

## Practical Paper

# Practical and theoretical guidelines for implementing the extended terminal subfluidization wash (ETSW) backwashing procedure

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### ABSTRACT

Extended terminal subfluidization wash (ETSW) is an advanced granular media filter backwashing strategy that can be employed for reducing or even eliminating the filter ripening turbidity spikes commonly encountered immediately after restarting a backwashed filter. ETSW is based on sound scientific principles, but there is not yet sufficient data and experience for making precise a priori predictions of the optimum ETSW rates under the varying conditions found in practice. ETSW is like many other water treatment strategies in the sense that it must be tailored to a treatment plant's unique operating conditions, and the technique may also need to be adjusted periodically to accommodate changes in the treatment process. The purpose of the following correspondence is to inform current and future users of the ETSW backwashing process of the underlying scientific principles and of a rational procedure that can be used in the implementation and optimization of this technique for use in any water treatment plant. Future experiences with the ETSW approach could provide more insight into how to most efficiently and effectively apply this technique.

**Key words** | backwashing, filter optimization, filter ripening, filtration theory

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### INTRODUCTION

Filter ripening is a common problem in drinking water treatment where filtered water quality is degraded relative to steady-state performance immediately following restart of a backwashed filter. Increasingly stringent water quality regulations and the threat of *Cryptosporidium* outbreaks have led to increased concern in recent years for minimising the impact of filter ripening on drinking water quality. Extended terminal subfluidization wash (ETSW) is an operational tool that can help reduce water quality problems associated with filter ripening. ETSW research has not been very extensive to date, but the completed research has demonstrated that ETSW can reduce or even eliminate the filter ripening turbidity and particle count

peaks for a variety of treatment schemes. ETSW has been successfully implemented at multiple pilot-scale and full-scale water treatment plants.

Amburgey *et al.* (2003) demonstrated that ETSW was effective in controlling filter ripening peaks at direct filtration and conventional treatment plants with deep-bed and conventional dual media (anthracite/sand) filters, respectively. Amburgey (2005) optimized the ETSW process for deep-bed anthracite and granular activated carbon (GAC) mono-media filters, and he also found ETSW to be equally effective for biological and conventional deep-bed filters. Amburgey & Amirtharajah (2005) describe a case in a conventional water treatment plant where ETSW was only

partially effective in reducing the filter ripening turbidity and particle count spikes. They observed that the initial portion of the filter ripening period (corresponding to backwash remnant particles) was effectively controlled via the ETSW procedure, but a delayed filter ripening spike was consistently observed and attributed to what the authors described as ‘cold-water impaired’ alum coagulation. The spike required more than 1 hour of filtration to subside as the accumulation of particles within the filter (to serve as additional collectors of the incoming particles) gradually improved the efficiency of the filter. No attempts to eliminate the delayed filter ripening spike by changing the coagulation conditions were made in that study.

### ETSW DEFINITION AND THEORY

ETSW is an advanced backwashing strategy that can be employed at the end of a standard backwash procedure. ETSW is intended to follow a fluidization wash step, rather than replace it. ETSW is a procedure that involves extending the normal backwash duration at a subfluidization flow rate (with very little or no bed expansion) for an amount of time sufficient to displace the entire volume of water contained within the filter box. The intent of ETSW is to remove the backwash remnant particles that are normally left within the media and above it following backwashing without generating further remnants that can pass into the finished water supply. The central tenet of ETSW theory is that the lower flow rates associated with the ETSW procedure produce smaller shear forces at the media surfaces and cause fewer particles to be detached from the media while the particles previously detached (i.e. potential backwash remnant particles) are transported out of the filter.

The backwash remnant particles can be particularly problematic when they have a large negative zeta potential, which increases the likelihood that they will pass through the filter following restart (Cranston & Amirtharajah 1987; Amburgey *et al.* 2003, 2004). Backwash remnants are the primary cause of the turbidity spike in the first bed volume of filtrate produced by a continuously operated filter, but elevated turbidities may also occur (under some treatment conditions) until the deposition of newly influent particles results in a gradual increase in collector efficiency and a

corresponding decline (or tailing) in filtrate turbidity and particle counts well after the remnants have already passed out of the filter (Amirtharajah & Wetstein 1980).

