

Research article

Evaluating *Cryptosporidium* oocyst removal in SSF: Impact of underwater skimming and dry skimming

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ABSTRACT

Cryptosporidium is a protozoan parasite that presents significant challenges to water supply security due to its resilience against conventional chemical disinfection. This study evaluates the effectiveness of two slow sand filter (SSF) skimming techniques—dry skimming (DS) and underwater skimming (UWS), in removing *Cryptosporidium* oocysts under pilot-scale conditions using 10 filters. Oocyst retention was monitored during dosing, post-dosing, and following the skimming event. Results demonstrated that UWS achieved superior pathogen removal, evidenced by fewer oocyst breakthroughs and higher cumulative log retention values (cLRtVs). During dosing, UWS filters attained cLRtVs consistently exceeding 6.6, whereas DS filters averaged 5.6. In the post-dosing period, UWS retained cLRtVs above 6.9, while DS averaged 5.9. A quantitative microbial risk assessment (QMRA) indicated a substantially lower probability of illness from oocyst breakthrough in UWS-treated water, with a daily risk of $\sim 2.6 \times 10^{-6}$ for immunocompetent individuals, compared to up to 8.2×10^{-6} in DS-treated water, equating to a 3.2-fold risk reduction. These findings highlight that the UWS maintenance technique enhances SSF operation by improving pathogen retention while enabling minimal filter downtime, thereby contributing to improved water safety and public health protection. The work also provides novel empirical data and theoretical predictions regarding the potential risk of *Cryptosporidium* penetration or compromised water quality arising from the routine requirement to skim SSFs.

Nomenclature

Symbol	Definition/Description	Typical Value
		[Units]
h_N	Normalised headloss	[mm]
h_m	Measured headloss at time t	[mm]
μ_N	Dynamic viscosity at 20 °C	[Pa·s]
μ_m	Dynamic viscosity at the measured temperature T	[Pa·s]
LRtV	Log retention value	[-]
C_{FM}	<i>Cryptosporidium</i> oocyst concentration in Fila-Max®	[oocysts L ⁻¹]
C_{IN}	<i>Cryptosporidium</i> oocyst concentration in the inlet	[oocysts L ⁻¹]
C_{OUT}	<i>Cryptosporidium</i> oocyst concentration in the filtrate	[oocysts L ⁻¹]
N_{IN}	Total number of oocysts in the inlet	[oocysts]
N_{OUT}	Total oocysts in the filtrate	[oocysts]
V_{IN}	Volume of inlet water	[L]
V_{OUT}	Volume of filtrate	[L]

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N_{FM}	Oocysts counted in the Fila-Max sample	[oocysts]
C_V	Volume correction coefficient	[-]
cLRtV	Time-cumulative log retention value	[-]
t		
$P(d)$	Probability of infection given a dose d	[-]
r_{comp}	Dose-response parameter for immunocompetent individuals	0.00419
r_{im}	Dose-response parameter for immunocompromised individuals	0.354
d	Ingested dose of oocysts	[oocysts]
$P_{daily,i}$	Daily probability of infection for regime i	[-]
$P_{phase,i}$	Infection probability over a specific phase	[-]
$P_{yearly,i}$	Annual probability of infection	[-]
$P_{illness,i}$	Probability of illness	[-]
DALY	Disability-adjusted life years	[years]
YLL	Years of life lost	[years]
YLD	Years lived with disability	[years]

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(continued)

N_{death}	Deaths attributable to cryptosporidiosis	10^{-5} [individuals]
L_{death}	Life expectancy at time of death	13.2 [years]
DW_n	Disability weight for watery diarrhoea	0.067
$L_{\text{remission}}$	Duration of illness	0.02 [years] (≈ 7.2 days)
N_{pop}	Population considered	1,000,000 [individuals]
I_{illness}	Incidence of illness	[Number of cases]
$P_{\text{ill,ic}}$	Probability of symptomatic infection for immunocompetent individuals	0.7
$P_{\text{ill,im}}$	Probability of symptomatic infection for immunocompromised individuals	1.0
v	Viable fraction of oocysts	[-]

1. Introduction

Cryptosporidium is a ubiquitous waterborne protozoan parasite that poses significant global public health challenges due to its ability to cause cryptosporidiosis, a severe diarrhoeal disease affecting both humans and animals (Chalmers and Davies, 2010). This disease is particularly hazardous for immunocompromised individuals, as it can become chronic and life-threatening (Hunter and Nichols, 2002). The parasite is highly prevalent in surface waters and is characterised by its high infectivity and prolonged environmental persistence, making it a major concern for water safety and public health (Efstratiou et al., 2017).

A key challenge in controlling *Cryptosporidium* in drinking water sources is that the oocyst life stage is exceptionally resilient, surviving harsh environmental conditions such as fluctuations in temperature, pH, and salinity (King and Monis, 2007). Oocysts are also innately resistant to conventional chlorine-based disinfection methods. Therefore, a combination of source protection and water treatments, including coagulation/flocculation, filtration, UV, or membrane processes, is commonly employed for oocyst inactivation or removal (Korich et al., 1990). Moreover, *Cryptosporidium* oocysts are small (4–6 μm) with hydrophobic surface properties that significantly influence their retention and transport, emphasising the importance of filtration methods such as rapid gravity filters (RGF) and slow sand filters (SSF) in achieving robust and consistent removal (Dai and Hozalski, 2002). Given these challenges, research on optimising SSF performance, particularly under various operating and maintenance conditions, remains a key focus for improving drinking water safety.

Slow sand filtration has been used for drinking water treatment for nearly two centuries, particularly in regions that prioritise low-energy, chemical-free, and sustainable methods, or that have a longstanding legacy of this approach, as in London in the United Kingdom (Huisman and Wood, 1974). SSF employs a gravity-driven process in which a fine sand bed removes contaminants through both physical and biological mechanisms (Hijnen et al., 2004). This technology effectively removes a broad range of impurities, including suspended particles, dissolved organic matter, algae, and protozoan pathogens such as *Cryptosporidium*, via physical straining and biological processes (Campos et al., 2002; Weber-Shirk and Dick, 1997a, 1997b). A key component of SSF performance is the Schmutzdecke, a biologically active layer formed on top of the sand bed (Haig et al., 2011). This layer harbours a diverse microbiome that develops in biofilms and is associated with turbidity and natural organic matter on and within the sand surface. Bed ripening and Schmutzdecke development facilitate the degradation of organic compounds and the capture of microbial contaminants (including bacteria, viruses, and protozoa), enhancing SSF's role as a robust barrier against waterborne diseases (Bellamy et al., 1985; Hendricks et al., 1991). Accordingly, the combination of physical and biological filtration processes delivers high levels of pathogen removal when used in conjunction with disinfection processes e.g., chlorination (Castro-Gutierrez et al., 2022).

The Schmutzdecke is one part of the functional SSF microbiome, and mature SSFs do not rely exclusively on this section of the filter, as has been shown in full-scale filters (Chan et al., 2018). Subsurface layers beneath the Schmutzdecke also contribute significantly to retaining smaller particles and pathogens not captured in the upper layers (Trikannad et al., 2023). These deeper layers further support physical removal and some biological activity (in terms of biofilm growth), reinforcing pathogen removal mechanisms (Trikannad et al., 2023). Nevertheless, it is widely held that the majority of contaminant removal occurs within the top (<50 mm) layers, where microbial activity, deposition and headloss are most pronounced (Chen et al., 2021).

The accumulation of organic and inorganic particulate matter in the Schmutzdecke during SSF operation clogs surficial pores and leads to an initial slow increase in headloss, which grows nearly exponentially as these interstitial spaces become filled, consequently reducing water flow through the filter (Rosenqvist et al., 2024). To maintain effective filtration, periodic maintenance is required (Collins et al., 1994). Skimming is the primary maintenance technique for SSF systems, involving the removal of the top layer of the sand bed (Collins et al., 1994). However, this skimming process reduces the overall performance of the SSF due to the need for the filter to ripen again prior to operation (Campos et al., 2002). Traditionally, this skimming is performed by draining the filter before sand removal, a method known as dry skimming (DS) (Graham, 1988). While DS effectively restores flow, it exposes the sand bed and its associated biological communities to ambient air, causing desiccation and thermal stress (Nasser, 2016). Such exposure can significantly delay the re-establishment of the microbial community, prolonging the time required for the SSF to return to optimal performance (Ellis, 1987).

To mitigate these drawbacks, underwater skimming (UWS) has been proposed as an alternative approach (WHO, 2017). UWS involves removing the top layer of sand while the filter remains submerged, minimising disturbance to filter biological communities and allowing for faster recovery of filtration efficiency (Hassard et al., 2022). It is hypothesised that UWS improves the consistency of pathogen retention while reducing downtime associated with filter maintenance (WHO, 2017), by maintaining an active microbial community and biofilm in the sand below the Schmutzdecke (Elemo et al., 2024).

There is a growing need for safe drinking water worldwide, driven by increasingly stringent standards mandating zero tolerance for *Cryptosporidium* oocysts (WHO, 2017). In this context, the present study evaluates the efficacy of slow sand filtration under two distinct skimming regimes — UWS and DS for cleaning SSF. Oocyst retention was monitored during dosing events, the post-dosing phase, and the critical period immediately following skimming. By comparing UWS and DS, this research informs enhanced SSF maintenance strategies to improve treatment reliability and reduce waterborne pathogen risks.

