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A Coagulation Process Combined with a Multi-Stage Filtration System for Drinking Water Treatment: An Alternative for Small Communities

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Abstract: As set out in the Sustainable Development Goals, it is necessary to achieve universal and equitable access to safe drinking water services for all the world's population. Appropriate water treatment alternatives for rural areas should be prioritised to achieve this goal. In this work, a simplified drinking water treatment system (SDWTS), which has great potential for application in small communities and rural areas, was evaluated on a pilot scale for turbidity and apparent colour removal using synthetic raw water. The SDWTS integrates Upflow Gravel Filter in Layers (UGFL) and Rapid Sand Filter (RSF) with previous coagulation. This evaluation was carried out using a 2^3 factorial experiment, with the factors: type of water, type of coagulant and flow. The factorial design showed that the SDWTS had the highest turbidity removal efficiencies (>98.7%) with type II (20 NTU) water and PACl coagulant, while flow rate had no significant effect on turbidity removal. Under optimal operating conditions (type II water, PACl and 1.0 m^3/d), the SDWTS produces treated water that meets the standards required by Colombian regulations and World Health Organisation recommendations for drinking water, concerning the variables: turbidity, apparent colour, total coliforms, *E. coli*, pH, electrical conductivity and Al. The SDWTS maintained its capacity to produce potable water when evaluated with the increased operating flow (up to 3.0 m^3/d) and raw water turbidity (up to 50 NTU). The SDWTS can be an efficient and innovative alternative for water treatment, and its implementation in small communities can contribute to equitable access to drinking water.

Keywords: coagulation; drinking water treatment system; hydraulic evaluation; multi-stage filtration; turbidity removal

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1. Introduction

The proper management of water resources has become a significant issue on global agendas. As a driver of community development, water resources have been under increasing pressure due to water stress, global climate change, changing population dynamics, and the substantial economic, logistical and operational gap between urban and rural areas [1]. According to the World Health Organization (WHO), two billion people lack access to safely managed drinking water services; for this reason, in the Sustainable Development Goals, the United Nations (UN) reiterated the need to achieve universal and equitable access to safe and affordable drinking water for all, as stated in its target 6.1 [2]. This target should primarily focus on the poorest and most vulnerable communities [3].

It is important to note that the treatment of water, regardless of its origin, responds to the need to adjust its physical-chemical and biological characteristics to values or ranges established by national legislation, to make it suitable for human consumption [4]. The selection of appropriate unit processes and their integration into a water treatment plant involves consideration of the following factors: (1) source water quality, (2) regulatory compliance, (3) process reliability and flexibility, (4) initial construction and annual operation and maintenance costs, (5) environmental impacts, (6) available site space, and finally, (7) waste management requirements and site constraints [5]. Despite advances in water treatment, access to safe drinking water in rural areas is still minimal; this is due to the dispersion of the population, which generates technical and economic limitations in the interconnection with water supply networks [6]. The predilection for conventional treatment systems that are difficult to implement in small communities and the abandonment of treatment systems due to the high costs of operation and maintenance exacerbate this problem [7].

Conventional drinking water treatment systems combine coagulation, flocculation, sedimentation, filtration and disinfection processes. These systems require high economic investments, large land areas, permanent technical staff for operation and maintenance, and extensive distribution networks [8]. However, although conventional drinking water technologies are effective in contaminant removal [9], they are not suitable for dispersed populations. Additionally, there is a need to develop effective and decentralised treatment alternatives that are simple, innovative, low cost and easy to operate [10–12].

Decentralised drinking water treatment options include physical treatments (e.g., filtration, absorption), ecological treatments (e.g., slow sand filtration), chemical treatments (e.g., coagulation with metallic salts and natural coagulants, chlorination), and hybrid treatments (e.g., multi-stage filtration, coagulation-filtration process) [13]. Physical treatments like the adsorption process using biochar alone [14] and combined with multi-stage filtration systems [15] have been studied, aiming to remove micro-pollutants such as pesticides, pharmaceuticals and personal care products. Successful results in implementing slow sand filtration systems are found in research such as that of Fabiszewski et al. [16], who adapted a BioSand filter to a small-scale point-of-use alternative. Additionally, Medeiros et al. [3] evaluated a slow sand filter with a dynamic gravel filter as a pretreatment. Both studies showed reductions of *E. coli* > 95%.

Chemical treatments using coagulation-flocculation, based on hydrolysing metallic salts, are referenced by Wu et al. [17], with numerous results in removing suspended colloidal particles, organic matter and turbidity. Likewise, the study by Lugo-Arias et al. [18] proposed alternatives for water treatment, using natural coagulants, bio-sand and activated carbon filters, with removals of 98.4% and 76.9% for turbidity and total coliforms, respectively after filtration.

Multi-stage filtration is a hybrid treatment that allows for a robust alternative for surface water sources of variable quality in rural communities with low operating and maintenance costs [19]. In the same trend, combining coagulants with multi-stage filtration improves the efficiency in removals of turbidity [20,21] and microorganisms such as total coliforms and *E. coli* [21].

The studies presented above have shown that simple and relatively inexpensive water treatment methods for small communities can contribute positively to water quality and reduce disease risks. This research evaluated a simplified drinking water treatment system (SDWTS) on a pilot scale. The SDWTS combines a coagulation process with multi-stage filtration (an Upflow Gravel Filter in Layers -UGFL-, and a Rapid Sand Filter -RSF-). Seeking to improve turbidity and colour removals in the UGFL and increase the SDWTS filtration run, the UGFL was designed with low filtration rates (7–14 m^3/d) compared to previous studies (24–77 m^3/d) [20,21]. The evaluated SDWTS can produce safe drinking water with the following advantages: Coagulant consumption reduction, fewer treatment units, low investment costs, ease of installation, operation and maintenance.

2. Materials and Methods

2.1. Pilot Drinking Water Treatment System

In order to carry out this research, a simplified drinking water treatment system (SDWTS) on a pilot scale was designed and constructed in glass fibre reinforced polyester (GRP). The system included the coagulation unit, Upflow Gravel Filter in Layers (UGFL) and Rapid Sand Filter (RSF) with downflow. Pumping systems were used to feed the system and backwash the RSF, while the UGFL was cleaned hydraulically. The cleaning of the UFGL was carried out through the rapid opening and closing of the purge valve generating the suction of the material deposited inside the filter. This procedure was repeated until the turbidity of the wash water decreased to values less than the turbidity of the influent. As for the RSF, it was backwashed with treated water using a pumping system at a rate of 42 m/h and for approximately 15 min to generate the expansion of the filter bed. Figure 1 shows a schematic of the drinking water treatment system, and Table 1 shows the main characteristics of the UGFL and the RSF.

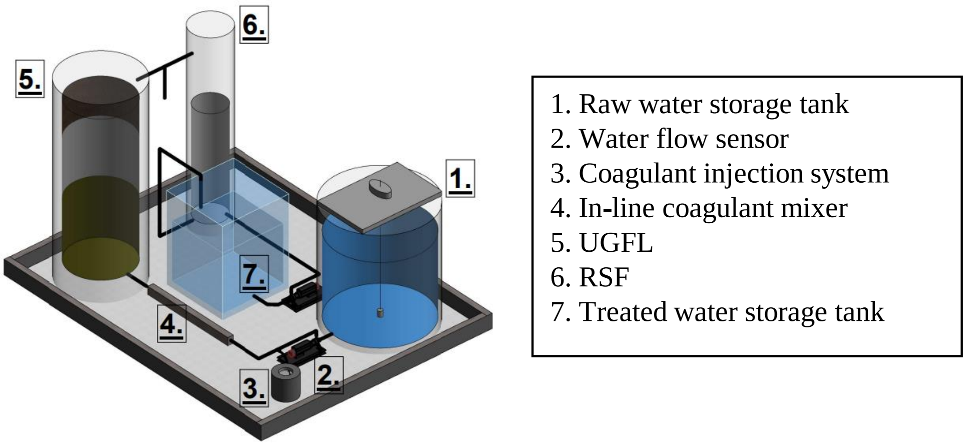

Figure 1. Sketch of the simplified pilot-scale water purification system.

