Water Supply

Water Supply Vol 22 No 2, 1244 doi: 10.2166/ws.2021.355

Hydrus-1D simulation of two-stage cross-flow pre-filtration of turbid river water

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ABSTRACT

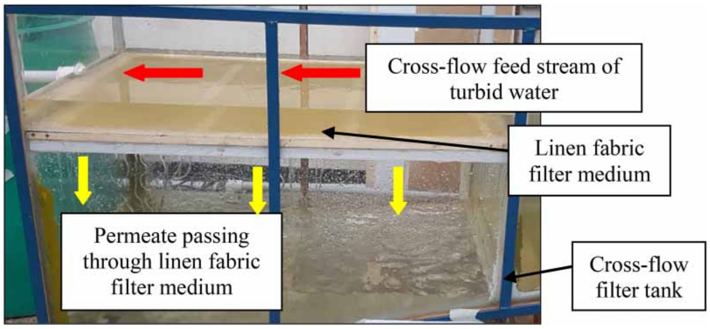
Simulation is a modus operandi often used for imitating real-world processes. It involves a system and set of assumptions used for computing a numerical model, from which the outcome is an estimate of the true characteristics of how the system behaves. The intention of this research was to investigate the efficiency of fabric in two-stage cross-flow filtration using linen, crepe-backed satin, burlap and cotton fabric filter media. The results from previous pilot-scale experiments performed showed that linen fabric was the most effective medium at retaining particles. In continuation of this research, the aim of this paper was to utilize Hydrus-1D simulation software to simulate cross-flow filtration with fabric filter medium. This was done to further confirm the efficiency of cross-flow filtration, in particular with linen fabric filter media. Simulation entailed investigating fabric water content versus pressure head; bottom pressure head versus time; fabric water storage versus time; and cumulative infiltration versus time with both single and four layers of fabric filter media. Hydrus-1D simulation was productive since it confirmed that cross-flow filtration with linen fabric filter media has the potential of becoming a pre-filtration step in surface water treatment, further adding to the results obtained from previous pilot-scale experiments.

Key words: cross-flow, fabric, filtration, Hydrus-1D simulation, surface water treatment

HIGHLIGHTS

- Pre-filtration step in surface water treatment.
- Removal of suspended particles from turbid river water using fabric filter media.
- The use of linen fabric as an essential filter media in the removal of particles from turbid river water.
- Increased efficiency of the removal of particles is enhanced by using four layers of fabric filter media.
- Successful simulations of turbid water filtration by varying fabric filter media types.

GRAPHICAL ABSTRACT



INTRODUCTION

The process of water filtration in water treatment involves water passing through a material for the purpose of removing particulate and impurities consisting of suspended particles and biological matter and which includes floc (EPA 1995, 9). O'Melia & Stumm (1967) in their theory of water filtration, state that water filtration is a physical and chemical phenomenon.

They believe that suspended particle removal within a filter bed entails two distinct steps of transport and attachment. They state that the transport step is a physical-hydraulic process governing mass transfer and the attachment step is a chemical process influenced by both physical and chemical parameters described by Van der Waal attractions. Furthermore, in surface water treatment, rapid sand filters or rapid gravity filters are commonly used. Rapid gravity filters are the last solid–liquid separation stage in treating water before human consumption. Moreover, public water supply systems consist of a filter with a bed of sand, coal and granular material (EPA 1995, 9).

Cross-flow filtration which is the main focus in this study is a solid–liquid separation process. The feed stream flow is tangential to the membrane (Connell *et al.* 1999). Membranes are thin films manufactured from ceramics, metals or polymers and can be dense or porous. Membrane shapes are flat sheets, spiral round, capillary, or tubular. During liquid permeation, some of the particles contained in the stream flow of liquid are deposited on the membrane forming a solid cake. Cake growth is limited as shear stress acts on the surface of the solid medium. Thus, one of the advantages of cross-flow filtration is thinner cake deposition, higher filtration flux and a continuous mode of operation (Connell *et al.* 1999). Also, the constant turbulent flow during cross-flow filtration prevents the accumulation of matter on the tangential surface. The feed flow is at an elevated pressure which causes and provides the driving force for filtration. It also provides a high flow speed which creates the turbulent condition (Calabrò & Basile 2011).

