Supplementary Materials

BSF Fine Sand Preparation

Five sand samples were prepared according to CAWST guidelines for BSF sand preparation [1]. Note that CAWST does not specify a required sieve type for sand preparation; rather, CAWST assumes that the BSF user will make their own sieves, using wire mesh and wooden frames, and manually sieve the sand [1]. In this study, handmade sieves were replaced with laboratory-grade sieves, and sand was sieved using a RoTAP sieve shaker machine.

First, a sieve column was created for a RoTAP sieve shaker machine that included (from top to bottom) five sieves lower than No. 24 (or greater than 0.7 mm mesh) in decreasing size order, a No. 24 (0.7 mm) sieve, and a catch pan. The sand samples (approximately 2 L each) were then individually processed through the sieve column using the RoTAP sieve shaker. To avoid overwhelming the weight threshold of the sieve mesh, the top sieve was filled with sand to about half capacity in each run, and sand sample processing was split into multiple runs. The RoTAP machine was run for five minutes per sand sample, and then sand grains that were caught on the No. 24 sieve or above were separated and removed from the sample because they were too large for use in the fine sand layer of the BSF. The sand that passed through the No. 24 sieve was stored for use as filtration sand in the BSF columns. This process was repeated for each of the five samples.

The filtration sand (with grain sizes less than 0.7 mm in diameter) was prepared for sand size characterization following CAWST guidelines. Briefly, the sand was added to a 2-gallon bucket (filling the bucket approximately ¼ full), and clear, dechlorinated tap water was added to the sand until the bucket was about ½ full. The sand was then swirled in the water by hand to wash, and the wash water was slowly decanted and discarded (taking care to minimize sand losses). This sand-washing process was repeated until the decanted rinse water was clear; the total number of washes was recorded for each sand sample. To check for proper washing, an aliquot of the washed sand sample was added to a 200-mL dilution jar (the sand was filled to about an inch in depth). The dilution jar was filled with clear, dechlorinated tap water and shaken until the sand was fully suspended. The jar was then placed on a flat surface and observed after four seconds: if the surface of the sand was not visible (i.e., the water was too murky), then the sand was too dirty and was washed more; if the water was clear and the surface of the sand was easily visible, then the sand was too clean - it was discarded, and the original sample was re-processed with fewer wash steps; if the sand fully settled within four seconds, with the sand surface visible but not fully clear, then the sample was accepted for use in a BSF [1,35]. Once accepted for BSF use, the remainder of the respective sand sample was prepared using the same number of wash steps as the accepted sample [1,35]. Once all sand samples were washed to CAWST standards, the sand was air-dried on a clean plastic sheet in the laboratory. The sand was raked by hand daily to check for moisture and hasten the drying process.

Sample Calculation of ES, d60, and UC

The procedure for calculating the ES, d60, and UC of a sand sample is provided below. The procedure is the same for both mass- and volume-based sand size parameters. The example shown below uses mass-based measurements to determine sand size parameters. To determine sand size parameters using volume-based measurements, replace "mass" with "volume" below.

Screen Size	Screen Hole Size (mm)	Sieve Mass (g)	Sieve and Sand Mass (g)	(a) Mass Remaining on Sieve (g)	(b) Cumulative Mass Remaining on Sieve (g)	(c) Percent Sand Finer than Sieve (%)
#25	0.71	399.2	409.9	10.7	10.7	96.6
#40	0.425	561.4	579.4	18	28.7	90.8
#60	0.25	464.4	596	131.6	160.3	48.5
#80	0.177	359.1	447.2	88.1	248.4	20.2
#140	0.105	398	459.7	61.7	310.1	0.4
Catch Pan	0	495.3	496.6	1.3	311.4	0

Note: Sample calculations are shown below for values in red.

1. Calculate the percent sand finer than each sieve. The percent of sand finer than sieve #40 is calculated in 1(a)-(c) below as an example.

(a) The mass remaining on each sieve was calculated as:

Mass remaining on the screen (g) = [Mass of Sieve and Sand (g)] - [Sand Mass (g)]
= 579.4 g - 561.4 g
= 18 g

(b) The cumulative mass remaining on each sieve was calculated as:

Cumulative Mass Remaining on Screen (g) = [Mass Remaining on Screen for all larger sieves (g)] + [Mass Remaining on Screen (g)]
= 10.7 g + 18 g
= 28.7 g

(c) The percent sand finer than each sieve was calculated as:

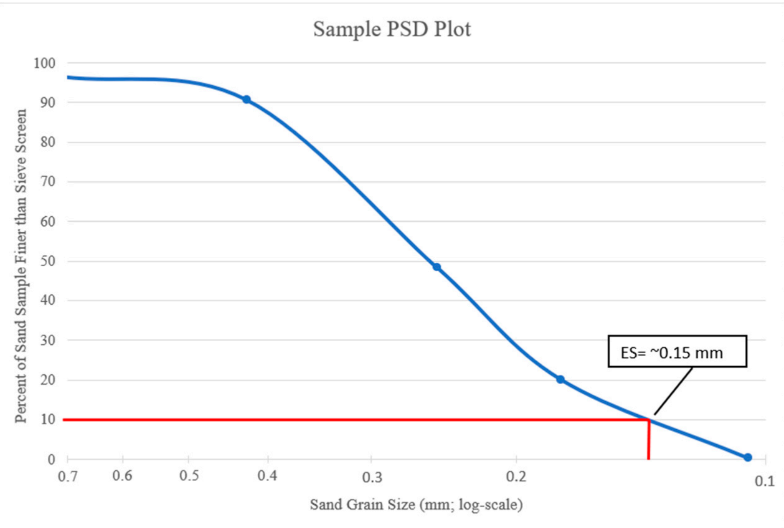
$$Percent\ sand\ finer = \left(1 - \frac{(Mass\ or\ volume)\ retained\ on\ a\ sieve\ and\ each\ sieve\ larger\ than\ that\ sieve}{Cumulative\ (mass\ or\ volume)\ retained\ on\ all\ sieves}\right) * 100\%$$

$$= \left(1 - \frac{28.7\ g}{311.4\ g}\right) * 100\%$$

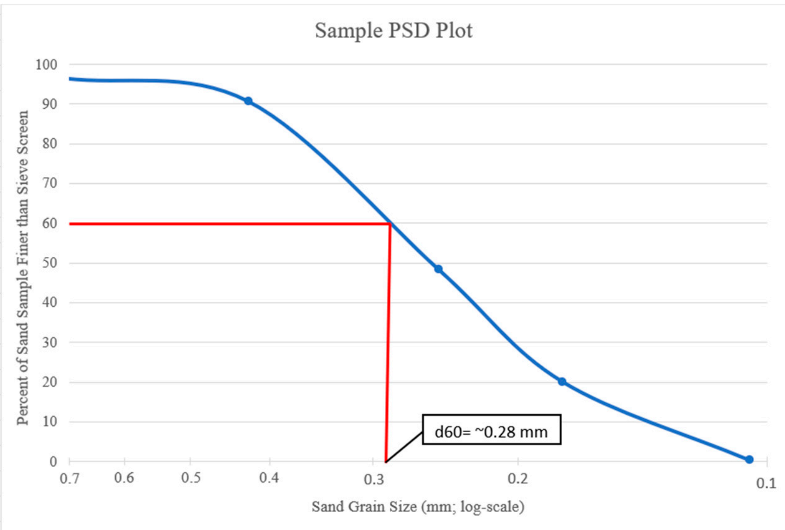
= 90.8%

2. Plot percent sand finer than the screen (Y-axis) against the sieve screen hole size (i.e., sand grain size) on a reverse-order, logarithmic scale (X-axis) to create a PSD plot.

3. Determine the ES value, where the ES value is the sand grain size (mm) corresponding to 10% of the sand sample finer than the sieve screen. An ES value of 0.15 mm is determined below as an example.



4. Determine the d_{60} value, where the d_{60} value is the sand grain size (mm) corresponding to 60% of the sand sample finer than the sieve screen. A d_{60} value of 0.28 mm is determined below as an example.



5. Calculate the UC value by dividing the d_{60} by the ES. A UC value of 1.87 is calculated below as an example.

$$UC = d_{60}/ES$$

= 0.28 mm / 0.15 mm

= **1.87**

Sand Characterization Data

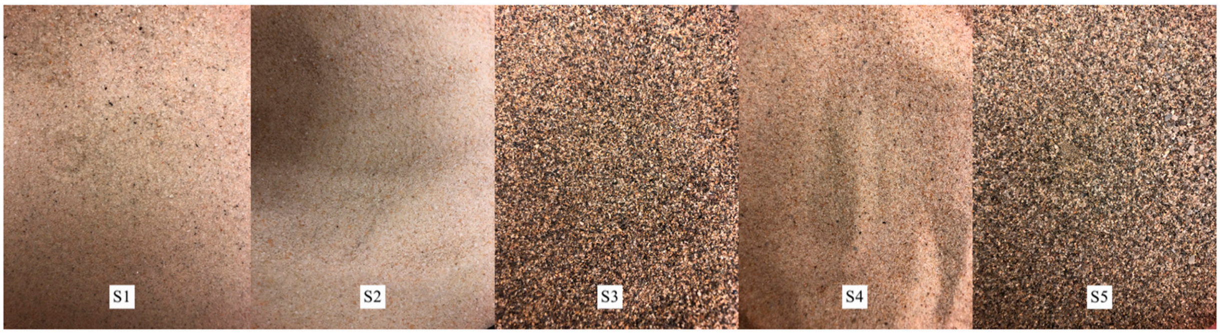
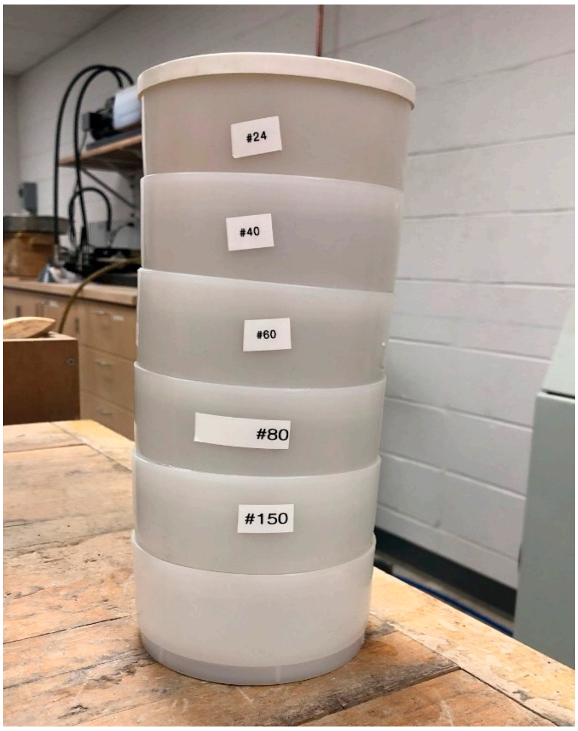


Figure S1. Five sand samples analyzed, in ascending order from S1 on the far left to S5 on the far right. Images not to scale; intended for visual comparison.