ETSW can be very effective at reducing the magnitude of the filter ripening turbidity spikes caused by backwash remnants, but the ETSW process itself is not thought to significantly alter the number of collector particles left on the filter media (Amburgey *et al.* 2003). However, the manner by which ETSW is incorporated into the entire backwash procedure could potentially alter the number of collector particles on the media at the conclusion of backwashing. In theory, the duration of air-scour, surface wash, and fluidization steps can be shortened with the intent of leaving additional particles on the media grains. An ETSW step would permit ending a typical backwash procedure at almost any point without concern over the high turbidity water remaining in the filter box since ETSW will remove those detached particles while removing far fewer of the particles remaining on the media grains than fluidization. One would have to be careful not to leave too many deposited particles on the grains since excess material might slough off during start up, increase the loss of head through the filter, and/or lead to mudball formation. Furthermore, residual deposits may have significantly different characteristics from those of bare filter media or freshly deposited particles that could also affect filter performance.

### Potential advantages of the ETSW procedure

- Reduction or elimination of the degraded filtered water quality during the filter ripening period and improved ability to comply with water quality guidelines on turbidity
- Decreased pathogen passage through filters following restart, and the production of safer and cleaner drinking water for consumers
- Possible reduction in backwash water usage and consequential hydraulic load on the backwash recycle stream system
- Reduction or elimination of the need to practise filter-to-waste
- Increased life of backwash water pumps and/or under-drain systems

- Filters will look cleaner before returning them to service, which will improve visual observation of the filter media and structures within the filter box

### Potential disadvantages of the ETSW procedure

- Could take a few extra minutes to complete the backwash procedure
- An additional step might need to be added to the original backwash procedure
- Might require additional washwater usage depending on implementation strategy
- Might lead to mudball formation if the other portions of the backwashing procedure are shortened too much and leave the filter media insufficiently clean after backwashing

## FILTER RIPENING WATER QUALITY AFTER ETSW AND NON-ETSW BACKWASHES

### Conventional water treatment plant

The Atlanta-Fulton County Water Treatment Plant draws its water from the Chattahoochee River (Atlanta, Georgia), practises prechlorination with alum as the sole coagulant, and has a media design consisting of 46 cm of 0.9 mm effective size (ES) anthracite over 30 cm of 0.5 mm ES sand. The backwash procedure used at this location was 3 min of air-scour, 1 min of low-rate water wash ( $15.4 \text{ m h}^{-1}$ ), 5 min of high-rate wash ( $45.9 \text{ m h}^{-1}$ ), and a final ETSW step of varying flow rates and sufficient duration to pass one complete filter-volume of water through the filter. Several ETSW rates were chosen based on minimum fluidization velocity ( $V_{mf}$ ) calculations for the  $d_{10}$ -,  $d_{60}$ -,  $d_{90}$ -sizes of each filter media at  $10^\circ\text{C}$ . The lower ETSW rates closest to the minimum fluidization velocity of the  $d_{60}$ - and  $d_{10}$ -sizes of the filter media ( $15.4$  and  $7.6 \text{ m h}^{-1}$ ) both produced relatively low filter effluent turbidities during the filter ripening period as shown in Figure 1. The ETSW rate of  $19 \text{ m h}^{-1}$  exceeded the minimum fluidization velocity of the upper anthracite layer ( $16.4 \text{ m h}^{-1}$ ) and produced higher filter effluent turbidities than the two lower ETSW rates. The maximum filter effluent turbidity of the filter without an

ETSW exceeded  $0.83 \text{ NTU}$  within 7 minutes after start-up and before the filter effluent flow was redirected to the filter-to-waste line that did not have a turbidimeter. Additional information about these experiments can be found elsewhere (Amburgey 2002).