Fabric filtration, conversely, is the physical separation of solids from a gas or liquid by passing it through a porous fabric medium, capable of retaining the solids. Fabric filtration is commonly used for controlling environmental pollutants in gas or liquid streams (Wang *et al.* 2004). The strength of a filtering medium is directly proportional to its thickness but the rate of flow of fluid through the medium is inversely proportional to the thickness (Adiletta 1962). One type of filter medium is that of woven glass cloth consisting of glass fibers bonded to the interstices of the cloth. The glass provides high tensile strength and can be used in hydraulic systems, filtration dialysis, light weight filters and air filtration (Adiletta 1962).

With simulation, the process of interest is called a system, whereas the state of a system is a collection of the variables used for describing the system. Research on simulation using FLUENT was done to model the flow through a porous zone made up of sand. This was performed to try to understand the mechanisms of filtration. Results showed that filtration rate is dependent upon water turbidity which affects both porosity and permeability of the filter bed (Kendoucia *et al.* 2013).

Additionally, research with simulation for the purpose of investigating cross-flow filtration entailed the three-dimensional flow regime of a cross-flow filter (Rainer *et al.* 2002). This filter was made up of rotating discs so as to assess the influence of differently shaped scrapers on the rotating discs. FLUENT 5.0.2 simulation software was used as it was deemed an advantage to filter performance optimization. Turbulence, dissipation and overflow velocities were the main parameters examined in this study. The scrapers were used as a means of generating turbulence between the filter discs so that cake formation would be avoided. The curvature of the scraper discs was altered, resulting in turbulence. The research discovered that filter performance could be increased by changing the shape of the scraper, without changing the geometry of the filter itself (Rainer *et al.* 2002).

Likewise, computational fluid dynamics (CFD) of cross-flow filtration was simulated using ANSYS FLUENT R13 (Dzhonova-Atanasova *et al.* 2018). This was, however, a numerical study of CFD in continuation of previous experiments conducted with antioxidants from the extracts of natural products by nano-filtration. The aim of the authors was to study the transfer processes in a cross-flow filtration cell so that a side-stream filtration module integrated with a bioreactor can have stable and efficient operation (Dzhonova-Atanasova *et al.* 2018). Simulation entailed observing flux behavior during the cross-flow nano-filtration of an organic solvent. It was deducted that there was no need for in-built mobile components, as the tangential flow near the membranes were sure to occur from cell-contained swirling flows which swept the membrane surface.

In similar manner, flow behaviors during cross-flow nano-filtration of concentrating antioxidants like polyphenols were investigated and CFD simulation performed. It was performed using a four flat-sheet membrane rig and numerical simulation using FLUENT was done. This research found that, as the concentration on the retentate side increased, the permeate flux decreased (Dzhonova-Atanasova *et al.* 2017).

Simulation was also performed using experimental data from distilled water. Incorporation of membrane filtration of oil-in-water analysis, to separate oil from the water was studied. Attention was paid to the fouling or gel layer which builds up on the membrane and flow inside the membrane was simulated using FLUENT. From this, velocity and pressure distribution were assessed. The results indicated that differential pressure and velocity was found to be interconnected after simulation with FLUENT (Khor *et al.* 2009).

Lydon and Moss tried to develop a software tool for modeling and simulation of filtration through woven fabric media. The software used was UniverFilter. UniverFilter entailed the geometric modeling of three-dimensional woven media interfaced with CFD. This software numerically determined fluid flow path as well as simulated filtration using particles of different shapes and sizes. The results revealed that the interstices and chamber downstream of the fabric has a major influence on fluid flow, from which fluid flow and pressure resistance result (Nazarboland *et al.* 2008).

Linen, burlap, cotton and crepe-backed satin were selected for use as fabric filter media in this study because they are cheap and readily available in any fabric store in Trinidad and Tobago and are also universally attainable. The properties of linen fabric include good strength and bulk. It is also very durable (Hall 1975). Crepe-backed satin fabric is weaved from cotton, silk, and artificial fibers. As it is made from silk and cotton, it possesses properties of both these fabrics including good strength and durability (MasterClass 2021). Burlap fabric has low stretch ability and medium heat retention ability (Sewport 2020). Cotton on the other hand is durable and resistant to abrasion (Cotton Incorporated 2021).

Fabrics have been used for filtering water. One prominent use is the practice of filtering water with cloth in Matlab, Bangladesh. In developing countries such as Bangladesh, diarrhea is a major cause of death in children, with cholera being the most severe form of diarrhea. Diarrhea leads to a massive loss of body fluids and electrolytes. In Bangladesh, *Vibrio cholerae* is native to the aquatic environment and when the contaminated water is drunk, it is transmitted to humans. As sari cloth is readily available, it was used in domestic filtration by the women of the village. They used single layer, two layers, three layers and even four layers of cloth for filtering the water. This reduced the bacteria in water by 90%. However, four layers were found to be optimal as it reduced the bacteria by greater than 99% (Huq *et al.* 2010).