Table 1. Main features of UGFL and RSF.

Feature	Component UGFL	Component RSF
Volume (m^3)	0.11	0.02
Height (m)	1.6	2.0
Diameter (m)	0.3	0.1
Superficial area (m^2)	0.07	0.008
Filter medium	Gravel	Sand
Filter medium length (m)	1.2	0.75
Particle size (mm)	1.6–25	0.4–1.2
Filter medium layers	5	1

2.2. Hydraulic Evaluation

A hydraulic evaluation of the UGFL and RSF was carried out to determine the flow characteristics of the SDWTS. The evaluation of both filters was carried out for operating flows of 0.5 and 1.0 m^3/d. At these flows, the UGFL worked with filtration rates of 7 and 14 m^3/m^2d and the RSF with 64 and 127 m^3/m^2d. These rates correspond to typical design and operation values recommended for these types of filters according to the Colombian technical standards for water treatment design plants [22,23].

Sodium chloride (NaCl) was used as a tracer substance with instantaneous dosing. NaCl is cheap and easy to acquire and quantify (with a simple conductivity meter), is non-toxic, and presents no risk of environmental pollution or human health consequences [24]. The NaCl concentration was determined by electrical conductivity measurement and correlation with the respective calibration curve. Tracer concentration trend graphs were generated, flow analysis was performed with the Wolf-Resnick method, and the Morrill index was calculated [25]. The conditions for each test are summarised in Table 2.

Table 2. Conditions for the conduct of tracer tests.

Feature	Test 1	Test 2	Test 3	Test 4
Component	**UGFL**	**UGFL**	**RSF**	**RSF**
Useful capacity (m^3)	0.048		0.006	
Flow (m^3/d)	0.5	1.0	0.5	1.0
Filtration rate (m^3/m^2d)	7	14	64	127
Theoretical hydraulic retention time (HRT) (min)	136.9	68.5	18.4	9.2
Expected NaCl concentration (mg/L)	200		500	
Mass of added NaCl (g)	9.60		3.01	
Concentration of NaCl solution (g/L)	50.0		250.0	

2.3. Synthetic Water

In order to evaluate the removal of turbidity and apparent colour in the SDWTS, two types of synthetic water (I and II), prepared from tap water with the addition of kaolin and humic acids, were used as influents. It was decided to work with synthetic water prepared with kaolinite to generate the same initial turbidity conditions during all tests and to compare the factorial design results in the system's evaluation. Type I water had a turbidity of 10 $\pm$ 0.6 NTU and an apparent colour of 20 CU, and type II water had a turbidity of 20 $\pm$ 0.6 NTU and an apparent colour of 30 CU.

The characteristics of the two types of water were defined based on the statistical analysis of raw water quality data from 315 surface water supply sources from 2013 to 2018 and provided by the Corporación Autónoma Regional del Centro de Antioquia–Colombia (Corantioquia).

2.4. Coagulants and Optimal Dosages

The commercial coagulants polyaluminium chloride (PACl) and ferric sulphate ($Fe_2(SO_4)_3$) were used to evaluate the SDWTS. PACl is a prehydrolised aluminium (Al) salt, while ferric sulphate is a conventional iron (Fe) salt. For the determination of the optimal dosage of each coagulant, jar tests were carried out with the two types of water and under the following conditions: (1) rapid mixing for 1 min with a velocity gradient (G) of 233 s^{-1}, (2) slow mixing for 15 min, with G of 21 s^{-1} and (3) sedimentation for 15 min [26]. The optimal doses were selected, considering the lowest amount of coagulant that produced turbidity of less than 2 NTU and colour of less than 15 CU in the settled water (permissible limits according to Colombian regulations). For both types of water, an optimum dose of 1.6 mg Al^{+3}/L for PACl and 1.6 mg Fe^{+3}/L for ferric sulphate was obtained.

2.5. Experimental Design

A 2^3 factorial experiment was designed to evaluate the SDWTS, with one replicate of each trial. The three factors studied, and their two levels were: (1) type of water (I and II), (2) type of coagulant (PACl and ferric sulphate) and (3) operating flow (low and high). The low (L) and high (H) flows were 0.5 and 1.0 m^3/d, respectively.

In addition to the treatments proposed in the factorial design, two tests were carried out with the high flow and without the addition of coagulant, namely control samples (C-I and C-II). These tests were carried out to determine the turbidity removal obtained in the SDWTS as an exclusive consequence of the filtration mechanisms for the particles in the two types of water studied. The final turbidity of the control samples was compared with the results of the treatments using a paired analysis. Table 3 describes the treatments evaluated, the controls, and their notation.

Table 3. Description of treatments and targets.

Type of Water	Type of Coagulant	Flow	Test	Notation
I	PACl (Al)	Low (L)	Initial-1	I-Al-L-1
			Replica-2	I-Al-L-2
		High (H)	Initial-1	I-Al-H-1
			Replica-2	I-Al-H-2
	Ferric sulphate (Fe)	Low (L)	Initial-1	I-Fe-L-1
			Replica-2	I-Fe-L-2
		High (H)	Initial-1	I-Fe-H-1
			Replica-2	I-Fe-H-2
	Coagulant-free	High (H)	Initial-1	C-I
II	PACl (Al)	Low (L)	Initial-1	II-Al-L-1
			Replica-2	II-Al-L-2
		High (H)	Initial-1	II-Al-H-1
			Replica-2	II-Al-H-2
	Ferric sulphate (Fe)	Low (L)	Initial-1	II-Fe-L-1
			Replica-2	II-Fe-L-2
		High (H)	Initial-1	II-Fe-H-1
			Replica-2	II-Fe-H-2
	Coagulant-free	High (H)	Initial-1	C-II

Each treatment had a duration equivalent to four times the actual hydraulic retention time (HRT) of the UGFL: one HRT to stabilise the system and the remaining three to assess turbidity and apparent colour removal. After the first HRT, samples were taken every 15 min from the effluents of the UGFL and the RSF to measure turbidity, apparent colour, pH, water temperature and electrical conductivity. The duration of the tests was 6 h for the 1.0 m^3/d flow and 10 h for the 0.5 m^3/d flow. At the end of each treatment, the SDWTS was cleaned entirely, guaranteeing the same initial conditions in each test.

At the end of the tests I-Fe-L-1, I-Al-L-1, I-Fe-H-1, I-Al-H-1, I-Al-H-1, II-Fe-L-1, II-Al-L-1, II-Fe-H-1 and II-Al-H-1, samples were taken from the SDWTS effluent to measure residual coagulant (Al or Fe, depending on the coagulant evaluated). The head loss in the RSF was also monitored.

2.6. Statistical Analysis

The factorial experiment response variable was the turbidity removal in UGFL and RSF. The raw water turbidity was used for both filters to calculate the turbidity removal; therefore, RSF turbidity removal represents the overall SDWTS turbidity removal. Operating times corresponding to 1, 2, 3 and 4 times the actual HRT of the UGFL or the complete system were evaluated in each case. The model's assumptions were evaluated (normal distribution of the data and constant variance) to ensure the results' validity. Minitab 20 software was used to validate the assumptions and analyse the factorial design.