(a)



(b)

Figure S2. Sieve sets used to perform sieve testing of five sand samples. (a) Laboratory-grade sieve set on RoTAP Sieve Shaker, (b) CAWST (handheld) sieve set.

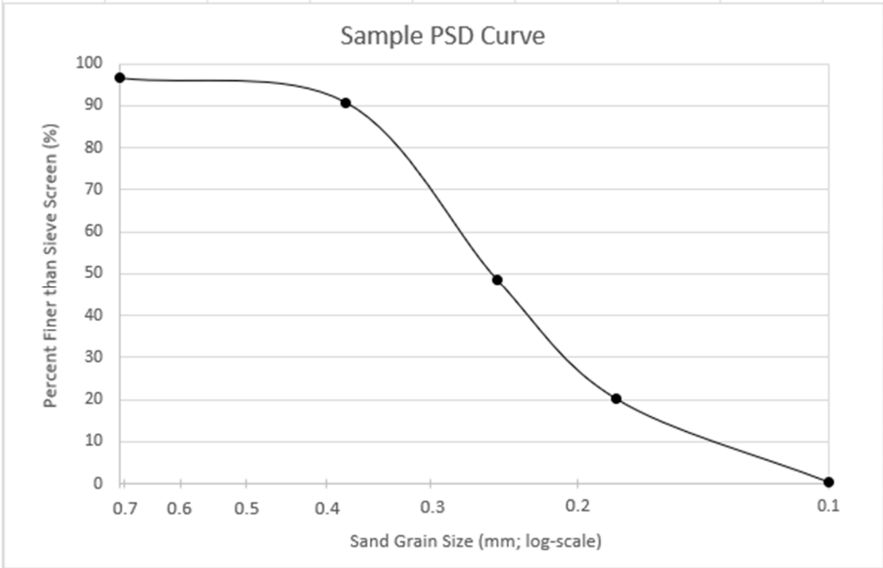
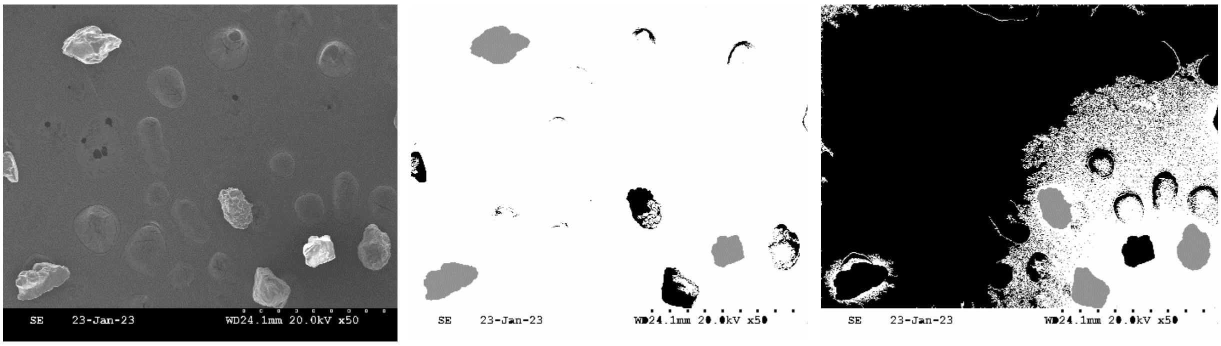


Figure S3. Example Particle Size Distribution (PSD) curve created using the Lab PSD protocols and S1.



(a) (b) (c)

Figure S4. SEM and ImageJ protocol for determining sand shape characteristics. (a) Sample 1 imaged using scanning Electron Microscopy (SEM), (b) Sample 1 SEM image converted to binary using ImageJ, (c) Sample 1 SEM image with enhanced contrast and converted to binary using ImageJ. The grey-filled sand grains in (b) and (c) were measured for area, perimeter, and Min-Feret (shortest along any axis) diameter using ImageJ.

Table S1. Mann-Whitney results for the fraction of a sample retained on a laboratory sieve using mass or volume measurements.

Sand	Sieve No.	Group	n	U-Statistic	p
S1	25	Mass	17	172	0.352
		Volume	17		
	40	Mass	17	200	0.057
		Volume	17		
	60	Mass	17	191	0.114
		Volume	17		
	80	Mass	17	80	**0.026**
		Volume	17		
	140	Mass	17	105	0.182
		Volume	17		
	Catch Pan	Mass	17	147	0.946
		Volume	17		
S2	25	Mass	17	200	**0.058**
		Volume	17		
	40	Mass	17	247	**<0.001**
		Volume	17		
	60	Mass	17	49	**0.001**
		Volume	17		
	80	Mass	17	81	**0.030**
		Volume	17		
	140	Mass	17	101	0.140
		Volume	17		
	Catch Pan	Mass	17	204	**0.042**
		Volume	17		
S3	25	Mass	17	163	0.540
		Volume	17		
	40	Mass	17	245	**<0.001**
		Volume	17		
	60	Mass	17	0	**<0.001**
		Volume	17		
	80	Mass	17	179	0.241
		Volume	17		
	140	Mass	17	208	**0.030**
		Volume	17		
	Catch Pan	Mass	17	251	**<0.001**
		Volume	17		
S4	25	Mass	17	231	**0.002**
		Volume	17		
	40	Mass	17	200	0.058
		Volume	17		
	60	Mass	17	143	0.973
		Volume	17		
	80	Mass	17	90	0.079

		Volume	17		
	140	Mass	17	104	0.168
		Volume	17		
	Catch Pan	Mass	17	233	**0.002**ᵻ
		Volume	17		
S5	25	Mass	17	213	**0.019**ᵻ
		Volume	17		
	40	Mass	17	173	0.335
		Volume	17		
	60	Mass	17	68	**0.009**ᵻ
		Volume	17		
	80	Mass	17	138	0.836
		Volume	17		
	140	Mass	17	178	0.256
		Volume	17		
	Catch Pan	Mass	17	204	**0.042**ᵻ
		Volume	17		

ᵻ two-tailed p-value <0.05

Table S2. Whether or not median ES values resulting from each determination method fell within the recommended ES range (0.15-0.20 mm).

Method	CAWST PSD		CAWST App		CAWST Graph		Lab PSD	
Sample	Mass	Volume	Mass	Volume	Mass	Volume	Mass	Volume
S1	Yes	Yes	No	No	No	No	No	No
S2	No	No	No	No	No	No	No	No
S3	No	No	Yes	No	No	No	No	No
S4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
S5	No	No	No	No	No	No	No	No

Table S3. Mann-Whitney U test results for mass versus volume comparison of CAWST sieves.

Sand	Method	Group	n	ES		UC	
				U Statistic	p	U Statistic	p
S1	CAWST PSD	Mass	17				
		Volume	17	142.5	0.958	146.5	0.959
	CAWST App	Mass	17				
		Volume	17	147	0.944	146.5	0.958
	CAWST Graph	Mass	17				
		Volume	17	138.5	0.847	150.5	0.850
S2	CAWST PSD	Mass	17				
		Volume	17	141	0.917	141.5	0.931
	CAWST App	Mass	17				
		Volume	17	122	0.445	180.5	0.221
	CAWST Graph	Mass	17				
		Volume	17	123	0.468	167	0.448
S3	CAWST PSD	Mass	17				
		Volume	17	95.5	0.082	217.5	**0.012**[ᵻ]
	CAWST App	Mass	17				
		Volume	17	76.5	**0.018**[ᵻ]	213.5	**0.018**[ᵻ]
	CAWST Graph	Mass	17				
		Volume	17	77.5	**0.018**[ᵻ]	223	**0.007**[ᵻ]
S4	CAWST PSD	Mass	17				
		Volume	17	127.5	0.557	176.5	0.269
	CAWST App	Mass	17				
		Volume	17	119	0.381	190.5	0.114
	CAWST Graph	Mass	17				
		Volume	17	127	0.551	167.5	0.438
S5	CAWST PSD	Mass	17				
		Volume	17	131.5	0.660	144.5	1.000
	CAWST App	Mass	17				
		Volume	17	107	0.186	189.5	0.120
	CAWST Graph	Mass	17				
		Volume	17	105.5	0.156	171.5	0.359

[ᵻ] Mann-Whitney, two-tailed p-value <0.05

Table S4. Mann-Whitney U test results for mass versus volume comparison of laboratory sieves.

