H(1)=6.1$, $p=0.014$; for HPC: $H(1)=45.1$, $p=0.001$), with the UWS filters having on average 2 MPN/100 mL (ranging from 1-109 MPN/100 mL) for coliforms as opposed to 25 MPN/100 mL (1-1414 MPN/100 mL) for DS filters. This shows that UWS filters may be returned to service faster, and potentially eliminates the need for any downtime in cases where UWS is accompanied by sweetening flow.

To further illustrate, in run 8 HPC levels post skim for the DS filters ranged from 300-2700 no/mL, while just before skimming HPC levels were between 10-11 no/mL. In contrast, the range of HPC levels for the UWS filters pre- and post-skimming were 1-9 no/mL and 3-12 no/mL respectively. The increase in HPC levels in the DS filters post-skimming may be attributed to bacteria released following period where bed was drained down. This deterioration in filtrate quality following DS is well understood. For instance, experiments by Bellamy et al., (1985b) showed that following filter cleaning (using DS), filtrate total coliform increased from 4,000 MPN/100 mL to 28,000 MPN/100 mL when operating at 0.4 m/h. Other cleaning methods such as backwashing showed similar performance when compared with DS, with a 1.3 log reduction recorded by backwashing and 1.5 log reduction by DS (de Souza et al., 2021b). These findings support the hypothesis that the gentler UWS method promotes more rapid bacterial elimination compared to DS.



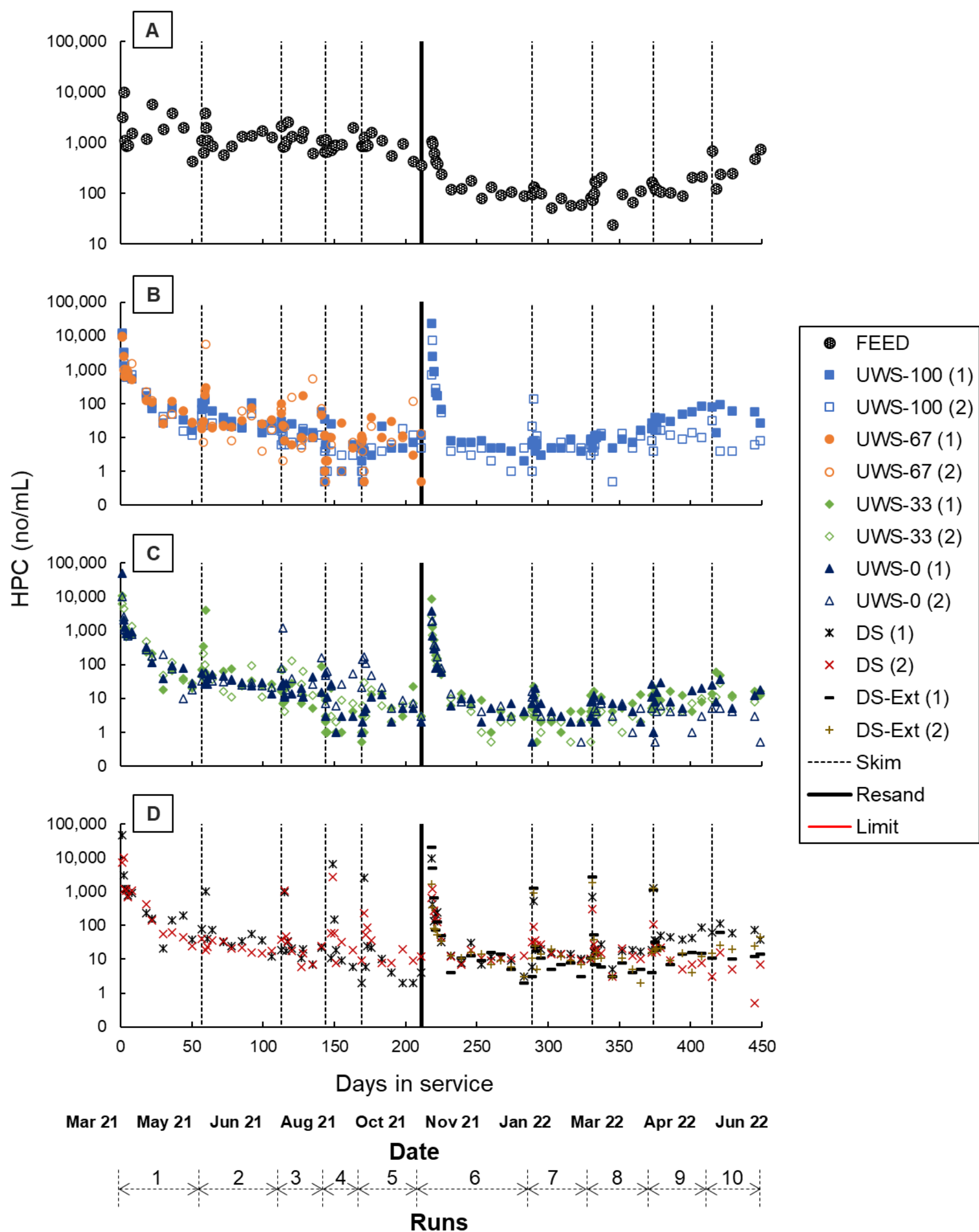


Figure 5.9: HPC in the feed and filtrate for the duration of pilot operation, indicating when skim and re-sanding events were done. (A) Feed; (B) UWS-100(1/2), UWS-67(1/2); (C) UWS-33(1/2), UWS-0(1/2); (D) DS(1/2), DS-Ext(1/2). Non-detections were 0.5 MPN/100mL as half limit of detection.

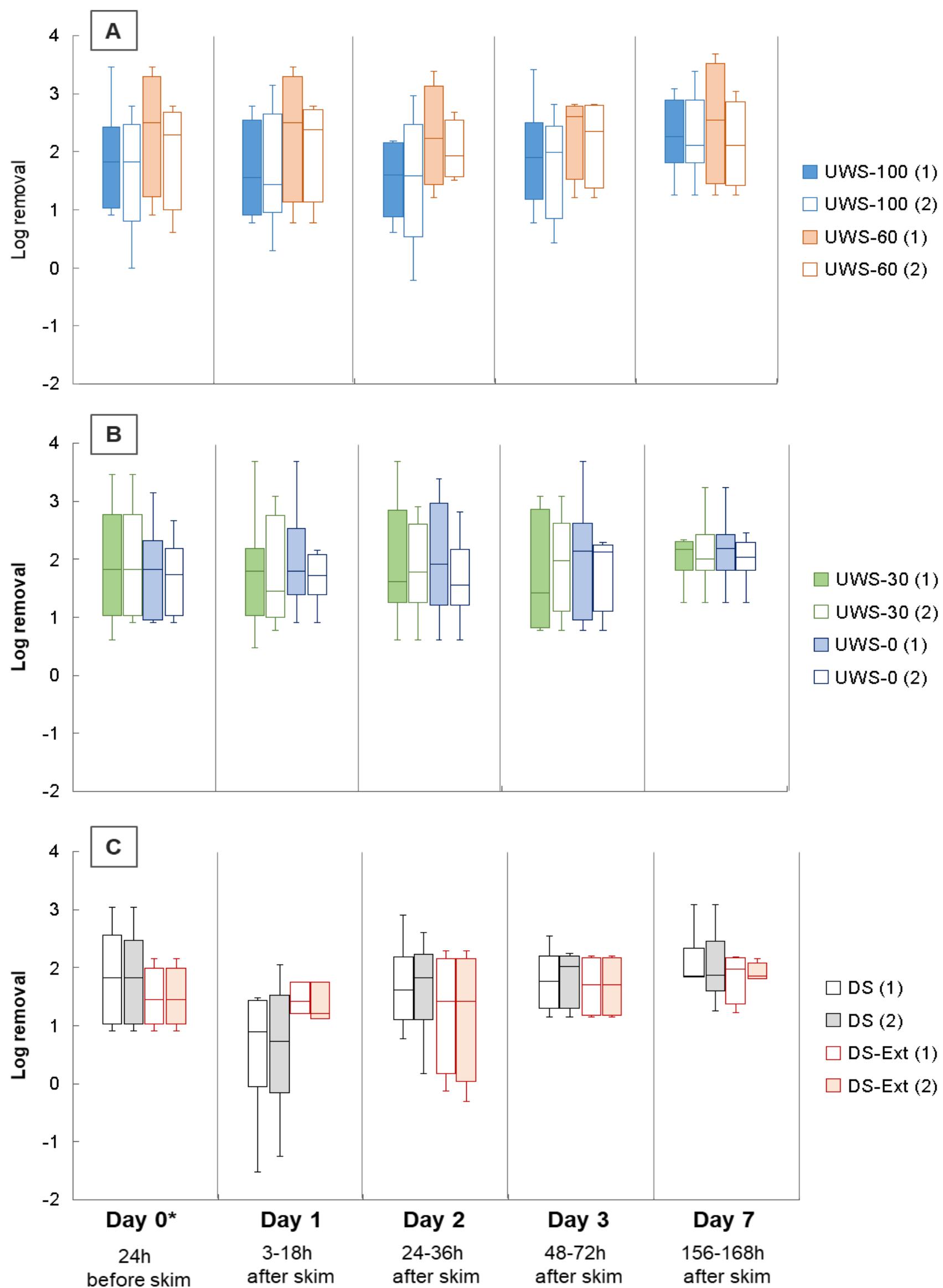


Figure 5.10: Log removal of total coliform

Focusing on the skimming window, i.e., immediately before and after a skim.

* Day 0 represents 24h before a skim.

To improve appreciation of the performance of UWS, FCM was used to directly measure the microbial water quality and skimming effects. FCM revealed UWS filters had more consistent post-skimming microbial quality, indicated by a lower average total cell count of 2.0×10^5 cells/mL in the first 24 h compared 2.8×10^5 cells/mL in DS (Figure 5.11). This difference was statistically significant (Kruskal Wallis: $H(1)=35.6$, $p=0.001$). UWS maintained a steadier microbial quality post-skimming, with a deviation of 0.3×10^5 cells/mL versus DS deviation of 0.5×10^5 cells/mL. Only a single flow cytometer was deployed, with UWS and DS filters monitored sequentially limiting direct comparison despite indistinguishable water quality.

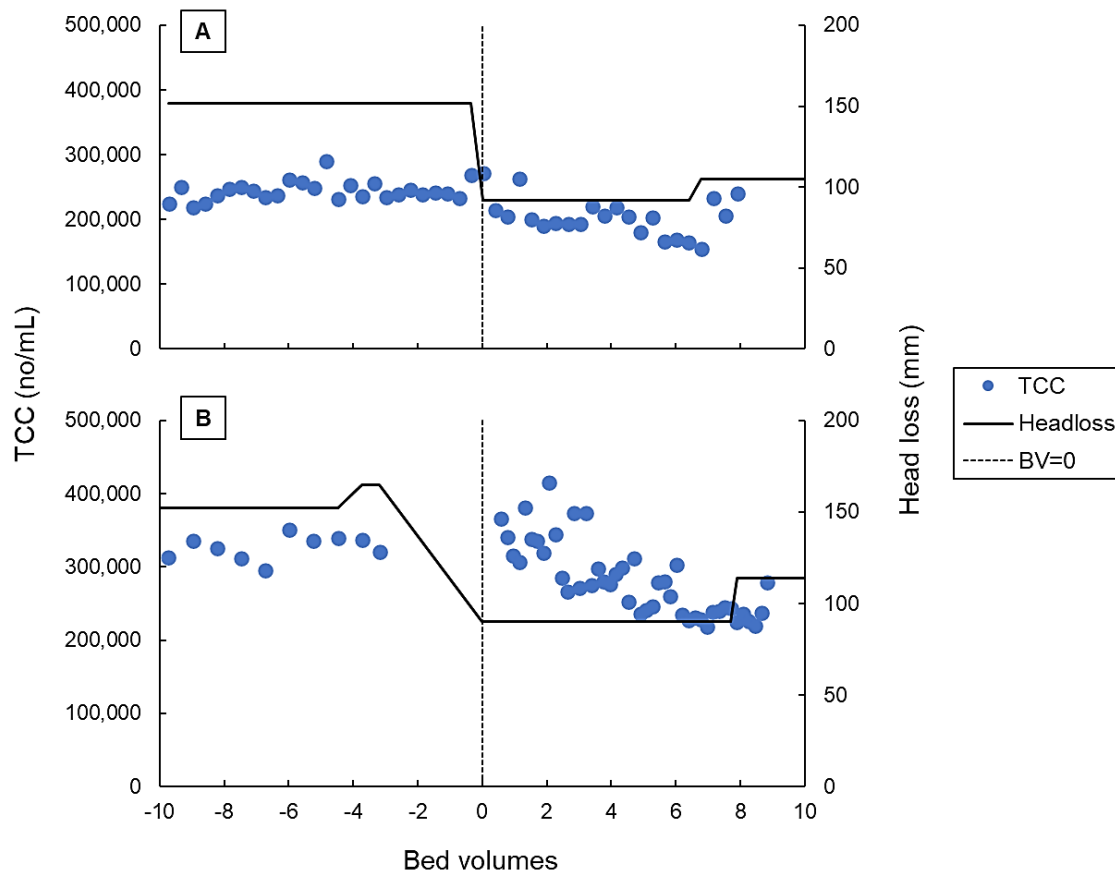


Figure 5.11: Filtrate total cell count (TCC) measured with FCM and head loss development for (A) UWS-0, and (B) DS.