The Anderson-Darling statistic was applied in the data analysis, which is a suitable test for analysing small-size distributions [27,28]. Bartlett's test of equality of variances was used to verify the constant variance assumption. The standardised effects of the factors and their interaction on turbidity removal were determined, and a cube diagram was generated to define the optimal operating conditions of the SDWTS. The apparent colour in the influent of the UGFL and RSF was lower than the detection limit of the method used for its quantification (<10 CU). Therefore, the statistical analysis for the results of this variable was not performed.

2.7. Microorganisms' Removal

With the optimal operating conditions of the SDWTS, the removal of total coliforms and *E. coli* were evaluated. *Enterobacter aerogenes* ATCC 13048 and *Escherichia coli* ATCC 11,775 strains were added to the influent of this test to obtain concentrations of

1553 × 10 NMP/100 mL of total coliforms and 24 × 101 NMP/100 mL of *E. coli*. These concentrations were also defined from the information provided by Corantioquia. Before adding the strains, the chlorine present in the feed water was abated by adding $Na_2S_2O_3$ [29]. The microorganisms' concentration in the feed water was determined at the beginning and the end of the third HRT experiment. Samples in the SDWTS effluent were taken at times of 90, 180, 270 and 360 min corresponding to 1, 2, 3 and 4 times the HRT, respectively, to quantify the concentration of the microorganisms.

2.8. Evaluation of the Increase in the Operating Flow

The response of the SDWTS in turbidity removal was evaluated with increases in the operating flow to 2.0 and 3.0 m^3/d. In these tests, the SDWTS was operated with type II water and PACl (dose of 1.6 mg/L Al^{+3}). The experimental times were 3 h for the 2.0 m^3/d flow and 2 h for the 3.0 m^3/d flow. These experimental times correspond to 4 times the respective theoretical HRTs.

2.9. Evaluation of the Increase in Raw Water Turbidity

In order to determine the system response to an increase in turbidity, a test was carried out with feed water prepared with a turbidity of 50 NTU and an apparent colour of 20 CU. The test was carried out at a flow of 1.0 m^3/d and with coagulant PACl (dose of 1.6 mg/L Al^{+3}). UGFL and RSF effluents were sampled for turbidity analysis every 15 min between 1 and 1.5 HRT.

2.10. Analytical Methods

Measurements of turbidity, apparent colour, pH, electrical conductivity (EC), total coliforms, *E. coli* and water temperature were performed according to the Standard Methods for the Analysis of Water and Wastewater of the American Public Health Association [29].

3. Results and Discussion

3.1. Hydraulic Evaluation

The trends in tracer concentration in the effluent of the UGFL and RSF are shown in Figures 2–5. In addition, the hydraulic parameters for each filter operated at flows of 0.5 and 1.0 m^3/d (calculated according to the Figures 2–5) are presented in Tables 4 and 5 for the Wolf-Resnick simplified model and analysis of the trend curve, respectively.

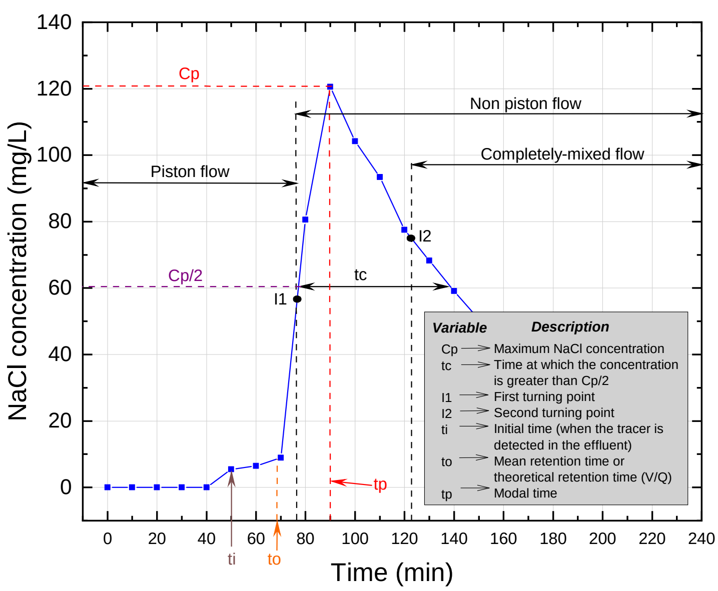

Figure 2. Variation of tracer concentration in the effluent of the UGFL–Flow 1.0 m^3/d.

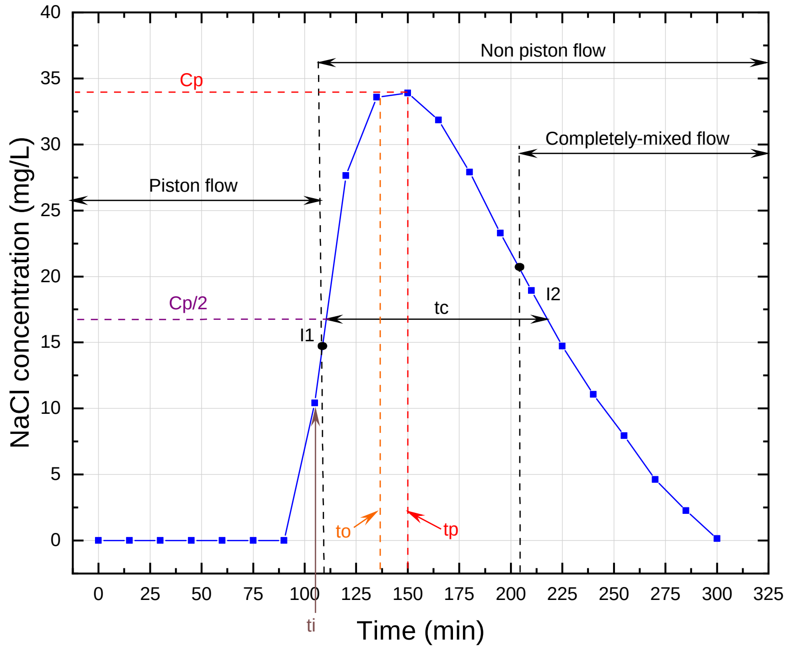

Figure 3. Variation of tracer concentration in the effluent of the UGFL–Flow 0.5 m^3/d.

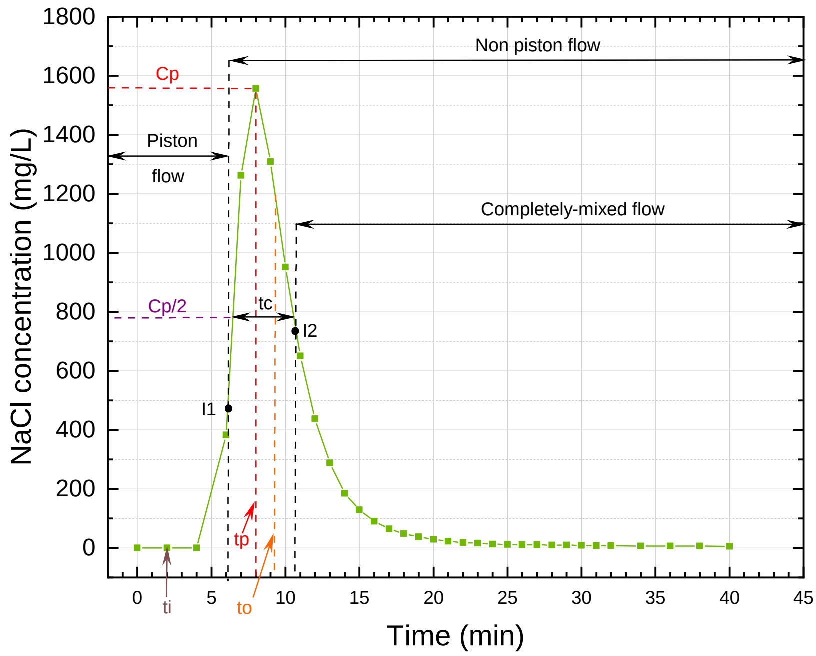

Figure 4. Variation of tracer concentration in RSF effluent–Flow 1.0 m^3/d.