This study asks whether UWS reduces *Cryptosporidium* breakthrough and increases time-cumulative log retention (cLRtV) relative to DS, and whether UWS operated with 33 % flow through during maintenance differs from UWS without flow through in retention and post-skim recovery. We also test whether routine water-quality and bacterial indicators predict breakthrough and introduce cLRtV with volume-normalised composite sampling as a sampling-aware alternative to conventional log removal value (LRV). Finally, a conservative quantitative microbial risk assessment evaluates public-health implications; our *a priori* view is that UWS outperforms DS and yields lower infection risk and health burden.

The work is novel in that it explicitly addresses the risk of *Cryptosporidium* penetration and potential for water quality impacts specifically associated with UWS. The work is also relevant as it was conducted on real water, pilot scale SSF systems which were fully ripened (2.5 years continuous operation prior to study) and cleaned with either UWS/DS during this period.

2. Methods and materials

2.1. Pilot SSF description

An eight-week dosing experiment was conducted from October to December 2023 using a pilot-scale system of ten slow sand filters (SSFs) that had been in continuous operation since March 2021 (2.5 years prior to trial starting) at Kempton Park Water Treatment Works (Thames Water Utilities Ltd.) with defined ‘cycles’ of filter operation and cleaning. The setup comprised a single metal tank divided into two halves, each containing five rectangular filters with an approximate surface area of 0.54 m² per filter. Each filter consisted of: (1) a 0.3–0.5 m sand layer (effective size $d_{10} = 0.3$ mm, uniformity coefficient $UC = 1.8$), with the uppermost 0.2 m subject to successive skimming; (2) a 0.1 m granular activated carbon (GAC) layer ($d_{10} = 0.6$ mm, $UC = 1.9$); and (3) a final 0.2 m sand layer. Beneath these layers was a 0.1 m gravel support base resting on a metal plate that housed 24 filter nozzles, each with 36 slots measuring 0.2 mm in width (Supplementary Information Fig. A1).

The SSFs received a continuous flow of reservoir-stored River Thames water at a hydraulic loading rate (HLR) of 0.3 m h⁻¹, reflecting full scale SSF operational practices (Huisman and Wood, 1974; Logsdon et al., 2002). Each gravity-fed filter was manually controlled via inlet and outlet valves and flow meters. Under normal operation in “overflow mode,” the influent exceeded each filter’s outlet flow, causing excess water to overflow and preventing the filters from draining dry. Filtered water exited through nozzles below the sand layers, and the filtrate was collected in individual 20 L vessels to enable continuous sampling without interrupting filtration. Excess water was discharged to the sewer.

Filters were operated until a maximum headloss trigger (i.e., when flow began to decline) or based on time, at which point skimming was undertaken (details in 2.3). Once the minimum media depth was reached, clean sand was added to the upper layers (re-sanding) to maintain optimal performance; the most recent re-sand took place in August 2023.

The installation was located outdoors under a translucent plastic roof that shielded the filters from most rainfall while allowing sunlight penetration and facilitating skimming activities. The filters were thus exposed to ambient weather and temperature variations comparable to full-scale operational SSFs.

2.2. Feed water characteristics and filter operation

The pilot plant influent water, drawn from reservoir-stored River Thames supplies, had an average total organic carbon (TOC) concentration of 3.18 ± 0.07 mg L⁻¹, turbidity of 0.6 ± 0.6 NTU, and a pH of 8.1 ± 0.2 . During the study, ambient air temperatures ranged from -4 °C to 17 °C, while water temperatures varied between 9 °C and 17 °C. Inlet and filtrate water characteristics are presented within Table A-1 in supplementary information.

Initially, all SSFs were backfilled with filtrate and started at a down-flow HLR of 0.1 m h⁻¹, which was increased daily by 0.1 m h⁻¹ until reaching an operational rate of 0.3 m h⁻¹. No pre-treatment was applied to the raw water, given its low turbidity (<1 NTU) and to promote faster headloss development in this pilot system.

2.3. SSF monitoring, skimming procedures and headloss calculation

To maintain optimal SSF performance, filter cleaning was carried out by removing the top 40 mm of sand. Operational triggers for skimming were either (i) a headloss of approximately 1300 mm or (ii) reaching the seasonal maximum runtime (40 days in summer and 70 days in winter). Filter runs were classified by season according to their start date: winter runs were defined as those starting between 1 November and 1 April (inclusive), and runs starting outside this period were classified as summer. A schematic of the UWS and DS approach is provided in the

Supplementary Information Figure A-2.

In this dosing experiment, two skimming techniques were employed. Under the DS method, four filters were fully drained, skimmed using a flat-bottom scoop, and then slowly backfilled to minimise disturbance of the remaining media. The other six filters were skimmed using UWS, which removed the same sand depth through vacuum suction of a sand slurry but without fully draining the filter (Figure A-1 in Supplementary Information). Two UWS conditions were tested: UWS 0 %, where flow was completely interrupted for 6 h during skimming, and UWS 33 %, where the outlet flow rate was reduced by two-thirds (to 0.1 m h⁻¹) without completely stopping flow. To simulate operational practices in full-scale London (UK) SSFs and account for the pilot’s smaller scale, the flow to UWS 0 % filters was interrupted for 6 h, whereas the DS filters remained drained and exposed to air for 28 h. UWS could be completed in one day, whereas the full DS drain, skim, and refill procedure required two days. After skimming, flow in all filters was gradually increased by one-third of the flow rate (0.1 m h⁻¹) every 24 h until reaching the operational HLR of 0.3 m h⁻¹ over three days (two days for UWS 33 %, as it started at one-third full flow), mirroring the operational conditions used on many full-scale SSFs. Each skimming regime was implemented for a year prior to the *Cryptosporidium* dosing experiment, allowing the development and acclimation of realistic microbial communities and ensuring the pilot plant operation closely resembled full-scale practice.

Daily monitoring of headloss in each SSF was performed using a manometer. Prior to each measurement, the flow rate was set to 0.3 m h⁻¹ (162 L h^{-1}) (162 L h^{-1}). Recorded values were then normalised to account for temperature-induced viscosity variations according to:

$$h_N = h_m \cdot \frac{\mu_N}{\mu_m} \quad (1)$$

Where h_N is the normalised headloss (mm), h_m is the measured headloss (mm) at time t , μ_N is the dynamic viscosity (Pa•s) at normalising temperature of 20 °C, and μ_m is the dynamic viscosity (Pa•s) at measured temperature at time t Eq. (1).

2.4. Dosing parameters

To ensure operator safety and prevent environmental contamination, inactivated γ -irradiated *Cryptosporidium parvum* oocysts (Iowa isolate; TCS Biosciences UK; 10^9 oocysts per vial) were used in this experiment. Alternative surrogates (e.g., *Bacillus subtilis* or *Clostridium perfringens* spores) were not employed due to their differing surface properties, size, and morphological factors that influence interactions with sand surfaces and biofilms, and thus overall behaviour in SSFs (Tufenkji et al., 2006). Oocysts were dosed at a target concentration of 3000 oocysts L⁻¹ over two separate four-day periods on weekdays. Each day’s dosing lasted approximately 8 h at a flow rate of 3.52 L h⁻¹ into 1616.5 L h⁻¹ of reservoir water into 1616.5 L h⁻¹ of reservoir water, yielding a daily theoretical dose of 3.89×10^7 oocysts and a total theoretical dose of 3.11×10^8 oocysts (Fig. 1). We used 3000 oocysts L⁻¹ to ensure detectable inlet verification and rare-event breakthrough under 24–96 h composite sampling, to conservatively stress-test SSF performance for risk assessment. This level is well above typical source-water concentrations in most UK source waters.

The dosing solution was prepared by adding 125 mL of a working solution to 28.3 L of reservoir water. The working solution consisted of 1.25 mL of vortexed oocyst stock solution (equivalent to 3.11×10^8 oocysts) suspended in 1 L of phosphate-buffered saline (PBS) containing 0.05 % Tween 20 (Sigma Aldrich, UK), which facilitated oocyst dispersion. The target dose was 3000 oocysts L⁻¹, with a dosing duration (two 4-day weekday periods; $\sim 8 \text{ h d}^{-1}$). Oocysts were visually inspected for integrity by epifluorescence microscopy prior to dosing (Fig. 2). Oocysts were stored less than a year prior to use. The mixture was fed into the SSF inlet through a static mixer and then distributed via a manifold to individual filters. During dosing events, the filters were

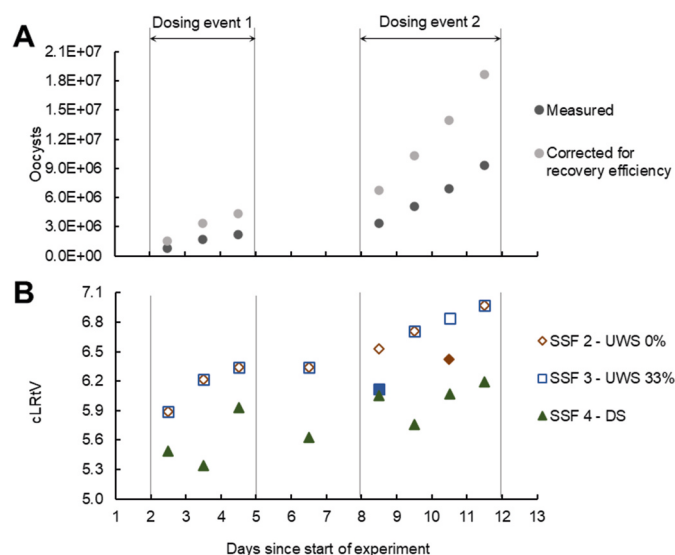


Fig. 1. – (A) Measured and corrected for estimated 50 % recovery cumulative load of inactivated *Cryptosporidium* oocysts dosed per filter over the 2 weeks of dosing (event 1 & 2). (B) Daily cLRtV calculated using the cumulative dose of oocysts for the dosing events and the first 72-h high volume sample (weekend). NB: empty symbols represent the cLRtV for total retention of the dosed oocysts. Full symbols represent data points with oocysts detected in the filtrate. The days indicated represent only the dosing period within the 243-day study.

operated in “non-overflow” mode to ensure equal oocyst distribution among all beds. The inlet flow rate was carefully matched to the outlet flow rate, preventing overflow and a potential uneven distribution of oocysts between adjacent beds. Once each dosing period concluded, the filters were returned to overflow mode for normal operation.