Sand	Method	n	ES		UC	
			U Statistic	p	U Statistic	p
S1	Mass	17	143.5	0.984	196.5	0.064
	Volume	17				
S2	Mass	17	134.5	0.734	167.5	0.432
	Volume	17				
S3	Mass	17	55.5	0.001[ᶦ]	248	**<0.001**[ᶦ]
	Volume	17				
S4	Mass	17	136	0.694	194	0.081
	Volume	17				
S5	Mass	17	136	0.759	171	0.363
	Volume	17				

[ᶦ] Mann-Whitney, two-tailed p-value <0.05

Table S5. Kruskal-Wallis and Dunn post-hoc test results for overall sample density.

Kruskal-Wallis Comparisons				Post-hoc Comparisons					
n	χ^2 Statistic	df	p	Sand/ Sand	S1 (n=17)	S2 (n=17)	S3 (n=17)	S4 (n=17)	S5 (n=17)
85	58.429	4	**<0.001**[ᶦ]	S1 (n=17)					
				S2 (n=17)	**p_{Holm}= 0.007**[ᵞ] (z-score= -3.203; p=0.001)				
				S3 (n=17)	**p_{Holm}<0.001**[ᵞ] (z-score= -4.836; p<0.001)	p_{Holm}= 0.410 (z-score= -1.633; p= 0.102)			
				S4 (n=17)	p_{Holm}= 0.410 (z-score= 1.508; p= 0.132)	**p_{Holm}<0.001**[ᵞ] (z-score= -4.711; p<0.001)	**p_{Holm}<0.001**[ᵞ] (z-score= 6.334; p<0.001)		
				5 (n=17)	p_{Holm}= 0.718 (z-score= 0.591; p= 0.555)	**p_{Holm}= 0.001**[ᵞ] (z-score= 3.794; p<0.001)	**p_{Holm}<0.001**[ᵞ] (z-score= 5.427; p<0.001)	p_{Holm}= 0.718 (z-score= -0.917; p= 0.359)	

[ᶦ] Kruskal-Wallis, two-tailed p-value <0.05; [ᵞ] Dunn, two-tailed Holm-adjusted p-value <0.05

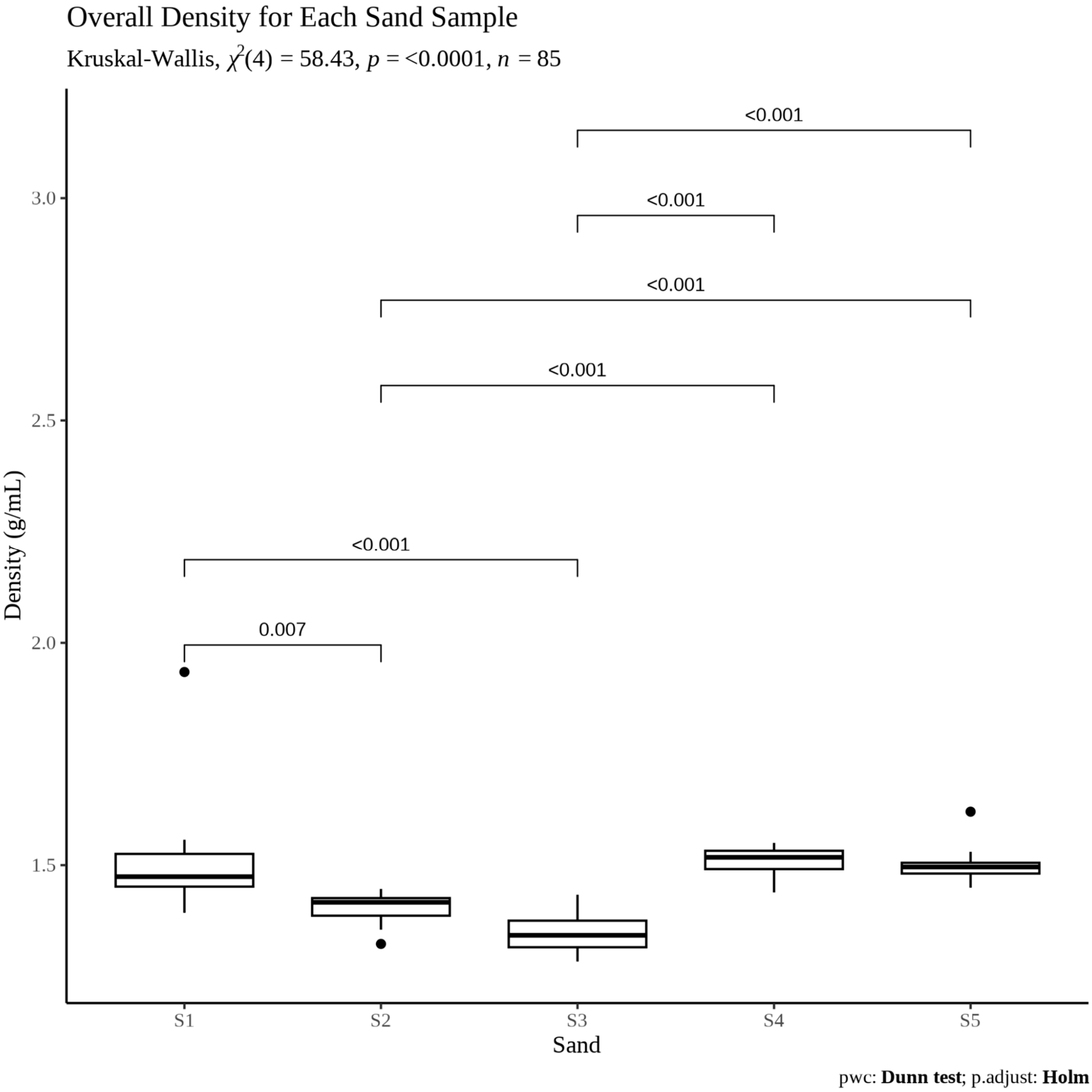


Figure S5. Plot of overall sand density and Kruskal-Wallis and Dunn post-hoc statistics.

Table S6. Kruskal-Wallis and Dunn post-hoc test results for the S1 densities of sand retained on each sieve.

Kruskal-Wallis Comparisons				**Post-hoc Comparisons**						
n	**χ^2 Statistic**	**df**	**p**	**Sieve No./ Sieve No.**	**25 (n=14)**	**40 (n=17)**	**60 (n=17)**	**80 (n=17)**	**140 (n=17)**	**Catch Pan (n=17)**
99	12.088	5	0.0336[ɪ]	25 (n=14)						
				40 (n=17)	p_{Holm}= 1 (z-statistic= 0.728; p= 0.466)					
				60 (n=17)	p_{Holm}= 1 (z-statistic= -0.140; p= 0.889)	p_{Holm}= 1 (z-statistic= -0.914; p= 0.361)				
				80 (n=17)	p_{Holm}= 1 (z-statistic= -1.473; p= 0.141)	p_{Holm}= 0.287 (z-statistic= -2.317; p= 0.021)	p_{Holm}= 1 (z-statistic= -1.403; p= 0.161)			
				140 (n=17)	p_{Holm}= 0.482 (z-statistic= 2.052; p= 0.040)	p_{Holm}= 0.052 (z-statistic= 2.926; p= 0.003)	p_{Holm}= 0.486 (z-statistic= 2.012; p=0.044)	p_{Holm}= 1 (z-statistic= 0.609; p=0.543)		
				Catch Pan (n=17)	p_{Holm}= 1 (z-statistic= -0.008; p= 0.994)	p_{Holm}= 1 (z-statistic= 0.448; p= 0.758)	p_{Holm}= 1 (z-statistic= -0.155; p= 0.877)	p_{Holm}= 1 (z-statistic= -1.558; p= 0.119)	p_{Holm}= 0.393 (z-statistic= -2.167; p= 0.030)	

[ɪ] Kruskal-Wallis, two-tailed p-value <0.05; [ɣ] Dunn, two-tailed Holm-adjusted p-value <0.05

Table S7. Kruskal-Wallis and Dunn post-hoc test results for the S2 densities of sand retained on each sieve.

Kruskal-Wallis Comparisons				**Post-hoc Comparisons**						
n	**χ^2 Statistic**	**df**	**p**	**Sieve No./ Sieve No.**	**25 (n=17)**	**40 (n=17)**	**60 (n=17)**	**80 (n=17)**	**140 (n=17)**	**Catch Pan (n=17)**
102	37.881	5	<0.001[ᵻ]	25 (n=17)						
				40 (n=17)	p_{Holm}= 0.418 (z-statistic= -1.814; p= 0.070)					
				60 (n=17)	**p_{Holm}<0.001**[γ] (z-statistic= -4.382; p<0.001)	p_{Holm}= 0.072 (z-statistic= -2.568; p= 0.010)				
				80 (n=17)	**p_{Holm}<0.001**[γ] (z-statistic= -4.541; p<0.001)	p_{Holm}= 0.056 (z-statistic= -2.727; p= 0.006)	p_{Holm}= 1 (z-statistic= -0.159; p= 0.873)			
				140 (n=17)	**p_{Holm}<0.001**[γ] (z-statistic= 4.550; p<0.001)	p_{Holm}= 0.056 (z-statistic= 2.736; p= 0.006)	p_{Holm}= 1 (z-statistic= 0.168; p= 0.867)	p_{Holm}= 1 (z-statistic= 0.009; p= 0.993)		
				Catch Pan (n=17)	p_{Holm}= 0.591 (z-statistic= 1.562; p= 0.118)	p_{Holm}= 1 (z-statistic= -0.252; p= 0.801)	**p_{Holm}= 0.048**[γ] (z-statistic= -2.820; p= 0.005)	**p_{Holm}= 0.034**[γ] (z-statistic= -2.979; p= 0.003)	**p_{Holm}= 0.034**[γ] (z-statistic= -2.988; p= 0.003)	

[ᵻ] Kruskal-Wallis, two-tailed p-value <0.05; [γ] Dunn, two-tailed Holm-adjusted p-value <0.05

Table S8. Kruskal-Wallis and Dunn post-hoc test results for the S3 densities of sand retained on each sieve.