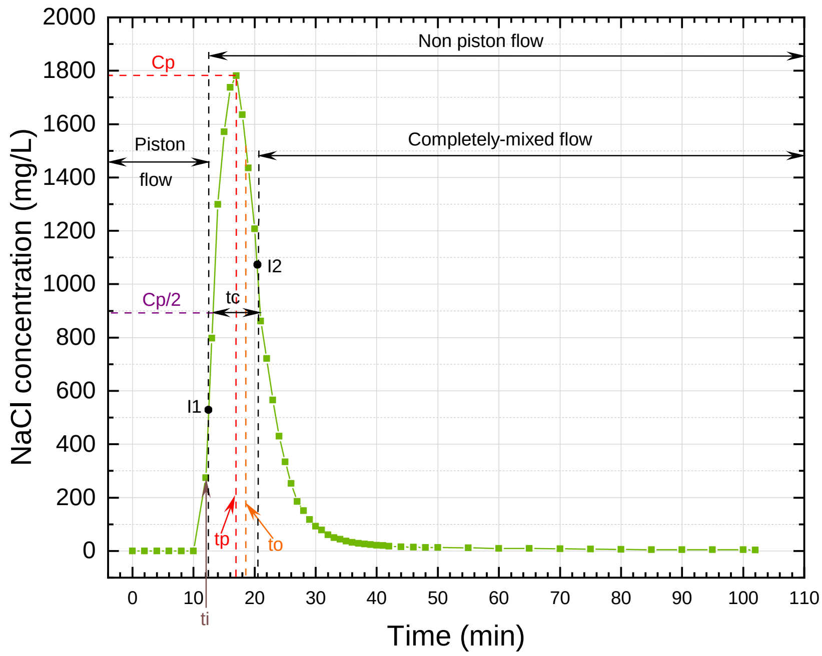

Figure 5. Variation of tracer concentration in RSF effluent–Flow 0.5 m^3/d.

Table 4. Results of the application of the simplified Wolf-Resnick model.

Wolf-Resnick Simplified Model			
Filter	**Parameter**	**Flow (m^3/d)** 0.5	**1.0**
UGFL	θ	0.9	1.2
	tan α	1.31	0.6
	$P(\%)$	73	62
	$m(\%)$	0	0
	$FM(\%)$	27	38
RSF	θ	0.9	0.8
	tan α	1.3	1.23
	$P(\%)$	74	70
	$m(\%)$	0	0
	$FM(\%)$	26	30

where: tan α: slope of the tangent line to the straight part of the tracer concentration curve; θ = intercept of the straight line with the ordinate axis; P = piston flow; m = fraction of dead zones; FM = mixed flow (Taken from: CEPIS [25].

According to the simplified Wolf-Resnick method, at a flow of 0.5 m^3/d, the UGFL and RSF had a piston flow (P) of 73% and 74%, respectively. When the flow was increased to 1.0 m^3/d, the piston flow was reduced to 62% and 70% for the UGFL and RSF, respectively. These results showed a predominance of piston flow over mixed flow (FM) for both filters at both operating flows. The predominance of piston flow was attributed to the inlet structure of the filters, which evenly distributed the flow over the surface area of the filter bed. In addition, in the case of the UGFL, the supernatant water layer collects the filtered water and carries it to the collector [30]. Similarly, the tp/to (close to 1.0) and ti/to (greater than 0.5) ratios confirmed the predominance of piston flow. The Morril index, with values close to 1.0, reaffirmed the predominance of piston flow obtained with the simplified Wolf-Resnick method.

Table 5. Results of the trend curve analysis.

Analysis of the Trend Curve			
Filter	**Parameter**	**Flow (m^3/d)**	
		0.5	**1.0**
UGFL	to (min)	136.9	68.5
	ti/to	0.77	0.73
	tp/to	1.1	1.31
	Morril index	1.32	1.21
	Real HRT (min)	150.0	90.0
RSF	to (min)	18.4	9.2
	ti/to	0.7	0.7
	tp/to	0.99	0.47
	Morril index	1.36	1.4
	Real HRT (min)	17.0	8.6

For the UGFL and RSF at the two operating flows, no dead zones (m = 0%) were evident. Furthermore, the ti/to ratio (>0.3) obtained for the UGFL and RSF indicated the absence of hydraulic short circuits for both filters and the two operating conditions.

The predominance of piston flow and the absence of dead zones and short circuits in both filters favoured flocculation and sedimentation of particles in the UGFL and particle transport and adhesion mechanisms in the RSF. These mechanisms generated surface interactions between the particles in the supernatant and the sand grains, allowing the capture and removal of suspended solids [31]. Similarly, the predominance of piston flow indicates a real contact time or HRT, close to the design or theoretical one.

3.2. Experimental Treatments

Figure 6 presents the average turbidity results and the error (standard deviations of each test and its replicate) of the UGFL and RSF effluents for the treatments presented in Table 3 and for the operating times evaluated, reported as HRT. This figure includes the variables water type (I and II), coagulant (Al and Fe) and operating flow (L and H).

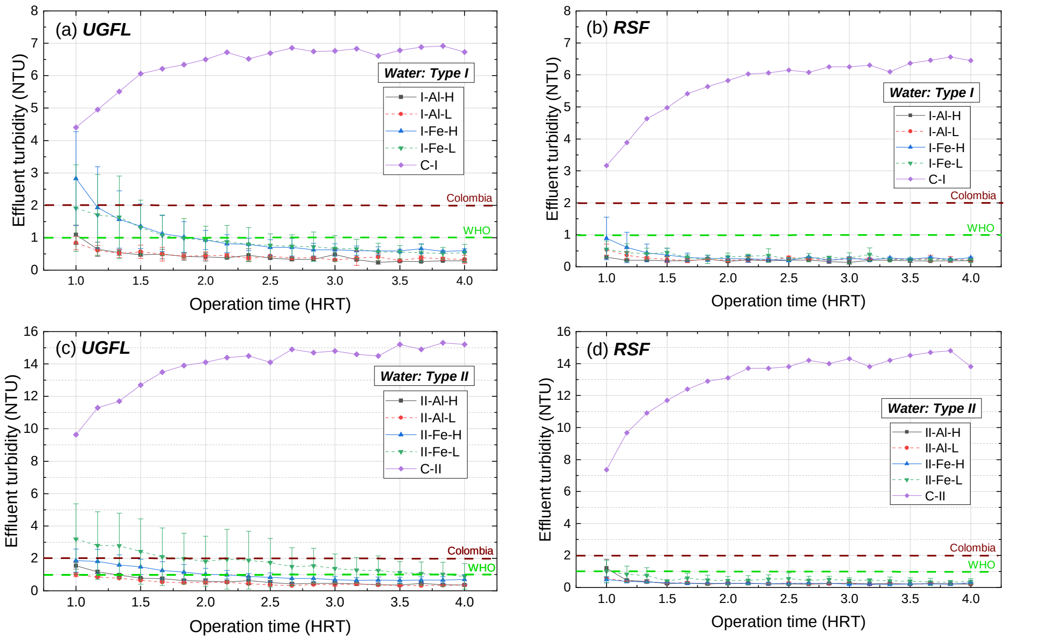

Figure 6. Effluent turbidity for treatments and blanks: (**a**) UGFL–Water type I, (**b**) RSF–Water type I, (**c**) UGFL–Water type II and (**d**) RSF–Water type II.