2.5. Sampling and analysis of *Cryptosporidium*

The 56-day experiment comprised four phases: (i) a 10-day dosing phase, (ii) a 24-day post-dosing observation, (iii) a 2-day skimming

event during which all filters were skimmed according to their assigned regimes, and (iv) a 17-day post-skim observation to monitor potential oocyst release. Filtrate from six SSFs (two replicates per skimming condition) was regularly sampled for *Cryptosporidium* oocyst enumeration and water quality analysis.

An industry-standard cumulative sampling technique was used for continuous filtrate monitoring. Each 20-Litre collection vessel contained a submersible pump supplying a constant flow to an IDEXX Filta-Max® cartridge, composed of compressed open-cell foam discs designed to capture *Cryptosporidium* oocysts. Filta-Max cartridges were replaced at 24-h intervals for one SSF per skimming condition and at 96-h intervals for the replicate filter on weekdays; over weekends, cartridges were replaced every 72 h (Table A-2 in supplementary information). The 24-h samples used a flow of 1 L min⁻¹ (approximately 37 % of filtrate outflow, ~1440 L filtered). However, to prevent premature clogging, flow rates for the 72-h and 96-h samples were reduced to 0.5 L min⁻¹ (approximately 18.5 % of filtrate outflow, which corresponds to ~2880 L filtered for 96-h and ~2160 L filtered for 72-h samples).

Daily samples were also collected using a modified 10-Litre standard method to monitor inlet *Cryptosporidium* oocyst concentrations during dosing. To reduce the risk of oocyst spread during handling or transport, these inlet water samples were diluted such that the total oocysts per sample did not exceed 50–60 counts, facilitating accurate enumeration via microscopy. A 15–20 mL subsample from SSF 10’s spiked inlet water, collected 1 h into dosing, was diluted into 10 L of non-chlorinated treated water obtained from a nearby drinking water treatment plant.

Before dosing, a 24-h Filta-Max control sample from SSF 2 (UWS 0 %) confirmed no detectable autochthonous *Cryptosporidium* oocysts in the filtrate of the pilot scale SSFs prior to dosing. Additionally, no oocysts were detected in the inlet reservoir stored raw water samples (N = 63) collected every 2–3 days prior to the start dosing and during the entire duration of the experiment. Oocyst isolation, staining, and enumeration by microscopy followed the Blue Book 234 method (Standing Committee of Analysts, 2014). Samples were kept in the dark at 5 ± 3 °C and analysis commenced as soon as practicable and ideally within 48 h of collection; post-concentration suspensions were stored at 5 ± 3 °C for ≤3 days before IMS/microscopy, with batch positive/negative QC slides processed alongside samples, as specified in Part 14.

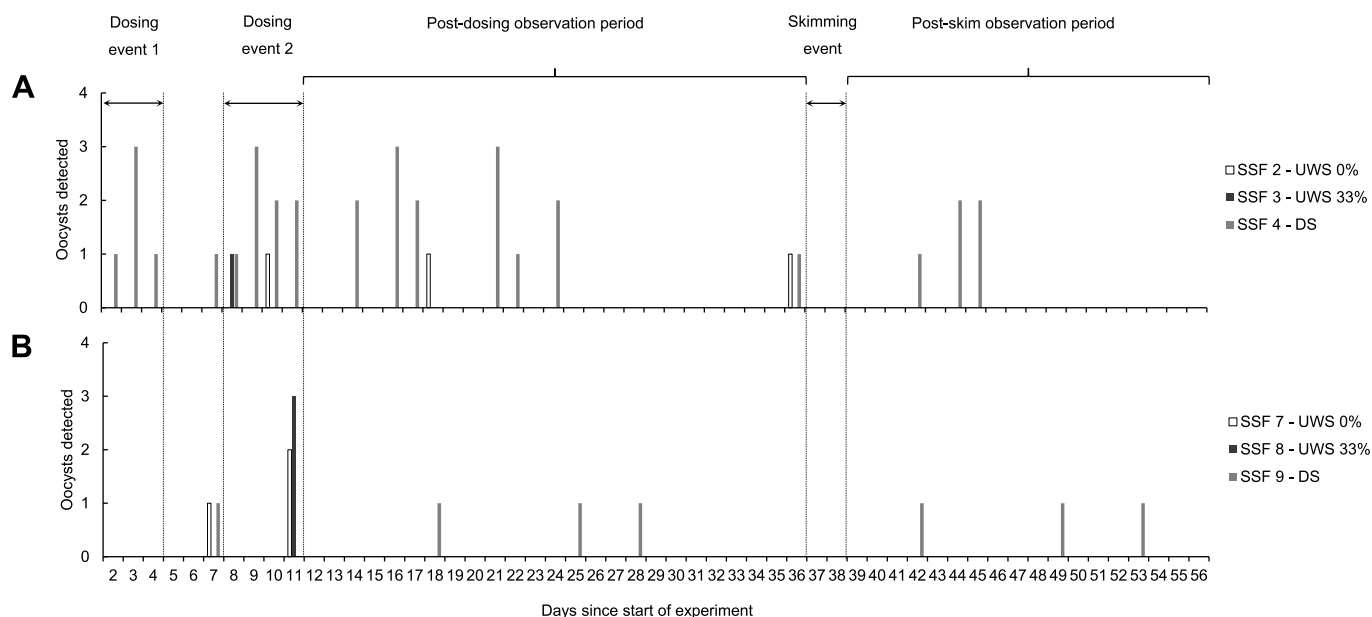


Fig. 2. – *Cryptosporidium* oocysts enumerated per high volume samples in SSF outlet over a sampling period of 24 h (A), which corresponds to ~1440 L filtered, and 96 h (B), which corresponds to ~2880 L filtered. Weekend samples are reported on the last days of the 72-h period (Sunday, ~2160 L filtered). These values represent data that is not adjusted for volume.

Cryptosporidium dosing introduced approximately three particles per millilitre into reservoir water (4–6 µm in size), which was not expected to affect SSF filtration or headloss.

2.6. Water quality parameters

Throughout the experiment samples were taken for physicochemical parameters. Total organic carbon (TOC) was analysed using an O.I. Analytical Carbon Analyzer, Model 1030 (Xylem Inc., Washington, D.C., USA) and inorganic nutrients including ammonium, nitrate, nitrite, and sulphate as well as alkalinity, were quantified using the discrete photometric analyzer Aquakem 600 (Thermo Fisher Scientific, USA). Bacterial analyses including *Clostridium perfringens* (Standing Committee of Analysts, 2010) (Blue Book 230, membrane filtration Tryptose Sulfite Cycloserine medium), Enterococci (Standing Committee of Analysts, 2012a) (Blue Book 237, membrane filtration Slanetz and Bartley (SB) medium), Coliforms and *Escherichia coli* (Standing Committee of Analysts, 2009) (Blue Book 223, Membrane Lactose Glucuronide Agar), and 22 °C heterotrophic plate counts (Standing Committee of Analysts, 2012b) (Blue Book 238, R2A media) were periodically collected to assess overall SSF performance (Table A-3, in supplementary information). Media/reagent lots were QC-checked with appropriate reference strains (target and non-target) before use; incubators, thermometers and balances were monitored/calibrated with records maintained; SOPs and control charts were used for routine checks. Field and laboratory blanks and duplicates were included each sampling round; method blanks accompanied each analytical batch.

2.7. Filtrate composite sampling with Filta-Max® and volume normalisation

Outlet (“filtrate”) was sampled using Filta-Max® capsules as time-composite samplers over preset windows of 24 h, 72 h, or 96 h. Sampler flows were flow-controlled and the actual processed volume for each composite (V_{FM}) was recorded from the inline totaliser at the start and end of each window. The corresponding filter production volume during the same window (V_{OUT}) was calculated using the outlet flow rate.

Post-elution and IMS/IFA microscopy yielded a count of oocysts per analytical batch (N_{FM}). To compare across different composite durations and to account for sampling deviations (e.g., minor flow drift), volume-normalised effluent concentrations were calculated and used for any further analysis.