Focusing on the skimming window, i.e., immediately before and after a skim. BV=0 indicates the skimming point and the start of a new filter run. Negative BV indicates previous filter run.

5.3.3 Skimming Regime on SSF Microbiome

Analysis of the interplay between SSF operation and its biological and physico-chemical phenomena has been hindered previously by sparse routine sampling (Graham and Collins, 2014) typically occurring only near the end of an SSF run, and/or recording peak head loss (Chen et al., 2021). This study used 16s rRNA DNA amplicon sequencing consistently throughout SSF operation to explore SSF microbiology, assessing UWS's impact on the SSF microbiome, based on sampling of the *Schmutzdecke*.

The Shannon diversity index averaged 5.73 ± 0.14 in all SSFs demonstrating no impact of UWS versus DS or the level of sweetening flow used (Figure 5.12 A). Diversity here was stable across a year, with slight rises per run and reductions post-cleaning (Figure 5.12 A). This disproved the hypothesis that flow maintenance and UWS would foster more diverse microbial communities and agrees with previous studies showing minimal biological changes from SSF operation shifts (Campos et al., 2002; Lautenschlager et al., 2014).

Genus-level beta-diversity in SSFs altered as a function of run number reflecting the influence of temperature and other seasonal changes (Figure 5.12 B-C). Importantly, the observed changes did not translate into microbial removal, with a total coliform log removal >2 across 2-18°C. Despite theories of higher temperatures boosting pathogen removal (Anderson et al., 2009; Jabur, 2006), removal rates were stable, meeting health standards and mirroring previous reports of consistent *Giardia* removal across prolonged periods of time (Bellamy, Silverman, Hendricks, et al., 1985b). This suggests either physical processes mainly drive removal, with biology as a secondary effect, or mature SSFs perform steadily despite temperature changes typically experienced in the environment (Arnold et al., 2016). The advantage of UWS over DS is pronounced immediately post-skimming, as clearly evidenced in the diminished HPC breakthrough and FCM. However, since skimming disruptions constitute merely 3.5% of the filter's lifespan, the overall impact on microbial assembly seems minimal.

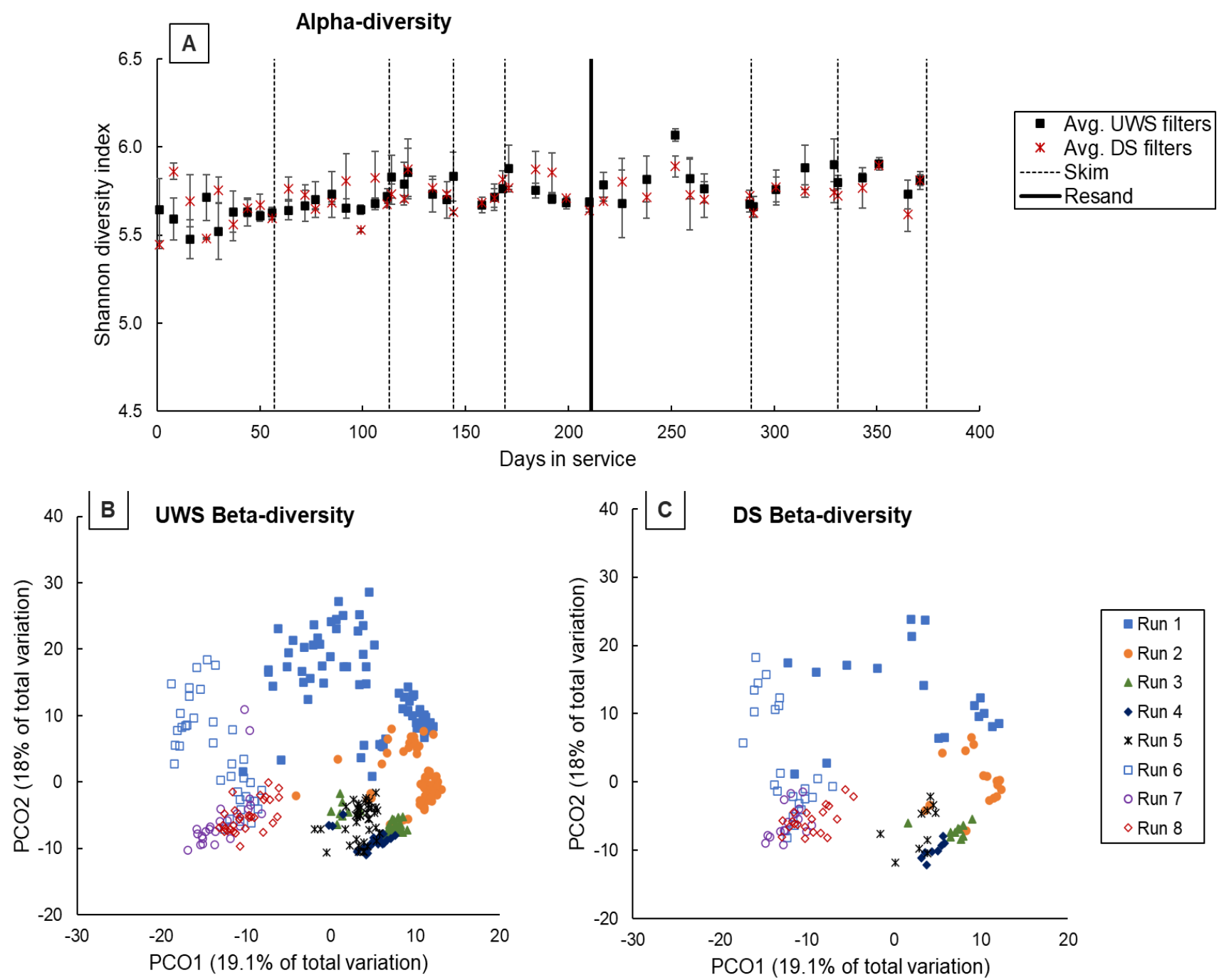


Figure 5.12: Microbial community of SSF *Schmutzdecke*.

(A) Genus level Shannon Diversity Index (H') displayed as average of UWS filters and DS filters, with error bars representing the standard deviation ($n=460$). **(B-C)** PCoA plot (beta-diversity) at genus level of bacterial community 16s rRNA gene amplicons for UWS filters ($n=338$) and DS filters ($n=122$) respectively.

While the major removal of pathogens is usually attributed to the *Schmutzdecke* and top sand layers of the bed (Chen et al., 2021), significant removal occurred following cleaning, consistent with Trikanad et al., (2023) 's theory of extensive subsurface biofilm activity. In conjunction with the consistency of treatment performance by UWS in this study, it is suggested there is a need to reassess the role of the *Schmutzdecke* in conjunction with the lower sand bed levels to provide a more holistic view of SSF throughout their depth. Support for this idea is provided by Oh et al., (2018) who found that biofilms below the *Schmutzdecke* matured quicker than expected, which was also supported by the study of Bai et al., (2013), where a rapid two-day development was observed. Further, Chan et al., (2018) emphasised the sand bed's superior organic matter degradation compared to the *Schmutzdecke*, reinforcing the high removal efficiencies seen in UWS filters post-*Schmutzdecke* removal in this study, and suggesting extensive biological activity across the filter's depth. Further, measurement of the respiration rate of the biofilm on the sand as a function of depth revealed activity throughout (Chapter 4).

5.4 Conclusions

This study has evaluated the performance and application of UWS in the cleaning of SSFs compared to traditional DS methods to assess the potential risk of adopting UWS. UWS was found to be comparable with DS in terms of treatment effectiveness, enhancing water quality and overall filter performance without posing additional public health risks. The results demonstrated that across all SSFs good turbidity removal was maintained, with filtrate turbidity values consistently low (<0.3 NTU) across both UWS and DS filters, and varying sweetening flows did not disproportionately affect turbidity. Although demonstrating a more rapid fast rate head loss development, up to three times as fast as DS in some instances, UWS filters adhered to regular seasonal operational cycles, indicating minimal particle in-bed intrusion and an improved, sustainable biological performance. Notwithstanding, up to 90% of the headloss was recovered for all filters post-skim.

Importantly, UWS filters exhibited less disruption post-skimming, allowing for quicker recovery to microbial compliance compared to DS filters. This was evidenced by lower coliform (2 MPN/100mL in UWS filters versus 25 MPN/100mL in DS filters) and HPC levels post-skimming. More stable microbial quality post-skim, as evidenced by consistent removals of coliform at 1.9 ± 0.2 log also indicates that UWS filters could potentially eliminate the need for downtime, especially when combined with sweetening flow. The various sweetening flow rates applied to the UWS did not impact filter operation, water quality, or head loss development. Therefore, incorporating a sweetening flow during skimming could enable continuous operation of SSFs while simultaneously cleaning, thereby increasing throughput and further minimising downtime. Overall, the work revealed that proper implementation of UWS should lead to continuous improvements in water quality and production.

5.5 Contributions

Tolulope Elemo	Methodology, Formal analysis, Investigation, Data curation, Writing-Original draft, Review and Editing, Visualisation.
Michael Chipps	Conceptualisation, Supervision, Methodology, Writing-Review and Editing.
Nigel Graham	Conceptualisation, Writing-Review and Editing.
Andrew Turner	Conceptualisation.
Sophie Bretagne	Formal analysis (DNA), Data curation.
Bruce Jefferson	Conceptualisation, Supervision, Writing-Review and Editing.
Francis Hassard	Conceptualisation, Supervision, Project administration, Visualisation.

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6 Implications of Cleaning Slow Sand Filters with Underwater Skimming: Uncertainties, Performance and Impacts

The overall aim of the research was to establish an evidence base to understand the risks associated with using underwater skimming (UWS) for cleaning slow sand filters (SSF). Throughout the thesis, uncertainties related to SSF performance using UWS were examined, and the performance of UWS-cleaned filters was compared with traditional dry skimming (DS). This discussion addresses these uncertainties, validating some proposed benefits and addressing perceived risks.

6.1 Does UWS Pose a Risk to SSF? Addressing the Uncertainties

Uncertainties associated with implementing UWS primarily stemmed from observations of other SSF cleaning methods and surface manipulations where issues arose, such as deterioration of filtrate quality after cleaning (Jenkins et al., 2011; de Souza et al., 2021) and shorter filter run times due to rapid clogging (Bauer et al., 1990; Burman and Lewin, 1961). In addition, the implementation of UWS may include a pause or reduction in flow while the filter is still fully submerged, potentially inducing anaerobic or anoxic conditions within the filter bed.

Rapid tests in biologically immature SSFs using kaolin clay as a surrogate for solids showed that although a UWS-induced surface agitation resulted in a deterioration in filtrate quality, it was only apparent in the upper layers of the filter bed and was effectively mitigated through the deeper layers (Chapter 3). Particles ranging from 2 to 10 μm were also effectively removed, achieving greater than a 2-log reduction, in a high-risk worst-case scenario filter. In the longer term SSF experiments with biological capabilities developed, there was no occurrence of increased turbidity in the filtrate either during or after UWS, as concentrations remained below 0.3 NTU (Chapter 5). In addition, post-UWS, filters sustained the

removal of microbial indicators, supporting the proposed benefit that UWS shortens filter ripening period, allowing a more consistent filtrate to be produced.