Kruskal-Wallis Comparisons				**Post-hoc Comparisons**						
n	**χ^2 Statistic**	**df**	**p**	**Sieve No./ Sieve No.**	**25 (n=17)**	**40 (n=17)**	**60 (n=17)**	**80 (n=17)**	**140 (n=17)**	**Catch Pan (n=17)**
102	54.809	5	<0.001[ᵻ]	25 (n=17)						
				40 (n=17)	p_{Holm}= 1 (z-statistic= 1.130; p= 0.258)					
				60 (n=17)	**p_{Holm}= 0.003**[ɣ] (z-statistic= -3.588; p<0.001)	**p_{Holm}<0.001**[ɣ] (z-statistic= -4.718; p<0.001)				
				80 (n=17)	p_{Holm}= 1 (z-statistic= -0.096; p= 0.924)	p_{Holm}= 1 (z-statistic= -1.226; p= 0.220)	**p_{Holm}= 0.004**[ɣ] (z-statistic= 3.492; p<0.001)			
				140 (n=17)	p_{Holm}= 1 (z-statistic= -0.698; p= 0.485)	p_{Holm}= 1 (z-statistic= 0.432; p= 0.666)	**p_{Holm}<0.001**[ɣ] (z-statistic= -4.286; p<0.001)	p_{Holm}= 1 (z-statistic= -0.794; p= 0.427)		
				Catch Pan (n=17)	**p_{Holm}= 0.003**[ɣ] (z-statistic= -3.646; p< 0.001)	p_{Holm}= 0.083 (z-statistic= -2.516; p= 0.012)	**p_{Holm}<0.001**[ɣ] (z-statistic= -7.234; p<0.001)	**p_{Holm}= 0.002**[ɣ] (z-statistic= -3.741; p<0.001)	**p_{Holm}= 0.026**[ɣ] (z-statistic= -2.947; p= 0.003)	

[ᵻ] Kruskal-Wallis, two-tailed p-value <0.05; [ɣ] Dunn, two-tailed Holm-adjusted p-value <0.05

Table S9. Kruskal-Wallis and Dunn post-hoc test results for the S4 densities of sand retained on each sieve.

Kruskal-Wallis Comparisons				**Post-hoc Comparisons**						
n	**χ^2 Statistic**	**df**	**p**	**Sieve No./ Sieve No.**	**25 (n=5)**	**40 (n=17)**	**60 (n=17)**	**80 (n=17)**	**140 (n=17)**	**Catch Pan (n=17)**
90	47.052	5	<0.001[ᵻ]	25 (n=5)						
				40 (n=17)	p_{Holm}= 1 (z-statistic= 0.625; p= 0.532)					
				60 (n=17)	p_{Holm}= 1 (z-statistic= -1.037; p= 0.300)	p_{Holm}= 0.137 (z-statistic= -2.465; p= 0.014)				
				80 (n=17)	p_{Holm}= 0.201 (z-statistic= -2.285; p= 0.022)	**p_{Holm}<0.001**[ɣ] (z-statistic= -4.316; p<0.001)	p_{Holm}= 0.449 (z-statistic= -1.851; p= 0.064)			
				140 (n=17)	p_{Holm}= 0.220 (z-statistic= 2.205; p= 0.027)	**p_{Holm}<0.001**[ɣ] (z-statistic= 4.198; p<0.001)	p_{Holm}= 0.498 (z-statistic= 1.733; p= 0.083)	p_{Holm}= 1 (z-statistic= -0.118; p= 0.906)		
				Catch Pan (n=17)	p_{Holm}= 1 (z-statistic= -1.276; p= 0.202)	p_{Holm}= 1 (z-statistic= -0.965; p= 0.202)	**p_{Holm}= 0.007**[ɣ] (z-statistic= -3.430; p= 0.001)	**p_{Holm}<0.001**[ɣ] (z-statistic= -5.281; p<0.001)	**p_{Holm}<0.001**[ɣ] (z-statistic= -5.163; p<0.001)	

[ᵻ] Kruskal-Wallis, two-tailed p-value <0.05; [ɣ] Dunn, two-tailed Holm-adjusted p-value <0.05

Table S10. Kruskal-Wallis and Dunn post-hoc test results for the S5 densities of sand retained on each sieve.

Kruskal-Wallis Comparisons				**Post-hoc Comparisons**						
n	**χ^2 Statistic**	**df**	**p**	**Sieve No./ Sieve No.**	**25 (n=17)**	**40 (n=17)**	**60 (n=17)**	**80 (n=17)**	**140 (n=17)**	**Catch Pan (n=16)**
101	37.348	5	<0.001[ᵻ]	25 (n=17)						
				40 (n=17)	p_{Holm}= 0.051 (z-statistic= -2.833; p= 0.005)					
				60 (n=17)	**p_{Holm}<0.001**[ɣ] (z-statistic= -5.385; p<0.001)	p_{Holm}= 0.096 (z-statistic= -2.552; p= 0.011)				
				80 (n=17)	**p_{Holm}<0.001**[ɣ] (z-statistic= -4.138; p<0.001)	p_{Holm}= 0.954 (z-statistic= -1.305; p= 0.192)	p_{Holm}= 0.954 (z-statistic= 1.247; p= 0.212)			
				140 (n=17)	p_{Holm}= 0.340 (z-statistic= 1.973; p= 0.049)	p_{Holm}= 0.954 (z-statistic= -0.860; p= 0.390)	**p_{Holm}= 0.008**[ɣ] (z-statistic= -3.412; p= 0.001)	p_{Holm}= 0.243 (z-statistic= -2.166; p= 0.030)		
				Catch Pan (n=16)	p_{Holm}= 0.954 (z-statistic= 1.381; p= 0.167)	p_{Holm}= 0.954 (z-statistic= -1.409; p= 0.159)	p_{Holm}= 0.001[ɣ] (z-statistic= -3.922; p<0.001)	p_{Holm}= 0.071 (z-statistic= -2.694; p= 0.007)	p_{Holm}= 0.954 (z-statistic= -0.561; p= 0.575)	

[ᵻ] Kruskal-Wallis, two-tailed p-value <0.05; [ɣ] Dunn, two-tailed Holm-adjusted p-value <0.05

Table S11. Kruskal-Wallis and Dunn post-hoc test results for average grain roundness.

Kruskal-Wallis Comparisons				**Post-hoc Comparisons**					
n	**χ^2 Statistic**	**df**	**p**	**Sand/ Sand**	**S1 (n=159)**	**S2 (n=225)**	**S3 (n=720)**	**S4 (n=150)**	**S5 (n=187)**
1441	15.951	4	**0.003**ᵻ	S1 (n=159)					
				S2 (n=225)	p_{Holm}= 0.063 (z-statistic= -2.696; p= 0.007)				
				S3 (n=720)	p_{Holm}= 1 (z-statistic= 0.017; p= 0.986)	**p_{Holm}= 0.002**ˠ (z-statistic= 3.677; p< 0.001)			
				S4 (n=150)	p_{Holm}= 1 (z-statistic= -0.444; p= 0.657)	p_{Holm}= 0.240 (z-statistic= 2.170; p= 0.030)	p_{Holm}= 1 (z-statistic= -0.580; p= 0.562)		
				S5 (n=187)	p_{Holm}= 0.802 (z-statistic= -1.500; p= 0.134)	p_{Holm}= 1 (z-statistic= 1.187; p= 0.235)	p_{Holm}= 1 (z-statistic= -1.990; p= 0.045)	p_{Holm}= 1 (z-statistic= -1.015; p= 0.310)	

ᵻ Kruskal-Wallis, two-tailed p-value <0.05; ˠ Dunn, two-tailed Holm-adjusted p-value <0.05

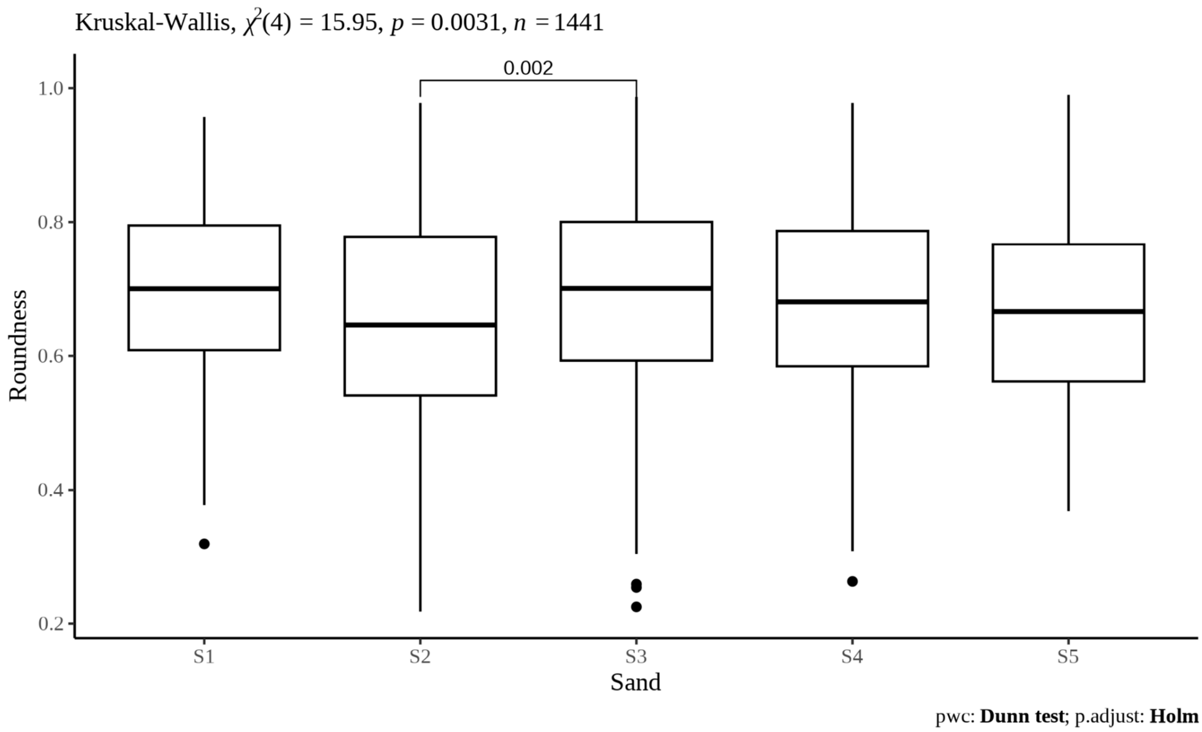


Figure S6. Distribution of sand sample roundness measurements determined with ImageJ, and Kruskal-Wallis and Dunn post-hoc results.

