Journal of Environmental Management 386 (2025) 125845

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Understanding the risk of enhanced particle penetration into slow sand filter beds when using underwater skimming techniques

Tolulope Elemo [a], Michael Chipps [b], Nigel Graham [c], Andrew Turner [d], Bruce Jefferson [a], Francis Hassard [a,*]

[a] Cranfield University, Cranfield, MK43 0AL, UK
[b] Thames Water Utilities Limited, Kempton Park AWTW, Hanworth, TW13 6XH, UK
[c] Imperial College London, Department of Civil and Environmental Engineering, London, SW7 2AZ, UK
[d] Essex and Suffolk Water, Chelmsford, CM3 8BD, UK

ARTICLE INFO

Handling editor: Raf Dewil

Keywords:
Water treatment
Slow sand filter (SSF)
Underwater skimming (UWS)
Particle penetration

ABSTRACT

This study evaluated abiotic slow sand filters (SSFs) to understand the risk of particle penetration during underwater skimming (UWS), focusing on clogging, headloss development, and particle breakthrough. Pilot-scale filters containing clean sand were challenged with dispersed kaolin particles to simulate surface accumulation, and the sand surface was agitated to mimic UWS procedures. The study was undertaken with no maturation period to consider the worst-case scenario corresponding to the period just after filter skimming. Agitating the surface and restarting flow released captured particles, some moving downward through the filter. Shallow filter depths resulted in particles appearing in the filtrate, but increasing the media depth beyond 500 mm minimized this effect. Since 90 % of headloss occurred in the upper layers, deeper particle penetration was insignificant. Increasing the hydraulic loading rate from 0.3 to 0.5 m/h reduced particle retention by 0.72 log, yet all abiotic SSFs achieved over 2 log particle capture. Small particles (2–10 μm) were removed by 2 logs, indicating sufficient non-viral pathogen retention under routine conditions. Effective capture of particles sized 2–125 μm suggested minimal risk to water quality and public health during UWS on full-scale SSFs. Using clean sand and kaolin represented a worst-case scenario, excluding biological maturation and particles. The findings suggest that under normal conditions, UWS does not increase deep particle penetration or breakthrough, supporting its safe implementation to enhance filter maintenance without compromising water quality.

1. Introduction

Slow sand filtration combines particle capture and biological activity leading to the development of headloss over time, which necessitates regular maintenance to prevent flow reduction (Abdiyev et al., 2023). Typically, this maintenance involves dry skimming (DS), where the *Schmutzdecke* (surface material) and top 10–50 mm of media are removed after draining the bed (Ellis and Aydin, 1993). To reduce the associated down time and thereby increase water production capacity, an innovative approach is being developed based on skimming whilst the bed is still submerged, called underwater skimming (UWS) (Hassard et al., 2022). Underwater skimming offers several practical advantages over the conventional DS approach that is still widely used to clean slow-sand filters. Because the schmutzdecke is removed while the filter bed remains fully submerged, UWS eliminates the 20–24 h drain-down/refill cycle (Elemo et al., 2024) and thereby increases filter uptime by circa 8 % on an annualised basis. The submerged operation also preserves the resident microbial community, avoiding desiccation stress and shortening the post-cleaning ripening period from the typical 48 h to <12 h observed in recent pilot-scale installations (Elemo et al., 2025). Finally, because no refill water is required the method reduces both ancillary water use and the energy consumed - yielding a small but measurable reduction in whole-life operational carbon. These operational benefits, corroborated by recent field evaluations, provide the motivation for the controlled pilot-scale assessment reported herein (Maiyo et al., 2023).

Before introducing UWS at full-scale, risks were identified and their significance assessed by pilot-scale testing. These included the effect that UWS could potentially dislodge particles into the supernatant water or fail to remove disturbed particles, causing filter clogging and reduced

* Corresponding author.
E-mail address: francis.hassard@cranfield.ac.uk (F. Hassard).

https://doi.org/10.1016/j.jenvman.2025.125845
Received 21 October 2024; Received in revised form 13 May 2025; Accepted 14 May 2025
Available online 17 May 2025

effectiveness by expediting headloss in the subsequent filter run (Singer et al., 2017). Additionally, UWS could reduce media compaction of the top layers with corresponding impacts on particle removal and headloss development. Understanding the risks of enhanced particle penetration within the filter beds associated with UWS procedures will help determine how UWS should be designed and operated to maintain filtrate quality and control particle breakthrough, ensuring the effectiveness of subsequent additional disinfection by chemical oxidants (Singer et al., 2017).

Slow sand filters (SSFs) differ to rapid gravity filters (RGFs) in terms of the media size used (0.2–0.3 mm versus 0.5–1.2 mm), the hydraulic loading rates (HLR) (0.1–0.5 $m^3/m^2/h$ versus 5–15 $m^3/m^2/h$) and the cleaning procedures (skimming versus backwashing) (Crittenden et al., 2012) and the development of a biologically active community in the surface layer of the media. In addition, the process of skimming reduces the bed height through removal of the top media layer. This continues until a limiting point is reached when 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, whilst not going below a minimum bed height of 0.3–0.5 m associated with effective removal of turbidity and bacteria (Ellis, 1985), or 0.6 m to maintain a required virus log reduction (Poynter and Slade, 1978). Importantly, these recommendations are based on conventional DS practice, highlighting a gap in understanding particle behaviour during UWS.