Also, numerical simulation was used to show that mass transfer during cross-flow filtration under steady-state boundary conditions quickly attained a steady state. Any unsteady nature was caused by changes in the hydraulic boundary conditions. Model verification was done using polystyrene latex suspensions, 0.064 mm to 2.16 mm in diameter subjected to constant trans-membrane pressure. The invention was successful (Lee & Clark 1998).

Conversely, Davis & Ekwue (2020) performed pilot laboratory experiments to explore the use of cross-flow filtration in surface water treatment. Cross-flow filtration experiments were carried out using four different types of fabric filter media, namely linen, crepe-backed satin, burlap and cotton. Their investigation first involved the examination of the properties of fabric which are listed in Table 1.

Then a pilot-scale two-stage cross-flow filter was constructed and used for executing two-stage cross-flow filtration experiments. The objective was to determine the capability of cross-flow filtration with fabric filter media at reducing river water turbidity. Linen was found to be the best fabric material for filtration. The results are summarized in Table 2. The targeted flow rate was 23 L/s as it is the actual flow rate of the Acono Water Treatment Plant located in Northeast Trinidad (WASA 2020) which supplies water from the Acono River to the rapid sand filter.

Table 1 | Summary of fabric properties measured and identified

	Fabric type			
Property	**Linen**	**Crepe-backed satin**	**Burlap**	**Cotton**
Inter-yarn pore size (μm)	41.98	66.88	408.28	76.67
Inter-yarn porosity (%)	95.16	93.90	98	95.32
Inter-fiber pore size (μm)	22.37	27.99	41.88	11.36
Fabric thickness (μm)	400.39	507.08	1,132.81	191.89
Warp spacing (μm)	441.67	528.75	1,443.58	496.57
Weft spacing (μm)	741.67	703.66	2,278.85	455.88
Warp diameter (μm)	13.26	17.52	14.42	11.58
Weft diameter (μm)	14.96	18.06	28.85	11.26
Fabric tensile strength (N)	402	194	462	211
Surface roughness (μm)	685.50	634.64	554.82	554.32
Maximum profile height (μm)	3,632.40	2,854.20	2,808	2,741.60
Weave type	Hop-sack plain	Satin	Plain	Plain

Source: Davis & Ekwue (2020).

Table 2 | Summary of two-stage cross-flow pre-filtration of turbid river water

	Fabric Type			
Parameter	**Linen**	**Crepe-backed satin**	**Burlap**	**Cotton**
Stage 1 Turbidity (NTU)	3.9	2.8	6.3	8.7
Stage 2 Turbidity (NTU)	3.4	3.4	4.7	4.6
Stage 1 Volume of permeate (m^3)	0.20	0.05	0.27	0.15
Stage 2 Volume of permeate (m^3)	0.12	0.23	0.26	0.07
Stage 1 Retentate turbidity (NTU)	1.8	4.3	No retentate	5.4
Stage 2 Retentate turbidity (NTU)	2.7	5.0	No retentate	5.3
Stage 1 Fraction of permeate to retentate	0.86	2.9	–	1.33
Stage 2 Fraction of permeate to retentate	3.19	4.0	–	0.46
Stage 1 Filtration flow (m^3/hr.)	3.28	1.69	0	2.63
Stage 2 Filtration flow (m^3/hr.)	1.86	1.69	0	2.56
Stage 1 Average hydraulic surface loading rate (m^3/min)	0.04	0.04	0.04	0.03
Stage 2 Average hydraulic surface loading rate (m^3/min)	0.02	0.04	0.04	0.02

Source: Davis & Ekwue (2020).

Previous investigations revealed to the authors that cross-flow filtration simulation was not performed for separating turbid particles from surface water. Continuation of this study entailed Hydrus-1D simulation of two-stage cross-flow filtration to investigate the effectiveness of previous pilot-scale experimentation with two-stage cross-flow filtration, to ensure that it could be included as a pre-filtration step in surface water treatment. The study involves not only the use of single layer fabric filter media which was experimented with in the pilot-scale experiments, but also utilized fabric folded four times, to assess if it is more efficient than just one layer. If successful, then it could be used as a pre-filtration step in surface water treatment to reduce water turbidity before it enters the rapid sand filter. The essence of this paper is thus Hydrus-1D simulation with single and four-layer fabric filter media to aid the authors in confirming the efficiency of cross-flow filtration using linen as the fabric filter medium.