Table S12. Kruskal-Wallis and Dunn post-hoc test results for average grain circularity.

Kruskal-Wallis Comparisons				**Post-hoc Comparisons**					
n	**χ^2 Statistic**	**df**	**p**	**Sand/ Sand**	**S1 (n=159)**	**S2 (n=225)**	**S3 (n=720)**	**S4 (n=150)**	**S5 (n=187)**
1441	186.594	4	**<0.001**[ɪ]	S1 (n=159)					
				S2 (n=225)	**p_{Holm}<0.001**[γ] (z-statistic= -7.466; p<0.001)				
				S3 (n=720)	p_{Holm}= 0.136 (z-statistic= 0.817; p= 0.068)	**p_{Holm}<0.001**[γ] (z-statistic= 8.034; p<0.001)			
				S4 (n=150)	p_{Holm}= 0.414 (z-statistic= 0.817; p= 0.414)	**p_{Holm}<0.001**[γ] (z-statistic= 8.220; p<0.001)	**p_{Holm}= 0.019**[γ] (z-statistic= 2.817; p= 0.005)		
				S5 (n=187)	**p_{Holm}<0.001**[γ] (z-statistic= -9.030; p<0.001)	p_{Holm}= 0.128 (z-statistic= -2.027; p= 0.043)	**p_{Holm}<0.001**[γ] (z-statistic= -9.920; p<0.001)	**p_{Holm}<0.001**[γ] (z-statistic= -9.735; p<0.001)	

[ɪ] Kruskal-Wallis, two-tailed p-value <0.05; [γ] Dunn, two-tailed Holm-adjusted p-value <0.05

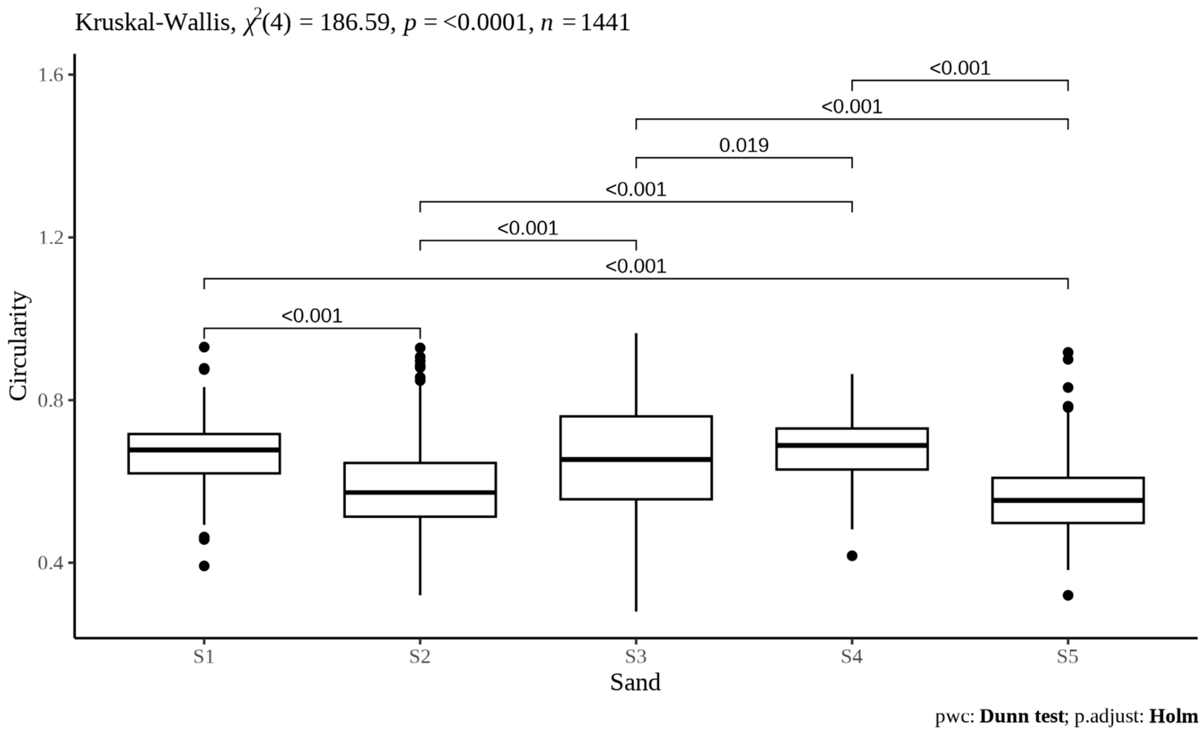


Figure S7. Distribution of sand sample circularity measurements determined with ImageJ, and Kruskal-Wallis and Dunn post-hoc results.

Table S13. Kruskal-Wallis and Dunn post-hoc test results for ES values from the three prescribed methods (CAWST App and CAWST Graph, using volume; and Lab PSD, using mass).

Sand	n	Kruskal-Wallis Comparisons			Post-hoc Comparisons								
		χ^2 Statistic	df	p	CAWST App (n=17) vs. CAWST Graph (n=17)			CAWST App (n=17) vs. Lab PSD (n=17)			CAWST Graph (n=17) vs. Lab PSD (n=17)		
					z-score	p	p_{Holm}	z-score	p	p_{Holm}	z-score	p	p_{Holm}
S1	51	1.996	2	0.369	0.120	0.905	0.905	-1.159	0.246	0.603	-1.279	0.201	0.603
S2	51	24.219	2	**<0.001**[ᵻ]	0.250	0.803	0.803	-4.132	<0.001	**<0.001**[ˠ]	-4.381	<0.001	**<0.001**[ˠ]
S3	51	3.824	2	0.148	0.767	0.443	0.481	-1.174	0.240	0.481	-1.941	0.052	0.157
S4	51	13.679	2	**0.001**[ᵻ]	-0.124	0.901	0.901	-3.263	<0.001	**0.003**[ˠ]	-3.139	0.002	**0.003**[ˠ]
S5	51	26.767	2	**<0.001**[ᵻ]	0.917	0.359	0.359	4.868	<0.001	**<0.001**[ˠ]	3.951	<0.001	**<0.001**[ˠ]

[ᵻ] Kruskal-Wallis, two-tailed p-value <0.05; [ˠ] Dunn, two-tailed Holm-adjusted p-value <0.05

Table S14. Kruskal-Wallis and Dunn post-hoc test results for UC values from the three prescribed methods (CAWST App and CAWST Graph, using volume; and Lab PSD, using mass).

Sand	n	Kruskal-Wallis Comparisons			Post-hoc Comparisons								
		χ^2 Statistic	df	p	CAWST App (n=17) vs. CAWST Graph (n=17)			CAWST App (n=17) vs. Lab PSD (n=17)			CAWST Graph (n=17) vs. Lab PSD (n=17)		
					z-score	p	p_{Holm}	z-score	p	p_{Holm}	z-score	p	p_{Holm}
S1	51	5.174	2	0.075	0.904	0.366	0.366	-1.356	0.175	0.350	-2.260	0.024	0.072
S2	51	8.996	2	**0.011**[ᵻ]	0.537	0.591	0.591	2.824	0.005	**0.014**[ˠ]	2.287	0.022	**0.044**[ˠ]
S3	51	0.158	2	0.924	-0.145	0.885	1.000	0.249	0.804	1.000	0.393	0.694	1.000
S4	51	6.848	2	**0.033**[ᵻ]	0.197	0.844	0.844	2.358	0.018	0.055	2.161	0.031	0.061
S5	51	29.324	2	**<0.001**[ᵻ]	0.603	0.547	0.547	-4.359	<0.001	**<0.001**[ˠ]	-4.962	<0.001	**<0.001**[ˠ]

[ᵻ] Kruskal-Wallis, two-tailed p-value <0.05; [ˠ] Dunn, two-tailed Holm-adjusted p-value <0.05

Table S15. Kruskal-Wallis and Dunn post-hoc test results for ES values from CAWST App, CAWST Graph, and Lab PSD methods, using mass only.

Sand	n	Kruskal-Wallis Comparisons			Post-hoc Comparisons								
		χ^2 Statistic	df	p	CAWST App (n=17) vs. CAWST Graph (n=17)			CAWST App (n=17) vs. Lab PSD (n=17)			CAWST Graph (n=17) vs. Lab PSD (n=17)		
					z-score	p	p_{Holm}	z-score	p	p_{Holm}	z-score	p	p_{Holm}
S1	51	1.896	2	0.387	-0.352	0.725	0.725	-1.329	0.184	0.552	-0.977	0.328	0.657
S2	51	19.405	2	**<0.001**[ɨ]	0.402	0.688	0.688	-3.598	<0.001	**0.001**[ɣ]	-4.000	<0.001	**<0.001**[ɣ]
S3	51	7.005	2	**0.030**[ɨ]	1.778	0.075	0.151	2.587	0.010	**0.029**[ɣ]	0.808	0.419	0.419
S4	51	9.704	2	**0.008**[ɨ]	-0.012	0.991	0.991	-2.704	0.007	**0.021**[ɣ]	-2.692	0.007	**0.021**[ɣ]
S5	51	33.354	2	**<0.001**[ɨ]	0.658	0.511	0.511	5.298	<0.001	**<0.001**[ɣ]	4.640	<0.001	**<0.001**[ɣ]

[ɨ] Kruskal-Wallis, two-tailed p-value <0.05; [ɣ] Dunn, two-tailed Holm-adjusted p-value <0.05

Table S16. Kruskal-Wallis and Dunn post-hoc test results for UC values from CAWST App, CAWST Graph, and Lab PSD methods, using mass only.