A SSF consists of a granular media bed within which complex ecological and biofilm processes develop as the media "matures". This study examines the performance of a SSF *without* biological enhancement to represent a worst-case examination of the proposed UWS procedure. In this case, particle removal mechanisms in SSFs are identical to those of RGFs and can be represented by 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 the transport of particles and improved filtration, with the removal of suspended solids increasing from an average of 66 %–87 % when the HLR was halved (Verma et al., 2017). 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. By eliminating the draining down of the filter bed, UWS presents a risk of particles being dispersed into the water above the filter if they are not fully removed, leading to increased particle penetration and passage through the "un-ripened" filter sand (i.e. sand with limited biological maturity after the *Schmutzdecke* has been removed). This is possible as disturbing the filter surface can reduce compaction, increase hydraulic conductivity, and consequently lead to greater particle infiltration. The research explores how UWS-induced agitation impacts particle behaviour in SSFs, and examines the role of sand depth and abiotic filter ripening in particle retention. The novelty of this work relates to generating data and theoretical prediction to inform on the risk of increasing particle penetration or compromising water quality when conducting underwater skimming. This is achieved through collecting particle removal data in controlled experiments to simulate the worst-case scenario of abiotic conditions (i,e, no *Schmutzdecke*) and resuspension of previously captured particles through agitation. Also, evaluating, at pilot-scale, whether UWS can be implemented in SSFs safely without increasing particle penetration or compromising water quality — even under challenging abiotic conditions. UWS is a rarely applied, practical approach to enhance treatment efficiency and reduce operational downtime.

2. Materials and methods

2.1. Pilot filtration setup

The experimental pilot filters consisted of 150 mm internal diameter uPVCcolumns with an area of ~0.018 m^2. The columns contained a range of depths of cleaned filter sand (effective size (ES) 0.3 mm, uniformity coefficient (UC) 1.75) above a 100 mm layer of 10 mm pea shingle, sitting on a filter nozzle separating the media from a filtered water chamber and outlet pipework, flow control valve and flow meter. Clear plastic piezometers for headloss monitoring were located below the nozzle plate (giving the total filter head loss) and on one column connected to pressure tappings which penetrated 30 mm horizontally into the filter media located in a spiral pattern at 50 mm intervals up the column height. The height of each filter from the nozzle plate to the inlet water overflow was 2.2m. Media was backwashed before each experiment using potable water and compacted each time by gently tapping the side of the column, without media replacement.

The SSF experiments were devoid of biological maturation or *Schmutzdecke* (abiotic) to represent the highest risk of particle penetration. Headloss was induced using a kaolin suspension to model rapid solids loading, chosen for its minimal biological reactivity and similar zeta potential and size to particulates present in operational *Schmutzdecke*. In the first set of experiments the kaolin solution was prepared by dispersing 100 g of kaolin into 10 L of SSF feed water (outlet from a pilot roughing filter of low suspended solids lowland reservoir water). The reservoir water fed a pilot scale roughing rapid sand filter. The outlet of this roughing filter had a turbidity of 0.29 ± 0.11 NTU (n = 48) which provided the inlet water for the experiments. The kaolin generated a size distribution of predominately <2 μm and 2–10 μm particles which made up to 94 % of the particle size distribution when suspended in reservoir water (Supplementary information, A.1).

The water had a turbidity range of 1400–2300 NTU which refers to the quiescent supernatant above the sand bed immediately after dosing with kaolin, not to the influent feed water itself. The remaining particles were in the 10–15 μm and 25–75 μm size ranges (Supplementary information, A.2). A constant mass of kaolin (100 g) was introduced to each column, but the supernatant volume declined with increasing sand depth; consequently, less dilution occurred in deeper beds, yielding higher turbidity readings. The kaolin suspension was introduced into the supernatant above the filter when there was no flow out of the filter. Kaolin was allowed to settle overnight (~20 h) before experiments were commenced.

To simulate the disturbance to the surface during UWS, a custom stirrer with a wooden paddle (110 mm wide x 70 mm tall x 10 mm deep) fixed to the end of a 3.8 m long 1″ diameter uPVC pipe, was powered by a battery drill, to mimic the UWS auger's action, agitating the top 40 ± 10 mm of sand at 100 rpm for 2 s, based on extrapolations from the design of the full-scale UWS machine.

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 experiments used the same range of media depths and kaolin challenge but without agitation (Fig. 1) with modifications to the experimental setup in Phase 2 (Fig. 2). In phase 1, the particle counts collected over 20 h were analysed automatically by separating signals into four distinct size bands to give the average filtrate results in Fig. 3A and the log removal results in Fig. 3B. Experiments were operated below 10,000 counts per ml, as the risk of optical coincidence increases above this point.

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 loading the filter with 25 g of kaolin, and after flow started measuring the headloss at 50 mm depths down a single 800 mm depth SSF. These experiments involved increasing the HLR from