Concerns regarding disproportionate clogging were dispelled by observations from rapid column tests (Chapter 3), which showed no significant head loss when monitored at 50 mm intervals over the short term. However, in the longer-term experiments (Chapter 5), UWS filters had more rapid head loss development, compared to DS, but notwithstanding, UWS filters sustained treatment within the regular seasonal operational cycles. Another observation made was the progressive increase in starting head loss on successive filter runs. However, this observation was across all the filters including those undergoing DS, suggesting that other factors were contributing to the head loss, one of which may have been decrease in media porosity because of presence of biofilm on media grains (Mauclaire et al., 2004).

The risk of reduced dissolved oxygen (DO) in the filter bed was examined using a mass balance model with empirically derived DO consumption rates supported by observations in the pilot SSFs (Chapter 4). It was observed that longer flow pauses during UWS increased the likelihood of anaerobic conditions, particularly at higher temperatures. However, the benefits of a 'sweetening flow' were evident, as it not only provided a constant supply of DO and nutrients to the filter but also maintained production and reduced downtime, with pilot observations showing no deterioration in water quality for all levels of sweetening flows (Chapter 5).

The overall position on UWS is that it poses no additional operational risks compared to DS for cleaning SSFs. The concern about negative impact on filtrate quality was also resolved, with UWS filters showing superior treatment over DS filters (albeit marginally) and especially immediately post-skim (Chapter 5), thus validating the hypothesis that UWS will not negatively affect treated water quality or disrupt filter operations. Table 6.1 summarises the perceived risks and the corresponding measures to address them in this thesis as well as the outcomes.

Table 6.1: Summary of potential risks of underwater skimming to dry skimming. compared to DS.

Risk	Consequences	Dry skimming	Underwater skimming
Deep penetration of particles	More rapid head loss development and shorter filter run lengths	<i>No</i>	<i>No</i> – within tested operating confines. <i>Maybe</i> – with longer run lengths.
	More frequent skimming (and media replacement) required.	<i>No</i>	<i>No</i> – within tested operating confines.
Anoxic/ anaerobic conditions within filter	Production of deleterious anaerobic byproducts	<i>No</i> – within tested operating confines	<i>No</i> – mitigated by shorter flow pauses or introducing sweetening flow.
	Reduced microbial removal post-skim leading to deteriorated filtrate quality	Yes – immediately post skim.	<i>No</i> – within tested operating confines.
	Increased disinfection (chlorine) demand of effluent.	Yes – immediately post skim.	<i>No</i> – not anticipated based on microbial performance
Disruption of filter treatment performance	Deterioration of physical and biological removal mechanisms and subsequent deterioration in water quality.	Yes – immediately post skim.	<i>No</i> – within tested operating confines.
	Modifications to the media, for instance from stratification, leading to more rapid head loss development.	<i>No</i>	<i>No</i> – within tested operating confines.

6.2 How Much Does the *Schmutzdecke* Contribute to Removal? An UWS Perspective.

The performance of the UWS filters supports the need to challenge the accepted belief around the *Schmutzdecke*'s function as the main treatment barrier in uncovered SSFs, as the beds were not vulnerable following its removal. This is not questioning the important contribution that the *Schmutzdecke* layer makes, rather that an adjustment with respect to the relative contribution it makes compared to the rest of the beds would provide a more complete picture of SSF operation. For instance, despite being credited with the removal of pathogens throughout literature (Chen et al., 2021; Schijven et al., 2013), the sustained removals in the absence of a *Schmutzdecke* as observed in this study with UWS filters (Chapter 5) reflect the redundant capacity provided by the lower layers and that the system works as a whole. Support for this is provided by previous research that explored the biofilm activity in the depth of the sand bed (Trikannad et al., 2023).

Considering the bed as a whole, rather than as separate components, changes the outlook on the risk of UWS, because the bed acts as a whole, it gives treatment redundancies when the *Schmutzdecke* has been removed. Therefore, it is necessary to re-assess and balance the role and importance of the *Schmutzdecke* in SSF operation. This idea, combined with a successful implementation of a cleaning method like UWS, opens the prospects for having a continuously operating SSF, moving from the batch / semi-batch process, to a more continuous one, where the *Schmutzdecke* may be removed before flow limiting head loss is attained and treatment and removal efficiencies are never compromised.

6.3 What is the Impact of UWS on Production Capacity?

Past trials have explored cleaning SSF without draining them, and the rationale and motivation for this approach are well-established. However, the specific method of UWS detailed in this study is novel, as it also offers the prospect of continuous filtration while cleaning. At the time of writing, only a prototype of the

UWS device exists, which is still undergoing development and refinement. Consequently, the costs (capital, operational, and maintenance) are highly uncertain. Prototype costs are highly variable and not representative of a commercial version, precluding a cost-benefit analysis at this stage. Nonetheless, other value propositions of the UWS technology, such as reduced downtime and increased production volume, warrant exploration.

One of the proposed benefits of UWS is the operational time saved and the potential to increase production capacity from the recovered downtime. When filters are drained and out of service for dry skimming, production capacity is inevitably reduced. This loss may be further compounded by the operational approach taken while a filter ripens, which can last from two days to two months (Chapter 2). As demonstrated in Chapter 5, under the conditions tested, the use of UWS eliminated the ripening period in pilot SSFs, allowing filters to be returned to service immediately after skimming. This innovation offers the potential for a continuously operating SSF, capable of producing water even during the skimming process via the application of sweetening flow. It is in fact more desirable to have sweetening flow, as this minimises the risk of anaerobic conditions in the filter bed during skimming (Chapter 4).

On an individual skim basis, UWS offers significant time savings (Figure 6.1). In the DS approach, draining and backfilling are notably time-consuming and cannot be sped up. In contrast, UWS requires no draining or backfilling. With UWS-100, routine skimming downtime is eliminated altogether. For UWS-0 and varying sweetening flow, skimming downtime is associated with the reduced flow during skimming (0%, 33% and 67% of the operational HLR for UWS-0, UWS-33, and UWS-67 respectively), and gradual ramping. However, going by the performance of UWS-100, ramping may not be required if operating UWS.

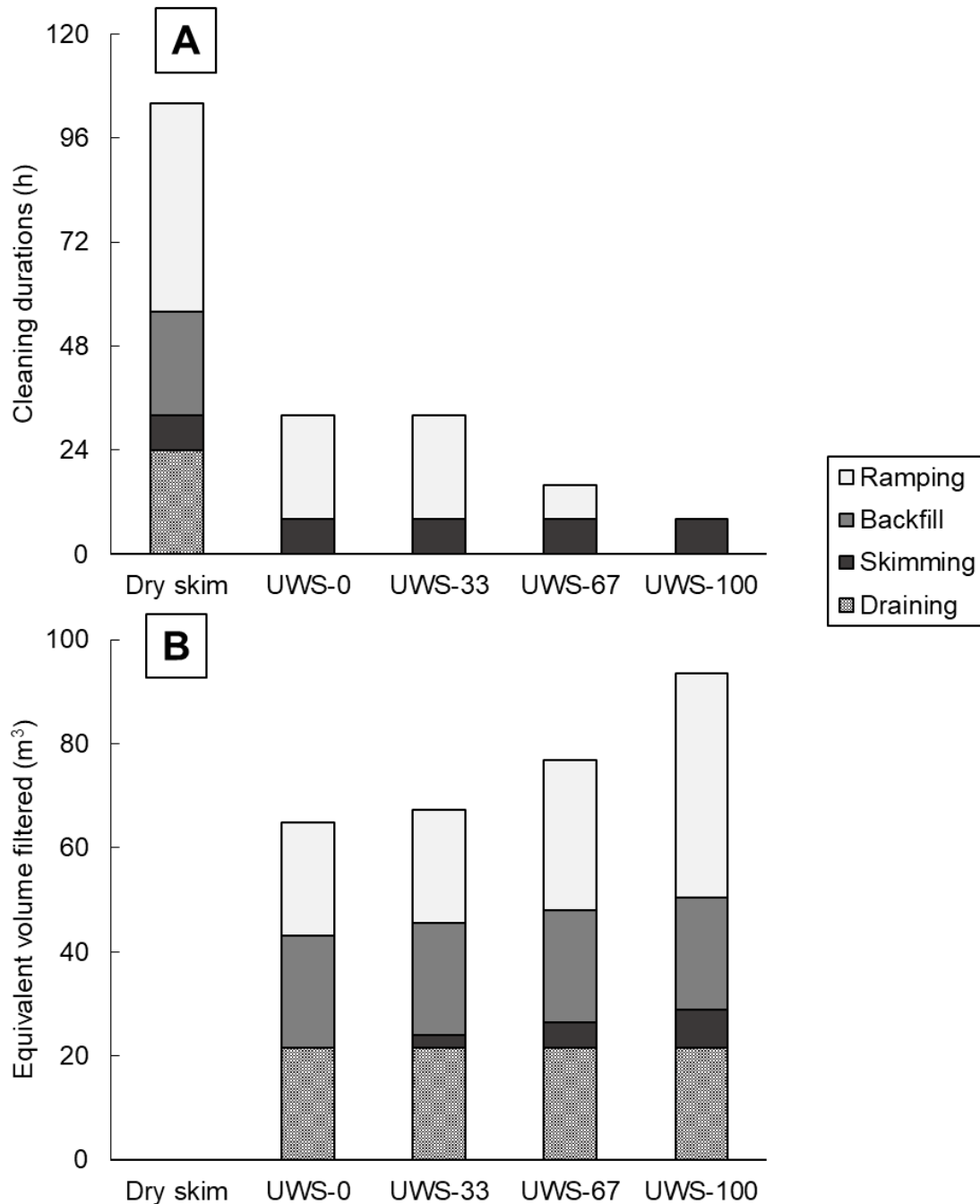


Figure 6.1: Cleaning duration and equivalent water production associated with DS (typical) and UWS (predicted) with different sweetening flows.

(A) Operational downtime associated with cleaning including draining, the actual skimming and post-skim backfilling and ramp-up; (B) Equivalent water produced for the UWS cleaning method compared to the DS cleaning steps, assuming an operational hydraulic loading rate (HLR) of 0.3 m/h and a filter with a surface area of 1,000 m².

In addition to routine skimming, SSF operation involves other sources of downtime, such as re-sanding once filters have reached minimum sand depth and replacement of the GAC (where applicable). The illustration in Figure 6.2 further shows the time benefits of the UWS over DS. It has been estimated that for DS, a filter will be in service for 94.4% of the time, and out of service for skimming 2.7%. Swapping to UWS will have the filter in operation for 96.2%, 96.4%, 96.8%, and 97% for UWS-0, UWS-67, UWS-33, and UWS-100 respectively. There is only a marginal benefit on UWS-100 (<1%) over the other UWS methodologies and thus only the UWS-100 will be reported here on.