Sand	n	Kruskal-Wallis Comparisons			Post-hoc Comparisons								
		χ^2 Statistic	df	p	CAWST App (n=17) vs. CAWST Graph (n=17)			CAWST App (n=17) vs. Lab PSD (n=17)			CAWST Graph (n=17) vs. Lab PSD (n=17)		
					z-score	p	p_{Holm}	z-score	p	p_{Holm}	z-score	p	p_{Holm}
S1	51	7.04	2	**0.030**[ɨ]	1.176	0.239	0.282	-1.472	0.141	0.282	-2.648	0.008	**0.024**[ɣ]
S2	51	2.42	2	0.298	0.445	0.656	0.656	1.513	0.130	0.391	1.069	0.285	0.570
S3	51	11.76	2	**0.003**[ɨ]	-0.348	0.728	0.728	-3.128	0.002	**0.005**[ɣ]	-2.780	0.005	**0.011**[ɣ]
S4	51	1.60	2	0.448	-0.365	0.715	0.771	0.868	0.385	0.771	1.233	0.218	0.653
S5	51	31.25	2	**<0.001**[ɨ]	0.116	0.908	0.908	-4.782	<0.001	**<0.001**[ɣ]	-4.898	<0.001	**<0.001**[ɣ]

[ɨ] Kruskal-Wallis, two-tailed p-value <0.05; [ɣ] Dunn, two-tailed Holm-adjusted p-value <0.05

Filter Efficacy Pilot Study

The efficacy of BSF filter columns (as a function of the ES and UC) and the utility of the upper (safety) limit of the CAWST-recommended ES range was also assessed using turbidity removal as a performance indicator. Turbidity removal was selected to evaluate the filter performance due to the visual appearance of turbid water reducing water acceptability for users and effectiveness of chlorination for water treatment [29,30].

The pilot BSF columns (Figure S6) used in this study were constructed in polyvinyl chloride (PVC) pipes and designed with supernatant (5 cm deep), fine sand (15 cm deep; total volume 1.9 L), coarse sand (4 cm deep; total volume 0.507 L), and gravel (4 cm deep; total volume 0.507 L) depths proportional to a 5-gallon bucket BSF and scaled-down v10 concrete BSF (target flow rate of 400 mL/min) [1,29]. Each column was constructed using a 4-inch internal diameter PVC pipe that was 20 inches in length, with a 4-inch Quik cap as the base and a 4-inch knock-out (KO) test cap as the lid. Ten filter columns (duplicate columns for each of the five sand samples) were constructed (Figure S6 Panel C). While the pilot columns used in this filter are based on a v10 concrete BSF design, the CAWST-recommended ES and UC ranges for filtration sand are used in other filter designs as well, broadening the implications of the pilot column study.

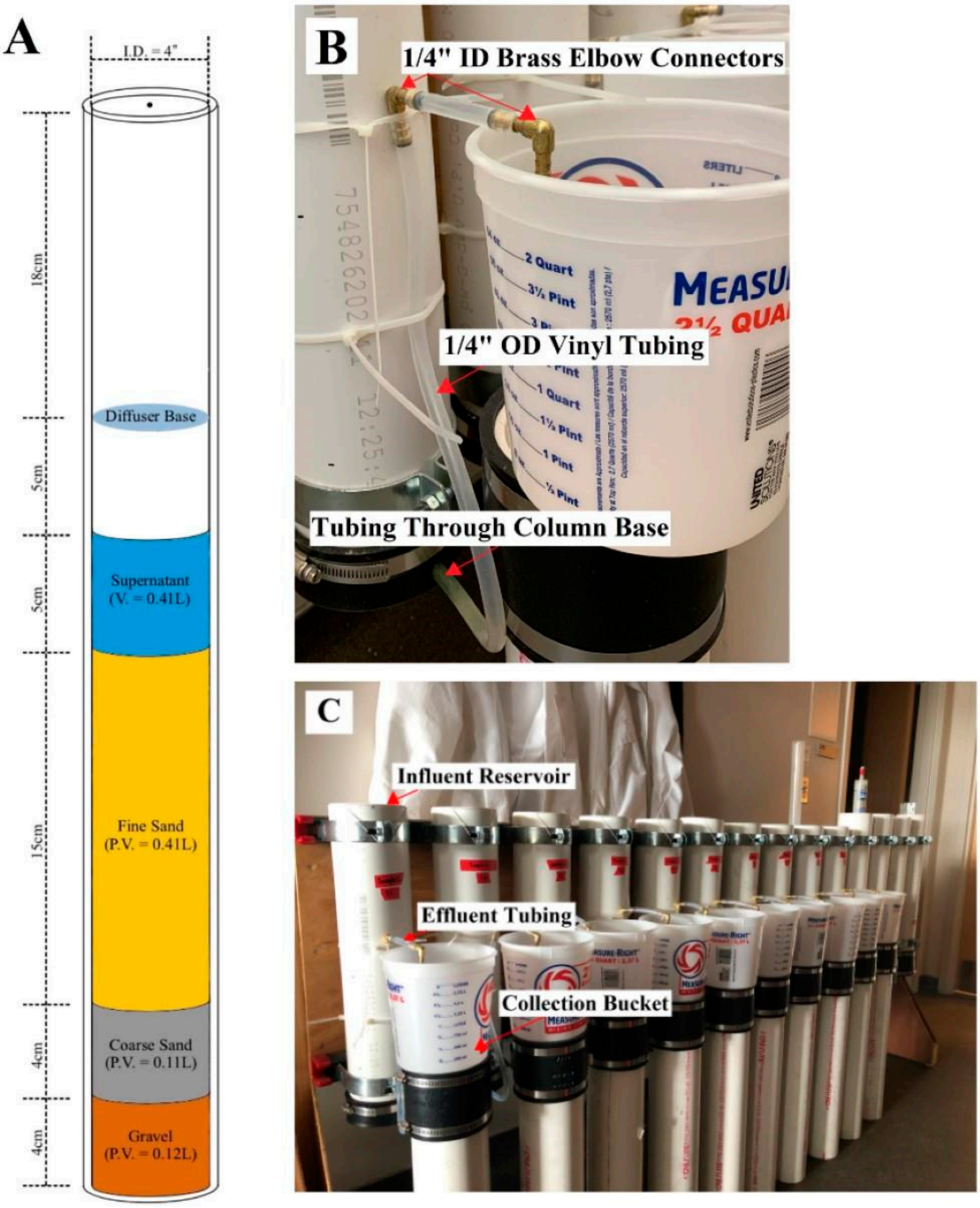


Figure S8. Pilot BSF column design. Panel A: Design schematic for a filter column. 'V.' represents volume and 'P.V.' represents pore volume of media; Panel B: Labeled image of effluent tubing for one filter column. OD=outer diameter; ID=inner diameter. Panel C: Labeled image of completed filter column set-up.

To construct the ten pilot BSFs, the base of each PVC column was plugged with a Qwik cap. Effluent tubing (7.6 cm of ¼-inch vinyl tubing) was inserted through a ¼-inch hole in the PVC wall at the bottom of the column using a threaded brass through-wall connection; this internal tubing had five (5) 3 mm (⅛ -inch) holes drilled along its length to capture filtered water collecting in the gravel underdrain. Another 28 cm of vinyl tubing was connected to the internal vinyl tubing at the outlet using brass elbow fittings; this external effluent tubing was held vertically against the PVC filter column with zip ties (Figure S6 Panel B). At the top of the 28-cm effluent tubing, two elbow fittings and a smaller (approximately 2-3 inches) piece of tubing were used to redirect the outlet flow into a collection bucket next to the column (Figure S6 Panel B). The gravel, coarse sand, and fine sand layers (in that order) were then added to the column up to their specified heights using a premarked meter stick. A funnel was connected to the outlet nozzle of the BSF tubing using an additional ¼-inch vinyl tubing. Dechlorinated water was poured into the funnel, which gradually backfilled the BSF with water from the base to the supernatant layer. The diffuser basin was built using a 10.3-oz coffee can: the base of the coffee can was coated with Aqua Epoxy to inhibit rusting and drilled with 3-mm (⅛-inch) holes spaced 2.5 cm (1 inch) apart in a gridded pattern. Two additional holes were drilled just below the upper perimeter of the can, and a piece of string was tied to the holes and used to hang the diffuser basin at the top of the column, about 1-2 inches above the supernatant layer. Finally, the BSF was capped with the KO lid. The estimated cost to construct the ten pilot columns (without sand) was about $250 (Table S17).

Table S17. Cost breakdown for pilot BSF columns used in filter testing.