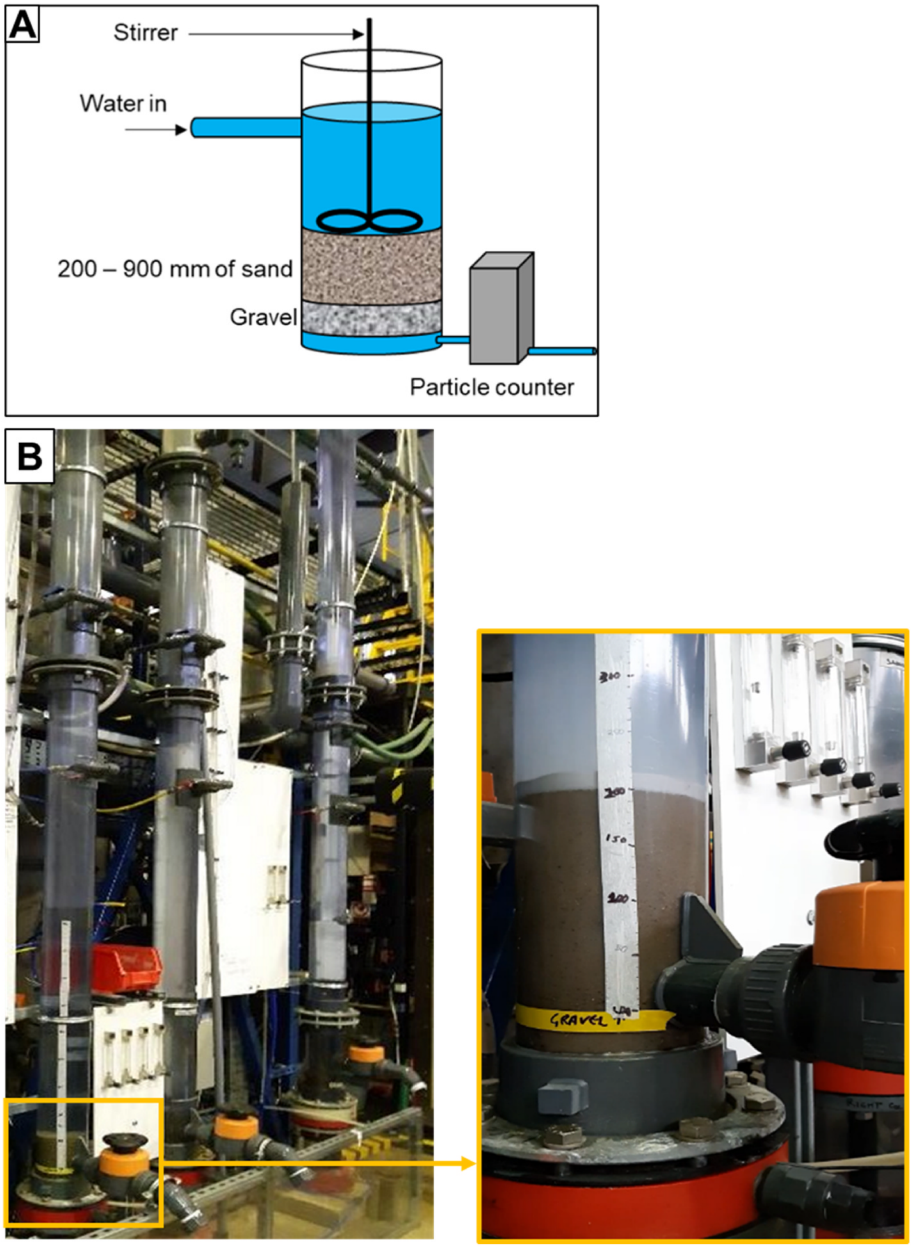

Fig. 1. Experimental set-up to monitor the effect of filter surface agitation and media depth on filtrate particle count. (A) Schematic of the experimental set-up showing the particle counter position; (B) Image of the columns.

zero to 0.3, 0.4 and 0.5 m/h, with a control filter where the filtration rate was increased to 0.3 m/h in 0.1 m/h increments with each test lasting ~24 h (Fig. 2). The development of headloss was recorded during the operational period.

Filtrate quality was monitored using grab samples of filtrate for turbidity and continuous on-line measurement of filtrate particle counts, using a Hach TU5200 (Hach, Loveland, Colorado, USA) turbidimeter for turbidity and a Liquilaz® E20 (Spectris plc, UK) for particle counts spanning 2–125 μm (Supplementary information, A.2).

The justification for the pilot filtration setup was that it replicated full-scale SSF conditions while controlling media depth, HLR, and surface agitation. The study was undertaken with no maturation period in order to consider the worst-case scenario corresponding to the period just after filter skimming. Agitating the surface and restarting flow released captured particles, causing some of them to move downwards through the filter.

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 can be calculated as the sum of the individual transport mechanisms of diffusion (η_D), gravity sedimentation (η_G), and interception (η_I)