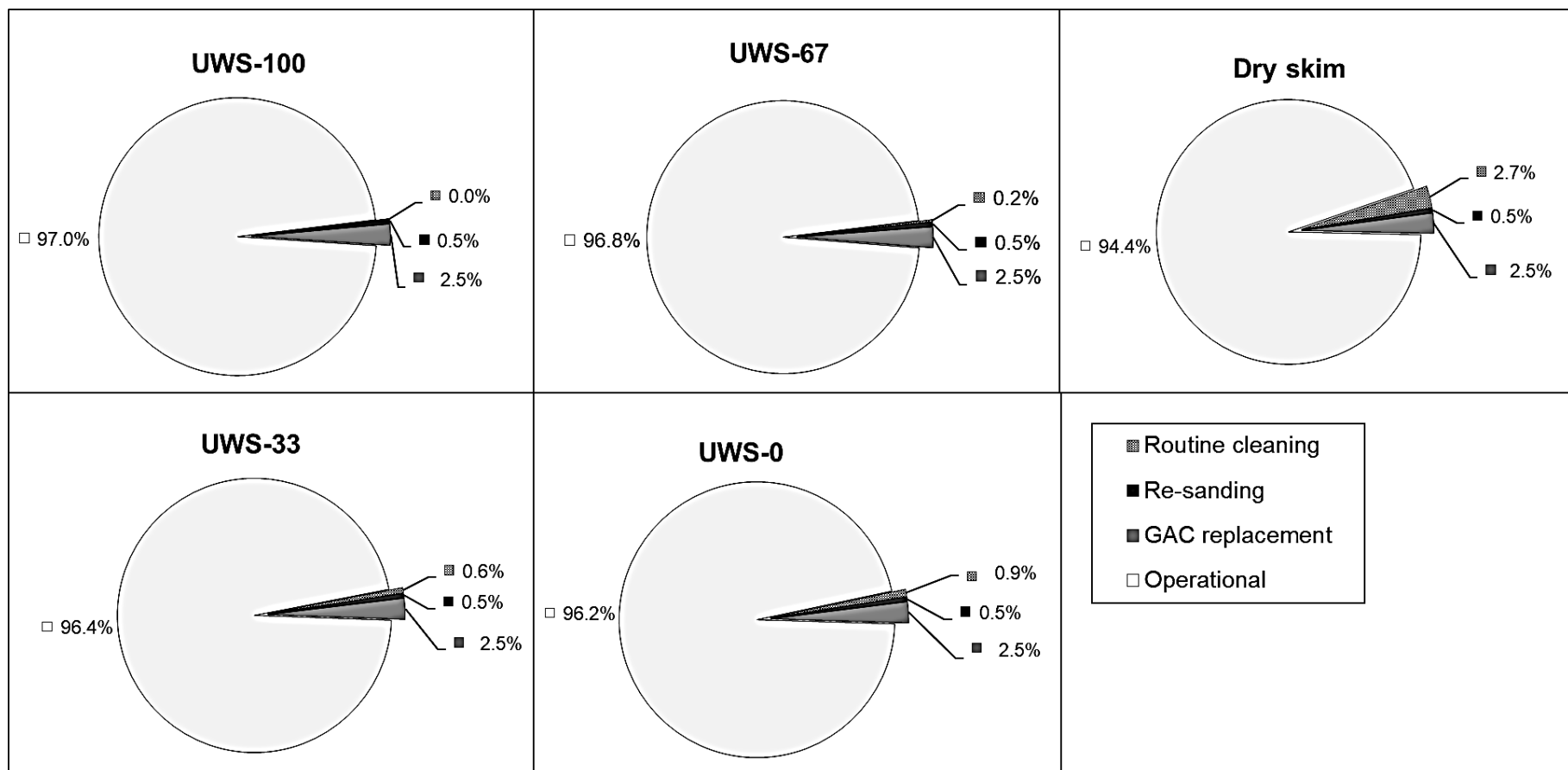


Figure 6.2: SSF operational duration and downtime over a 10-year period using DS and UWS. Assuming three GAC replacement and re-sanding activities each in the period.

The time savings directly translate to increased production volume. Using the information provided by the companies surveyed in Chapter 2, it was found that switching from DS to UWS-100 could increase production capacity by 31-610 litres per square meter of SSF area per day ($\text{L/m}^2/\text{d}$). A description of the methodology used for this estimation and a breakdown of the calculations can be found in 7.3Appendix F. This wide variation in benefits is due to the varying operational parameters and cleaning practices of the various companies. For example, company H reported a typical filter run length of six years (2,190 days) with a 14-day downtime for cleaning and a weighted average HLR of 0.3 m/h across all their SSF assets. Switching to UWS-100 would increase their production capacity by 31 $\text{L/m}^2/\text{day}$, totalling an additional 1.2 million litres per day (ML/d) across their 37 filters. Conversely, company C, with a shorter filter run of 70 days, more frequent cleaning requirements, and a shorter downtime of 3 days, also operating at a similar HLR, reported a normalised capacity increase of 610 $\text{L/m}^2/\text{day}$, resulting in an additional 241 ML/d across their 114 SSFs (Chapter 2). The frequency of skimming affects the magnitude of the benefit; longer run lengths result in diminished benefits.

The additional capacity afforded by switching to UWS methodology means companies can service more customers without any other modifications to their operational practices or addition of new assets (Table 6.2). This provides the benefits of off-setting some of the water deficits from increased demand. For instance, company C will have additional capacity within their treatment works to be able to supply an equivalent of 1.66 million customers.

Table 6.2: Estimated benefits of switching to UWS for companies surveyed in Chapter 2

Company	Average filter run length (days)	Additional capacity (ML/d)^{1, 2}	Equivalent customers serviced (x1,000)³
A	180	1.6	11
B	120	8.5	58
C	70	241	1,655
D	182	10.9	75
E	2555	2.4	17
F	112	4.9	34
G	180	11.4	78
H	90	1.2	8
I	2190	4.7	32
1. This is the difference between the estimated production volume using DS and UWS-100. 2. Additional capacity based on the information provided by individual companies for all their SSF assets. Weighted averages of surface area, HLR, run length and cleaning downtime used in model. 3. Additional customers serviced estimated using per capita water consumption rates for the locations of the companies. These values are in thousands.			

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7 Conclusions, Future Direction and Further Research

7.1 Conclusions

The novelty of this research lies in its comprehensive approach to exploring the risks and uncertainties associated with underwater skimming (UWS) for cleaning slow sand filters (SSF). It provides insights into the performance of UWS, both considering worst-case scenarios and operation in an optimised manner. It explores how UWS-induced surface agitation may impact particle penetration and further buttresses the importance of a safe media depth to safeguard filter integrity and water quality. A significant aspect of this work is the development of a predictive model for dissolved oxygen (DO) utilisation during UWS, which is crucial for maintaining optimal DO levels and avoiding anaerobic activities within the filter bed which is deleterious. Additionally, the study offers a real-time, side-by-side comparison of UWS and traditional dry skimming (DS) in a real-world water treatment setting. It uniquely explores the effects of varying sweetening flows on UWS performance and filter recovery post-skim. The research provides a holistic assessment by evaluating hydraulic and water quality impacts, as well as examining microbiological factors using traditional microbial indicators, flow cytometry, and rapid rRNA monitoring.

The overall outcome of this research demonstrates that using UWS for cleaning slow sand filters SSF does not negatively impact treated water quality or disrupt filter operations. It was found that maintaining the bed in an undrained state during cleaning proved to be beneficial, enabling sustained treatment without deteriorating filtrate water quality. The initial objectives set at the beginning of this thesis have been successfully addressed, with key findings and outcomes are detailed below.

The first objective was to review practices in slow sand filtration, by examining literature and consulting experts on effective methodologies, with the aim of establishing a baseline to compare the efficiency of the new underwater skimming regime. A survey of nine water companies in the UK, Sweden and Netherlands (Chapter 2) showed similarities in the design and operation across practitioners.

However, a fundamental difference was noted in the placement of the SSF within the treatment train – either as a main treatment step or final polishing step – which significantly influenced filter run length and cleaning frequency. Although most operational challenges were related to water quality, issues with time management and scheduling were also significant, prompting operators to seek methods to minimise downtime and reduce costs.

Biologically immature pilot column SSFs with a surface area of 0.018 m²) were utilised to examine how UWS-induced agitation influences particle breakthrough and retention (Chapter 3). Reduced removal efficiency due to filter surface agitation was mitigated by increasing the filter depth, with depths >500 mm significantly improving filtrate particle load. Despite increased breakthrough when hydraulic loading rate (HLR) was heightened, a removal efficiency of over 2 log was maintained for particles in the 2-10 µm size range, which represents currently monitored microbial contaminants in water. Monitoring of head loss at 50 mm intervals in one of the filters showed minimal disproportionate clogging or significant head loss beyond the top 100 mm layer, indicating that risks from UWS can be effectively mitigated.

Larger SSF pilot filters (surface area 0.54 m²) set up in a real-world, full-scale water treatment works (WTW) were operated for over 15 months using media and influent water from an operational SSF plant. This setup directly compared the performance, filtrate quality, and head loss development of filters cleaned using UWS with those employing traditional dry skimming (DS) (Chapter 5). Both methods were equally effective in removing monitored contaminants such as turbidity, organic carbon, true colour, and microbial indicators. However, filters cleaned using UWS were superior in removing microbial indicators immediately post-skim, with no deterioration in water quality observed. Rapid head loss development in UWS filters did not raise concerns, as the run lengths remained within the predefined duration.

Varying ‘sweetening flows’ during UWS did not disproportionately affect treatment and there was no significant difference in their performance with

regards to head loss development or water quality (Chapter 5). However, assessment of dissolved oxygen (DO) utilisation under varying flow interruption durations and temperatures, with the aid of a mass balance model, showed that increasing the rate of sweetening flow during UWS considerably improved DO supply and reduced the emergence of anoxic conditions (Chapter 4). The requirements for DO management during UWS were found to have a temperature dependency, favouring the utilisation of the sweetening flow.

In addition to addressing the uncertainties, the underpinning hypothesis was that UWS, by minimising SSF ecosystem disruption, quickening ripening, and lessening water quality impacts, will result in reduced filter downtime, subsequently increasing production capacity of SSFs without changing any other operational parameter. This study was able to establish these benefits of UWS as summarised in Table 7.1.

Table 7.1: Benefits of UWS

Benefit	Evidence	Reference in thesis
No negative impact on filtrate quality and filter performance	UWS does not negatively impact treatment performance, with sustained water quality post-skim.	Chapter 3 Chapter 4 Chapter 5
Shorter downtime	UWS reduces long ripening periods after skimming compared with DS Employing UWS methodology reduces cleaning downtime from between 70% (UWS-0) to up to 100% (UWS-100)	Chapter 5 Chapter 6
Increased production	Swapping DS for UWS can increase production capacity of a single filter by up to 610 L/m ² /day, and consequently the number of customers served.	Chapter 6

The main recommendations for the practical implementation of UWS is to maintain the use of a sweetening flow through the filter. This can be as low as

33% of the operational HLR, however, lower flows may be considered, taking account of any hydraulic constraints on individual SSSF systems. This has multiple benefits as it endures the continuous supply of DO and nutrients to the filter during cleaning and mitigates anoxic conditions especially at elevated temperatures. It also contributes to the production capacity, as water quality was found not to deteriorate.

7.2 Future Direction and Further Research

7.2.1 Implementation of UWS in Full-Scale Filters

Following the success of underwater skimming (UWS) at pilot scale, and the confirmation of its benefits along with the mitigation of potential risks, the next logical step is full-scale implementation. This scale-up will help validate pilot study findings by comparing key water quality parameters, including turbidity, microbial indicators, and dissolved oxygen (DO), against baseline data using various statistical tools like the ones used in this study. While this study addressed many uncertainties, certain issues—such as operational logistics, resource management, and waste handling—will only become apparent and effectively addressed at a larger scale. Implementing UWS at full-scale will thus provide comprehensive insights into its practical viability and efficiency. These tests are currently underway as at the time of this thesis revision (December 2024).

Waste Management and Resource Recovery Prospects from SSF Using UWS.

One of the advantages of slow sand filter (SSF) operation is the minimal production of sludge, which is predominantly organic (Bayley, 2007). With dry skimming (DS), the skimmed waste, consisting of biomass and sand, is handled as solid waste and transported to the sand washing location using trucks and dumpers. However, UWS produces a sand-water slurry, presenting new challenges for waste handling and transportation. Additional research is required to understand the slurry's nature and the logistical issues it may pose. This can be achieved by quantifying the rheological properties of the slurry and

investigating well-established processes and unit operations used for similar substances, such as in the mining industry.

Moreover, to make SSF operation more circular, it is desirable to explore the potential for resource recovery from the organic portion of the slurry. Although it is known that the waste has organic components (for example algae, microfauna, etc.), the potential for resource recovery is unclear, depending on whether concentrations in the water phase will restrict or enhance this process. In addition, it is unclear what other type of contaminants may be present, for example if feed water has high pesticide contamination. Further investigation is needed to determine the feasibility and practicality of utilising these resources.