### Pilot-scale direct filtration water treatment plant

The following data were obtained from a pilot plant using  $6 \text{ mg l}^{-1}$  of ferric chloride as the sole coagulant at a final pH of 6.0 to treat lake water with an initial turbidity of 1 NTU and total organic carbon (TOC) concentration of approximately  $2 \text{ mg l}^{-1}$ . The filters contained 1.2 m of anthracite coal (ES = 1.5 mm; uniformity coefficient (UC) = 1.3) and 0.30 m of sand (ES = 0.64 mm; UC = 1.4), and the  $V_{mf}$  of  $d_{10}$  sizes of the anthracite and sand were calculated to be  $26.9 \text{ m h}^{-1}$  and  $13.8 \text{ m h}^{-1}$ , respectively. The filters were backwashed with 3 minutes of combined air and water wash followed by fluidization wash at  $75 \text{ m h}^{-1}$  for 7 min. For the ETSW backwash, the total volume of washwater was held constant by reducing the fluidization time by 2 min and applying an ETSW at  $30 \text{ m h}^{-1}$  for 5 min. The turbidity and particle counts (larger than 2 microns in diameter) in the filtered water immediately following the backwash routine are shown in Figure 2 and demonstrate the impact of ETSW on initial water quality produced by a filter. Even though the applied ETSW rate was more than double the  $V_{mf}$  of the  $d_{10}$  sized sand, it was possible to visually observe that the sand beneath the 1.2 m of anthracite was not fluidized nor was the top of the anthracite layer during the ETSW. These results indicate that the upper layer of filter media can dominate the fluidization behaviour of the entire dual media filter bed under these conditions, but similar behaviour is not guaranteed in other systems.

## DESIGNING AN ETSW PROCEDURE

### Overview

ETSW is a relatively simple process comprising an appropriate duration subfluidization wash step at the end of a backwash procedure. However, the ETSW procedure must be tailored to the conditions existing at a given water

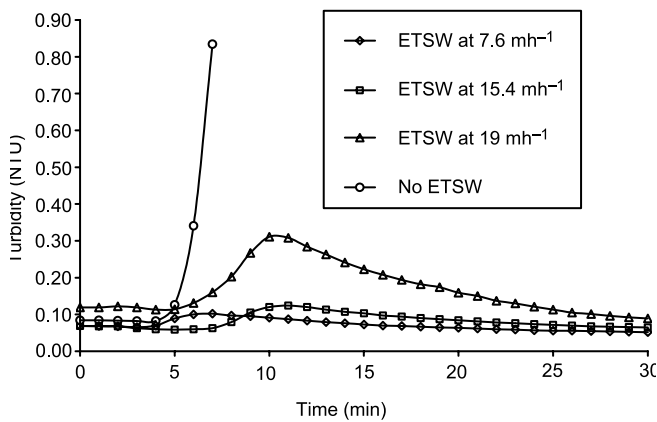


Figure 1 | Initial turbidities following different final (ETSW) backwash rates.

treatment facility for maximum benefit, which requires an understanding of the fundamental principles behind this process. This paper presents a rational approach to implementing the ETSW procedure based on the current understanding of the process.

This ETSW implementation approach begins with the collection of required data, and some typical values are supplied herein to assist the user. Next, a range of potential ETSW backwash rates is calculated based on the properties of the filter media and the expected range of water temperatures. After determining a range of potential ETSW rates, it is necessary to calculate an appropriate duration for the ETSW step at each backwash flow rate. A trial and error approach is recommended for determining the shortest and/or most effective ETSW procedure for a given facility. Advice is given on how to modify the existing backwash procedure when adding in the ETSW step and on

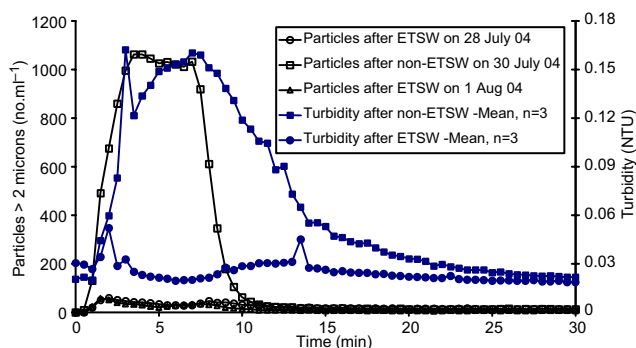


Figure 2 | Filter ripening water quality after ETSW and non-ETSW backwashes.

how to modify the ETSW procedure should performance begin to deteriorate due to changing treatment conditions.