The measured oocyst concentration was determined using recorded processed volume V_{FM} and the detected number of oocysts from the Filta-Max® N_{FM} .

$$C_{FM} = \frac{N_{FM}}{V_{FM}} \quad (2)$$

The volume-normalised oocysts concentration was obtained by applying a correction coefficient c_v to C_{FM} for each SSF.

$$C_{out} = C_{FM} \times c_v \quad (3)$$

Where the volume correction coefficient c_v is defined as the ratio of the V_{IN} and V_{FM} .

$$c_v = \frac{V_{IN}}{V_{FM}} \quad (4)$$

2.8. *Cryptosporidium* oocyst retention calculation

Most studies report a Log Removal Value based on a simple comparison between inlet and filtrate concentrations. While this approach may be appropriate for membrane processes, where loading is effectively instantaneous, it can be overly simplistic for SSFs. In SSFs, transport, attachment, detachment, and potentially biologically

mediated relocation of oocysts can occur over many hours or days. This complexity can lead to apparent anomalies, such as a negative Log Removal Value if an oocyst appears in the filtrate long after it was last detected in the influent.

A timing issue also arises due to hydraulic considerations. At an approach velocity of 0.3 m h^{-1} , with 0.8 m of filter media and a porosity of ~ 0.4 , plus 0.6 m of water above the filter, it could take approximately 5 h for the first *Cryptosporidium* oocysts to exit if capture efficiency is low. Additionally, while oocysts were dosed for only 8 h under supervision, the minimum Filta-Max sampling time was 24 h from the start of dosing. To address these aspects, a new parameter, the Log Retention Value (LRtV) was introduced to quantify oocyst reduction between the inlet and outlet, accounting for the extended residence times in SSFs. The following equations detail how LRtV was calculated and adjusted for sampling constraints, allowing comparison of different skimming methods for *Cryptosporidium* removal.

$$LRtV = \log_{10} \left(\frac{C_{IN}}{C_{OUT}} \right) = \log_{10} \left(\frac{N_{IN}/V_{IN}}{N_{OUT}/V_{OUT}} \right) \quad (5)$$

Where C_{IN} represents the *Cryptosporidium* oocyst concentration in the inlet over the sampling period, N_{IN} denotes the total number of oocysts in the inlet during this time, C_{OUT} is the concentration of oocysts detected in the filtrate, and N_{OUT} is the number of oocysts measured in the filtrate. For SSFs, the inlet volume is assumed equal to the filtrate volume. A correction coefficient accounts for the portion of the filtrate (e.g., 18 % for 96 h samples, 37 % for 24 h samples) processed by the Filta-Max cartridge, rendering the LRtV independent of the total volume.

The cumulative LRtV over time (t), $cLRtV$, was calculated using sum of dosed oocysts and those recovered in the filtrate:

$$cLRtV(t) = \log_{10} \left(\frac{\sum N_{IN,t}}{\sum (N_{FM,t} \cdot c_{v,t})} \right) \quad (6)$$

Where t is the time since the start of the experiment, c_v the volume correction coefficient and N_{FM} is the oocysts count found in the Filta-Max sample.

If no oocysts were detected in the filtrate, 100 % retention was assumed, yielding $cLRtV = \infty$. For practical comparison with other SSF systems, the $cLRtV$ in these cases was approximated as:

$$cLRtV_{100\%}(t) \Rightarrow \log_{10} \left(\sum N_{IN,t} \right) \quad (7)$$

Finally, no post-skim $cLRtV$ was calculated, as an unknown fraction of the dosed oocysts would have been physically removed along with the Schmutzdecke.

2.9. Quantitative microbial risk assessment

A quantitative microbial risk assessment (QMRA) was conducted assuming a contamination event at a WTW and a consumer population of one million individuals. Neither scenario is common in UK treatment works; however, the QMRA assessed a worst-case scenario wherein SSF was the sole treatment step, with no additional barriers and an elevated *Cryptosporidium* load. Daily water consumption was set at 1.2 L per person, consistent with UK National Health Service guidelines of 6–8 cups per day (NHS, 2024). For the QMRA, all oocysts present in the finished water were considered viable and infectious. The oocyst concentration in the treated water was assumed constant over 24 h, matching the sampling interval. The proportion of immunocompromised individuals was estimated at 3.9 %, based on national statistics for England (Evans et al., 2023).

An exponential dose-response model was used to estimate the probability of infection $P(d)$ from ingesting *Cryptosporidium* oocysts,

relating the risk of infection to the ingested dose:

$$P(d) = 1 - e^{-rd} \quad (8)$$

Where r is the dose-response parameter and d the ingested dose of oocysts.

Two values of r were used: $r = 0.00419$ for immunocompetent individuals, based on a study in which healthy volunteers ingested varying doses of *Cryptosporidium* oocysts (DuPont et al., 1995) and $r = 0.354$ for immunocompromised individuals, derived from studies involving immunocompromised mice (Yang et al., 2000).

The daily probability of infection for skimming regime i was calculated using:

$$P_{daily,i} = 1 - e^{-rd_i} \quad (9)$$

where d_i is the corresponding daily oocyst dose derived from measured breakthrough in the filtrate. The infection probability over a specific phase, P_{phase} was determined by combining daily risks over that period:

$$P_{phase,i} = 1 - \prod_{phase} (1 - P_{daily,i}) \quad (10)$$

For the annual probability of infection, P_{yearly} the average daily risk was used:

$$P_{yearly,i} = 1 - (1 - P_{avg,i})^{365} \quad (11)$$

To account for the likelihood of developing clinical cryptosporidiosis, the probability of illness, $P_{illness}$ was calculated:

$$P_{illness,i} = P_{ill,inf} \times P_{y,i} \quad (12)$$

Where $P_{ill,inf}$ represents the probability of developing symptoms after infection at 0.7 for immunocompetent individuals and 1.0 for immunocompromised individuals (Limaheluw et al., 2019). The overall health impact was quantified, using the Disability-Adjusted Life Years (DALYs), which combines years of life lost (YLL), and years lived with disability (YLD):

$$DALY = YLL + YLD \quad (13)$$

The YLL was calculated as:

$$YLL = N_{death} \times L_{death} \quad (14)$$

Where the $N_{death} = 10^{-5}$ persons represents the number of deaths due to cryptosporidiosis in developed countries and $L_{death} = 13.2$ years is the standard life expectancy at the age of death (Havelaar and Melse, 2005).

$$YLD = I_{illness} \times DW_{illness} \times L_{remission} \quad (15)$$

Where the Incidence of illness, $I_{illness}$ is defined as:

$$I_{illness} = N_{pop} \times P_{illness,i} \quad (16)$$

$DW_{illness} = 0.067$ is the disability weight for watery diarrhoea (Global Burden of Disease project), and $L_{remission} = 0.02$ years (7.2 days) is the average illness duration from outbreak data (Havelaar and Melse, 2005). For N_{pop} , a consumer base of 1,000,000 was assumed. The final DALY values were expressed per 1000 cases of cryptosporidiosis, providing a comparable metric of disease burden linked to this water supply.

The parametric uncertainty in the QMRA was quantified with a 10,000-iteration Monte Carlo simulation and assessed influence with one-way sensitivity analyses, carried out separately for DS, UWS 0 %, and UWS 33 %. For each iteration the independent inputs were sampled from literature-informed distributions: dose-response coefficients for immunocompetent and immunocompromised cohorts (lognormal, geometric means 0.00419 and 0.354 with a geometric standard deviation of 1.8), the viable fraction of oocysts (Beta scaled to 0.25–1.0), daily water intake (truncated Normal, mean 1.2 L d⁻¹, SD 0.3, bounds 0.6–2.0 L d⁻¹), the probability of illness given infection (Beta with mean 0.7, SD

0.1 for immunocompetent; mean 0.98, SD 0.02 for immunocompromised), disability weight for watery diarrhoea (triangular 0.04–0.11; mode 0.067), and illness duration (lognormal with median 7.2 days and 95 % range ~4–14 days, converted to years). Mortality per case was set at 10⁻⁵ with 13.2 years of life lost. Population was partitioned as 96.1 % immunocompetent and 3.9 % immunocompromised. For each filter, the observed daily ingestion series from the filtrate dataset (computed at a baseline intake of 1.2 L day⁻¹) was rescaled by the sampled intake and viable fraction, and daily infection and illness probabilities were computed using the exponential model; these were averaged across observed days to obtain an average daily illness probability, then converted to an annual individual risk and multiplied by cohort sizes to yield expected annual cases. DALYs were calculated as cases times the sampled per-case burden (Eq. (13)–(16)). Medians and 95 % uncertainty intervals (UI, 2.5th–97.5th percentiles) for annual risk, cases, and total DALYs were reported. One-way sensitivity (“tornado”) analyses held all parameters at their Monte Carlo medians and varied each parameter individually across its 5th–95th percentile range, recording the change in total DALY to rank influences. Implementation was performed in Python (NumPy/Pandas/Matplotlib) with 10,000 iterations and a fixed random seed (42), and truncated normals generated via rejection sampling. A separate analytical-recovery term was not included, as the ingestion series already reflect measured concentrations and adding recovery would double-count that effect.

2.10. Statistical analysis

To evaluate whether *Cryptosporidium* oocyst retention correlates with water quality or bacteriological indicators, all data points corresponding to positive oocyst detections were examined and matched to the associated water quality parameters of interest. Prior to analysis, data distributions were checked for normality (e.g., via a Shapiro–Wilk test: $W(37) = 0.96$, $p = 0.266$). Where normality assumptions and sphericity were satisfied, the Pearson correlation coefficient (r_p), the one sample t-test and two-factor ANOVA with replication were calculated. Statistical analysis and QMRA were undertaken in Microsoft Excel.