As shown in Figure 6a, when the SDWTS was evaluated with water type I (10 NTU) and the coagulant ferric sulphate (Fe), the average turbidity in the UGFL effluent for the first HRT ranged between 2 and 3 NTU for both operating flows (L and H). With increasing operating time, the turbidity for the two flows was similar with a decreasing trend, reaching stability (around 0.6 NTU) from 3.0 HRT onwards. When the SDWTS was operated with the coagulant PACl (Al), the turbidity in the UGFL effluent showed less variability and was lower than the one with the coagulant ferric sulphate for all HRTs. Concerning the operating flows, with the coagulant PACl, similar turbidity values were also obtained in the UGFL effluent at both flows and its stability was reached from 1.5 HRT onwards, achieving average turbidity values of less than 0.5 NTU.

The average turbidity in the effluent of the RSF with water type I is presented in Figure 6b. In this figure, it is observed that for the flows and coagulants evaluated, the effluent turbidity of the RSF was similar and, in all cases, lower than 1.0 NTU. As in the UGFL, the effluent turbidity of the RSF showed a decreasing trend with increasing operation time, reaching minimum values between 0.2 and 0.3 NTU before 2.0 HRT. These turbidity levels are lower than those reported by Alsaeed et al. [32] for a conventional system (between 3.2 and 3.6 NTU) that treated water with initial turbidity of 10 NTU at pH values between 7 and 8 with the coagulant PACl (dose 5 mg/L).

Regarding the evaluation of SDWTS with water type II (20 NTU), Figure 6c shows the average turbidity of the UGFL effluent. In this test, for all HRTs, the highest average turbidity (between 3.2 and 0.9 NTU) corresponded to the SDWTS operation with coagulant ferric sulphate and low flow (L). In this treatment, the highest variability between replicates was reported, and no stability was evident during operation, reaching the minimum turbidity (0.9 NTU) at 4.0 HRT. For the high flow (H) and the coagulant ferric sulphate, the response in the turbidity of the UGFL was decreasing, obtaining stability from 3.0 HRT with turbidity close to 0.7 NTU. On the contrary, with the coagulant PACl, less variability was observed in the UGFL effluent turbidity, and similar turbidity was reported for the two operating flows, achieving minimum turbidity between 0.40 and 0.5 NTU from 2.5 HRT.

When the SDWTS was evaluated with water type II, the effluent turbidity of the RSF (Figure 6d) presented a similar trend to that obtained with type I water (Figure 6b), with stabilisation at 1.5 HRT for all treatments. From this time onwards, the turbidity in the RSF effluent remained between 0.2 and 0.4 NTU with the flows and coagulants evaluated.

When the SDWTS was operated at flow H and without the addition of coagulants (controls), an increase in the effluent turbidity of the UGFL and RSF was observed with increasing operating time for both types of water (Figure 6a–d). With type I water (C-I), SDWTS turbidity effluent (RSF) higher than 6 NTU was reported at 2.2 HRT, while with type II water (C-II), turbidity higher than 13 NTU was reached at the identical HRT. This turbidity increase was due to an accumulation of particles in the filter bed, which decreased the effective area available for sedimentation. This difference is explained by the fact that in the control experiments, turbidity removal occurs due to the sedimentation of particles present in the types of water studied. In contrast, in the tests with the presence of coagulant, the phenomena of destabilisation of the surface charges, adsorption and adherence to the particles had an influence, increasing turbidity removal in these cases [5].

Additionally, the paired analysis between the controls and the treatments [(C-I and I-Al-H), (C-I and I-Fe-H), (C-II and II-Al-H) and (C-II and II-Fe-H)] shows that the effluent turbidity in the treatments was significantly lower than that obtained in the controls, given that the p-value obtained (<0.001) is lower than the significance level of 0.05. Therefore, in all the treatments evaluated, the improvement of water clarification was evidenced with the incorporation of the coagulation stage, prior to the UGFL. Similar results were reported by Sánchez et al. [21] and Franco et al. [20], using as coagulants aluminium sulphate and Moringa oleifera seeds, respectively.

Then, from 1.5 HRT operation time in all treatments, treated water (RSF effluent) with turbidity less than 1.0 NTU was obtained, complying with the recommendations of the WHO [33] and Colombian regulations [34] to promote effective disinfection. In Figure 6, the horizontal dashed lines represent the turbidity limits recommended by WHO and Colombia, respectively.

Figure 7 presents the average results for pH and EC in the effluent of the SDWTS system, for both types of water (I and II), with the coagulants PACl (Al) and ferric sulphate (Fe). In this figure, it can be observed that the EC did not present significant variations in the effluent and all the values obtained were lower than the maximum limit (1000 µS/cm) established in the Colombian regulations for drinking water [34]. It can also be observed that the effluent pH for treatments with the coagulant ferric sulphate presented values close to the lower permissible limit established for this parameter in water for human consumption (6.5 to 9.0 pH units). The WHO does not propose any reference value for this parameter because pH levels found in drinking water do not represent a health concern. However, pH is one of the most important operational parameters of water quality. The optimum pH required will vary in different supplies according to the composition of the water and the nature of the construction materials used in the distribution system, but it is usually in the range 6.5–8.5 [35]. In the case of treatments with the coagulant PACl, values closer to neutrality were presented, also complying with Colombian regulations for drinking water [34]. This neutral pH was because the coagulant PACl has basicity (70%) in its chemical composition, implying a lower alkalinity consumption and a lower pH reduction in the treated water compared to the ferric sulphate coagulant [36]. The temperature of the effluent water was also monitored as a control variable, with an average value of 24.6 °C.

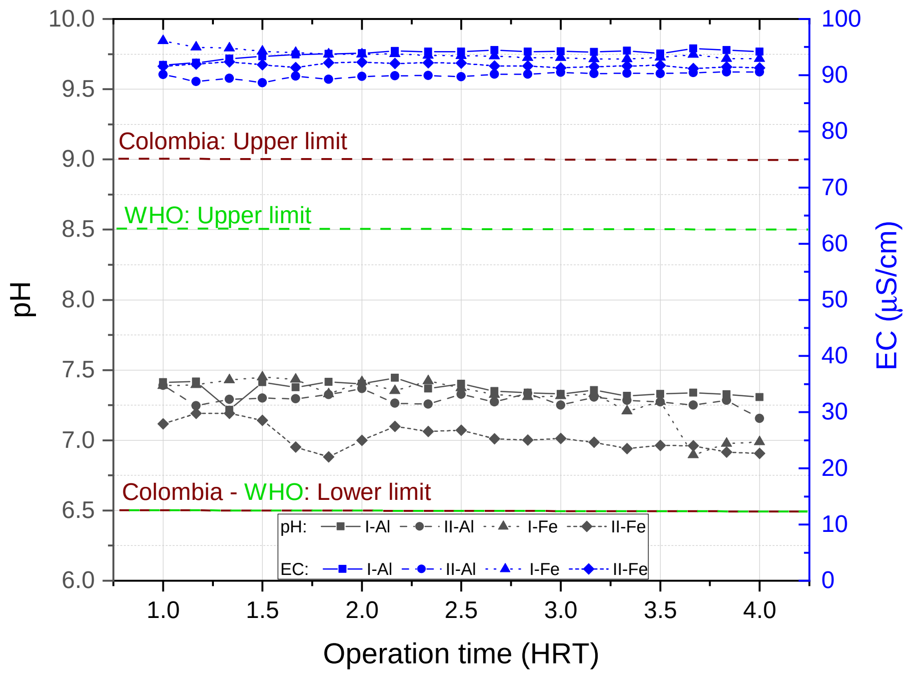

Figure 7. Average results of pH and EC in effluent from the SDWTS.