$$\eta_{total} = \eta_I + \eta_G + \eta_D$$

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

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

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,

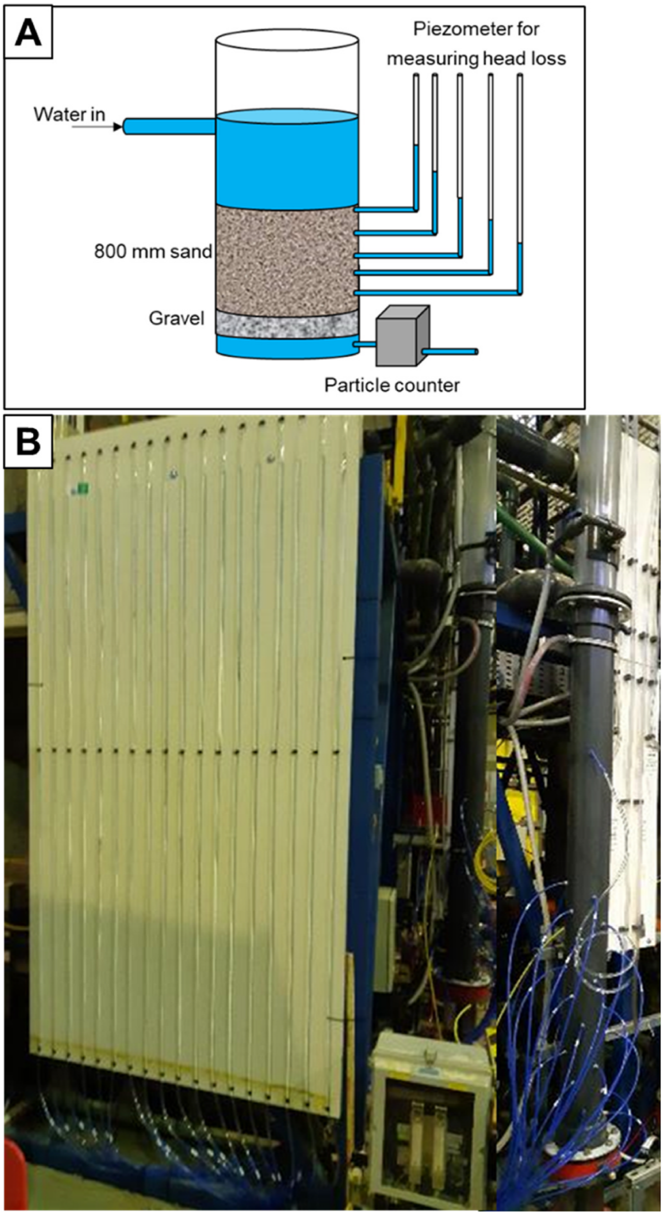

Fig. 2. Experimental set-up to monitor the effect of filter surface agitation on particle penetration and impacts of increased filtration rates. (A) Schematic of the experimental set-up showing the particle counter position (not all piezometer ports shown); (B) Image of the columns showing the 50 mm interval piezometer tubes.

with the corresponding equations, as follows:

$$N_R = \frac{d_p}{d}$$

$$N_{Pe} = \frac{3\pi\mu d_p du}{k_B T}$$

$$N_V = \frac{H}{k_B T}$$

$$N_G = \frac{(\rho_p - \rho) g d_p{}^2}{18\mu u}$$

where k_B is the Boltzman constant (kg.m^2/s^2/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 (kg.m^2.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 (K) and μ is the water viscosity (kg/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:

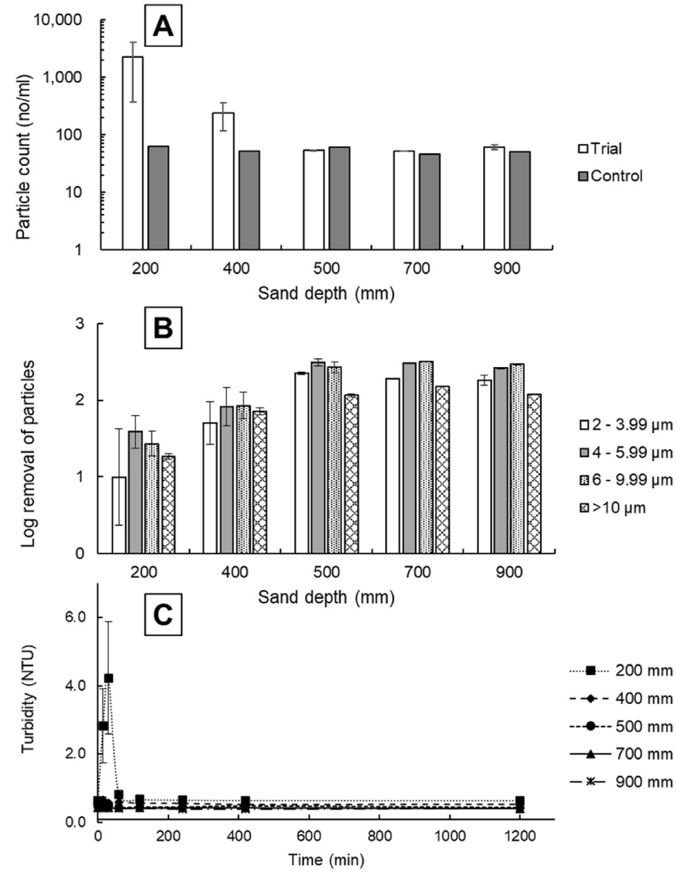

Fig. 3. (A) Average filtrate particle count (2–125 µm) at different media depths following filter surface agitation (Trial) and without surface agitation (Control). (B) Average log removal of particles in different size ranges following surface agitation. Error bar is the range of duplicate trial runs. (C) Filtrate turbidity at different media depths following filter surface agitation, based on grab samples collected at seven times throughout experiment period. Time 0 min is immediately after the agitation. 100 g kaolin challenge, HLR = 0.3 m/h.

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

where γ is based on the porosity of the bed (ε):

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

The resultant correlation for the single collector efficiency is then:

$$\eta_{total} = 2.4 A_s^{\frac{1}{3}} N_R{}^{-0.08} Pe^{-0.72} N_V{}^{0.05} + 0.55 A_s N_R{}^{1.55} Pe^{-0.13} N_V{}^{0.13} + 0.22 N_G{}^{1.11} N_R{}^{-0.24} N_V{}^{0.05}$$

The removal of particles through the depth of the bed can then be calculated by modelling the filter as a reactor:

$$\frac{C_L}{C_0} = exp\left(-\frac{3(1-\varepsilon)\alpha\eta}{2d}.L\right)$$

where α is the attachment efficiency, and exp = exponent.

3. Results and discussion

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 a deteriorated filtrate in the former (Fig. 3A). To illustrate this, for the 200 mm depth agitated filter, the 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, suggesting that the impact of agitation is 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 considered as a series of connected filter layers (Bai and Tien, 1997). Lower particle retention at lower media depths, below 500 mm, was observed for all particle size ranges (Fig. 3B). No significant difference in particle removal was observed for each of the size ranges at depths beyond 500 mm. There was no measurable impact of a sudden start up with a high suspended solids load on all the control filters. A range of 50–70 counts/ml for all the control filters and the agitated filters with a depth≥500 mm represented a high quality water.