3. Results and discussion

3.1. Treatment performance

In this study, the filter maturation period was defined on the basis of specific criteria: filtrate coliform (<100 MPN 100 mL⁻¹), *Escherichia coli* (<10 MPN 100 mL⁻¹), intestinal Enterococci (<10 CFU 100 mL⁻¹) and *Clostridium perfringens* (0 CFU 100 mL⁻¹), together with a turbidity threshold of <0.3 NTU, which is the operational target for the WTW. All ten SSF satisfied these criteria ($N = 30$) and were deemed ‘mature’ before the first dosing event commenced, which occurred three to four days after a skim. The observed maturation period aligned with that of full-scale slow SSFs in London (UK), with no significant differences detected between DS and UWS filters regarding filtrate pH (two factor ANOVA with replications $F(2, 60) = 2.375$, $p = 0.11$), or TOC levels (two factor ANOVA with replications $F(2, 138) = 3.081$, $p > 0.05$) (Table A-1, in supplementary information). Furthermore, turbidity reduction during the dosing experiment remained consistent with pre- and post-challenge conditions for all SSFs, indicating that the *Cryptosporidium* dosing did not adversely impact SSF performance (Fig. 3). Although the average ($\pm$ s.d) inlet turbidity during dosing was relatively low (0.6 ± 0.66 NTU), all SSFs achieved approximately a ten-fold reduction, yielding filtrate turbidity values ranging from 0.08 to 0.09 NTU (Table A-1 in supplementary information).

Headloss development during Cycle 3 of the dosing experiment (75–158 days since the last re-sanding) was consistent with pre-dosing observations for both UWS and DS filters (Fig. 4). Over the first 35 days of Cycle 3, the viscosity-normalised headloss increased gradually for all six monitored SSFs. The daily rate of headloss increase ranged

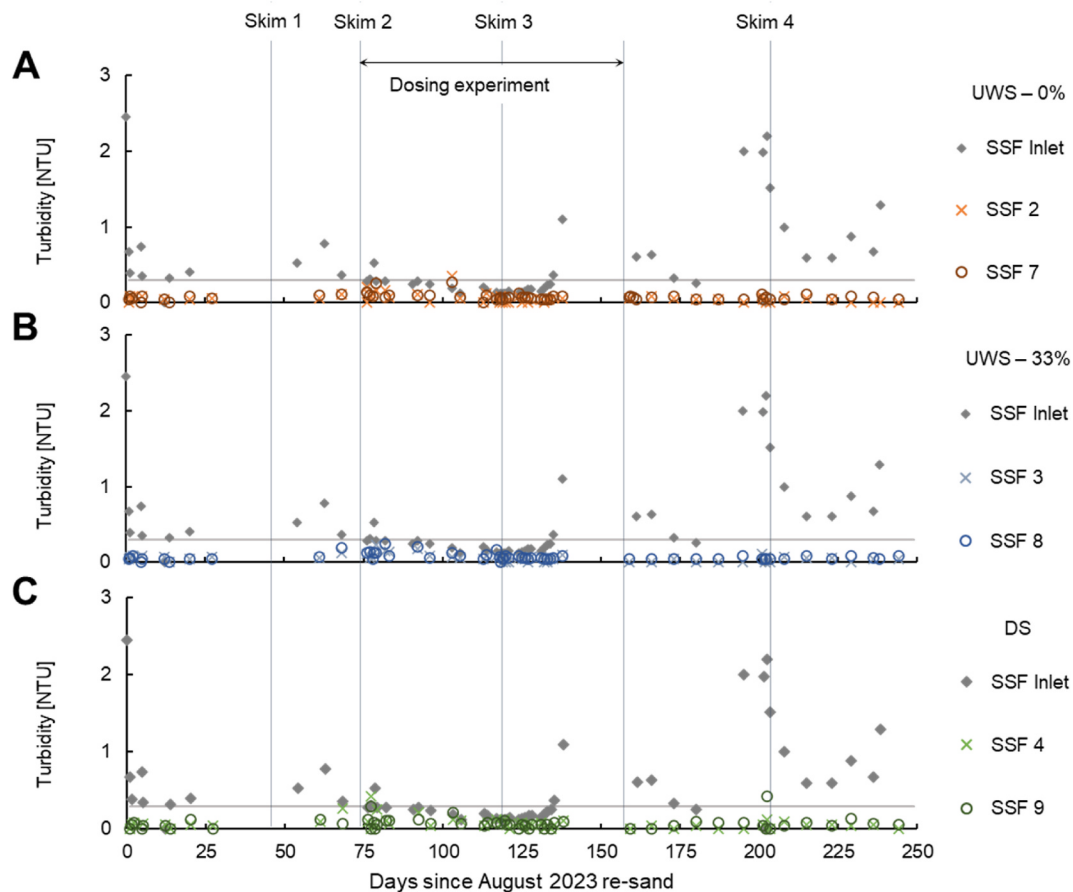


Fig. 3. – Turbidity reduction post SSF over the 6 cycles since the re-sand beginning Aug 2023 for duplicate skimming regime SSF beds: UWS 0 % (A), UWS 33 % (B) and DS (C). The WTW operational target is set to 0.3 [NTU] (grey line on graphs) Skimming events are indicated by the dashed lines.

from 2.4 to 2.8 mm d⁻¹ for UWS 0 %, 2.6–5.3 mm d⁻¹ for UWS 33 %, and 3.3–3.4 mm d⁻¹ for DS filters (Table 1). None of the filters reached terminal headloss indicative of clogging. The cycle was deliberately shortened just before reaching 40 days and all filters were skimmed, allowing a 17-day post-skim observation period to monitor oocyst release before the experiment was concluded. During the post-skim observation period (Cycle 4, day 119–201), headloss build-up remained gradual. In SSF 2 and SSF 8, this low-rate phase lasted approximately 40 days, with a daily headloss increase ranging from 5.5 to 8 mm d⁻¹. In contrast, SSF 3, SSF 4, and SSF 9 maintained a low-rate phase for about 70 days, with increases of 4.8–5.6 mm d⁻¹. Eventually, all filters entered a clogging phase where the headloss rose sharply to 27.9–46.1 mm d⁻¹. Uniquely, SSF 7 required an additional mid-cycle skim at day 158.

In previous periods of operation, UWS filters exhibited exponential headloss increases near terminal headloss, unlike DS filters, which were skimmed earlier in the gradual headloss development phase, triggered by a single SSF reaching terminal headloss regardless of other filters' status. Had DS filters not been skimmed prematurely, they would likely have shown a similar rapid rise in headloss. The shorter interval to maximum headloss in UWS beds may stem from less efficient fine-particle removal during underwater skimming (assuming comparable <0.5 NTU loading) and/or enhanced biofilm retention, faster recovery, or additional biofilm development under gentler conditions. Despite these variations, performance remained consistently high throughout the study. Once filters attained a stable, mature operating condition (i.e., “steady-state”), UWS presented no risk of compromising treatment efficacy—even at different sweetening flows (0 % or 33 %). These findings align with prior research indicating that once SSFs are fully matured, their performance remains consistent regardless of cleaning

method (de Souza et al., 2021; Elemo et al., 2024; Hassard et al., 2022).

3.2. *Cryptosporidium* dosing and retention in SSF

The cumulative concentration of inactivated *Cryptosporidium* oocyst dosed during the two events was quantified using grab samples (Fig. 1) which showed that in dosing event 1, approximately 7.32×10^5 oocysts were added daily, culminating in a total of 2.2×10^6 oocysts by the end of the event. A similar pattern was observed in dosing event 2, with daily additions of about 1.8×10^6 oocysts, reaching a cumulative total of 9.34×10^6 oocysts per SSF by the end of dosing event 2.

The pilot-scale SSFs exhibited high *Cryptosporidium* oocyst retention efficiency. Across the entire study, only 50 oocysts were detected in the filtrate, representing a mere 0.0004 % of the total oocysts dosed. The highest daily oocyst count in the filtrate was 3 oocysts, observed in both 24-h (36 % of flow) and 96-h (18 % of flow) high-volume samples (Fig. 2). During the initial 11 days (encompassing both dosing events), oocyst breakthrough was detected in all SSFs. DS SSF 4 exhibited daily breakthroughs, averaging approximately 2 oocysts per day, totalling 14 oocysts over the period. By contrast, just one oocyst was detected in SSF 2 (UWS 0 %) and SSF 3 (UWS 33 %) each in that period (Fig. 2A). In weekly 96-h samples, fewer breakthroughs were noted: SSF 8 (UWS 33 %, replicate of SSF 3) showed a maximum of 3 oocysts, as did SSF 7 (UWS 0 %, replicate of SSF 2), while SSF 9 (DS, replicate of SSF 4) recorded just one oocyst in a 72-h weekend sample (Fig. 2B). In the post-dosing phase, oocyst breakthrough continued. SSF 4 (DS) had a total of 14 oocysts detected, averaging approximately 1 oocyst per day during the first two weeks after dosing ceased. Its duplicate, SSF 9 (DS), exhibited fewer breakthroughs, with a total of 3 oocysts detected over the 25-day post-dosing period. SSF 3 and its duplicate SSF 8 showed no