Item	Quantity	Total Cost ($)	Unit Cost ($)
1/4" OD Vinyl Tubing (20')	14.5'	7.93	0.79
Zip Ties	20	1.99	0.20
String (250')	150"	5.85	0.59
2 PC Stencil Brush Set	1	2.97	0.30
GE Silicone II W&D (Window and Door) Clear 10.1 oz (Aqua Epoxy)	1	6.57	0.66
2.5 Qt Measure-Right (Mixing) Container	10	25.8	2.58
10.3 oz Chock Full o'Nuts Coffee Container (metal)	10	49.9	4.99
4" Qwik Cap	10	46.5	4.65
4" Knock Out (KO) Test Cap	10	4.8	0.48
4" x 10' PVC40-DWV PE Pipe	2	43.68	4.37
Brass Barbed Hose Fitting, Elbow Connectors for 1/4" Hose ID, Packs of 5	4	49	4.90
	Total ($)	244.99	24.50

The pore water volume in each BSF porous media layer was determined by calculating the porosity of the gravel, coarse sand, and fine sand samples. A known volume (about 20 mL) of dry media was saturated with tap water from a graduated cylinder, where the initial water volume in the cylinder was known. Porosity was calculated as the pore water volume (*i.e.*, the difference between the initial and final volumes of water in the graduated cylinder) divided by the total saturated volume of soil (*i.e.,* volume of dry media and pore water volume). Porosities for the gravel (n=3), coarse sand (n=3), and average of fine sand layers (n=15 total; 3 measurements per sand sample) were calculated to be 38.2% ± 2.5 s.d., 34% ± 2.5 s.d., and 33.4% ± 1.9 s.d., respectively (Table S18). The average pore water volume in the gravel, coarse sand, and fine sand layers were 0.12 L, 0.11 L, and 0.41 L ± 0.023 s.d., respectively (Figure S6 Panel A); the volume of water in the supernatant was 0.41 L. Based on these values, the daily fill volume (*i.e.,* the combined volume of water in the fine sand and supernatant layers) was 800 mL.

Table S18. Porosity testing results for fill volume determination in pilot BSF columns.

Sand Type	Fine Sand #1	Fine Sand #2	Fine Sand #3	Fine Sand #4	Fine Sand #5	Fine Sands (#1-5)	Coarse Sand	Gravel
Average Porosity (%)	$\bar{x}$= 31.7 s.d.=2.7 n=3	$\bar{x}$= 33.3 s.d.=1.1 n=3	$\bar{x}$= 34.7 s.d.=1.6 n=3	$\bar{x}$= 32.7 s.d.=1.4 n=3	$\bar{x}$= 34.6 s.d.=1.5 n=3	$\bar{x}$= 33.4 s.d.=1.9 n=3	$\bar{x}$= 34 s.d.=2.5 n=3	$\bar{x}$= 38.2 s.d.=2.5 n=3

Turbid creek water (*i.e.*, creek water mixed with bottom sediments) was diluted with dechlorinated tap water to obtain a target influent turbidity range of 18-25 NTU. Turbidity was measured using a 2100P Turbidimeter (Model No. 46500-00, Hach Company, Loveland, OH, USA) and following APHA's Method 2130 ("Turbidity") [36]. Once the influent turbidity was properly adjusted, 800 mL of influent water was stirred often (to keep particles in suspension) and poured into the top of the first BSF column. A collection bucket was placed under the nozzle to collect the filter effluent. This process was repeated for each of the remaining nine pilot-scale BSF columns. For each filter, the volume of effluent produced by the filter after one minute was recorded to calculate the flow rate; once the effluent stopped flowing into the collection bucket, the treated water in the bucket was hand-stirred and the effluent turbidity was measured. This process was repeated daily for 89 days, except for days 43-44 and 66-67.

When flow rates in the BSFs slowed to about half of the maximum flow rate, a swirl-and-dump cleaning procedure was performed. Briefly, the top of the sand layer (no more than ~2 cm deep) was gently raked using clean fingertips. The supernatant water was then scooped out using a small cup. Care was taken to avoid sand removal along with the turbid water. Clean dechlorinated water was then added to the BSF to maintain a constant-depth supernatant layer. This process was repeated until the supernatant was clear after raking. On day 66, columns S1A, S2A, S3A, S3B, S5A, and S5B were cleaned.

Kruskal-Wallis tests were used to identify significant differences among filter performance (i.e., percent turbidity removal). The Kruskal-Wallis tests were performed with a significance level of 5%, and Holm adjustments were used to control for a family-wise error rate of 5% (α=0.05).

Ten pilot column filters (two filters per sand sample) were used to evaluate filtration efficacy, measured by turbidity removal, during an 89-day study (Table S19). Only the turbidity removal measurements recorded after the recommended 30-day ripening period for BSFs [1] were used to evaluate filter performance. Excluding measurements before day 31 and days 43-44 and 66-67, n=55 turbidity measurements per filter column and n=110 turbidity measurements per sand sample (since duplicate columns were used per sand sample). S1 had the highest median percent turbidity removal, and the median turbidity removals of S1-S4 were all within one standard deviation. In contrast, the median percent turbidity removal of S5 was greater than five (S3) standard deviations below S3, the next worst-performing sand (Table S19).

Table S19. Median percent turbidity removal flow rate, post-ripening period (after day 30), and maximum flow rate for pilot column filters.

Sand/ Performance Metric	**S1**	**S2**	**S3**	**S4**	**S5**
Percent Turbidity Removal (%)	Med.= 96.8 s.d.= 2.62 n= 55[1]	Med.= 95.6 s.d.= 1.39 n= 55[1]	Med.= 94.7 s.d.= 1.82 n= 55[1]	Med.= 95.8 s.d.= 1.18 n= 55[1]	Med.= 83.9 s.d.= 7.33 n= 55[1]
Flow Rate (mL/min)	Med.= 107.5 s.d.= 10.5 n= 55[1]	Med.= 135.5 s.d.= 21.7 n= 55[1]	Med.= 153.0 s.d.= 50.9 n= 55[1]	Med.= 87.0 s.d.= 14.6 n= 55[1]	Med.= 115.0 s.d.= 42.6 n= 55[1]
Maximum Flow Rate[2]	148	266	248	145	226

[1] 110 total, daily measurements were taken on duplicate filters, post-ripening period, and averaged to 55 daily values
[2] Average maximum flow rate is the average flow rate of duplicate filters recorded on day 0

For each sand sample, the UC values determined by the prescribed methods all fell into the recommended range, so the ES was used to explore the CAWST recommended ranges. Two outcomes - either no method or all methods meeting the recommended ES range - were observed among the five samples. Figure S7 shows each sand sample's median turbidity removal as a function of meeting the CAWST-recommended ES standard; only S4 met the ES standards using any of the three prescribed methods.

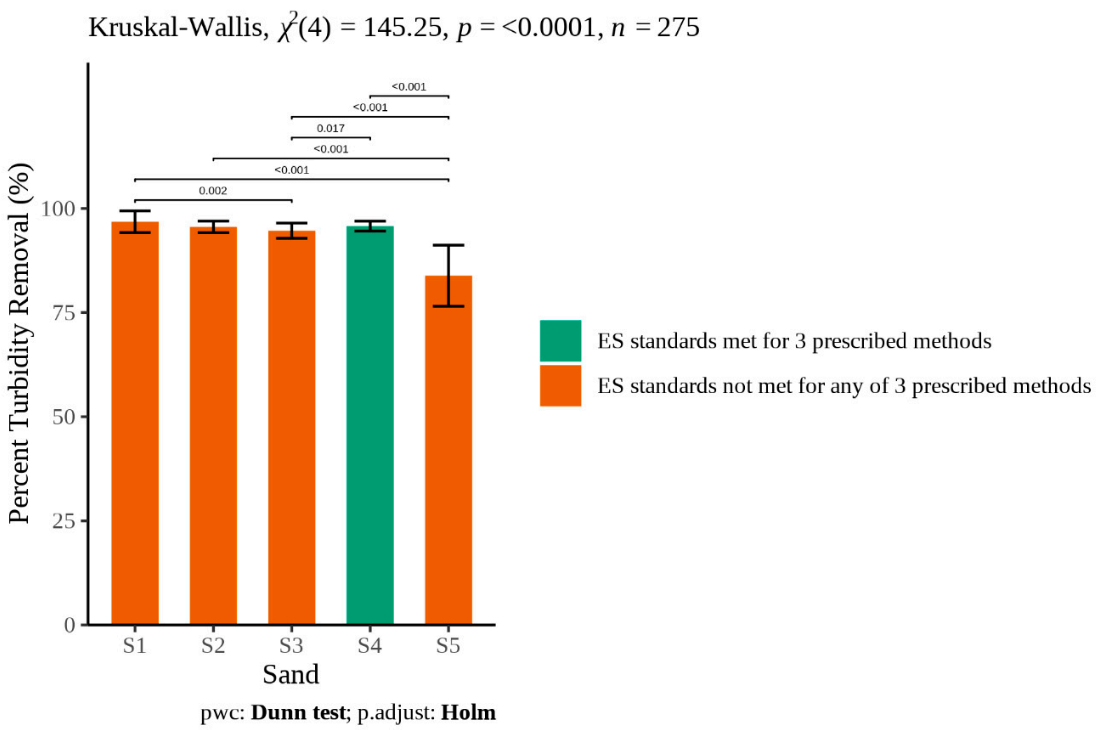


Figure S9. Comparison of median percent turbidity removal (n=110 per sample), post-ripening period (after day 30), for sand samples as a function of median ES meeting the CAWST-recommended ES standard. Error bars represent one standard deviation.

S1, S2, S3, and S5 median ES values were not within the CAWST-recommended range for any prescribed method (Figure S7). However, S5 had the lowest median turbidity removal (83.9%; Table S19), while the turbidity removals of S1, S2, and S3 (96.8%, 95.6%, and 94.7%, respectively; Table S19) were higher and within one standard deviation of S4, which fell within the recommended ES range for all prescribed methods. The performance differences between S1, S2, and S3, and S5, despite the samples all being above the recommended ES for the prescribed methods, may be attributed to the ES value of S5 being further from the upper CAWST-recommended limit. Using the Lab PSD results (*i.e.*, the standard method for sand characterization), S5 had the highest (and furthest from the recommended upper limit) ES value (Med.=0.27 mm, s.d.=0.01 mm), while the recommended upper ES limit (0.20 mm) was within one standard deviation of S2 and S3's ES value (Med.=0.21 mm, s.d.= 0.01 mm). These results suggested that the CAWST upper limit for ES is effectively set for safety concerns related to effluent water quality.