### Required information and typical values

Potential ETSW backwash flow rates can be calculated based on the minimum fluidization velocities of the filter media. The effective size (ES), uniformity coefficient (UC), and density of each media can be used in calculating the minimum fluidization velocities of each media. The range of velocities considered also depends on the range of water temperatures expected at a given location. The surface area of each filter is required to convert calculated values per unit area into the total flow rates for a given filter.

After determining a range of potential ETSW rates, it is necessary to calculate an appropriate duration for the ETSW step at each backwash rate. The depth and porosity of the media along with the distance from the top of the media to the overflow for the washwater are needed to calculate the volume of water to displace with the ETSW step. A factor of safety may be applied to the calculated value to compensate for uneven distribution of backwash water, dispersion, operator error, and settling of backwash remnant particles during the ETSW procedure. A value of 1.3 for the factor of safety has been used by the authors, but the conditions prevailing at a given facility may vary widely necessitating some individual judgement. It is often possible to be able to observe the displacement of backwash remnant particles near the end of the ETSW procedure by changes in water quality near the level of the washwater troughs. The size of the underdrain and the characteristics of the media support material need not be considered since this volume of water is essentially free of backwash remnant particles at the beginning of the ETSW step. Some typical filter media design values are provide in Table 1.

### Calculation of minimum fluidization velocities

Cleasby & Logsdon (1999) reference the work of Wen & Yu (1966) to describe a method used to calculate the minimum fluidization velocity for a uniform-sized media. The equation used to calculate the minimum fluidization velocity ( $V_{mf}$ ) is:

$$V_{mf} = \frac{\mu}{\rho d_{eq}} (33.7^2 + 0.0408Ga)^{0.5} - \frac{33.7\mu}{\rho d_{eq}} \quad (1)$$

where  $Ga$  is the Galileo number defined as:

$$Ga = d_{eq}^3 \frac{\rho(\rho_s - \rho)g}{\mu^2} \quad (2)$$

where  $g$  is the acceleration due to gravity ( $\sim 9.81 \text{ m s}^{-2}$ ),  $d_{eq}$  is the diameter of media,  $\mu$  is the dynamic viscosity of the fluid, and  $\rho_s$  and  $\rho$  are the mass density of the filter media and the fluid, respectively. The  $d_{10}$  value is typically chosen for  $d_{eq}$  for calculating an ETSW starting point for a graded bed of filter media, but the  $d_{90}$  value is typically chosen for  $d_{eq}$  for calculating the minimum fluidized backwash velocity for a graded bed of filter media. The smaller  $d_{eq}$  values are chosen for ETSW because the intent is not to fluidize even the smallest grains near the top of the bed, but the larger  $d_{eq}$  values are chosen for fluidization backwash where the goal is to fluidize all of the media grains.

The  $V_{mf}$  for dual media filters can be calculated as follows (Amirtharajah *et al.* 1991):

$$(V_{mf})_{dual} = (V_{mf})_{anthracite} \left[ \frac{(V_{mf})_{sand}}{(V_{mf})_{anthracite}} \right]^{X_{sand}^{1.69}} \quad (3)$$

when the anthracite has a higher  $V_{mf}$  than the sand, otherwise the sand and anthracite terms must be interchanged. In Equation (3),  $X_{sand}$  is the mass fraction of sand in the filter.

### Initial selection of a range of potential ETSW rates

In practice, effective ETSW rates have ranged from the  $V_{mf}$  of the  $d_{90}$  sized grains (for the large media and polymer-

aided coagulation typical of direct filtration) to the  $V_{mf}$  of the  $d_{10}$  sized grains (for the smaller media and alum floc typical of conventional treatment plants) (Amburgey *et al.* 2003). Since effective ETSW rates depend on many variables (e.g. floc strength and media size), it is generally advisable to calculate a range of potential ETSW values that begins with the ETSW rate based on the  $V_{mf}$  of the  $d_{10}$  sized grains at the coldest annual water temperature and progresses upward towards the ETSW rate based on the  $V_{mf}$  of the  $d_{90}$  sized grains at the warmest annual water temperature. Equation (4) can be used to calculate an approximate  $d_{90}$  grain size based on the effective size ( $d_{10}$ ) and uniformity coefficient (UC) of the media (Cleasby & Logsdon 1999).

$$d_{90} = d_{10}(10^{1.67 \text{LogUC}}) \quad (4)$$

Higher ETSW rates offer the advantage of faster backwashes, but the faster backwash cycles can come at the expense of filtered water quality during the filter ripening period (above a threshold ETSW rate that typically must be determined experimentally). After calculating the ETSW rates in terms of flow per unit area, these values may be converted into flow rates via multiplying by the surface area of the filter.