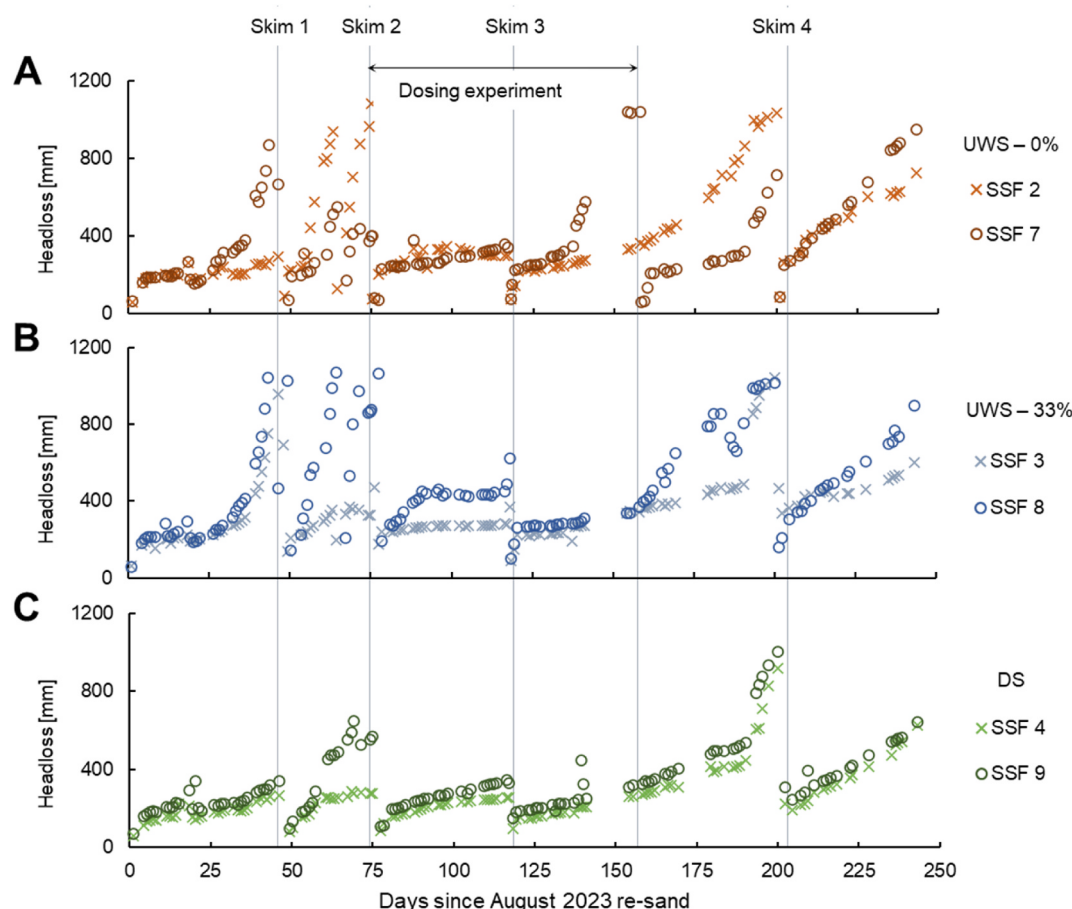


Fig. 4. – Change in normalised headloss measurements over the 6 cycles since the re-sand beginning Aug 2023 for duplicate skimming regime SSF beds: UWS 0 % (A), UWS 33 % (B) and DS (C). Skimming events are indicated by the dashed lines.

Table 1

– Average slow and fast rates of headloss development [mm/d] in each SSF since the last re-sand in Aug 2023. Derived from constants from log-linear regression of headloss curves.

	Days of operation	UWS 0 %		UWS 33 %		DS	
		SSF 2	SSF 7	SSF 3	SSF 8	SSF 4	SSF 9
Cycle 1	4–22	1.2	0.8	1.8	1.4	2.5	1.5
	26–46	4.5	37.4	36.2	34.3	4.2	6.1
Cycle 2	49–75	33.4	8.2	13.1	35.7	7.7	18.4
Cycle 3	78–118	2.4	2.8	2.6	5.3	3.3	3.4
Cycle 4	119–134	5.5	10.4	5.6	8.0	4.8	5.4
	137–158	5.5	29.5	5.6	8.0	4.8	5.4
	159–190	16.7	3.8	5.6	21.9	4.8	5.4
	193–201	16.7	36.2	27.9	21.9	46.1	31.6
Cycle 5	202–228	11.2	16.9	4.8	15.5	7.5	11.1
	228–243	11.2	16.9	11.7	24.6	19.2	11.1

oocyst detections, while SSF 2 (UWS 0 %) had only 2 oocysts detected. Following the skimming event, oocysts were detected only in SSF 4 and SSF 9, with 5 and 3 oocysts, respectively. These results emphasise the consistently high pathogen removal efficiency of the SSF, despite elevated oocyst loading rates. Furthermore, the variability between filter replicates highlights the importance of operational factors, such as skimming technique in minimising pathogen breakthrough.

To calculate the cLRtV, filtrate counts were scaled to the total volume passing through each filter over the sampling period and then compared

with the cumulative oocyst dose by the end of that interval. The averaged cLRtV for all SSFs during the dosing experiment was 5.52, rising from 5.34 at the outset to over 6.97 by its conclusion (Fig. 1B). In SSF 2 (UWS 0 %) and SSF 3 (UWS 33 %), the near-complete absence of detected oocysts for most of the experiment was treated as 100 % retention. Post-dosing cLRtVs, calculated under the assumption that no oocysts were removed or escaped other than by filtration, ranged from 5.74 to 5.94 in DS beds and from 6.24 to over 6.97 in UWS filter beds (Table 2).

Comparable studies have reported wide variability in *Cryptosporidium* retention by SSFs. For instance, an Log Removal Value of 0.3 was observed under cold conditions with relatively coarse sand, likely reflecting diminished straining and lower biological activity (Fogel

Table 2

– Average cumulative log retention values (cLRtV) with standard deviation for 24-h and 96-h high volume samples during dosing events.^a Only includes samples during the post-dosing observation phase, oocysts detected post-skim are not included in this calculation.

	24-h samples			96-h samples		
	UWS 0 %	UWS 33 %	DS	UWS 0 %	UWS 33 %	DS
Dosing event 1	>6.15 ± 0.23	>6.15 ± 0.23	5.59 ± 0.31	>6.34	>6.34	>6.34
Weekend 1	>6.34	>6.34	5.63	5.62	>6.34	5.58
Dosing event 2	6.66 ± 0.24	6.66 ± 0.39	6.02 ± 0.18	5.94	5.77	>6.97
Post-dosing ^a	6.24	>6.97	5.94	>6.97	>6.97	5.74

et al., 1993), whereas an Log Removal Value of 5.3 was reported in a mature SSF (Hijnen et al., 2007). In this present pilot study, extended operation (2.5 years) promoted a well-developed biofilm/SSF ecosystem, leading to retention efficiencies higher than most previously published SSF trials. Nevertheless, the filtered water still contained oocyst concentrations one to two orders of magnitude above the WHO health-based target for *Cryptosporidium* in drinking water (of 10^{-5} oocysts L^{-1} (WHO, 2017), consistent with the challenge posed by an elevated oocyst dose. The WHO health-based target (10^{-5} oocysts per litre) is so small that, when applied to typical volumes, it yields a fractional expected count e.g., 1.2×10^{-5} oocysts for a person-day (1.2 L) and only 0.014–0.029 oocysts for 24–96 h composite samples (1440–2880 L); “fractional” here means that across many such samples most would contain zero oocysts and only rarely would one contain a single oocyst. Because the target implies far fewer than one oocyst per large sample, observing even one oocyst in these composites back-calculates to $\sim 3.5\text{--}6.9 \times 10^{-4}$ oocysts- L^{-1} , about 35–69 $\times$ higher than the target, so a one-oocyst detection by itself indicates exceedance (Table A-4). This highlights the need for multiple treatment barriers in drinking water treatment.

3.3. Comparative analysis of *Cryptosporidium* oocysts retention between UWS versus DS

The filtrate samples indicate that SSFs employing UWS capture and retain *Cryptosporidium* oocysts more effectively than those using DS. During the dosing events (first 11 days), only 12.5 % of 24-h high-volume samples from UWS 0 % and UWS 33 % filters tested positive, compared to a 100 % positivity rate in the DS filter, which also yielded a positive 72-h weekend sample following the final dosing day (Fig. 2A). This pattern is also reflected in the cLRTVs calculated for the dosing events, with UWS filters consistently achieving average cLRTVs above 6 (Table 2). All 96-h samples were oocyst free during the first dosing week; however, during the second dosing event, 3 and 2 oocysts were detected in the weekly 96-h samples from UWS 33 % and UWS 0 % filters, respectively (Fig. 2B), while no oocysts were detected in the DS filtrate—indicating 100 % retention (cLRTV >6) for the DS filter during this period. However, the cLRTVs for UWS filters in the 96-h high-volume samples dropped below 6, with a minimum of 5.58 (Fig. 2B).

During the post-dosing observation phase, positive oocyst detections were predominantly observed in DS filtrate, with 41.2 % of 24-h high-volume samples containing at least one oocyst. In contrast, only two oocysts (11.8 % of 24-h samples) were detected in the UWS 0 % filtrate, and no oocysts were detected in UWS 33 % filters. The 96-h samples corroborated this trend, yielding three positive samples from DS filters during the same period (Fig. 2B).