7.2.2 Exploring Impacts of UWS on Microbial Aspects of SSF

Biofilm Dynamics: UWS vs DS

Extended drain-down times during SSF cleaning are believed to increase the likelihood of microorganisms in the biofilm being washed off when the filter is brought back into operation (Ellis, 1985; Goddard, 1980). The gentler approach of UWS, which keeps the bed submerged during cleaning, mitigates this issue. However, biofilms have not been directly tested in this study. To confirm, a comparative study of biofilm attachment to media grains between UWS and DS filters, similar to the current study, would be beneficial. Using microscopy techniques to monitor biofilm attachment and detachment before and after cleaning, as well as analysing the composition and morphology of biofilms, could provide insights into the long-term impacts of UWS. This would demonstrate the advantages of keeping the bed submerged during cleaning.

Using Flow Cytometry to link Biological Markers and Head Loss Development as a Cleaning Trigger.

This thesis demonstrated that UWS for cleaning SSFs does not compromise water quality, ensuring consistent microbial quality post-skimming. In-line flow cytometry (FCM) measurements from one of the pilot experiments also confirmed stable water quality during skimming (Chapter 5), addressing public health

concerns about introducing SSF filtrate into the water supply during skimming. However, this study did not extensively explore the potential of rapid FCM measurements. Further research on the relationship between filtrate microbiology and other parameters, particularly head loss development, could be valuable. Using FCM as a predictive tool for SSF cleaning could be investigated through similar pilot-scale experiments, incorporating in-line monitoring of both feed and filtrate, and allowing filters to run to maximum head loss instead of time-based cleaning. This will further build on work by Chan et al. (2018) who proposed the use of FCM to indicate when cleaning / skimming will be required by the change in microbial footprint in the filtrate. Establishing a correlation between microbial fingerprints and head loss would clarify whether significant investments in FCM or similar rapid measurement tools are warranted, or if trusted monitoring parameters are sufficient.

7.2.3 Exploring Modifications to Operational Parameters

This study has focused solely on the use of UWS in place of DS, keeping all other operational parameters constant.

Optimising Skimming Depths and Cleaning Frequency

For both UWS and DS filters, the media depth will gradually decrease after each skimming, eventually necessitating re-sanding to restore safe media depths. However, the benefits of UWS might allow for shallower skimming, potentially extending the filter's lifespan before re-sanding is needed. The less aggressive nature of UWS suggests that less media may be removed during skimming, although this could affect initial head loss and its development, potentially leading to shorter filter run lengths. A pilot experiment that monitors head loss development and key water quality parameters while varying skimming depths with UWS is necessary to conclusively determine the advantages of reducing skimming depth. This approach might require more frequent cleaning cycles for UWS, but the time-saving benefits in other areas could result in a net positive impact on water production.

Increased HLR for UWS SSF – Potential for Further Increased Productivity from SSF

Increasing the hydraulic loading rate (HLR) following UWS-induced agitation in biologically immature SSF experiments showed a marginal deterioration in water quality, but no negative impacts on head loss development (Chapter 3). Varying the HLR, although limited in this study, alludes to the prospects of increased filtration rates in SSFs and further contributing to the increased production capacity afforded by using UWS. Moreover, some practitioners have reported increased HLR is feasible within the hydraulic confines of physical assets (Chapter 2), however, there is uncertainty about its long-term sustainability. Using a factorial design of pilot filters to evaluate the impact of different HLR on filtrate water quality using UWS, this approach will enable a statistically rigorous assessment of the relationship between HLR and water quality.

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Appendices

Appendix A Ethical Approval Letter

A.1 Ethical approval letter – Research



2 July 2024

Dear Miss Elemo ,

Reference: CURES/22831/2024

Project ID: 7978

Title: Understanding the risk of underwater skimming of slow sand filters

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your project title change request, reference CURES/22831/2024 has been approved.

If you have any queries, please contact CURES Support.

Regards,

CURES Team

A.2 Ethical approval letter – Survey



1 October 2019

Dear Miss Elemo ,

Reference: CURES/9349/2019

Title: Best Practice Guide for Slow Sand Filter Operation

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/9349/2019 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B Consent Form and Questionnaire Used for Survey – Supplementary Information

B.1 Consent and Information Form

Best Practice Guide for the Operation of Slow Sand Filters

Aim of the Activity

The aim of this project is to identify the best slow sand filtration operating practices within the industry. This will include practices that have been verified based on experience and research. It will also provide scientific explanation and rationale for some commonly used practices. In the end, the guide is intended as a valuable resource for managers and operators of slow sand filters (and can be applicable to other biological filtration techniques).

Purpose of this activity

This activity is a survey of the current practices among practitioners, users, managers and operators of Slow Sand Filters. It is a part of an ongoing Engineering Doctorate (EngD) project titled: *“Transforming Slow Sand Filter Operations for Drinking Water Supply”*.

What is expected of you?

You are expected to provide your company's operational practices for slow sand filters and any clarifications as regards the documentation or information you have provided.

Consent to participate

1. I confirm that I have been informed about this research project and I agree to take part.
2. I understand that the researchers will not record any personal information.
3. I understand that I can leave the exercise at any point with no adverse effect.
4. I understand that anonymised information will be taken and stored on the Cranfield University network.

5. I understand that the anonymised notes and aggregated results will be shared with others.
6. I understand that the information provided will be used for research purposes only and not for any commercial benefits.
7. By taking part in this exercise, I am giving my consent to participate.

Name of the researcher: Tolulope Elemo

Researcher's contact details (email and phone no.): Tolulope-nwabiani.n.elemo@cranfield.ac.uk
 [REDACTED] or [REDACTED]

Date:

You will receive a copy of this form.

B.2 Questionnaire Form

Table A.1: Questionnaire shared with respondents for the survey

	Comments
Company	
Site location	
Number of filters	
Size/area of each filter (m ²)	
Volume of water treated (MLD)	
Source water	
Source	Highland, lowland, river, stream, borehole, etc.
Major contaminant	E.g. pesticides, algae
<i>Cryptosporidium</i> challenge	Specify if this contaminant is a problem to the works
Pre-treatment	
Storage	Is water stored in a reservoir/dam/bank side storage before treatment?
Pre-treatment process flow	Briefly list all the required pretreatment
Post-treatment	
Post-SSF Unit operation	If any
Disinfection and disinfectant	E.g. chlorination using chlorine dioxide, or UV disinfection
Structure/ Design	
Material of construction	E.g. concrete, metal, etc.
Type of structure	straight or sloped walls; any special features
Depth of supernatant water	
Covering	Yes, or no? Specify the type of covering (whether permanent or temporary)

	Comments
Access ramps to filter beds	
Under bed drainage systems - type	
Media properties (ES and UC)	
Sand (nature and source)	Whether locally sourced or purchased
Sand effective size	
Sand uniformity coefficient	
Depth of sand	
Minimum sand depth for treatment	
GAC Layer	Yes or no; sandwich or not - specify
GAC effective size	
GAC capacity (bed volumes)	
GAC Iodine Number	
Depth of GAC	
Gravel / support layer (nature and type)	
Gravel size and size distribution	
Depth of gravel	
Operating parameters	
Hydraulic loading rate (normal operating)	i.e., filtration rate
Hydraulic loading rate (maximum)	
Average maturity time	
Turbidity (working)	What is the average influent turbidity (NTU) for normal operation of the SSF
Maximum allowable turbidity	
Cleaning/skimming	
Typical cleaning cycle (or filter runtime)	
Cleaning frequency (summer)	If there is any difference between the two seasons
Cleaning frequency (winter)	
Trigger for cleaning	E.g. head loss or a time-based scheduling
Type of cleaning/ practiced	E.g. dry skimming, wet harrowing, etc.
Equipment used for cleaning	
Duration out of service for cleaning purposes	
Skimming depth	If skimming is used, what is the typical depth of sand removed
Average time before bed is refilled/ topped-up	
Average time before media is replaced	
Average time before GAC removed/regenerated/replaced	
Start-up and shut-down	
Start-up procedures	
Shut down procedures	
Volume of water wasted per cleaning time	
Sand management	
Sand management practice	Is the sand reused or not? Is the sand disposed of.
Sand cleaning practice	If sand is cleaned, how?
Sand hygiene tests done	Is there any test done on the sand?
Maintenance practices	These are practices that directly influence operation and filter performance

	Comments
Underdrainage maintenance	
Physical structural maintenance	
Monitoring devices	
Other management practices	
Pest and animal management	
Housekeeping practices	
Sampling and Monitoring	To include both those online and in a lab
Parameters monitored	
Samples taken	
Online monitoring done	
Risk factors in operation	
Seasonal issues	E.g. algal blooms in the summer, high turbidity in early spring
Most common problems	E.g. pests such as birds, rodents, etc., time management or cleaning scheduling, etc.
Major emergency event	What constitutes as an emergency and will require the plant to be shut down
Effluent water quality standards	
Regulations	
Misc. questions	
% of potable water produced within the company from SSF	

Appendix C Understanding The Risk of Enhanced Particle Penetration into SSF Beds When Using UWS Techniques – Supplementary Information

C.1 Particle Characterisation of Kaolin Powder and *Schmutzdecke*

The particle size distribution and surface charge of the kaolin used were compared to those of typical particles found in the *Schmutzdecke* of biologically matured SSF. This was achieved by collecting a composite sample of *Schmutzdecke* from a full-scale SSF at Kempton Park WTW that had been in operation for more than 40 days. The composite sample was a blend of three *Schmutzdecke* samples obtained from different locations on the filter bed. This sample was then re-suspended in deionised water and homogenised using a magnetic stirrer. This suspension was passed through the particle counter to determine the particle size distribution. The suspension's surface charge (zeta potential) was measured with a ZetaSizer Nano (Malvern Instruments, Westborough, MA). In a similar manner, kaolin was suspended in deionised water and the zeta potential was measured. Deionised water was chosen for re-suspension due to its neutral zeta potential of ~ 0 mV. Both the kaolin powder and *Schmutzdecke* exhibited negative zeta potentials (-19.8 ± 4.9 mV and -16.0 ± 2.1 mV, respectively). However, the particle size distribution differed, with the *Schmutzdecke* having a broader range of particle sizes, while the kaolin was more consistent with around 50% of the particles being ≤ 2 μm (Figure A.1). This discrepancy further emphasised and magnified the subpar performance, as larger particles are more efficiently eliminated in SSFs.

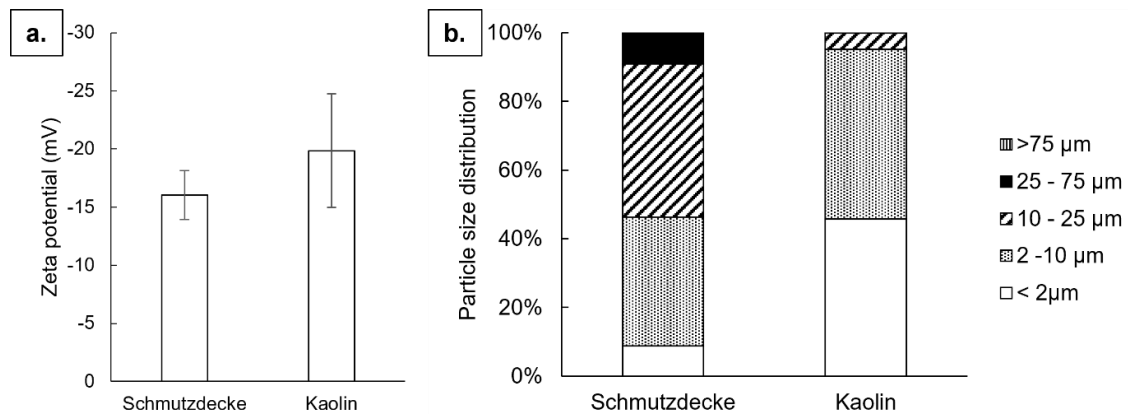


Figure A.1: Comparison of the properties of Kaolin used in this study and *Schmutzdecke* sample obtained from a full-scale SSF.

(a) Zeta potential (with standard deviation as error bar) and (b) percentage particle size distribution.