Time based turbidity profiles were consistent with the particle count data, showing a peak in the turbidity of 4.2 ± 1.6 NTU across the 200 mm filter, which lasted for 45 min before stabilising at 0.7 NTU (Fig. 3C). 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 a negligible impact on turbidity, aligning with the particle count trends (Fig. 3A and B) and this suggested a minimum safe depth of 500 mm. This is greater than that previously recommended for achieving good water quality (Ellis, 1985). After the initial peak, stable turbidity values were observed at the outlet of each filter 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 removals of 99.96 %, 99.97 %, 99.97 %, 99.98 % and 99.98 % with an overall removal efficiency of greater than 99 %. This indicates that the top of the bed was responsible for almost all of the removal and that the lower layers were effectively redundant over the time period of the trial. This is consistent with theory and practice, reflecting the plug flow nature of depth filtration, such that the lower layers of sand start to remove particles only when the upper layers are fully loaded. 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. Turbidity removals in excess of 99.9 % down to 0.7 NTU suggest that the challenge turbidity was greater than 1000 NTU and estimated values (SI A2). This level of influent turbidity is outside well-established guidelines for SSF design. To illustrate the significance of this, the solids loading of 5555 g/m^2 (based on 100 g kaolin/0.018 m^2 filter surface area) in these tests was much greater than normal solids loadings of operational SSF; Toms and Bayley (1988) suggested that a SSF would require cleaning when trapped particulate carbon was in the range 100–300 g/m^2. Surface agitation from simulated UWS significantly reduced particle removal efficiency at shallower media depths (≤400 mm). The agitation re-suspended settled kaolin particles into the supernatant, increasing the particle load entering the filter upon restart and challenging its capacity to retain particles. This suggests that filters with depths less than 500 mm lacked sufficient media for effective particle capture, leading to increased breakthrough. Agitation may also disrupt the compaction of the upper sand layers, increasing porosity and allowing particles to penetrate deeper into the filter. This highlights the importance of sufficient media depth to compensate for disturbances caused by surface agitation during UWS.

3.2. Impact of varying HLR on headloss and particle removal

The results from the second tests with 25 g of kaolin added to an 800 mm deep filter show that the headloss increase was mainly observed within the top 100 mm of the filter, with minimal headloss at greater depths (Fig. 4A). The top 50 mm, accounted for 48 %, 42 %, 57 % and 55 % of the total headloss in the control, 0.3 m/h, 0.4 m/h and 0.5 m/h filters, respectively. This increased to 53 %, 48 %, 60 % and 60 % by 100 mm. Within the lower layers, the difference in headloss between the 50 mm intervals ranged between 1 and 10 mm. This concentration of headloss within the top layers of sand is lower than in previously reported trials where over 80 % of the headloss occurred across the top 50 mm of the sand, and minimal variation between 50 and 400 mm depths (Campos et al., 2006). This is likely because of their non-abiotic conditions where the reduced porosity that occurs in these layers is due to particle retention from biofilm growth (Ojha and Graham, 1994). The presence of biofilm and biological activity in the previous studies shows the difference in headloss development between typical SSFs and the abiotic SSFs in this study. It should be noted that the variation between the measured headloss values in the different trials was relatively small and not statistically significant (Kruskal Wallis: H (3) = 0.7, p = 0.863).

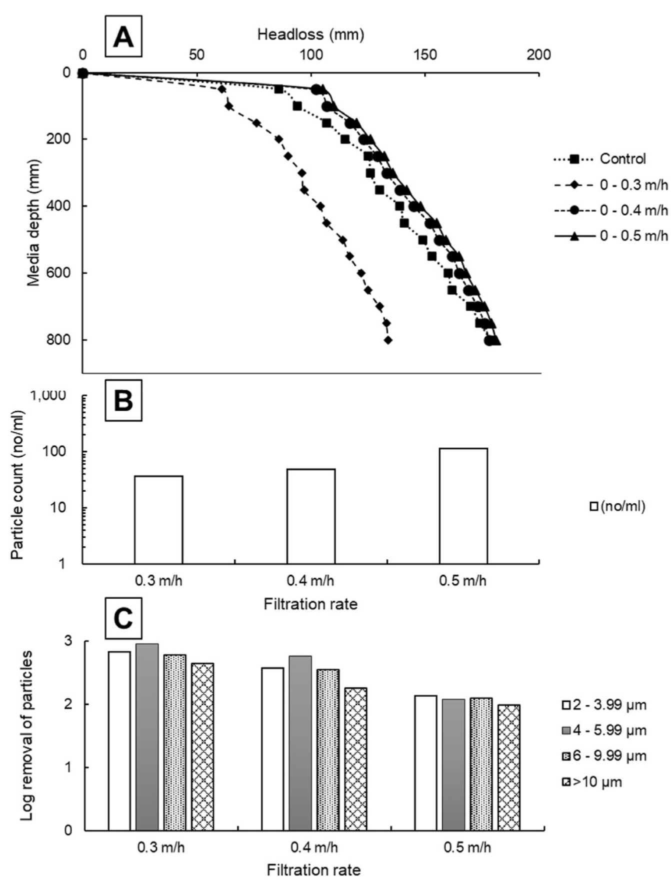

Fig. 4. (A) Differential headloss (mmH_2O) between piezometer tubes placed at 50 mm intervals along the depth of filter, measured at different HLR following filter surface agitation. (B) Filtrate particle count at various HLR after filter surface agitation. (C) Log removal of particles in different size bands (Kaolin loading 25 g. Filter depth was 800 mm).