Furthermore, the daily oocyst retention capacity during the post-dosing phase was markedly higher for UWS filters than for DS filters. In DS filters, 47 % of both 24-h and 96-h samples were positive, with peak filtrate concentrations exceeding 2 oocysts L^{-1} . In contrast, UWS filters exhibited lower positive detection frequencies, ranging from 7.9 % to 13.3 % for UWS 0 % (24-h and 96-h samples) and from 2.6 % to 6.7 % for UWS 33 % filters (Table 3). No oocyst breakthroughs were observed during the skimming event, and post-skimming detections were again confined to DS filters (3 positive samples from each DS filter). These results show the superior performance of UWS in maintaining oocyst retention during extended post-dosing operations, thereby reducing the risk of pathogen breakthrough.

Skimming events are notable disturbances for SSFs, as they remove a substantial portion of the microbiome from the Schmutzdecke (Maiyo et al., 2023) and, in the case of DS, expose the aquatic ecosystem of the filter to air, potentially causing desiccation and compromising filter integrity. However, data collected during and after skimming suggest that the event did not result in a major release of retained oocysts into the filtrate; one oocyst was detected each DS filter from the 72-h high-volume sample initiated 48 h post-skimming, and no oocyst

Table 3

– Frequency and concentration of oocysts breakthrough and percentage of filtrate sampled for each skim regime and sampling period (24- and 96-h) high volume samples.^a Excluding 72-h (weekend) samples.

	24-h samples			96-h samples		
	UWS 0 %	UWS 33 %	DS	UWS 0 %	UWS 33 %	DS
Max. oocysts conc. [oocysts L^{-1}]	7.4×10^{-4}	6.9×10^{-4}	2.32×10^{-3}	7×10^{-4}	1.04×10^{-3}	5.3×10^{-4}
Max. oocysts per sample	1	1	3	2	3	1
Frequency of positive detections [%]	7.89	2.56	47.37	13.33	6.67	46.67
Number of samples	38	39	38	15	15	15
Subsample for high volume sampling [%] ^a	37.52	38.07	37.41	19.45	19.03	17.66

breakthroughs were detected in UWS filters. These findings suggest that SSFs could potentially be operated continuously using UWS (i.e., without flow interruptions) (Elemo et al., 2025), provided the filters maintain a mature macro- and microfauna (Haig et al., 2014). Future work should explore whether SSFs with less established ecosystems would exhibit similar oocyst release patterns.

3.4. Delayed oocyst breakthrough: mechanisms and treatment implications

Cryptosporidium oocysts were detected in the filtrate up to 45 days after dosing ceased in DS beds and up to 25 days in UWS 0 % beds (Fig. 2A). In DS beds, ten breakthrough events resulted in 19 oocysts detected post-dosing and 12 oocysts during the post-dosing phase (across six events in the first two weeks) and five during the post-skimming phase. Delayed breakthroughs were also observed in the 96-h high-volume samples (Fig. 2B). In UWS 0 % beds, only two oocysts were detected post-dosing: one approximately a week after dosing and another one day before skimming. No additional breakthroughs were observed in UWS 33 % beds following the second dosing event. These delayed breakthroughs lacked a consistent pattern. While post-skimming releases might be attributed to disturbances caused by the skimming process, the pre-skimming breakthroughs appeared sporadic. The persistence of oocyst detections after the inlet concentration had dropped to zero suggests that, although SSFs are highly retentive, they are not absolute barriers; occasional oocyst release may occur due to delayed migration of retained oocysts.

This observation raises important questions about the fate and distribution of retained oocysts within SSFs. Captured oocysts may be influenced by physical or biological processes that affect their integrity or facilitate their movement through the filter media (Fayer et al., 2000; Scheid and Schwarzenberger, 2011). The elevated oocyst concentrations used in this study, higher than typical environmental levels, may have increased the likelihood of breakthroughs. Despite the low number of detections, sampling 18–37 % of the filtrate provides a substantial representation of the total filtrate volume and risks of pathogen detection which reduces sampling bias and increases the likelihood of detecting rare oocysts. In contrast, analysing only 0.001 % of the water, typical in large-scale UK facilities, raises the risk of missing oocysts entirely, potentially leading to an overestimation of the filter's removal efficiency. Thus, by sampling a higher percentage of the filtrate, this method provided a more accurate and representative estimate of overall pathogen removal, ensuring that even low-level breakthrough events were captured and quantified.

3.5. Impact of oocyst breakthrough on slow sand filter performance

To assess whether *Cryptosporidium* oocyst breakthrough coincided with fluctuations in water quality, key parameters including headloss, TOC, nutrient concentrations, and bacteriological removal rates were monitored. Statistical analysis showed no significant correlation between oocyst concentration in filtrate and headloss variations in either UWS 0 % filters (Pearson's r (21) = 0.01, p = 0.963) or DS filters (Pearson's r (21) = 0.12, p = 0.574) from the onset of dosing until skimming. TOC removal exceeded the expected 30 % observed in mature SSFs, with consistent performance across all filters and no significant differences between skimming regimes. Two factor ANOVA $F(2, 138)$ = 3.081, p > 0.05. Alkalinity, nitrate, and sulphate concentrations remained stable before and after filtration, while a slight increase in nitrite levels was observed, likely reflecting ammonia transformation by nitrification. Bacteriological analyses revealed significant reductions in *C. perfringens* (One Sample T Test (M = 1.67 t (32) = 5.35 p < 0.001)), Enterococci (One Sample T Test (M = 14.65 t (33) = 2.2 p < 0.05)), coliforms (One Sample T Test (M = 108.53 t (35) = 2.2 p < 0.001)), and *E. coli* (One Sample T Test (M = 18.61 t (35) = 2.2 p < 0.003)) across all filters, except for SSF 9 for Enterococci (One Sample T Test (M = 14.65 t (33) = 1.5 p = 0.147)), where bacterial removal was less consistent post-skim prior to the start of the dosing experiment.

Despite these variations, no statistical correlation was found between oocyst breakthrough and bacterial removal efficiencies or nutrient reductions in either UWS 0 % or DS filters. A control sample from SSF 2 (UWS 0 %) collected prior to dosing confirmed that the filters were not releasing autochthonous oocysts. Furthermore, no *Cryptosporidium* oocysts were detected in the regulatory samples of the raw feed water to the treatment works and the pilot plant over the duration of the experiment.

3.6. Quantitative microbial risk assessment

Using an exponential dose-response model, the daily probability of illness due to occasional *Cryptosporidium* oocyst breakthrough in the filtrate was assessed. The sporadic detection of a single oocyst in approximately 1.5 m³ of filtered water observed during both dosing and post-dosing periods for both the UWS 0 % and UWS 33 % filters resulted in daily illness probabilities ranging from 2.4×10^{-6} to 2.6×10^{-6} for immunocompetent individuals. The daily illness probabilities for immunocompromised individuals were higher, ranging from 2.8×10^{-4} to 3.1×10^{-4} . In a hypothetical consumer base of one million people, including 3.9 % immunocompromised individuals, these estimates translate to approximately 2 immunocompetent and 11 immunocompromised cases of cryptosporidiosis on days when breakthrough occurs (Table 4).

For DS, across the dosing, post-dosing, and post-skimming phases, the daily probability of illness for immunocompetent individuals ranged

from 1.6×10^{-6} to 8.2×10^{-6} (corresponding to 2–8 symptomatic cases), while for immunocompromised individuals it ranged from 1.9×10^{-4} to 9.9×10^{-4} (approximately 8–38 cases). The higher daily risk observed for DS filters is attributable to breakthrough events detecting up to three oocysts in the filtrate, compared to the occasional single oocyst in UWS filters. The immunocompromised population is particularly vulnerable, with illness probabilities roughly 100 times higher than for immunocompetent individuals across both skimming regimes, consistent with findings by Cummins et al. (2010), who reported daily risks of 4.79×10^{-6} for healthy individuals and 6.02×10^{-4} for immunocompromised individuals using an exponential dose-response model.

Cumulative illness probabilities over the dosing, post-dosing, and post-skimming phases reflect these daily risks. The highest risk was observed during dosing for DS filters (Table 4), where probabilities of illness reached 5.52×10^{-5} for immunocompetent individuals (approximately 34 cases) and 4.24×10^{-3} for immunocompromised individuals (about 165 cases). During the post-dosing phase, risks decreased slightly to 3.2×10^{-5} (31 cases) for immunocompetent individuals and 3.86×10^{-3} (151 cases) for immunocompromised individuals, with further reduction post-skimming due to fewer breakthrough events. For UWS filters, oocyst breakthroughs post-dosing doubled the risk for immunocompetent individuals—from 2.41×10^{-6} during dosing to 5.18×10^{-6} post-dosing, with expected cases increasing from 2 to 5. Similarly, the risk increased for immunocompromised individuals from 2.91×10^{-4} to 6.26×10^{-4} , and the expected number of cases increased from 11 to 24.

Yearly, the probability of illness for an individual consuming the filtered water ranged from 2.26×10^{-5} for UWS 33 % filters to 7.08×10^{-5} for UWS 0 % filters (Table 5). In contrast, DS filters exhibited a tenfold higher risk, reaching 7.18×10^{-4} , corresponding to approximately 690 cases of cryptosporidiosis per year among immunocompetent consumers—while immunocompromised individuals faced illness probabilities 100 times greater (up to 8.51×10^{-3} , or an estimated 3239

Table 5

Yearly probability of illness, incidents in model population of 1,000,000 individuals (including 3.9 % immunocompromised) and DALY per 1000 cases for UWS and DS slow sand filtration.