Regarding apparent colour, in all tests and for all operating times, values lower than 10 CU (limit of quantification of the method) were obtained in the effluents for both UGFL and RSF, thus complying with the maximum permissible value of 15 CU established in Colombia for drinking water [34]. No health-based guideline value is proposed for colour in drinking water by the WHO. However, levels of colour below 15 TCU (True Colour Units) are often acceptable to consumers [35].

In addition, because of the importance of optimizing coagulation to prevent microbial contamination and the need to minimize deposition of aluminium floc in distribution systems, it is important to ensure that average residuals do not exceed 0.2 mg Al/L in small facilities like the SDWTS. The WHO does not propose a guideline value for iron in drinking water because not of health concerns at levels found in drinking water. The taste and appearance of drinking water will be affected by Fe concentrations. However, there is usually no noticeable taste at iron concentrations below 0.3 mg Fe/L [35]. The residual coagulant concentrations in the SDWTS effluent for the PACl and ferric sulphate treatments were lower than 0.2 mg Al/L and 0.3 mg Fe/L, respectively. These results indicate that for both coagulants, the maximum acceptable levels for iron and aluminium in drinking water in Colombia were met [34] and are within the WHO recommended ranges [35].

During the operation of the SDWTS for the evaluation of the treatments and controls, no head loss was observed in the RSF piezometer, indicating that the load of solids reaching this filter was low and their accumulation during the time of each test (6–10 h) did not generate clogging of the filter bed.

3.3. Factorial Design Analysis

Table 6 presents the results of verifying the assumptions of normal distribution and constant variance for each filter's turbidity removal data and the operating times evaluated (HRT). The Anderson-Darling Normality Test results indicated that all turbidity removal data for the two filters and the four operating times evaluated follow a normal distribution (p-value > 0.05).

Table 6. Results of the normality and equality of variance tests.

Test		Anderson-Darling Test			Bartlett's Test
Filter	**Operation Time**	**Median**	**Standard Deviation**	**p-Value**	**p-Value**
UGFL	1 HTR	9.77×10^{-15}	5.159	0.330	0.239
	2 HTR	-5.33×10^{-15}	2.270	0.330	0.407
	3 HTR	5.33×10^{-15}	1.546	0.352	0.342
	4 HTR	-7.11×10^{-15}	1.247	0.346	0.040
Complete system (RSF effluent)	1 HTR	7.11×10^{-15}	1.939	0.958	0.090
	2 HTR	-1.60×10^{-14}	0.4505	0.352	0.580
	3 HTR	1.07×10^{-14}	0.5055	0.860	0.156
	4 HTR	1.33×10^{-14}	0.2994	0.941	0.508

Anderson-Darling Normality Test (Residue Probability Graph).

Similarly, Bartlett's test shows that for most of the conditions evaluated, there was equality or homogeneity in the turbidity removal variances (p-value > 0.05). Only the turbidity removal data in the UGFL for 4 HRT did not meet the assumption of constant variance (p-value = 0.040). In order to stabilise the variance of these data, a Box-Cox transformation with an estimated λ = 39.5122 was applied before analysing the factorial design results.

Table 7 presents the standardised effects of the three factors: coagulant (C), type of water (W), flow (F) and Table 8 shows the results of their interactions (C*W, C*F, W*F and C*W*F) on the turbidity removal in the UGFL and RSF for the four SDWTS operating times. Additionally, Figures 8 and 9 present the cube plots for the turbidity removals (adjusted means) with the relationships between the three factors and for UGFL and RSF, respectively.

Table 7. Standardised effects of the factors.

Test		C		W		F	
Filter	**OT**	**Effect**	***p***	**Effect**	***p***	**Effect**	***p***
UGFL	1 HTR	9.370	0.029	6.330	0.111	−1.250	0.732
	2 HTR	4.372	0.023	1.590	0.336	1.134	0.487
	3 HTR	2.598	0.040	1.414	0.219	0.574	0.603
	4 HTR	2.036	0.022	1.677	0.048	−0.073	0.921
Complete system (RSF Effluent)	1 HTR	0.939	0.499	1.340	0.342	−0.195	0.887
	2 HTR	0.636	0.073	0.783	0.035	0.455	0.178
	3 HTR	0.461	0.220	0.832	0.043	0.621	0.111
	4 HTR	0.407	0.082	0.722	0.008	0.064	0.763

OT: Operation time, C: Type of coagulant, W: Type of water, F: Flow, *p*: *p*-value.

Table 8. Standardised effects of the factors' interaction.

Test		C*W		C*F		W*F		C*W*F	
Filter	**OT**	**Effect**	***p***	**Effect**	***p***	**Effect**	***p***	**Effect**	***p***
UGFL	1 HTR	−3.210	0.390	−1.320	0.718	3.020	0.417	−3.210	0.389
	2 HTR	−0.198	0.902	−1.163	0.476	0.535	0.740	−0.942	0.561
	3 HTR	0.377	0.731	−1.546	0.182	0.871	0.435	−0.289	0.792
	4 HTR	0.240	0.747	0.218	0.770	−0.067	0.928	−0.196	0.792
Complete system (RSF Effluent)	1 HTR	−1.614	0.259	−0.246	0.858	−0.160	0.907	−2.575	0.088
	2 HTR	−1.198	0.540	−0.332	0.313	−0.033	0.917	−0.099	0.756
	3 HTR	−0.177	0.622	−0.082	0.820	−0.082	0.819	−0.540	0.157
	4 HTR	0.112	0.599	0.158	0.464	0.268	0.227	−0.300	0.182

OT: Operation time, C: Type of coagulant, W: Type of water, F: Flow, *p*: *p*-value.