C.2 Turbidity Measurement in the pilot SSF supernatant

Turbidity was not directly measured in the supernatant of the filter following the addition of kaolin. However, the turbidity value was extrapolated using a calibration curve generated to compare turbidity to the total suspended solids concentration of kaolin in water (Figure A.2). The turbidity of the water in the supernatant immediately after filter surface agitation was quoted as >1000 NTU as the turbidity measurement is not accurate at values greater than 1000 NTU (Hach Co. TU5200 turbidimeter measurement range is between 0.01-1000 NTU). Table A.2 summarises the supernatant water parameters at the different sand depths.

Table A.2: Estimating the turbidity in the supernatant water assuming complete mixing.

		Media depth				
		200mm	400mm	500mm	700mm	900mm
Estimated Kaolin TSS*	mg/l	2,902	3,234	3,430	3,903	4,527
Estimated Turbidity	NTU	1,467	1,635	1,735	1,974	2,290

* 100 g Kaolin added

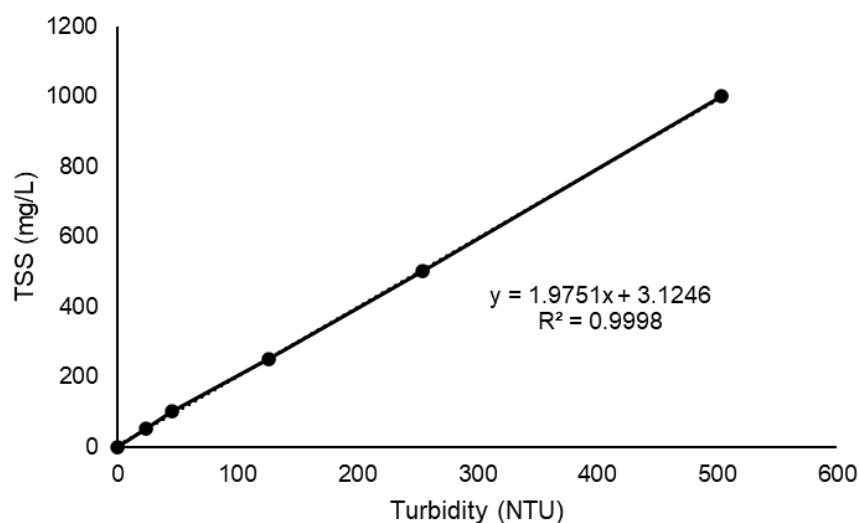


Figure A.2: Calibration curve for Kaolin TSS and turbidity

C.3 Limitations and Assumptions

The operation of SSF includes both physical and biological aspects. The complex ecology of SSF contributes to both physical and biological mechanisms observed in filters. The nature of these experiments (abiotic) means that only the physical aspects have been considered, however, this is not the full picture, and results have been interpreted with that consideration. For example, better collector efficiency and therefore less particle breakthrough is expected with a biologically mature filter as the *Schmutzdecke*, and interstitial biofilm will more efficiently filter the water by reducing effective pore size distribution in interstitial and physically straining via the *Schmutzdecke*. Also, both sets of experiments considered only immediate short-term effects of worst-case scenarios. It is assumed that in full-scale operation, where one or more of the conditions described in this report occurs, that the filter will be re-skimmed with a functioning UWS.

These experiments were not repeated with these column filters including a biological component as the other sections of the thesis address this using larger pilot filters which are outdoors and better replication of real-life conditions. In addition, the time taken to develop a viable *Schmutzdecke* with the column filters was restrictive (exceeded 100 days).

Appendix D Impact of UWS on Dissolved Oxygen Consumption in SSF For Potable Water Treatment – Supplementary Information

D.1 Dissolved Oxygen Consumption of Gravel

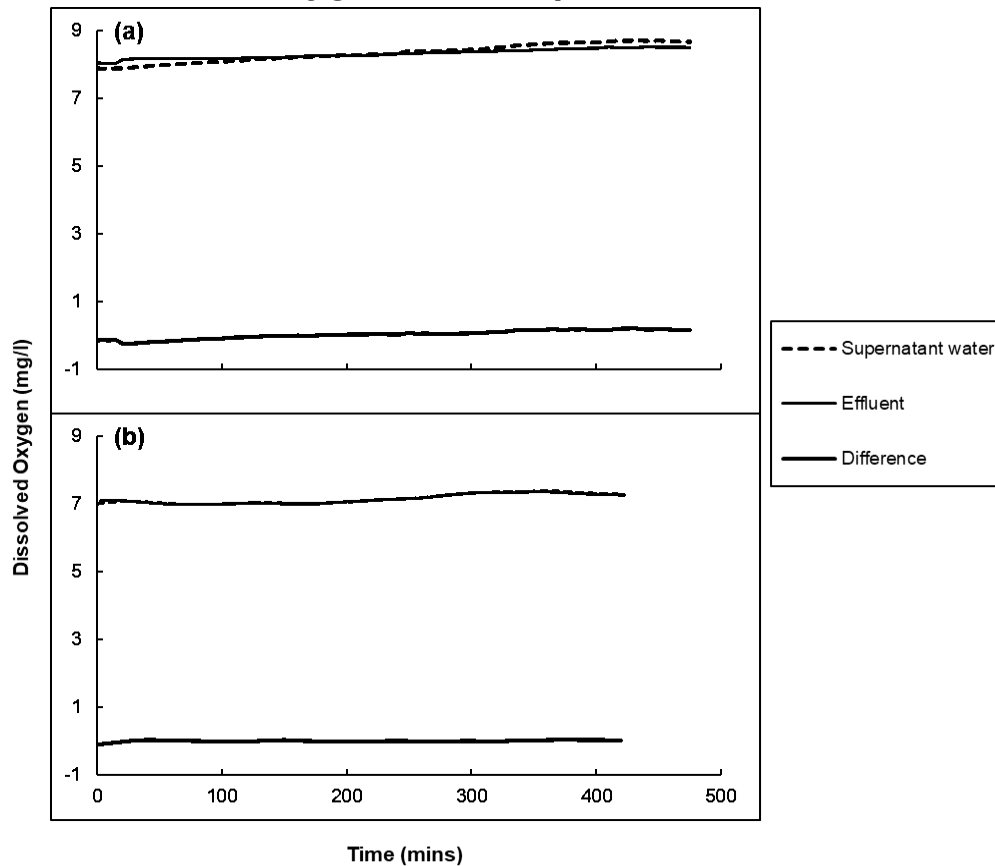


Figure A.3: Experiment conducted with gravel only showing that the DO consumption in the gravel layer is negligible.

DO in the supernatant and filtrate after (a) 0 BV and (b) 360,000 BV of feed water flow.

Appendix E Understanding the Impact of Underwater Skimming on Slow Sand Filter Performance and Operation – Supplementary Information

E.1 Feed Water Quality and Temperature

Table A.3: Quality of feed water supplied to the pilot slow sand filter (SSF) rig throughout operational duration (March 2021 to June 2022)

Parameter	Unit	Avg.	SD	Max	Min	Count
Colour	HU	8.2	0.9	10.5	6.0	117
Conductivity	μS/cm	584	19	622	553	117
Dissolved oxygen	mg/L	10.5	2.3	13.8	4.9	17,689
pH		8.1	0.2	8.9	7.0	380
Total organic carbon	mg/L	3.6	0.2	4.0	3.2	111
Turbidity	NTU	0.6	0.4	2.2	0.2	367
Avg	Average / mean values					
SD	Standard deviation					
HU	Hazen units					

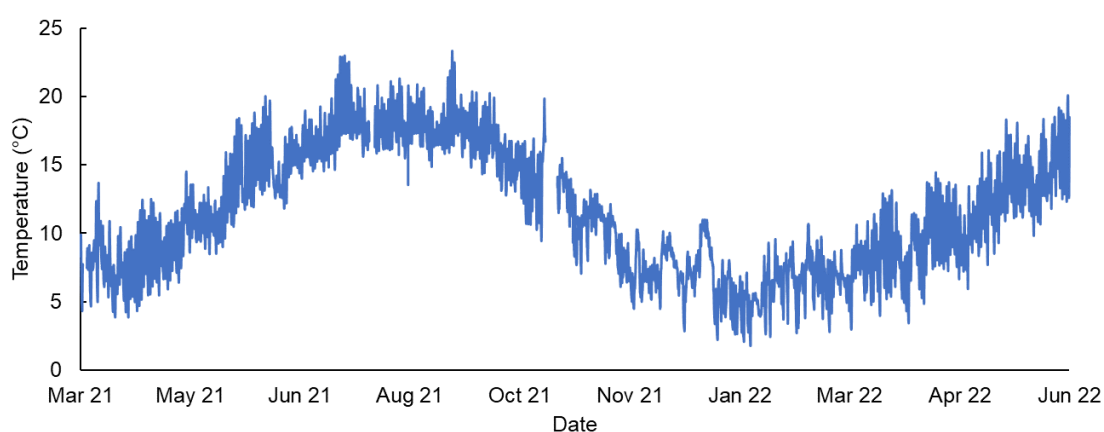


Figure A.4: Average hourly filtrate temperature.

Monitoring from slow sand filter (SSF) pilot filters throughout the operational period (March 2021 – June 2022).

E.2 Skimming Procedure

Table A.4: Skimming procedures applied to individual filters in the SSF pilot.

	SSF number	Skimming UWS ¹ / Dry	Sweetening flow ²	Total time left dry (h) ³	ID ⁴
Phase 1 (Mar 2021 – Jan 2022)	01	UWS	100%	0	UWS-100 (1)
	02	UWS	67%	0	UWS-67 (1)
	03	UWS	33%	0	UWS-33 (1)
	04	UWS	0%	0	UWS-0 (1)
	05	Dry	n/a	14	DS (1)
	06	UWS	100%	0	UWS-100 (2)
	07	UWS	67%	n/a	UWS-67 (2)
	08	UWS	33%	n/a	UWS-33 (2)
	09	UWS	0%	n/a	UWS-0 (2)
	10	Dry	n/a	14	DS (2)
Re-sanding done					
Phase 2 (Jan 2022 – Jun 2022)	01	UWS	100%	0	UWS-100 (1)
	02	UWS	33%	0	UWS-33 (1)
	03	UWS	33%	0	UWS-33 (2)
	04	UWS	0%	0	UWS-0 (1)
	05	Dry	n/a	14	DS (1)
	06	UWS	100%	0	UWS-100 (2)
	07	UWS	0%	0	UWS-0 (2)
	08	Dry	n/a	14	DS (2)
	09	Dry	n/a	28	DS-Ext (1)
	10	Dry	n/a	28	DS-Ext (2)

¹ UWS – Underwater skimmed SSF; ² Sweetening flow is a portion of the filtration rate (0.3 m/h) during skimming; ³ Total dry time is period a filter stays dry around skimming; ⁴ ID is the identity of each treatment.

Phase 1

	01 UWS-100 (1)	02 UWS-67 (1)	03 UWS-33 (1)	04 UWS-0 (1)	05 DS (1)
	06 UWS-100 (2)	07 UWS-67 (2)	08 UWS-33 (2)	09 UWS-0 (2)	10 DS (2)

Phase 2

	01 UWS-100 (1)	02 UWS-33 (1)	03 UWS-33 (2)	04 UWS-0 (1)	05 DS (1)
	06 UWS-100 (2)	07 UWS-0 (2)	08 DS (2)	09 DS-Ext (1)	10 DS-Ext (2)

Figure A.5: Pilot plant arrangement layout showing which treatments assigned to which filter.

E.3 Filtrate Water Quality

Table A.5: Average feed and filtrate water conductivity and pH.

Measured across all 10 filters in the slow sand filter (SSF) pilot rig throughout operational duration from March 2021 to June 2022.