The Hydrus-1D software is used for simulating one-dimensional variably saturated water flow and the transport of solutes and heat movement, all of which involve sequential first-order decay reactions (Šimůnek *et al.* 2013). It is made up of the Hydrus computer program and the Hydrus-1D interactive graphics-based user interface. Both water and solute movement in unsaturated, partially saturated, or fully saturated porous media through soil is analyzed using this software. Flow and transport can be analyzed vertically, horizontally or at an inclined direction (Šimůnek *et al.* 2013). However, in this study, it was used for analyzing the water flow and solute transport through fabric filter media in a tangential or cross-flow direction. Furthermore, Hydrus-1D was selected for simulation as it is readily and easily accessible online for download, no costs entailed. Research conducted by the authors has found that thus far, it has not been used for simulating flow through fabric, but only what it was designed for, that is simulation of flow through different soil types (Šimůnek *et al.* 2013).

METHODOLOGY

Hydrus-1D simulation programming

Programming cross-flow filtration with fabric filter media first entailed equating the parameters used for soil with that of fabric. These parameters were water, water flow and geometry information. Tables 3 and 4 provide a summary of the description of the fabric equivalent parameters while Table 5 provides both a description and some of the values used during programming. Then, programming cross-flow filtration with single layer fabric filter media was done using the values listed in Tables 5–7. This was done by setting the main processes, geometry information and depth of soil profile. The time was set followed by the soil hydraulic model in which the values from the respective tables were inputted. Charts for water content vs. pressure head; bottom pressure head vs. time; fabric water storage vs. time; and cumulative infiltration vs. time for each individual fabric type were generated. This resulted in a total of 16 individual charts. However for ease of viewing and comparison, the data were extrapolated and plotted in Microsoft Excel 2010 charts. See Figures 1–4.

Table 3 | Hydrus-1D simulation water parameters description

Water flow parameter symbol	Units	Description for soil	Fabric equivalence
Q_r	[–]	Residual soil water content	(100% – fabric porosity)
Q_s	[–]	Saturated soil water content	Fabric porosity
Alpha	[1/m]	Hydraulic shape parameter	Length of fabric over which water passes
n	[–]	Parameter in the soil water retention function	Fabric surface roughness
K_s	[m/min]	Saturated soil hydraulic conductivity	Fabric permeability which was taken as the average of {(Inter-yarn pore size + Inter-fiber pore size)/2}
l	[–]	Tortuosity parameter in the conductivity function	0.5 (Default value)

Table 4 | Description of Hydrus-1D simulation water flow parameters

Water flow parameter	Description for soil	Fabric equivalence
Bulk density (μm)	Soil compaction	Fabric density or weft thickness of woven fabrics
Displacement (μm)	Movement of soil from one place to another	Weft Spacing

Table 5 | Hydrus-1D simulation geometry information values for selected fabrics

			Fabric type			
Geometry information	Units/Quantity	Fabric equivalence	Linen	Crepe-backed satin	Burlap	Cotton
Length units	m	m	m	m	m	m
Number of soil materials present in system (number of soil horizons)	1	Numbers of filter media	1	1	1	1
Number of layers for mass balances	1	Number of layers of fabric	1	1	1	1
Decline from vertical axis	0	0	0	0	0	0
Depth of soil profile	m	Thickness	400.39e-6	507.08e-6	1,132.81e-6	191.89e-6

Table 6 | Hydrus-1D simulation water flow parameters for selected fabrics

Water flow parameter	Linen	Crepe-backed satin	Burlap	Cotton
Q_r [–]	0.0484	0.061	0.02	0.0468
Q_s [–]	0.9516	0.9390	0.98	0.9532
Alpha [1/m]	1.0936	1.0936	1.0936	1.0936
n [–]	685.50e-6	634.64e-6	554.82e-6	554.32e-6
K_s [m/min]	64.35e-6	94.87e-6	88.03e-6	450.16e-6
l [–]	0.5	0.5	0.5	0.5
Depth of soil profile	400.39e-6	507.08e-6	1,132.81e-6	191.89e-6

Table 7 | Hydrus-1D simulation solute transport parameter values for selected fabrics

Solute transport parameter	Linen	Crepe-backed satin	Burlap	Cotton
Bulk density (μm)	14.96e-6	18.06e-6	28.85e-6	11.26e-6
Displacement/weft spacing (μm)	741.67e-6	703.66e-6	2,278.85e-6	455.88e-6