	Immuno-competent			Immuno-compromised		
	UWS 0 %	UWS 33 %	DS	UWS 0 %	UWS 33 %	DS
Yearly Probability of illness P_{yearly}	7.08×10^{-5}	2.26×10^{-5}	7.18×10^{-4}	8.51×10^{-3}	2.72×10^{-3}	8.31×10^{-2}
Incidents of illness	68	22	690	332	106	3239
DALY [1000 cases ⁻¹]	87.6	28.0	887.0	426.5	136.6	4162.4

Table 4

– Probability of illness from *Cryptosporidium* oocysts breakthrough and incidents of cryptosporidiosis in model population of 1,000,000 individuals (including 3.9 % immunocompromised) for dosing, post-dosing and post-skim periods for UWS and DS slow sand filtration.

		Immunocompetent			Immunocompromised		
		Dosing	Post-dosing	Post-skim	Dosing	Post-dosing	Post-skim
UWS	Daily Probability of illness P_{daily}	2.38×10^{-6} - 2.41 $\times 10^{-6}$	2.57×10^{-6} - 2.62 $\times 10^{-6}$	–	2.87×10^{-4} - 2.91 $\times 10^{-4}$	3.1×10^{-4} - 3.16 $\times 10^{-4}$	–
	Probability of illness during period P_{phase}	2.38×10^{-6} - 2.41 $\times 10^{-6}$	5.18×10^{-6}	–	2.87×10^{-4} - 2.91 $\times 10^{-4}$	6.26×10^{-4}	–
	Incidents of illness I_{illness}	2	5	–	11	24	–
DS	Daily Probability of illness P_{daily}	1.61×10^{-6} - 8.16 $\times 10^{-6}$	2.41×10^{-6} - 7.67 $\times 10^{-6}$	4.74×10^{-6} - 4.79 $\times 10^{-6}$	1.94×10^{-4} - 9.85 $\times 10^{-4}$	2.9×10^{-4} - 9.25 $\times 10^{-4}$	5.72×10^{-4} - 5.79 $\times 10^{-4}$
	Daily incidents of illness I_{illness}	2–8	2–7	≤5	8–38	11–36	22–23
	Probability of illness during period P_{phase}	5.52×10^{-5}	3.20×10^{-5}	9.53×10^{-6}	4.24×10^{-3}	3.86×10^{-3}	1.15×10^{-3}
	Incidents of illness I_{illness}	34	31	9	165	151	45

cases annually). These values are lower than those reported by Cummins et al. (2010), who found yearly probabilities ranging from 1.75×10^{-3} for immunocompetent individuals to 1.9×10^{-1} for immunocompromised individuals under higher oocyst contamination levels in Irish source water treated by conventional slow sand filtration followed by chlorination.

A similar trend is observed in the calculated DALYs, with values ranging from 28 to 87.6 for UWS filters and up to 887 per 1000 cases for DS filters among immunocompetent individuals (and even higher for immunocompromised individuals; DALYs range from 136 to 426 for UWS filters, peaking at 4162). Though these DALY values are higher than the burden of disease calculated for the Netherlands, 1.47 per 1000 cases (Havelaar and Melse, 2005), the difference is not statistically significant (One Sample T Test, $p = 0.139$ exceeding $\alpha = 0.05$), but reflects the greater initial oocyst load in this study ($3000 \text{ oocysts L}^{-1}$, ~ 1000 times higher than typical concentrations in UK surface waters, averaging over 5 oocysts L^{-1}). These results are more comparable to disease burdens reported for lower-income countries (Limaheluw et al., 2019).

Using 10,000-draw Monte Carlo (with a population split of 96.1 % immunocompetent and 3.9 % immunocompromised), UWS consistently outperformed DS. The median total yearly probability of illness (95 % UI) was 0.143 (0.040–0.541) for UWS 33 %, 0.447 (0.125–1.686) for UWS 0 %, and 4.446 (1.255–15.859) for DS, which correspond to the following annual incidents of illness 94 (31–297), 294 (96–924), and 2919 (966–8623) respectively.

Risk-reduction ratios were large and precise where DS:UWS 33 % ≈ 31.1 (28.9–31.7) and DS:UWS 0 % ≈ 9.93 (9.27–10.10) and remained stable across assumptions. One-way tornado analyses (Figure A-3, in supplementary information) identified immunocompromised dose-response (r_{im}), illness duration (L_{years}), and the viable fraction of oocysts (v) as the dominant drivers. Disability weight (DW) and water intake (Q) contributed moderately and immunocompetent dose-response (r_{comp}) and the probability of symptomatic infection for both immunocompromised ($P_{ill_{im}}$) and competent ($P_{ill_{ic}}$) populations had smaller effects. This order and pattern of dominant drivers was observed for all three skim regimes with different resulting total DALY values, ranging from 0.05 to 0.35 for UWS 33 %, from 0.15 to 1.1 for UWS 0 % and from 1.51 to 10.4 for DS (Figure A-3). The results were robust under uncertainty but reflected a single-barrier, independent-parameter framing. A multi-barrier or correlated-parameter scenario would likely widen the intervals without changing the UWS < DS ordering.

Although such acute oocyst concentrations in raw water are unlikely to occur under natural conditions, this QMRA highlights the potentially severe public health consequences of oocyst breakthrough in finished water. While healthy adults generally recover from cryptosporidiosis, vulnerable populations, such as infants, the elderly, and immunocompromised individuals, face considerably higher risks of severe illness or mortality. It is important to note that this risk estimation does not reflect current water industry practices, where slow sand filtration is typically complemented by additional treatment processes before distribution. International guidelines consider an acceptable microbial risk in drinking water to be one case per 10,000 individuals per year (1×10^{-4} annual risk) (WHO, 2017). Overall, these findings highlight the need to optimise filtration practices to minimise oocyst breakthrough and protect public health, particularly for vulnerable groups. By aligning water treatment practices with the natural ecology of the system, such as preserving beneficial biofilms and minimising disruptive interventions, facilities could achieve improved pathogen removal, increased water throughput, and enhanced regulatory compliance. This ecologically compatible approach ultimately supports more resilient and efficient water treatment operations.

3.7. Implications and future work

Precise estimates of *Cryptosporidium* dosing and retention are vital for evaluating SSF performance, especially under challenging operational or high-loading conditions. By comparing both the measured and corrected oocyst loads, this study highlights potential underestimations in filter efficacy, indicating that current sampling and analysis methods may overlook removal capacity. Ultimately, more accurate recovery assessments can inform improved maintenance and design practices, such as tailoring skimming strategies, thereby reinforcing the multiple-barrier approach to drinking water treatment. Moreover, translating these conservative estimates into risk models shows how SSF-based treatment systems can aid in preventing *Cryptosporidium* outbreaks or compliance issues, especially where conventional disinfection (e.g., chlorine treatment) is insufficient.

Further studies should include the investigation of the vertical distribution of oocysts in the SSF media, as well as biofilm development over time. Evaluating higher loading challenges would help establish the upper operational limits of SSF. Examining filters shortly after re-sanding would clarify the role of filter maturity in oocyst retention, providing insights into how quickly filters recover their full protective capacity. Additionally, assessing the reliability of conventional microbiological indicators (e.g., coliform bacteria) in predicting *Cryptosporidium* breakthrough is warranted, given existing evidence of limited correlation. This could be coupled with investigations into the effect of sample volume relative to total flow, to determine whether larger sample proportions might improve detection rates and enhance risk assessments. Finally, addressing uncertainties in recovery efficiency, for instance, would offer a more accurate understanding of SSF performance and strengthen the validation of oocyst removal estimates.

4. Conclusion

This study demonstrates that underwater skimming (UWS) of SSFs yields more efficient and consistent retention of *Cryptosporidium* oocysts compared to dry skimming (DS). UWS filters exhibited fewer breakthrough events during both dosing and post-dosing phases, leading to lower daily and annual probabilities of illness, particularly among immunocompromised individuals. Despite high overall retention, occasional oocyst detections in the filtrate indicate that SSFs are not absolute barriers; delayed breakthroughs likely result from filter inherent retention limitations. These findings highlight the need to optimise SSF operations and validate the use of multiple treatment barriers to meet water quality standards.

Moreover, while this study confirmed that oocysts are retained within the filter media, the vertical distribution and ultimate fate of these retained oocysts remain unclear. Understanding where the oocysts accumulate is essential information for assessing long-term filter effectiveness and planning maintenance strategies. Further investigation into the potential for biological degradation of oocysts within the SSF ecosystem is warranted. In summary, adopting UWS enhances SSF performance in retaining *Cryptosporidium* oocysts, thereby reducing the risk of pathogen breakthrough and thus potential for waterborne disease transmission, making UWS a preferable maintenance practice over traditional DS methods.

CRedit authorship contribution statement

Sophie L. Bretagne: Writing – original draft, Visualization, Formal analysis, Data curation. **Michael Chipps:** Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Ian Doggett:** Writing – original draft, Resources, Investigation. **Michael C.J. Bradwell:** Writing – original draft, Methodology. **Heide Hardiman:** Writing – original draft, Methodology. **Jim Harris:** Writing – review & editing, Supervision, Funding acquisition. **Francis Hassard:** Writing – review & editing, Supervision, Project administration, Methodology, Funding

acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2025.128062>.

Data availability

Data for this work is available at: <https://doi.org/10.6084/m9.figshare.28911410.v1>.

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Evaluating Cryptosporidium oocyst removal in SSF: impact of underwater skimming and dry skimming

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