Run	Conductivity @ 20°C (µs/cm)		pH	
	Feed (mean ± SD)	Filtrate (mean ² ± SD)	Feed (mean ± SD)	Filtrate (mean ² ± SD)
1	569±5 (n ¹ = 13)	580±37 (n = 130)	8.2±0.2 (n = 35)	8.1±0.2 (n = 350)
2	565±6 (n = 13)	567±4 (n = 108)	7.9± 0.2 (n = 32)	7.7± 0.2 (n = 294)
3	567±6 (n = 13)	563±11 (n = 90)	7.9±0.1 (n = 39)	7.7±0.1 (n = 316)
4	575±9 (n = 10)	578±6 (n = 68)	8.1±0.1 (n = 32)	7.8±0.1 (n = 248)
5	582±13 (n = 11)	585±17 (n = 90)	8.0±0.2 (n = 35)	7.8±0.1 (n = 322)
6	577±13 (n = 15)	583±22 (n = 150)	7.8±0.3 (n = 64)	7.8±0.1 (n = 640)
7	601±9 (n = 10)	604±8 (n = 96)	8.0±0.2 (n = 40)	7.9±0.1 (n = 382)
8	612±6 (n = 11)	617±6 (n = 104)	8.2±0.1 (n = 43)	8.0±0.1 (n = 418)
9	607±6 (n = 10)	612±8 (n = 96)	8.3±0.1 (n = 37)	8.0±0.1 (n = 352)
10	598±4 (n = 8)	606±9 (n = 72)	8.2±0.1 (n = 23)	7.9±0.1 (n = 206)
SD	Standard deviation			
1	Number of measurements			
2	This is the average across all 10 filters for the whole duration of the experiment			

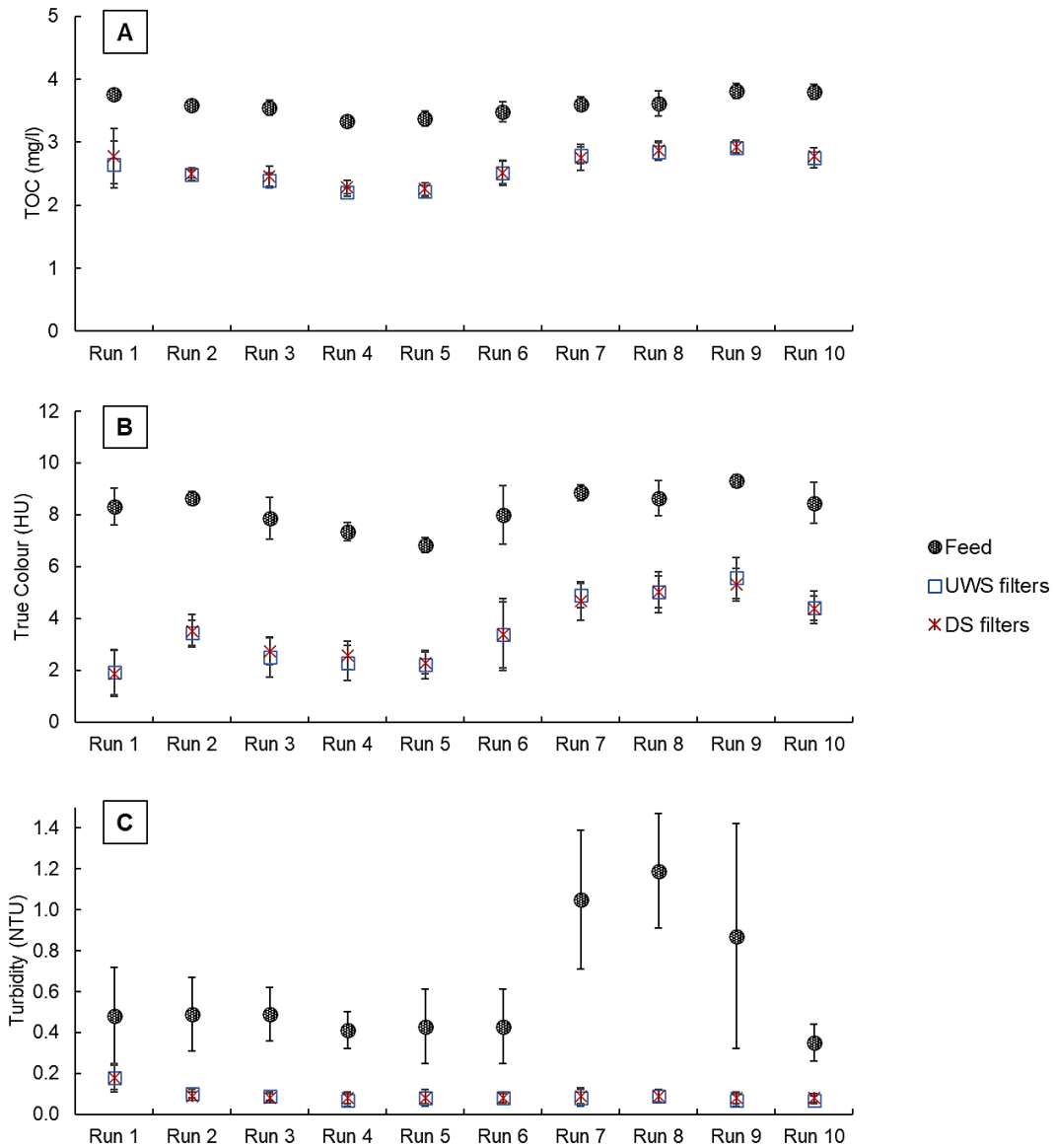


Figure A.6: Average feed and filtrate water quality for the different filter runs comparing UWS and DS treatment.

(A) Total organic carbon (n = 111 for feed; n=961 for filtrate), **(B) True colour** (n = 117 for feed; n=1004 for filtrate), and **(C) Turbidity** (n = 367 for feed; n=3478 for filtrate). Values are averaged across the filters for UWS and DS. Error bars are the standard deviation.

Table A.6: Average turbidity (in NTU) for the different treatments and filter runs.

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Feed	0.48±0.24 ^a (n = 35)	0.49±0.18 (n = 33)	0.49±0.13 (n = 39)	0.41±0.09 (n = 32)	0.43±0.18 (n = 34)	0.43±0.18 (n = 64)	1.07±0.32 (n = 38)	1.19±0.28 (n = 43)	0.87±0.54 (n = 38)	0.35±0.09 (n = 23)
UWS-100 (1)	0.19±0.08 (n = 35)	0.11±0.04 (n = 29)	0.11±0.04 (n = 31)	0.09±0.03 (n = 25)	0.08±0.03 (n = 32)	0.09±0.03 (n = 64)	0.1±0.05 (n = 37)	0.11±0.03 (n = 43)	0.08±0.03 (n = 36)	0.08±0.02 (n = 22)
UWS-100 (2)	0.16±0.08 (n = 35)	0.09±0.01 (n = 29)	0.08±0.02 (n = 31)	0.07±0.02 (n = 25)	0.06±0.02 (n = 32)	0.07±0.03 (n = 64)	0.09±0.01 (n = 37)	0.09±0.03 (n = 43)	0.07±0.03 (n = 36)	0.07±0.02 (n = 21)
UWS-67 (1)	0.19±0.09 (n = 35)	0.1±0.03 (n = 29)	0.09±0.03 (n = 31)	0.07±0.02 (n = 25)	0.08±0.03 (n = 32)	n/a	n/a	n/a	n/a	n/a
UWS-67 (2)	0.17±0.06 (n = 35)	0.09±0.02 (n = 29)	0.08±0.02 (n = 31)	0.07±0.02 (n = 25)	0.08±0.03 (n = 32)	n/a	n/a	n/a	n/a	n/a
UWS-33 (1)	0.17±0.07 (n = 35)	0.1±0.02 (n = 30)	0.08±0.02 (n = 31)	0.07±0.02 (n = 26)	0.07±0.02 (n = 31)	0.09±0.03 (n = 64)	0.08±0.02 (n = 37)	0.09±0.02 (n = 43)	0.07±0.02 (n = 36)	0.07±0.01 (n = 22)
UWS-33 (2)	0.17±0.06 (n = 35)	0.1±0.03 (n = 30)	0.08±0.02 (n = 31)	0.07±0.02 (n = 26)	0.08±0.03 (n = 31)	0.07±0.02 (n = 64)	0.07±0.02 (n = 37)	0.09±0.04 (n = 43)	0.08±0.03 (n = 36)	0.07±0.02 (n = 22)
UWS-0 (1)	0.19±0.13 (n = 35)	0.09±0.02 (n = 30)	0.09±0.02 (n = 31)	0.08±0.06 (n = 26)	0.08±0.06 (n = 31)	0.08±0.02 (n = 64)	0.08±0.03 (n = 37)	0.1±0.03 (n = 41)	0.07±0.03 (n = 36)	0.07±0.02 (n = 22)
UWS-0 (2)	0.17±0.07 (n = 35)	0.09±0.01 (n = 30)	0.08±0.02 (n = 31)	0.08±0.03 (n = 26)	0.07±0.03 (n = 31)	0.08±0.03 (n = 64)	0.08±0.02 (n = 37)	0.09±0.02 (n = 41)	0.07±0.03 (n = 36)	0.08±0.02 (n = 21)
DS (1)	0.19±0.14 (n = 35)	0.1±0.02 (n = 29)	0.08±0.02 (n = 33)	0.08±0.05 (n = 22)	0.08±0.04 (n = 30)	0.08±0.03 (n = 64)	0.09±0.03 (n = 35)	0.1±0.03 (n = 41)	0.09±0.04 (n = 34)	0.08±0.02 (n = 20)
DS (2)	0.17±0.08 (n = 35)	0.09±0.02 (n = 29)	0.08±0.02 (n = 33)	0.08±0.02 (n = 22)	0.08±0.03 (n = 30)	0.08±0.03 (n = 64)	0.08±0.03 (n = 35)	0.1±0.05 (n = 41)	0.07±0.03 (n = 34)	0.07±0.01 (n = 20)
DS-Ext (1)	n/a	n/a	n/a	n/a	n/a	0.07±0.02 (n = 64)	0.09±0.04 (n = 35)	0.09±0.03 (n = 41)	0.08±0.02 (n = 34)	0.08±0.02 (n = 18)
DS-Ext (2)	n/a	n/a	n/a	n/a	n/a	0.07±0.02 (n = 64)	0.09±0.06 (n = 35)	0.09±0.03 (n = 41)	0.08±0.03 (n = 34)	0.07±0.01 (n = 18)

^a Standard deviation; (1) and (2) used to differentiate the two filters with similar skimming done. Numbers in samples are in bracket.

E.4 Methodology for Inline Flow Cytometry (FCM)

Automated and inline FCM measurements were performed using a BactoSense instrument (bNovate, Switzerland). This instrument features a built-in laser operating at a wavelength of 488 nm, a side scatter (SSC) detector, and two fluorescence detectors equipped with bandpass filters for green-light (FL1, 525/45 nm band pass) and red-light (FL2, 715 nm long pass) emissions. At specified intervals (set to 30 min for this study), 135 μ L water samples were automatically collected, buffered using a proprietary solution to pH 8 and stained with 15 μ L of 10x SYBR Green using reagents within the Total Cell Cartridge. Following a 10-minute incubation at 37°C, 90 μ L of the sample was analysed. To prevent biofilm formation and cross-contamination, the microfluidic tubing was automatically purged between each measurement with 0.1% NaClO and rinsed with 0.05% NaN₃. The sample flowline (to the instrument) was periodically rinses with dilute NaClO solution on account of distance between SSF and instrument. Flow rates to the instrument were maintained within manufacturer recommendations.

The flow cytometer was connected to the outlet of the individual SSF being measured. This was achieved using a 2 mm pipe and valve to maintain the flow requirement of the equipment (approximately 180 mL/min). Due to the sensitivity of the equipment, it was housed in a cabin where the ambient temperature was maintained above 10°C and was protected from the elements.

E.5 DNA Extraction, Microbial Sequencing and Data Analysis

DNA Extraction

Prior to extraction, samples were thawed, homogenised and then a centrifugation step was conducted to eliminate excess water. Genomic DNA was extracted from 0.6 g of each sample using a NucleoSpin Soil DNA extraction kit (Macherey-Nagel, Düren, Germany), adhering to the manufacturer's instructions.

The samples (contained in 15 mL falcon tubes) were completely thawed, then homogenised by hand, ensuring thorough mixing of the liquid and solids. Under sterile conditions, a sterilised spatula (washed with soap and water, then sterilised in isopropanol and flame) was used to retrieve an aliquot, which was then transferred to a sterile 1.5 mL Eppendorf tube, along with 0.5 mL of the supernatant. The aliquot samples were centrifuged at 10,000xg for 1 min and excess water removed under sterile conditions. 0.6 g of the subsample material was weighed into the MN Bead Tube and frozen for further analysis.