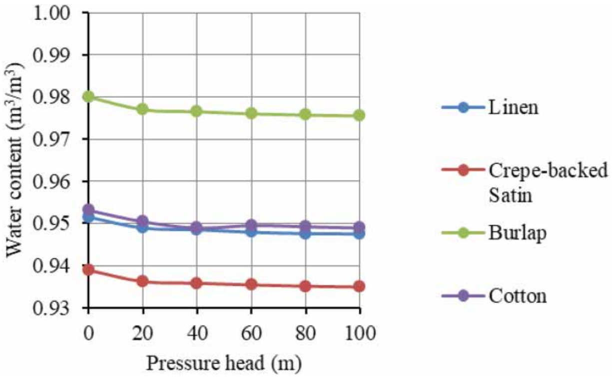


Figure 1 | Water content vs pressure head for single layer fabric filter media.

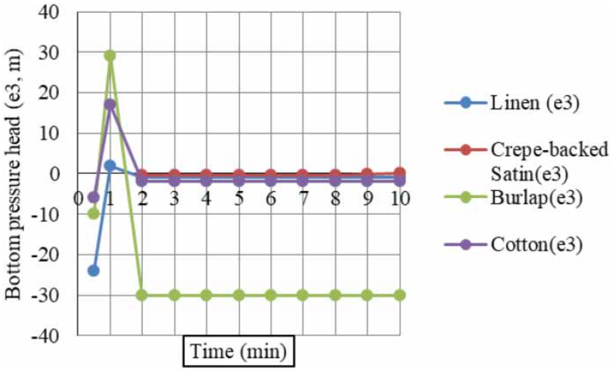


Figure 2 | Bottom pressure head vs time for single layer fabric filter media.

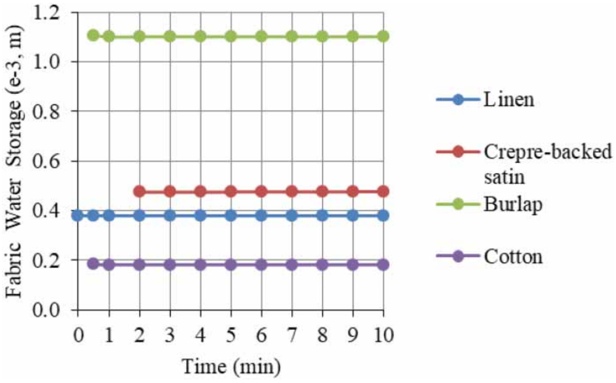


Figure 3 | Fabric water storage vs time for single layer fabric filter media.

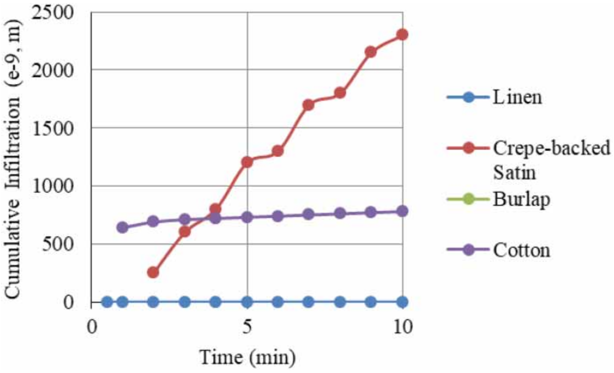


Figure 4 | Cumulative infiltration vs time for single layer fabric filter media.

Upon completion, the same procedure was repeated for four layers of fabric. For four layers of fabric, the number of layers of mass balances and other parameters was adjusted to '4' and the values for the water flow parameters were adjusted by multiplying by four. Hydrus-1D simulation results showed 16 individual charts, from which the data were again extrapolated and plotted as combined figures. See Figures 5–8.

RESULTS AND DISCUSSION

The variation of water content with pressure head is shown in Figure 1 for simulation of two-stage cross-flow filtration of water flow and solute transport through single layer fabric filter media. Water content is the amount of water held in a unit quantity of soil (Cooper 2016). In this study, it was water held in individual fabrics. Pressure head is pressure exerted by the weight of a fluid as a result of the height of the column of the fluid (Oxford English Dictionary 2018). The height of the water was dependent on the height of the cross-flow turbid water passing over the fabric during filtration, before passing through the fabric. The water content and fluid height were highly dependent on the properties of the respective fabrics as listed in Table 1.