### Choosing the appropriate duration for a new ETSW procedure

Once a range of potential ETSW rates has been determined, it is necessary to determine the appropriate length of time to perform the ETSW procedure. The intent of the ETSW

**Table 1** | Typical filter media design values

Media	Sand	Anthracite	Deep bed anthracite	Garnet	GAC
Density ( $\rho_s$ ) ( $\text{g cm}^{-3}$ )	2.55–2.65	1.45–1.75	1.45–1.75	3.6–4.3	1.3–1.5
Porosity	0.40–0.47	0.50–0.60	0.50–0.60	0.45–0.55	0.5
ES (mm)	0.40–0.55	0.8–1.1	1.4–1.6	0.20–0.30	0.9–1.5
UC	1.3–1.8	1.2–1.3	1.2–1.3	1.5–1.8	1.2–1.4
Depth (m)	0.15–0.30	0.45–0.75	1.2–1.8	0.10	0.45–1.8

Sources: AWWA & ASCE (1998); Cleasby & Logsdon (1999)

procedure is to displace the entire volume of backwash remnant water in the filter box (i.e. the pore volume of the media plus the volume of the headspace above the media). The duration of the ETSW procedure at each rate can be calculated by dividing the volume of water that needs to be displaced during the ETSW procedure by the ETSW flow rate. A factor of safety (e.g. 1.3) can be applied to the ETSW duration to account for human error and non-ideal behaviour during the ETSW step.

### Optimizing a new ETSW procedure

Once the potential range of ETSW rates has been calculated, the procedure usually has to be optimized by trial and error. The optimization criteria will be determined by the operator (e.g. minimum turbidity/particle counts peak, minimum total particles passing into the finished water, minimum backwash duration to meet filtrate quality goals, etc.). Previous research has identified a trend towards decreasing filtrate quality with increasing ETSW rates beyond a threshold value, so the authors recommend beginning with the ETSW rate based on the  $V_{mf}$  of the  $d_{10}$  sized grains at the coldest annual water temperature and progressing upwards in an incremental fashion to identify the optimum value. The intent of this approach is to avoid situations where the ETSW procedure is initially ineffective and promotes the passage of particles into the finished drinking water supply.

If the ETSW procedure will not be adjusted for temperature variations, then it is important to ensure that adequate performance is obtained at the lowest temperature when the viscosity of the water is the highest and the shear strength of the floc is often the weakest. For the initial experiments with ETSW, it is recommended that the ETSW step simply be added on to the end of the existing backwash procedure. This will facilitate straightforward comparisons between the various ETSW and non-ETSW backwashes, and there should not be any concern over lack of cleaning due to a modified backwash procedure. Whenever possible, the authors recommend monitoring both turbidity and particle counts during the initial ETSW trials because trends for different size ranges of particles can be significantly different. The turbidity of the water flowing into the backwash troughs at the conclusion of the ETSW procedure

and/or the cloudiness of the water in the filter box may provide an early indication of the success (or failure) of a particular ETSW procedure.

### MODIFYING AN EXISTING ETSW PROCEDURE

The optimum ETSW rate is likely to change with water temperature, and this behaviour is similar to the changing minimum fluidization velocity of any filter media with water temperature. The temperature dependency of ETSW and fluidization rates stems from fundamental changes in the properties of water with temperature. The dynamic viscosity and density of water both change with the temperature of the water. The change in density of water with temperature is relatively minor, but the changes in the viscosity of water with temperature are substantial. The values for density and viscosity of water between 0 and 30°C are given in Table 2. It is possible to use extreme values of washwater flow to ensure that the media does (or does not) fluidize throughout the entire range of water temperatures, but this approach will not necessarily yield the best results or be practical to implement.