Increased particle breakthrough was observed when operating at higher HLR, following surface agitation (Fig. 4B). To illustrate this, outlet particle counts were 36 no/mL at 0.3 m/h, rising to 49 no/mL at 0.4 m/h and 115 no/mL at 0.5 m/h. Correspondingly, the log removal decreased as HLR increased, with a 0.25 log reduction from 0.3 m/h to 0.4 m/h and a 0.72 log reduction from 0.4 to 0.5 m/h. However, the overall log removal remained over 2 across all size ranges and HLR (Fig. 4C). Schijven et al. (2013) also noted a slight reduction in pathogen log removals with increased HLR, where a decrease in the HLR of full-scale SSFs by 0.08–0.15 m/h resulted in a small improvement of the log removals of pathogens (bacteriophage and *E. coli*) by 0.06–0.27 log. In another study, van der Hoek et al. (1996) found that filtration rate changes did not significantly affect particle removal. In our tests, despite varying the HLR from 0.3 to 0.5 m/h, particle removal remained consistently above a 2-log reduction, which indicated that within the tested range, the SSFs' removal efficiency was not significantly sensitive to changes in filtration rate. One possible explanation for this is that the dominant removal mechanisms — such as sedimentation and interception — were effective across these flow rates due to the small particle sizes and media characteristics. The filtration velocities were still within the laminar flow regime, ensuring stable particle transport and capture dynamics. Moreover, the increased shear forces at higher HLRs did not substantially dislodge retained particles, indicating the filter bed was robust for particle capture under operational variations of SSF.

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 (Fig. 5). The transport efficiency for 2 μm particles when using a collector diameter of 0.3 mm and a porosity of 0.4, decreased from 2.95 x 10^{-2} at 0.3 m/h to 2.23 x 10^{-2} and 0.4 m/h and 1.81 x 10^{-2} at 0.5 m/h. For this particle size, the predominant transport mechanism is sedimentation (based on the fluid and media properties in this study, sedimentation overtakes interception for particles >1 μm). The reduction was thus associated with the sedimentation mechanism, which dominated transport and represented 81 % of the collision efficiency at 0.3 m/h, and 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 (Fig. 5B). For all filtration rates, the removal efficiency of 2 μm particles increased from between 32 % and 47 %, with a bed depth of 100 mm, to between 86 % and 96 % at a bed depth of 500 mm. The impact of filtration rate was observed for bed depths of 500 mm and below. For example, at a bed depth of 500 mm, the removal efficiency was 96 %, 91 % and 86 % for filtration rates of 0.3 m/h, 0.4 m/h and 0.5 m/h, respectively. This compares well with the experimental filtration efficiency data that yielded an estimated 2 log removal (99 %, as a minimum), which means the model slightly underestimated the experimental data.

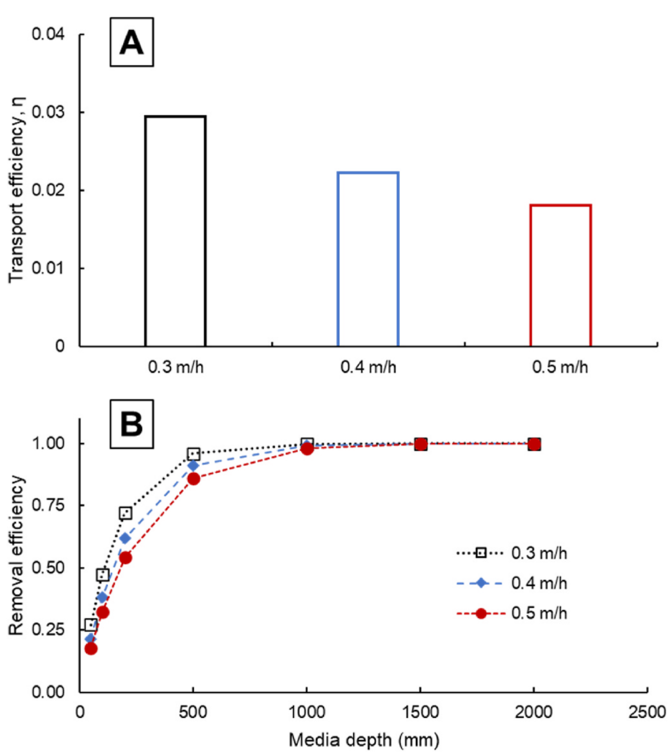

Fig. 5. Impact of different HLR on: (a) transport efficiency, η, and (b) removal efficiency of a 2 μm sized particle at different filter depths.

3.3. Removal of different particle sizes

A comparison of the experimental data and model predictions for the 4–6 μm range is particularly interesting as it corresponds to the size of *Cryptosporidium* oocysts (which are of concern in SSF treatment, especially for surface water sources which contain high levels of faecal contamination). This size range (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 depths greater than 500 mm, log reductions were more consistent between 2.4 and 2.5 log reductions. This compares to literature values 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 in the size range that could contain protozoan oocysts. The 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. For instance, in the two examples referenced above, there were differences in the media depth, operational HLR and location of filter (outdoors vs indoors).