In Figure 1, the fabric with the largest water content was burlap, around 0.980. However, because of its extremely large pore sizes and its warp and weft spacing, the volume of permeate from it shown in Table 2 was the greatest. This meant that it was able to retain some water within its thick fibers but most passed through as permeate. Similarity, water contents for linen and cotton were close to 0.951 and 0.953 respectively, but linen had the greater volume of permeate. Crepe-backed satin had a water content of 0.938 and the volume of permeate was the smallest compared to the other fabrics after stage 1 filtration. Linen fabric is not very thick and had quite small warp spacing. Hence, it had the second smallest water content in Figure 1. Linen thus proved its capability at retaining particles on its surface as well as in its pores during filtration. In addition, the rate at which permeate passed through each fabric was fairly constant in each experiment. This was also observed from the shape of the curves in Figure 1. The volume of water which passed through the fabric was also dependent

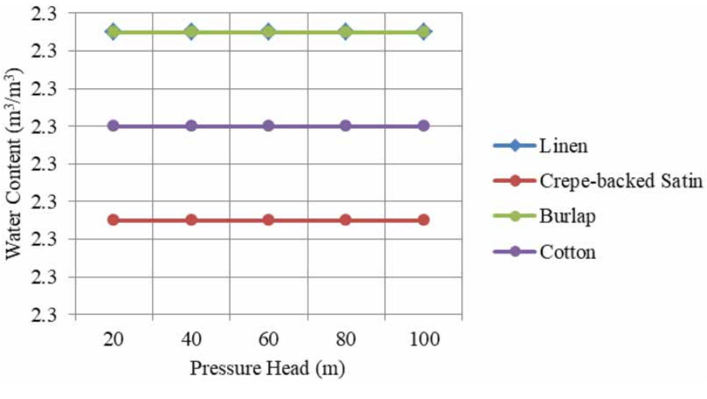


Figure 5 | Water content vs pressure head for four layers of fabric filter media.

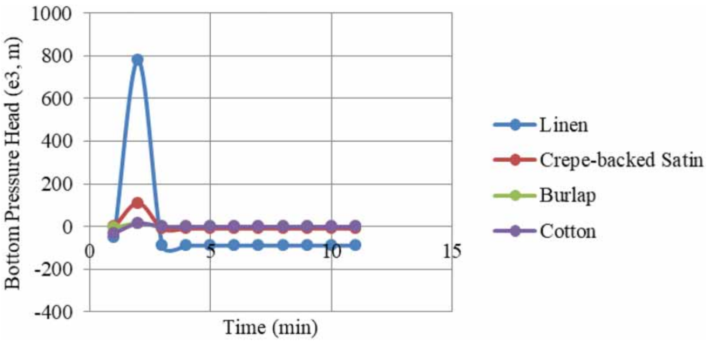


Figure 6 | Bottom pressure head vs time for four layers of fabric filter media.

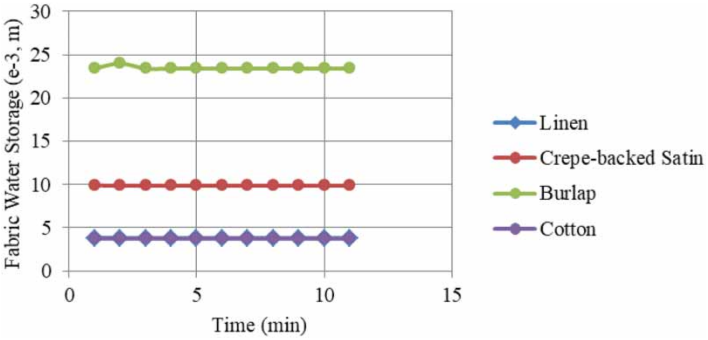


Figure 7 | Fabric water storage vs time for four layers of fabric filter media.

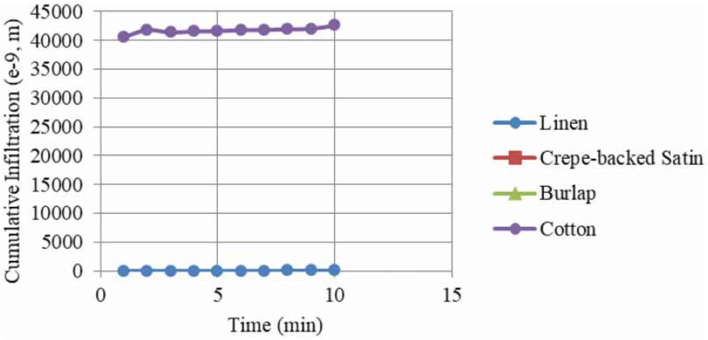


Figure 8 | Cumulative infiltration vs time for four layers of fabric filter media.

on how tightly woven a fabric is. The pressure head investigated in this study was also the height of water on the bottom of the filter tank, that is the bottom pressure head. It represents the volume of permeate which passed through the fabric filter media during pilot-scale cross-filtration with the individual fabric types. Figure 2 is an indication of bottom pressure head vs. time after simulation with Hydrus-1D. Figure 2 further added to the observation of water content versus pressure head in Figure 1.