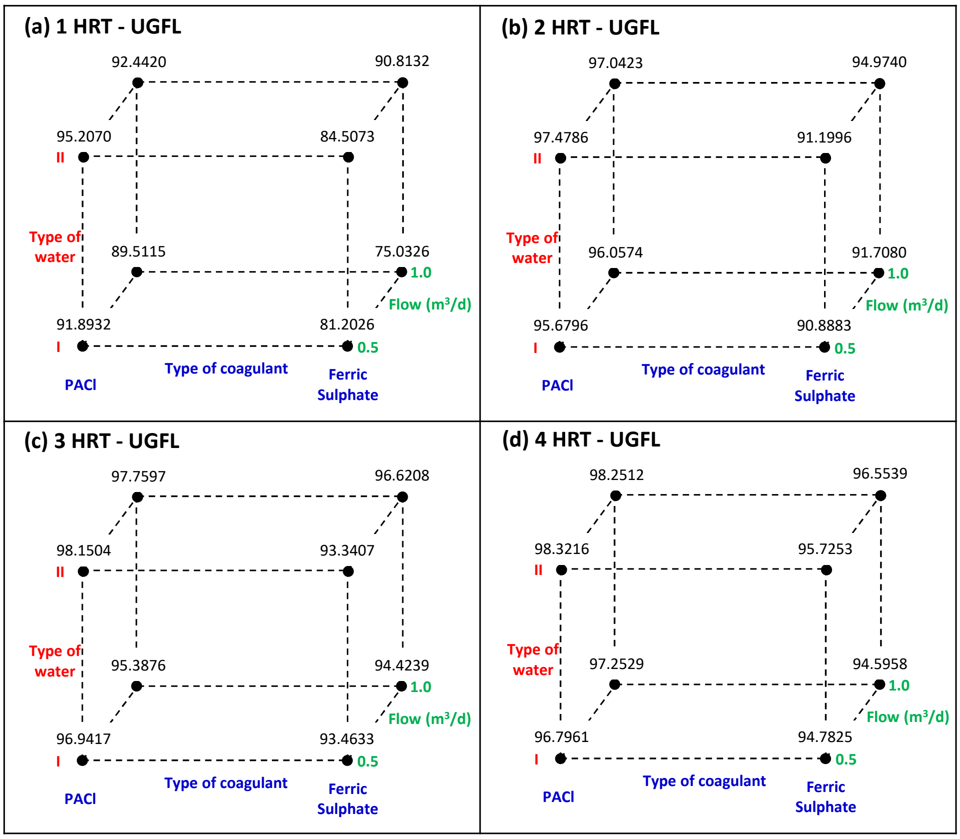

Figure 8. Cube plot (adjusted means) for turbidity removal (%) in UGFL.

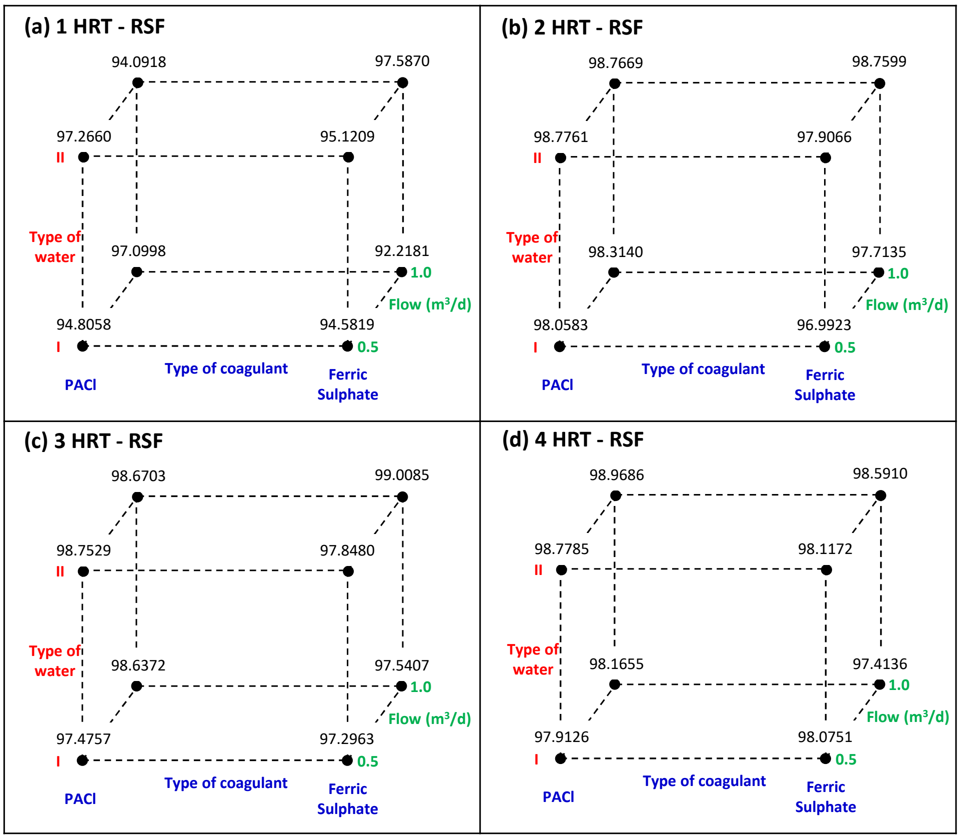

Figure 9. Cube plot (fitted means) for turbidity removal (%) in the SDWTS (RSF effluent).

Table 7 shows that, for the UGFL, the coagulant type is a significant factor (*p* values < 0.05) and it had the greatest effect on turbidity removal (between 9.370 and 2.036) for all HRTs. These positive values indicated that higher turbidity removals were achieved with the coagulant PACl compared to ferric sulphate, as shown in Figure 8. Also, the higher removals correspond to lower turbidity in the UGFL effluent, as shown in Figure 6a,c. In these Figures, it was also observed that as the operating time (HRT) increases, a more negligible difference in UGFL effluent turbidity is obtained when comparing the coagulants. This is consistent with the decrease in the standardised effect of coagulant type on UGFL as the HRT increases (Table 7).

Water type factor only had a significant (*p*-value = 0.048) and positive effect on turbidity removal at 4 HRT of UGFL operation. This result indicates that at the end of the UGFL experiment, the maximum turbidity removals (>98%) were achieved with water type II (initial turbidity = 20 NTU) and PACl, as shown in Figure 8d.

For the RSF (in Table 7), only the water type factor significantly affected turbidity removal after 2 HRT of system operation (*p* values < 0.05). The positive effects indicated that the highest turbidity removals in the SDWTS were achieved with water type II (>98.7%), as can be seen in Figure 9b–d. These high removals corresponded to low turbidity in the effluent of the SDWTS (between 0.2 and 0.4 NTU), as can be seen in Figure 6b,d. Similar turbidity levels (0.15 NTU) were reported in the drinking water treatment with initial turbidity of 15.4 NTU through a coagulation/flocculation system combined with advanced filtration (ultrafiltration) also using PACl [37].

The flow factor (Table 7), two-factor and three-factor interaction (Table 8) had no significant effect on turbidity removal for UGFL and RSF (*p* values > 0.05).

From the analysis of the results of the "experimental treatments" section and the factorial design, the optimal conditions were defined as the operation of the SDWTS with type II water (higher levels of turbidity and colour) and the use of the coagulant PACl. In addition, as the flow did not significantly affect turbidity removal in both filters, the higher flow was selected as the optimum condition that allows a greater volume of water to be treated.

3.4. Operation and Maintenance

The filtration run was evaluated for the complete system under optimal conditions. The filtration run for the RSF was 172 h and a total production of treated water by the system of 7083 L. The maximum available head loss (75 cm) was reached during this time. During the filtration run, the average turbidity in the UGFL and RSF effluents were 0.30 ± 0.06 NTU and 0.27 ± 0.09 NTU, respectively.

The UFGL washing required 142 L of water and a time of 114 s. The average washing flow was 75.1 ± 6.0 L/min. The wash water reached maximum turbidity of 7600 NTU (at 5 s) and a minimum of 13.8 NTU at the end of the wash. Likewise, the RSF backwash required 83 L of water and a time of 15 min. The average backwashing rate was 42 ± 3.3 m/h and is in the range of typical values for this operation (30 to 60 m/h-Crittenden et al. [38]). The total volume of washing water generated in the cleaning of the system was 225 L. Considering the filtration run, the effective production of treated water by the system after cleaning the units was 96.9% (6858 L).

The estimated cost of the treatment system (initial investment) is USD 2100. This cost includes UFGL and RSF and all their components, the pumping system for backwashing, the raw and treated water storage tanks, the necessary accessories, and the system's installation. The system can effectively produce 6858 L/week, considering weekly maintenance with an average water consumption for cleaning of 225 L.

3.5. Removal of Microorganisms

Figure 10 shows the results of total coliform and *E. coli* inactivation and effluent turbidity in the SDWTS, for water type II, with the coagulant PACl and a flow of 1.0 m^3/d. Under these conditions, *E. coli* concentrations below the method's limit of quantification (<1 NMP/100 mL) were obtained in the SDWTS effluent for all the HRTs evaluated, which are equivalent to removals greater than 99% (>2 log inactivation, LI).