The quality and quantity of the extracted DNA was then verified using a Jenway Genova Nano spectrophotometer (Cole Parmer, St. Neots, UK) and Qubit II (Invitrogen, UK) using either the HS or BR DNA kits.

Illumina NovaSeq Sequencing, Noise Removal and Taxonomic Assignment.

Extracted DNA was processed by Novogene (Cambridge, UK) for amplification of the 16S rRNA gene via the NovaSeq PE250 platform (Illumina Inc.). Amplification of the hypervariable V3–V4 regions was achieved using forward primer 5'-TCG TCG GCA GCG TCA GAT GTG TAT AAG AGA CAG-5' and reverse primer 5'-GTC TCG TGG GCT CGG AGA TGT GTA TAA GAG ACA G-3' (Mori et al., 2014), yielding approximately 300 bp long tags. The raw sequence data obtained from the Illumina sequencing were processed via QIIME2 (version 2018.11) and its associated plugins (Bolyen et al., 2019). Specifically, we employed the “dada2” plugin (Callahan et al., 2016) to truncate reads (–p-trim-left 0, –p-trunc-len 280). The vsearch uchime_ref method was utilised to identify chimeric feature sequences, and sequences related to mitochondria and chloroplasts were subsequently removed. For predictions of KEGG Orthology (KO) based on 16S data, the PICRUST2 plugin from QIIME 2 (Douglas et al., 2020) was applied. Taxonomy was assigned to the Amplicon Sequence Variant (ASV) by contrasting it with a SILVA 16S/18S rDNA non-redundant reference dataset (SSURef 132 NR) (Quast et al., 2012) using the feature-classifier classifier.

Data and Statistical Analysis

For the analysis of rRNA DNA amplicon sequence data, we used PRIMER v7/PERMANOVA+ software (Primer-e, UK). One-way ANOVA was used to test for differences in the Shannon diversity index among the samples. To illuminate variations within microbial communities at the genus level, Bray-Curtis dissimilarity calculations to create a resemblance matrix was employed. This was then visually depicted using Principal Co-ordinates Analysis (PCoA), a technique that maps similar and dissimilar observations based on their microbial makeup in a reduced dimensional space. PCoA plots similar observations close together and dissimilar ones farther apart in a reduced dimensional space, allowing it to handle non-linear patterns and various types of data. This approach helps elucidate the effects of distinct skimming regimes, seasons, and types of SSF by effectively visualising shifts in microbial composition. The sequence data was not subjected to transformation prior to the construction of the resemblance matrix to more accurately reflect the impact of the cleaning events on *Schmutzdecke* microbiome by preserving the original scale of the species abundances.

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E.6 Anatomy of a Typical SSF Head Loss Development Curve

Head loss development in an SSF can be characterised using the principles of deep bed filtration, with the head loss development curve segmented into distinct phases based on the prevailing filtration mechanisms. For this study, these phases are defined as follows: an initial phase of gradual head loss increase (slow rate), an intermediate phase with a more pronounced incline, and a final phase characterised by a sharp ascent (fast rate). These phases are observed under a constant hydraulic loading rate.

The initial phase, marked by a slow rate of head loss development, begins at the start of the filter run. During this phase, head loss increases gradually as particles begin to accumulate on the filter media, as illustrated in segment (a) of Figure A.7. The intermediate phase corresponds to the filter's regular operation, where a steady increase in head loss occurs, indicating effective contaminant capture, shown in segment (b) of Figure A.7. Eventually, head loss development accelerates in the fast rate phase, just before reaching terminal or maximum head loss, beyond which flow is significantly restricted and the hydraulic loading rate starts to decline, depicted in segment (c) of Figure A.7.

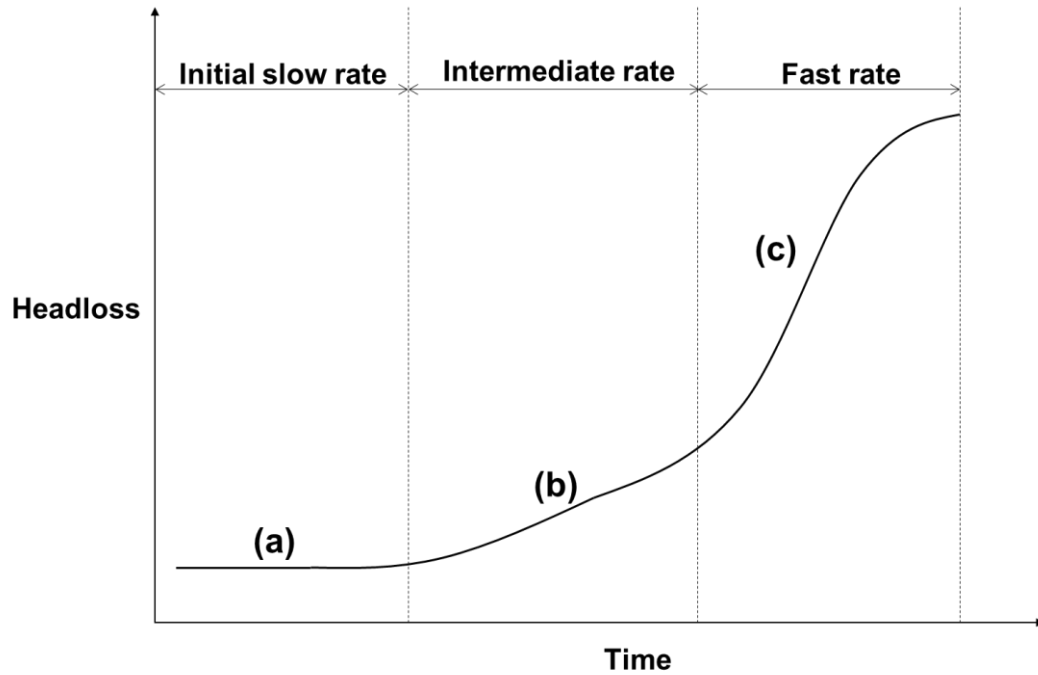


Figure A.7: Anatomy of the head loss development curve of a typical SSF.

For this study, these phases were characterised based on the slope of the head loss curves, with a slope of <10 characterising the slow rate and the fast rate based on the increase where the slope is >15 . With the slope, k calculated as:

$$k = \frac{\Delta h}{\Delta t}$$

Where Δh is the change in normalised head loss and Δt is the change in time in days.

This characterisation provides a framework for understanding the dynamics of head loss in SSFs. Utilising the slope as a basis for comparison offers a quantitative method to evaluate the performance differences between DS and UWS filters.

Appendix F Methodology for Estimating Production Benefits from UWS

Benefits of UWS as used in this analysis has been limited to the SSF only, and any activities that will change in duration and / or frequency as a result of implementing UWS. These include the routine skimming and associated downtime, filter media replacement, and where applicable GAC replacement frequency. Other activities that may potentially affect operational downtime, but only minimally and have been excluded are activities such as maintenance of the underdrains and piping which can be done alongside other activities, e.g. during re-sanding or GAC replacement.

Utilising the information provided by the companies surveyed, additional production capacity was estimated for the individual companies. Additional water produced from individual filters was calculated based on assumptions in Table A.7. Weighted average of individual filter surface area and HLR were calculated for companies where the various sites used different HLRs.

Daily water produced using the average HLR and surface area was calculated for both DS and UWS as:

$$Volume\ produced\ (m^3) = HLR\ (m/h) \times Average\ area\ (m^2) \times 24$$

A fixed cycle was set using the filter run length and the filter cleaning downtime provided by the companies. Adjustments were made to the HLR to account for DS (using the whole downtime provided) and for the UWS with the varying sweetening flows to reflect the continued flow. This was repeated for daily water production for a 10-year period. This was done to allow for inclusion of re-sanding downtime and also GAC replacement (where applicable).

Total volume of water produced was then calculated per filter per day. Gross water produced by the company was calculated by multiplying by the total number of filters. Estimations on the number of additional people served was based on national per capita water consumptions for the country in which the company is

located. These per capita values used are shown in Table A.7. An example for one of the companies surveyed is presented in Table A.8.

Table A.7: Summary of assumptions and parameters for additional production capacity modelling.

Filtration rate (m/h)	Weighted average <i>Average HLR (m/h)</i> $= \frac{\sum \text{Site HLR (m/h)} \times \text{number filters at site}}{\text{Total number of filters}}$
Surface area of individual filter (m ²)	Weighted average <i>Average filter area (m²)</i> $= \frac{\text{Total surface area of all filters (m2)}}{\text{Total number of filters}}$
Total SSF surface area (m ²)	As provided
Number of filters	As provided
Filter run length (days), i.e. skimming frequency	Weighted average
Cleaning downtime for DS (days)	As provided
Re-sanding frequency	10 skimming cycles – based on values reported in survey (Average time before bed is refilled/ topped-up)
GAC replacement frequency	3 years or 70,000 bed volumes of treatment – based on values reported in survey
UWS duration	Actual cleaning estimated to take 8 h. - UWS-100 – 100% flow during cleaning - UWS-67 – loss of a third of flow during cleaning. - UWS-33 – loss of two-thirds of flow during cleaning and 24 h after; loss of a third of flow for 24 h - UWS-0 – Loss of flow during cleaning; loss of two-thirds of flow for 24 h after; loss of a third of flow for 24 h
Per capita water consumption	United Kingdom ¹ = 146 L/day; Sweden ² = 140 L/day; Netherlands ³ = 134 L/day
1. Ofwat (2023) <i>Water Company Performance Report 2022-23</i>. The Water Services Regulation Authority (Ofwat), London, UK. Available at: https://www.ofwat.gov.uk/regulated-companies/company-obligations/outcomes/water-company-performance-report-2022-23/ [Last accessed: 24 June 2024]. 2. Statistics Sweden (2022) <i>Water withdrawal and water use in Sweden</i>. Official Statistics of Sweden, Solna, Sweden. Available at: https://www.scb.se/mi0902-en [Last accessed: 24 June 2024]. 3. CBS (2021) <i>The Netherlands in numbers</i>. Central Beureau voor de Statistiek, The Hague, Netherlands. Available at: https://longreads.cbs.nl/the-netherlands-in-numbers-2021/how-much-water-do-we-consume/ [Last accessed: 24 June 2024].	

Table A.8: An example of the calculations for additional treatment capacity and equivalent customers.

Parameter	Unit					
Site ¹		Site 1	Site 2	Site 3	Site 4	Site 5
No of filters ¹		32	25	12	33	12
Area of each filter ¹	m ²	3,082	4,520	3,037	3,320	3,087
HLR ¹	m/h	0.35	0.35	0.25	0.30	0.20
Bed area ²	m ²	3,462	<i>(Weighted average)</i>			
HLR ²	m/h	0.31	<i>(Weighted average)</i>			
HLR 100% ³	ML/d	25.7	<i>(Estimated for UWS)</i>			
HLR 67% ³	ML/d	17.1	<i>(Estimated for UWS)</i>			
HLR 33% ³	ML/d	8.6	<i>(Estimated for UWS)</i>			
No flow ³	ML/d	0.0	<i>(Estimated for UWS)</i>			
		DS	UWS-0	UWS-33	UWS-67	UWS-100
Run length ¹	days	55	55	55	55	55
Skimming Down time ¹	days	3	1	0.7	0.3	0
Cycle duration ³	days	58	56	56	55	55
Volume produced per filter						
Annual ⁴	ML/yr	8,607	9,223	9,223	9,326	9,378
Daily ⁴	ML/d	23.6	25.3	25.3	25.6	25.7
Total volume produced (all SSFs)						
Total number of filters ¹		114				
Daily ⁴		149.3	149.3	150.1	150.5	150.5
Customers serviced						
Per capita consumption ⁵	L/d	146				
Customers supplied		18,475,269	19,798,871	19,798,871	20,019,471	20,129,771
Additional customers supplied		0	1,323,601	1,323,601	1,544,202	1,654,502
1. Values provided by company in the survey. 2. Weighted average of all the values provided by company. 3. Estimated values assuming UWS used. 4. Calculated value 5. Per capita consumption as shown in Table A.7						