The relationship between filter efficacy (*i.e.,* turbidity removal) and the CAWST-recommended ES range was further investigated. Kruskal-Wallis tests identified that at least one sand sample had statistically different percent turbidity removal from the others (Kruskal-Wallis $p<0.05$; Figure S8; Table S20). Dunn post-hoc tests found S3 had significantly lower percent turbidity removal than S1 and S4 (Dunn $p_{Holm}=0.002$ and Dunn $p_{Holm}=0.017$, respectively), and S5 had significantly lower percent turbidity removal than all other sand samples (Dunn $p_{Holm}<0.001$; Figure S8; Table S20).

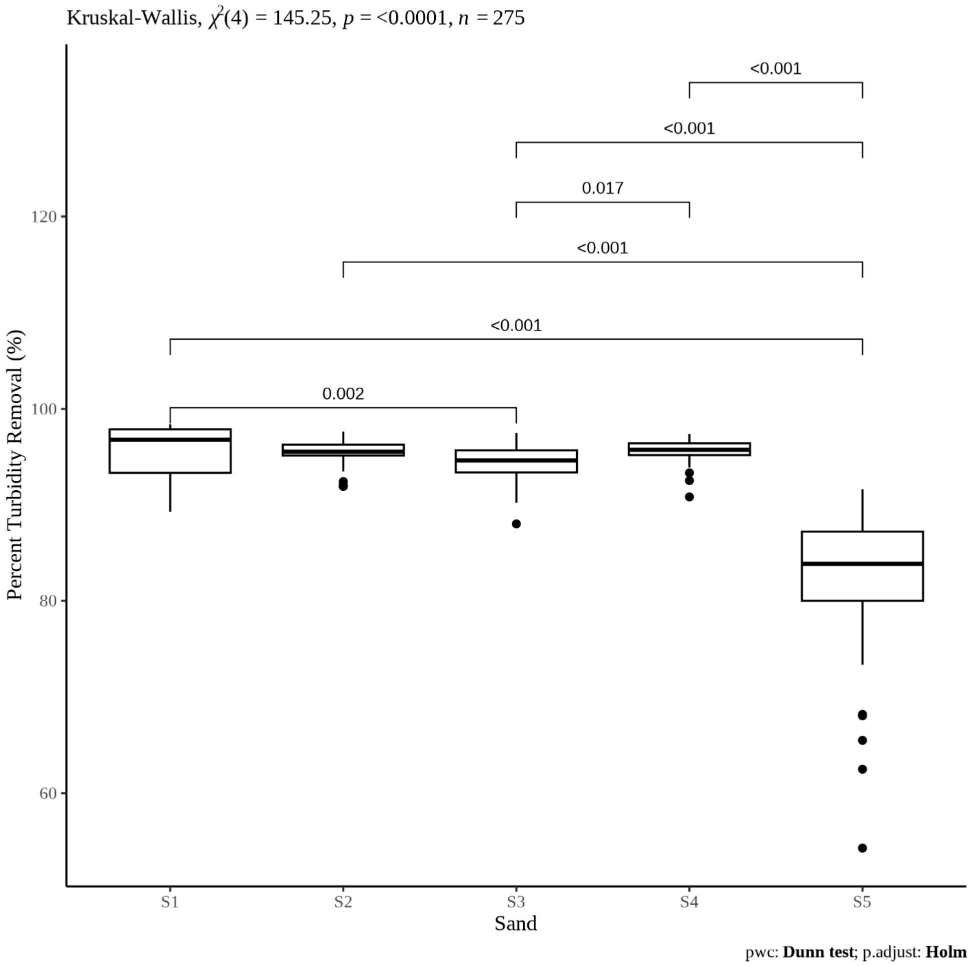


Figure S10. Plot of sample percent turbidity removal and Kruskal-Wallis and Dunn post-hoc statistics, post-ripening period (after day 30).

Table S20. Kruskal-Wallis and Dunn post-hoc test results for sample percent turbidity removal, post-ripening period (after day 30).

Kruskal-Wallis Comparisons				Post-hoc Comparisons					
n	χ^2 Statistic	df	p	Sand/ Sand	S1 (n=85)	S2 (n=85)	S3 (n=85)	S4 (n=85)	S5 (n=85)
275	145.246	4	**<0.001**[ı]	S1 (n=55)					
				S2 (n=55)	p_{Holm}=0.454 (z-score= -1.435; p=0.151)				
				S3 (n=55)	**p_{Holm}=0.002**[γ] (z-score= -3.603; p<0.001)	p_{Holm}= 0.120 (z-score= -2.169; p= 0.030)			
				S4 (n=55)	p_{Holm}= 0.884 (z-score= --0.665; p= 0.506)	p_{Holm}= 0.884 (z-score= 0.769; p= 0.442)	**p_{Holm}= 0.017**[γ] (z-score= 2.938; p= 0.003)		
				S5 (n=55)	**p_{Holm}<0.001**[γ] (z-score= -10.458; p<0.001)	**p_{Holm}<0.001**[γ] (z-score= -9.024; p<0.001)	**p_{Holm}<0.001**[γ] (z-score= -6.855; p<0.001)	**p_{Holm}<0.001**[γ] (z-score= -9.793; p<0.001)	

[ı] Kruskal-Wallis, two-tailed p-value <0.05; [γ] Dunn, two-tailed Holm-adjusted p-value <0.05

Figure S9 demonstrates that as the ES (calculated using the prescribed Lab PSD method) of a sand sample increased, the percentage of turbidity removal decreased. Differences in turbidity removal, however, were only significant between S5 and S1-S4. This relationship likely occurred because a high ES value would indicate larger pores within the fine sand, resulting in a higher flow rate and poorer contaminant removal [11].

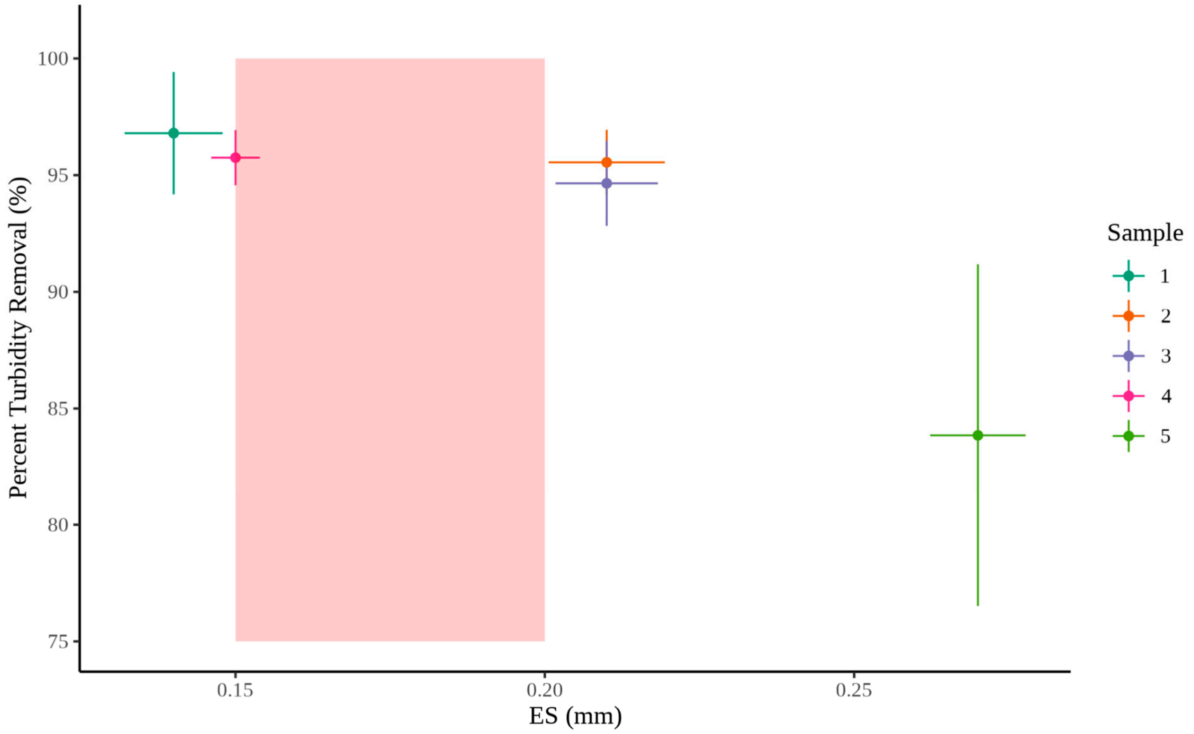


Figure S11. Comparison of median percent turbidity removal (n=110 per sample), post-ripening period (after day 30), for sand samples as a function of median ES calculated from the prescribed Lab PSD method. Error bars represent one standard deviation. Red-shaded area represents the ES range recommended by CAWST for filtration sands. Note that S2 and S3 have the same average ES and UC values using the Lab PSD method.

Based on the results of this pilot study, the use of 0.20 mm as the upper (safety) limit of the CAWST-recommended ES range is efficacious because filter performance, as a function of turbidity removal, worsened as the ES increased above 0.20 mm. These preliminary findings support the need for an upper limit to CAWST's recommended ES range to ensure adequate removal of contaminants, like turbidity and pathogens [37], from effluent BSF water.

This study was limited by a single parameter, turbidity removal, as a measure of filter performance. Furthermore, this work may have been improved by cleaning all duplicate filter columns at the same time, once the flow rate of one column declined to about half the maximum flow rate. Additional filtration studies are warranted to confirm that the results from this study hold for a wider variety of sand samples. Future work should evaluate additional filter performance metrics (e.g., *E. coli* removal, biofilm characterization, and filter aging over time).

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