The impact of bed depth was further investigated for two size ranges where the greatest change was observed: 2–3.99 μm and 4–5.99 μm (Fig. 6). In the case of the 4–5.99 μm particles, a bed depth of 500 mm was required before stable removal was observed. Specifically, the removal was 86.9 %, 95.8 % and 99.4 % at bed depths of 200 mm, 400

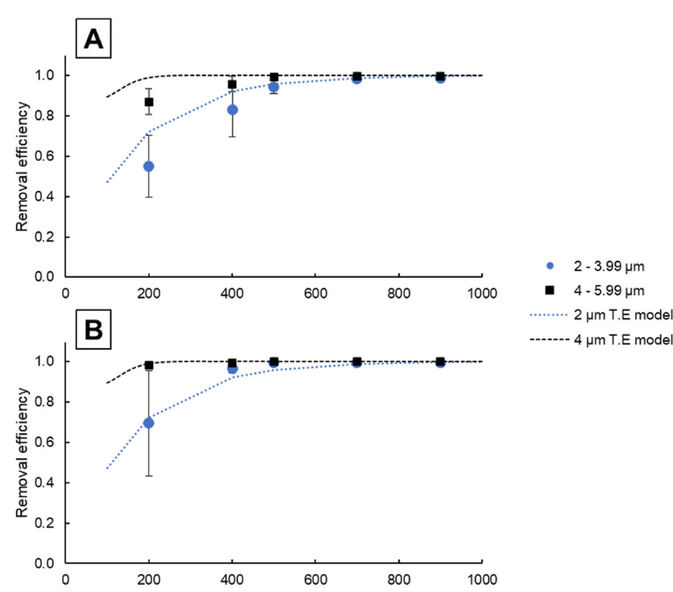

Fig. 6. Filter removal efficiency following surface agitation at various media depths after: (A) one bed volume, and (B) six bed volumes of flow, for particle size ranges 2–3.99 μm and 4–5.99 μm. The T.E. model is the model developed by Tufenkji and Elimelech (2004).

mm and 500 mm, respectively. After six bed volumes the removal levels had increased to 98.2 %, 99.3 % and 99.9 % respectively, which suggests a degree of filter ripening took place. 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 1 h in an analogous RGF system (Darby and Lawler, 1990). No specific size range was disproportionately affected by surface agitation, similar to observations in RGF where flow disturbances did not selectively impact particle sizes (Glasgow and Wheatley, 2001).

4. Conclusions

This study examined abiotic 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 headloss, and particle breakthrough, using kaolin to represent particle accumulation and a stirrer paddle to simulate skimmer movement. The findings indicated that surface agitation reduced removal efficiency, but deeper media (>500 mm) 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 500 mm. Similar observations showed improvement in turbidity with depth. In addition, there was no discernible disproportionate clogging or significant headloss beyond the top 100 mm. Increasing HLR from 0.3 to 0.5 m/h increased particle breakthrough during agitation, but the filters maintained a greater than 2 log particle removal, indicating effective filtration.

Particle removal for sizes 2–10 μm, covering the 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, examining potential negative impacts if UWS were to malfunction, 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.

Based on the desire to improve the efficiency of slow sand filtration the idea of underwater skimming was developed. By eliminating a typical 24 h period for draining down and refilling, the days of useful filtrate production can be increased. Furthermore, as the SSF is an aquatic ecosystem, it is possible that avoiding draining and exposure to extremes of heat or cold, could reduce filter maturation periods.

To address concerns about a failure to remove particles from the filter surface and stirring deposits into the supernatant, this study considered a worse case test scenario involving the stirring up of a high load of non-biological particles that had been allowed to settle onto the SSF sand that had not been biologically matured. It examined the risks of particle penetration and breakthrough, and headloss development at depth within the filter, as the filter returned to operation after a pause for underwater skimming. Addressing the risk of unsatisfactory underwater skimming could mean that the operation of the SSF might need to be changed compared to conventional dry skimming. Remarkably, the results showed that this was not the case, and that there was no need to change the recommended safe depths of filter media, or the start-up procedures post skimming. Furthermore, it is expected that the UWS technology will be able to remove the surface sand and attached deposits far more efficiently than the stirring approach that was used in these experiments.

This study has demonstrated that UWS in SSF does not significantly increase particle penetration or breakthrough when filter depths exceed 500 mm. Even under worst-case abiotic conditions, UWS poses a minimal risk to water quality, through maintaining effective filtration of particles corresponding to non-viral pathogens. The findings support the safe implementation of UWS to improve filter efficiency without compromising filtrate quality, contributing valuable insights into SSF maintenance practices.

CRediT authorship contribution statement

Tolulope Elemo: Writing – original draft, Methodology, Formal analysis. **Michael Chipps:** Writing – review & editing, Supervision. **Nigel Graham:** Writing – review & editing. **Andrew Turner:** Writing – review & editing. **Bruce Jefferson:** Writing – review & editing, Supervision. **Francis Hassard:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, 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.

Acknowledgements

The authors acknowledge the financial support of the Engineering and Physical Sciences Research Council (ESPRC), through the STREAM Industrial Doctorate Centre (EP/L015412/1), and financial support from Thames Water and Northumbrian Water Group. The authors also appreciate the support provided by Affinity Water. The authors are grateful to Dr. Jenny O'Reilly, Ian Doggett and Dr. Richard Lake for their valuable contributions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125845.

Data availability

A link is included to the data 10.6084/m9.figshare.27094813

References

Abdiyev, K., Azat, S., Kuldeyev, E., Ybyraiymkul, D., Kabdrakhmanova, S., Berndtsson, R., Khalkhabai, B., Kabdrakhmanova, A., Sultakhan, S., 2023. Review of slow sand filtration for raw water treatment with potential application in less-developed countries. Water 15 (11), 2007.

Bai, R., Tien, C., 1997. Particle detachment in deep bed filtration. J. Colloid Interface Sci. 186 (2), 307–317.

Campos, L.C., Smith, S.R., Graham, N.J.D., 2006. Deterministic-based model of slow sand filtration. II: model application. J. Environ. Eng. 132 (8), 887–894.