Bottom pressure head in Figure 2 also demonstrated the variation in fabric pore sizes, thickness and to some extent the fabric absorption capabilities. Burlap, owing to its large inter-yarn and inter-fibre pore sizes was seen to have the largest bottom pressure head of ≈ 30e3 m. Crepe-backed satin was the lowest of ≈ −0.38e3 m. Linen was ≈ 2e3 m and then lastly cotton of ≈ 17e3 m. These values are directly related to the results in Table 2, hence the reason for no retentate obtained during cross-flow filtration with burlap filter media. Burlap fabric had the greatest porosity of 98%. Also, Figure 2 is an indication of the difference in the fraction of permeate to retentate for each fabric type. Linen's fraction of permeate to retentate, although being low in comparison to crepe-backed satin and cotton proved that it affected filtration flow as seen in Table 2 and was thus seen as being a good filter media with a good porosity.

Conversely, fabric water storage or its water absorption capacity is important to filtration. A fabric is not required to have a high absorption capacity as it will take very long before water passes through it. This can greatly delay the filtration process and in turn the entire surface water treatment process. Figure 3 thus evaluated fabric water storage versus time to determine the quantity of water each fabric type absorbed before permeate began filtering through it.

Fabric water storage for linen was 38.03e-5 m, 47.4e-5 m for crepe-backed satin, 110.64e-5 for burlap and 18.23e-5 m for cotton. So, burlap fabric being the thickest fabric had the highest absorption capacity meaning that it took some time, approximately 0.5 minutes before water began filtering through it. This low indication of time recorded was due to burlap's porosity of 98%. Cotton conversely had the lowest absorption capacity, taking similar amount of time to absorb water. The longer the time a fabric takes to absorb water also affected the filtration flow of turbid water over the fabric filter media. Thus, as shown in Table 2, linen was found to have a high filtration flow during both stages of filtration. Filtration flow was also affected by fabric surface roughness. What further reflected fabric storage capacity was the fraction of permeate to retentate. There were no readings for burlap as no retentate was produced during filtration.

The Hydrus-1D simulation represented in Figure 3 therefore supported preceding experimental findings in that linen was once again the most suitable fabric for filtration when it comes to assessment of its water storage capability. Furthermore, linen immediately began absorbing water in less than 5 minutes, the least amount of time in comparison to the other selected fabrics, thereby indicating that the thickness of linen is suitable to the purpose of this study.

Figure 4 likewise, illustrated the cumulative infiltration versus time for each of the individual fabric types. Cumulative infiltration was the total amount of water which passed through each fabric during experimentation. Simulation of cumulative infiltration with Hydrus-1D once again linked the results obtained from pilot-scale experimentation of two-stage cross-flow filtration. In Figure 4, cumulative infiltration was constant for linen, that is 0.48e-9 m and was the lowest of all fabrics. When water began filtering through it, cumulative infiltration remained constant. As for crepe-backed satin, the infiltration gradually increased with time until cumulative infiltration was ≈ 2,300e-9 m. Figure 4 did not show any indication of cumulative infiltration for burlap as all the turbid water was immediately filtered through it.

For cotton, 640e-9 m of water immediately infiltrated through the fabric after a period of 1 minute. Cumulative infiltration is representative of the volume of permeate in Table 2. The bottom pressure head in Figure 2 also represented the cumulative infiltration. Linen was the most suitable once again in reference to its pore sizes, porosity and thickness.

Conversely, since the recommended practice of filtering water with sari cloth was by folding the sari cloth four times (Huq *et al.* 2010), it was decided that simulation be executed to show what would take place if each of the selected fabrics were also folded four times each. So, each of the parameters investigated in Figures 1–4 for single layer fabrics, were also investigated for four layers of fabric. The first parameter of water content versus time is represented in Figure 5.