### TYPICAL CALCULATED VALUES

Table 3 lists the most relevant physical properties of some typical types of filter media. The values in Table 3 were used to determine the minimum fluidization velocities of the  $d_{10}$ -sized media grains in each of the hypothetical filter designs at a range of water temperatures, shown in Table 4 using Equations (1) to (3). The impact of water temperature on fluidization velocity is apparent, and this impact is an excellent reason to consider modifying backwash flow rates for fluidization wash and ETSW with seasonal changes in water temperature.

Table 5 contains the calculated minimum fluidization velocities for the  $d_{90}$ -,  $d_{60}$ -, and  $d_{10}$ -sizes of the selected filter media at a constant water temperature of 20°C. The effect of grain size on minimum fluidization velocity is also substantial. The initial range of potential ETSW rates will be based on a range of calculated values similar to those in Table 5. Some experimentation will be necessary in order to

select the final ETSW rate(s) and duration(s). It is theoretically possible that effective ETSW rates will exist at flows less than the minimum fluidization velocity of  $d_{10}$  sized grains, but the aforementioned value is generally a good place to start. If water quality during the ripening period begins to worsen with increases in ETSW rate above the minimum fluidization velocity of the  $d_{10}$  sized grains, then it may be necessary explore lower ETSW rates to achieve the desired water quality goals.

### OTHER INFLUENCES ON ETSW RATE SELECTION

The range of backwash flow rates at which ETSW will be effective will depend on multiple parameters, and the ETSW rates that work well at one treatment facility may not work well at a similar facility (even if both facilities have the same media design and water temperature). The strength of the floc can vary with the efficiency of the coagulation process, which is itself sensitive to multiple parameters including coagulant type, coagulant dose, coagulated water pH, natural organic matter concentration and temperature. The optimality of the coagulation process also has an impact on the ETSW procedure and the resulting filter ripening turbidity spikes since the ETSW never removes 100% of the backwash remnant particles. The proportion of remaining backwash remnant particles that return through

the filter into the finished water will be influenced by the surface charge (or zeta potential) of the backwash remnant particles.

Since degraded filtered water quality during the ripening period has two potential causes as mentioned above (i.e. backwash remnants and the need for additional collectors to be deposited on the filter media), it is possible that some utilities will find that ETSW is of a limited benefit to them because of their particular treatment conditions. ETSW is intended to modify only the initial portion of the filter ripening period (corresponding to backwash remnant particle passage). A delayed filter ripening spike could be observed even with an optimized ETSW procedure (and potentially be attributed to ineffective coagulation) requiring an hour or more of the filter run to subside as particles accumulate within the filter media and begin to serve as additional collectors of the newly incoming particles thereby increasing the removal efficiency of the filter. In many instances, there is no need for additional collector accumulation to achieve excellent filtered water quality in continuously operated filters, but in the case of sub-optimal coagulation the likelihood of a particle being retained on a single media grain is decreased thereby requiring additional collectors to be present in order to achieve same level of removal observed in a filter under optimal coagulation conditions.

If the degraded filtered water quality associated with filter ripening persists well beyond the first bed volume of filtrate, then it is likely that changes in the coagulation conditions will be necessary (in addition to the ETSW procedure) to solve this type of water quality problem. Based on the current understanding of the filtration process, the additional collector phenomenon is due to either the lack of sufficient depth of filter media (i.e. an insufficient number of collectors) or the unfavourable conditions at the particle-media interface that hinder the attachment efficiency following collisions of particles with the media surfaces (i.e. poor collision efficiency). The problem of poor collision efficiency is typically solved by proper chemical pretreatment of the source water. A summary of other approaches for dealing with the filter ripening problem can be found elsewhere (Logsdon *et al.* 2002; Amburgey *et al.* 2003, 2004).

**Table 2** | Viscosity and density of water as a function of temperature

Temperature (°C)	Density ( $\rho$ ) ( $\text{g cm}^{-3}$ )	Absolute viscosity ( $\mu$ ) ( $\text{g cm s}^{-1}$ )
0	0.9999	0.01792
5	1.0000	0.01519
10	0.9997	0.01310
15	0.9991	0.01145
20	0.9982	0.01009
25	0.9971	0.00895
30	0.9957	0.00800

Source: Kawamura (1991).