Crittenden, J.C., Trussell, R.R., Hand, DavidW., Howe, K.J., Tchobanoglous, G., 2012. MWH's Water Treatment: Principles and Design. John Wiley & Sons, Inc., Hoboken, NJ, USA.

Darby, J.L., Lawler, D.F., 1990. Ripening in depth filtration: effect of particle size on removal and head loss. Environ. Sci. Technol. 24 (7), 1069–1079.

Elemo, T., Chipps, M., Graham, N., Turner, A., Jefferson, B., Hassard, F., 2024. Predicting the impact of underwater skimming on dissolved oxygen consumption in slow sand filters for potable water treatment. Sci. Total Environ. 954, 176730.

Elemo, T., Chipps, M., Graham, N., Turner, A., Bretagne, S., Jefferson, B., Hassard, F., 2025. Evaluating the impact of underwater skimming on slow sand filter performance and operation. Water Res., 123234

Ellis, K.V., 1985. Slow sand filtration. CRC Crit. Rev. Environ. Control 15 (4), 315–354.

Ellis, K.V., Aydin, M.E., 1993. A study of three slow sand filters at various flow rates with constant temperature. Aqua 42 (2), 88–96.

Farooq, S., Al-Yousef, A.K., 1993. Slow sand filtration of secondary effluent. J. Environ. Eng. 119 (4), 615–630.

Fogel, D., Isaac-Renton, J., Guasparint, R., Moorehead, W., Ongerth, J., 1993. Removing *Giardia* and *Cryptosporidium* by slow sand filtration. J. AWWA (Am. Water Works Assoc.) 85 (11), 77–84.

Glasgow, G.D.E., Wheatley, A.D., 2001. Particle ripening, removal and breakthrough in drinking-water filtration: implications for the capture of *Cryptosporidium* and *Giardia* cysts. J. Chart. Inst. water Environ. Manag. 15 (3), 193–197.

Hassard, F., Elemo, T., Chipps, M., Turner, A., Jefferson, B., Graham, N., 2022. Underwater remote skimming of slow sand filters for sustainable water production. ACS ES&T Water 2 (9), 1471–1474.
Hijnen, W.A.M., Schijven, J.F., Bonné, P., Visser, A., Medema, G.J., 2004. Elimination of viruses, bacteria and protozoan oocysts by slow sand filtration. Water Sci. Technol. 50 (1), 147–154.
Maiyo, J.K., Dasika, S., Jafvert, C.T., 2023. Slow sand filters for the 21st century: a review. Int. J. Environ. Res. Publ. Health 20 (2), 1019.
Meng, Q., Shi, F., Fan, W., Wen, Z., Sun, K., Wang, Z., 2024. SiO2 and microparticle transport in a saturated porous medium: effects of particle size and flow rate. Appl. Water Sci. 14 (3), 50.
Ojha, C.S.P., Graham, N.J.D., 1994. Computer-aided simulation of slow sand filter performance. Water Res. 28 (5), 1025–1030.
Poynter, S.F.B., Slade, J.S., 1978. The removal of viruses by slow sand filtration. In: Eighth International Conference on Water Pollution Research. Pergamon, pp. 75–88.
Schijven, J.F., Van den Berg, H.H.J.L., Colin, M., Dullemont, Y., Hijnen, W.A.M., Magic-Knezev, A., Oorthuizen, W.A., Wubbels, G., 2013. A mathematical model for removal of human pathogenic viruses and bacteria by slow sand filtration under variable operational conditions. Water Res. 47 (7), 2592–2602.
Singer, S., Skinner, B., Cantwell, R.E., 2017. Impact of surface maintenance on BioSand filter performance and flow. J. Water Health 15 (2), 262–272.
Steele, M., 2004. Investigating Best Operational Practice Procedures for Granular Activated Carbon Enhanced Slow Sand Filters. University of Surrey. PhD thesis.
Toms, I.P., Bayley, R.G., 1988. Slow sand filtration: an approach to practical issues. In: Graham, N. (Ed.), Slow Sand Filtration: Recent Developments in Water Treatment Technology. Ellis Horwood Limited, Chichester, pp. 11–28.
Tufenkji, N., Elimelech, M., 2004. Correlation equation for predicting single-collector efficiency in physicochemical filtration in saturated porous media. Environ. Sci. Technol. 38 (2), 529–536.
van der Hoek, J.P., Bonne, P.A.C., Kors, L.J., te Welscher, R.A.G., 1996. Slow sand filtration: effect of grain size and filtration rate on operation and performance. In: Graham, N., Collins, R. (Eds.), Advances in Slow Sand and Alternative Biological Filtration. John Wiley & Sons, Inc., Hoboken, NJ, USA, pp. 201–210.
Verma, S., Daverey, A., Sharma, A., 2017. Slow sand filtration for water and wastewater treatment – a review. Environ. Technol. Rev. 6 (1), 47–58.
Verma, S., Daverey, A., Sharma, A., 2019. Wastewater treatment by slow sand filters using uncoated and iron-coated fine sand: impact of hydraulic loading rate and media depth. Environ. Sci. Pollut. Control Ser. 26 (33), 34148–34156.

Understanding the risk of enhanced particle penetration into slow sand filter beds when using underwater skimming techniques

Elemo, Tolulope

2025-06-01

Elemo T, Chipps M, Graham N, et al., (2025) Understanding the risk of enhanced particle penetration into slow sand filter beds when using underwater skimming techniques. Journal of Environmental Management, Volume 386, June 2025, Article number 125845

https://doi.org/10.1016/j.jenvman.2025.125845