Figure 5 demonstrates that for each fabric, the water content was once again constant for simulation with four layers of fabric. The shape of the curves in Figure 5 is like those in Figure 1. However, in folding the fabric four times, it was discovered that cotton and linen water contents were the same that is 2.2 m^3/m^3 with burlap being the highest that is 2.4 m^3/m^3. This was the quite similar for single layer fabric. In like manner, the same was reverse for crepe-backed satin and linen when the fabrics were folded four times. However, when folded, they had moderate water content in comparison to the other fabrics. Furthermore, by folding the fabric, more particles could be retained both on and within the fabric. This proved linen's capability and effectiveness for the purpose of this study.

The dissimilarity in fabric properties for four layers of fabric, was more clearly depicted in Figure 6. There was an overall increase in bottom pressure head for all fabric types as compared to that in Figure 2. It was deduced that time also varied, that is for single layer fabric, bottom pressure head began increasing after a period of 0.5 minutes. But in folding the fabric four times, bottom pressure head increased after 1 minute before remaining constant, as more layers of fabric entailed that the permeate will take a longer time to pass through the filter media. Moreover, the bottom pressure head was greatest for four layers of linen i.e. ≈ 780e3 m, followed by crepe-backed satin, ≈ 110e3 m then cotton ≈ 15e3 m and burlap ≈ 8e3 m. This meant that more permeate filtered through the fabrics, a good indication that increasing the number of layers of fabric filter media can be an advantage. It is also a representation of fabric porosity. Thus, filtration with linen fabric was in no way affected as the fabric continued to exert signs of being suitable for filtration and as mentioned earlier.

At the same time, Figure 7 continued to prove that four layers of linen is just as efficient as single layer linen. Linen once again displayed its absorption capability in Figure 7 which showed that linen stored the least amount of water. This behavior was similar to that of cotton. Fabric pore sizes were not affected and remained constant although the number of layers of fabric through which permeates passed increased. In Figure 7, fabric water storage capacity was also dependent on thickness. Though containing large inter-yarn and inter-fiber pore sizes, burlap was seen to have ≈ 23e-3 m of water stored in it. Linen conversely was ≈ 3.8e-3 m, crepe-backed satin ≈ 9.8e-3 m and cotton was ≈ 3.7e-3 m. Cotton and linen had similar water storage hence the reason why linen was not distinctly shown in Figure 7. In contrast, when comparing the results obtained from Figure 3, the fabric water storage increased for all the selected fabrics when folded. The reason for this is that water must first be absorbed by all the individual layers of fabric and become fully saturated before permeates could pass through them. Fabric water storage remained constant with time for each fabric as seen in Figures 3 and 7 since both depict almost entirely straight lines of fabric water storage.

Cumulative infiltration versus time, conversely, is represented in Figure 8, which revealed that after a time period of 1 minute, infiltration took place within linen fabric. Cumulative infiltration is the total amount of permeate which passed through the fabric during cross-flow filtration. Simulation with four layers of fabric resulted in no cumulative infiltration taking place with crepe-backed satin and burlap fabrics. Almost all of the water was absorbed and stored in the fabric, hence no water passing through. What was not absorbed passed over the fabric as retentate. Cumulative infiltration was also affected by how tightly woven a fabric is and was found to increase as the number of layers of fabric increased. This comparison is clear from Figures 4 and 8. However, this did not affect the performance of linen during filtration. This was clearly seen and was once again represented by linen's volume of permeate as well as the fraction of permeate to retentate after cross-flow filtration experimentation. In like manner, Figures 4 and 8 show that the cumulative infiltration for linen was constant.

CONCLUSION

Hydrus-1D simulations of cross-flow filtration with single and four layers of fabric using linen, crepe-backed satin, burlap and cotton were successful. Hydrus-1D software, although novel to simulating cross-flow filtration with fabric filter medium, was also absolutely efficacious and provided much insight to the authors in their research of two-stage cross-flow filtration with linen fabric filter medium. Simulation results with single layer fabric supported the results from the pilot-scale experiments previously performed in that it validated linen to be quite capable for use as a fabric filter medium. The results for simulation with four layers of fabric filter media were also successful. The same was substantiated for simulation with four layers of linen fabric in comparison to crepe-backed satin, burlap and cotton fabrics. Therefore, linen fabric will be capable of filtering turbid water whether it is used as a single layer or folded four times.

ACKNOWLEDGEMENT

In writing this paper, much encouragement and advice was provided by Professor Hazi Azamathulla of the Department of Civil and Environmental Engineering, University of the West Indies, St Augustine, Trinidad and Tobago.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 9 June 2021; accepted in revised form 28 September 2021. Available online 19 October 2021