**Table 3** | Specifications and properties of some typical graded beds of filter media

	Sand	Anthracite	450 mm anthracite and 300 mm sand	Deep bed anthracite
Effective size (ES) $d_{10}$ (mm)	0.55	1.1	1.1 and 0.55	1.6
Uniformity coefficient (UC = $d_{60}/d_{10}$ )	1.4	1.3	1.3 and 1.4	1.3
$d_{60}$ (mm)	0.77	1.43	1.43 and 0.77	2.08
$d_{90}$ (mm)	0.96	1.70	1.70 and 0.96	2.48
Media density ( $\text{g cm}^{-3}$ )	2.6	1.55	1.55 and 2.6	1.55

### STRATEGIES FOR INCORPORATING ETSW INTO EXISTING BACKWASH PROCEDURES

The incorporation of an ETSW step may in some cases allow substantial modifications to the rest of the backwash procedure. When using air scour or surface wash, most of the particle detachment from the media grains during backwashing occurs prior to fluidization, and it might be possible to shorten the fluidization phase without significantly altering the cleaning efficiency of the backwashing process. However, if the current backwash protocol only entails fluidization, then shortening the fluidization stage when adding an ETSW step might significantly decrease the overall cleaning efficiency of the backwash. ETSW is not intended to detach particles from the media grains. On the contrary, ETSW is intended to avoid detaching particles

from the media grains while flushing already detached particles out of the filter. It is recommended that modifications to the backwash procedure be followed up with measurements of the initial headloss, the headloss accumulation rate and the degree of mudball formation to avoid potential problems. Since ETSW can carry the majority of detached particles out of the filter box at a lower flow rate than fluidization, it is often possible to practise some water conservation by decreasing the total amount of washwater used per backwash.

**Table 4** | Calculated minimum fluidization velocities for typical  $d_{10}$ -sized media

	Sand	Anthracite	450 mm anthracite and 300 mm sand	Deep bed anthracite
$V_{mf}$ (0°C) ( $\text{m h}^{-1}$ )	5.8	7.8	6.9	16.0
$V_{mf}$ (5°C) ( $\text{m h}^{-1}$ )	6.7	9.1	8.1	18.4
$V_{mf}$ (10°C) ( $\text{m h}^{-1}$ )	7.8	10.5	9.3	20.9
$V_{mf}$ (15°C) ( $\text{m h}^{-1}$ )	8.9	11.9	10.6	23.3
$V_{mf}$ (20°C) ( $\text{m h}^{-1}$ )	10.1	13.4	12.0	25.8
$V_{mf}$ (25°C) ( $\text{m h}^{-1}$ )	11.3	14.9	13.4	28.2
$V_{mf}$ (30°C) ( $\text{m h}^{-1}$ )	12.6	16.4	14.8	30.4

### SUMMARY AND CONCLUSION

This paper provides a brief theoretical overview of the ETSW procedure along with a list of potential benefits of using ETSW. However, the primary intent of this paper is to assist the readers in implementing the ETSW procedure at new locations. A summary of required information, typical values, physical constants and useful equations are supplied for calculating the range of potential ETSW flow rates and durations. Advice is provided on optimizing the ETSW procedure and on modifying it to accommodate changing treatment conditions. Some calculated values are provided to illustrate the importance of media characteristics and water temperature on the ETSW procedure and to help users to verify their own calculations. Finally, some advice is given regarding how to incorporate the ETSW procedure into an existing backwash protocol. The authors hope that new users can realize some of the many potential advantages of this advanced backwashing technique. More widespread use of this technique should also lead to



**Table 5** | Calculated minimum fluidization velocities for various media sizes at 20°C

	Sand	Anthracite	450 mm anthracite and 300 mm sand	Deep bed anthracite
$V_{mf}$ d <sub>10</sub> -sized media (m h <sup>-1</sup> )	10.1	13.4	12.0	25.8
$V_{mf}$ d <sub>60</sub> -sized media (m h <sup>-1</sup> )	19.1	21.4	20.5	38.4
$V_{mf}$ d <sub>90</sub> -sized media (m h <sup>-1</sup> )	28.6	28.5	28.5	48.5

improved understanding of the various factors that influence its performance and to improved optimization strategies.

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