This *E. coli* inactivation is similar to those reported by Souza and Sabogal [39] for a slow filtration system with coagulation as pretreatment for rural community supply (close to 3.0 LI) and Terin et al. [40] in a multi-barrier system with pretreatment and filtration in Household Slow Sand Filters (close to 2.6 LI). It is also higher than the removals obtained by Medeiros et al. [3] in a multi-stage filtration system (around 1.0 LI).

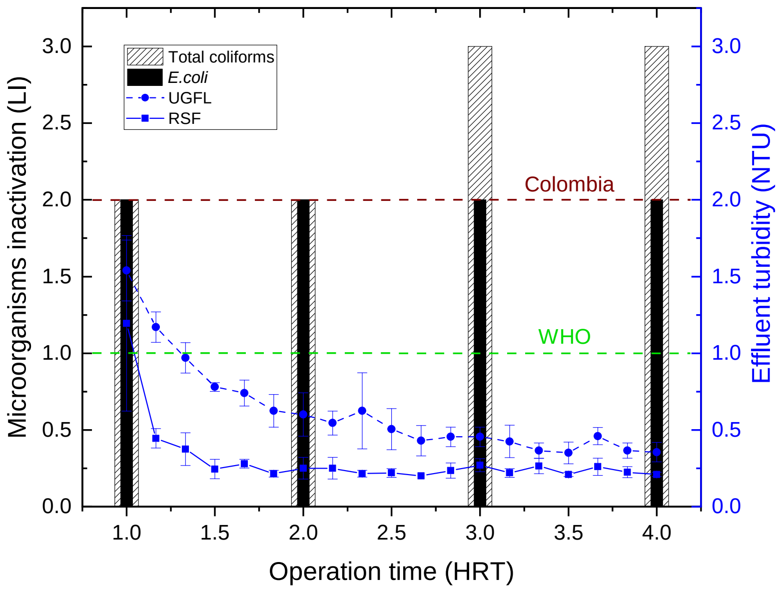

Figure 10. Test results for the evaluation of the removal of microorganisms (water type II, PACl and 1.0 m^3/d).

As shown in Figure 10, total coliform removal was 99% (2 LI) for 1 and 2 HRT, corresponding to UGFL effluent turbidity between 1.5 and 0.6 NTU. From 3 HRT, the turbidity in the UGFL effluent stabilised at values between 0.35 and 0.46 NTU, and the removal of total coliforms increased to 99.9% (3 LI). This removal corresponded to a total coliform concentration below the method's limit of quantification (<1 NMP/100 mL) in the SDWTS effluent. The microorganism removal test shows that the SDWTS can generate water free of total coliforms and *E. coli* from 3 HRT (<1 MPN/100 mL).

Coagulation/flocculation processes are an essential barrier in drinking water treatment to reduce the concentration of viruses, bacteria and bacterial spores. Additionally, if these processes are used before the RSF, they improve its performance in removing microorganisms, as shown in the research reported by Hijnen and Medema [41]. The high inactivation of microorganisms shown by the SDWTS can be attributed to adsorption (a mechanism responsible for the attachment of small-sized microorganisms to different charged surfaces of the filter media) and the natural death process of pathogenic microorganisms due to factors such as ageing and stress on the filter media [42,43]. In addition, the disinfection process (not evaluated in this work) would complement the inactivation of microorganisms and the protection of treated water during its transport through the distribution network to end users.

3.6. Evaluation of the Increase in the Operating Flow

Figure 11 shows the turbidity in the UGFL and RSF effluents for the tests with increasing operating flow, with water type II and with the coagulant PACl, for operating times between 1 and 4 times the actual HRT. This figure shows that for 1 HRT, the lowest effluent turbidity is achieved for the flow of 2 m^3/d (1.23 NTU and 0.39 NTU for UGFL and RSF, respectively). When the flow is increased to 3 m^3/d, the effluent turbidity increases to values of 2.53 in UGFL and 0.87 in RSF.

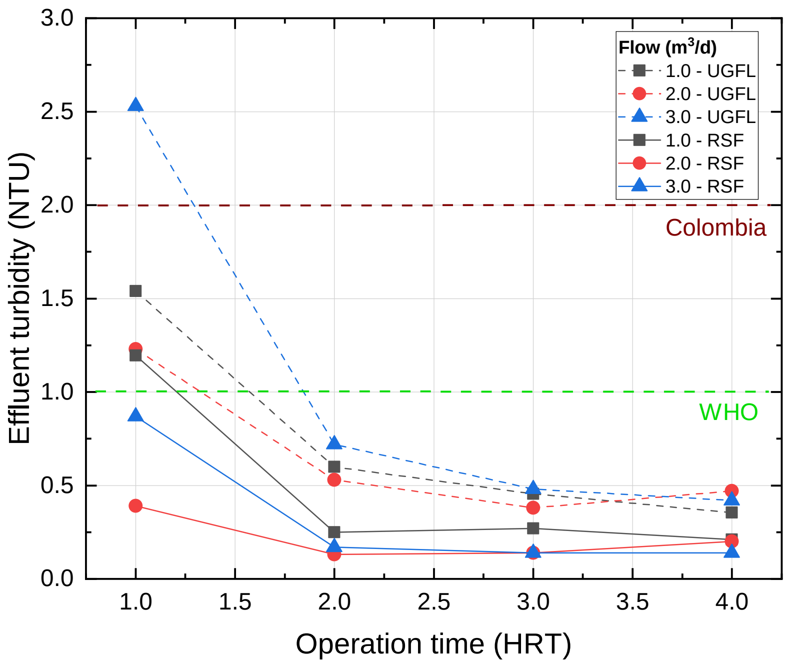

Figure 11. Results for the evaluation of the increase in operating flow (water type II and PACl).

After an operating time of 2 HRT, it was observed that the turbidity in the effluent of the UGFL was similar for the three flows evaluated, reaching values between 0.36 and 0.47 NTU at the end of the test. Similar behaviour was observed in the RSF, achieving effluent turbidity between 0.14 and 0.21 NTU for an operating time of 4 HRT for the three flows.

For the tests and for all operating times evaluated, the SDWTS effluent reported values for apparent colour (≤10 CU, for both flows), pH (2.0 m^3/d: 6.68 ± 0.10–3.0

m^3/d: 6.85 ± 0.08), and electrical conductivity (2.0 m^3/d: 99.1 ± 1.6 µS/cm–3.0 m^3/d: 97.8 ± 2.7 µS/cm) that comply with the maximum permissible limits for drinking water [34].

3.7. Evaluation of the Increase in Raw Water Turbidity

The response of the SDWTS operation to an increase in influent turbidity (50 NTU) compared to previously evaluated turbidity (10 and 20 NTU) is presented in Figure 12. This test was carried out between 1.0 and 1.5 HRT, with a flow of 1.0 m^3/d and with the coagulant PACl. This figure shows that for an operating time of 1 HRT, the minimal turbidity in the UGFL and RSF effluents are for the minimal initial turbidity. However, with the increment of initial turbidity in the raw water and operation time greater than 1.17 HRT, the SDWTS was able to produce treated water (RSF effluent) with low turbidity levels (0.5 NTU), which complies with WHO [33] and Colombian regulations [34] for drinking water.

With the increase in raw water turbidity to 50 NTU, the SDWTS also generated treated water with levels of apparent colour (≤10 CU), pH (7.05 ± 0.07) and electrical conductivity (100.9 ± 1.1 µS/cm) that meet the maximum permissible limits for drinking water for all operating times [34].

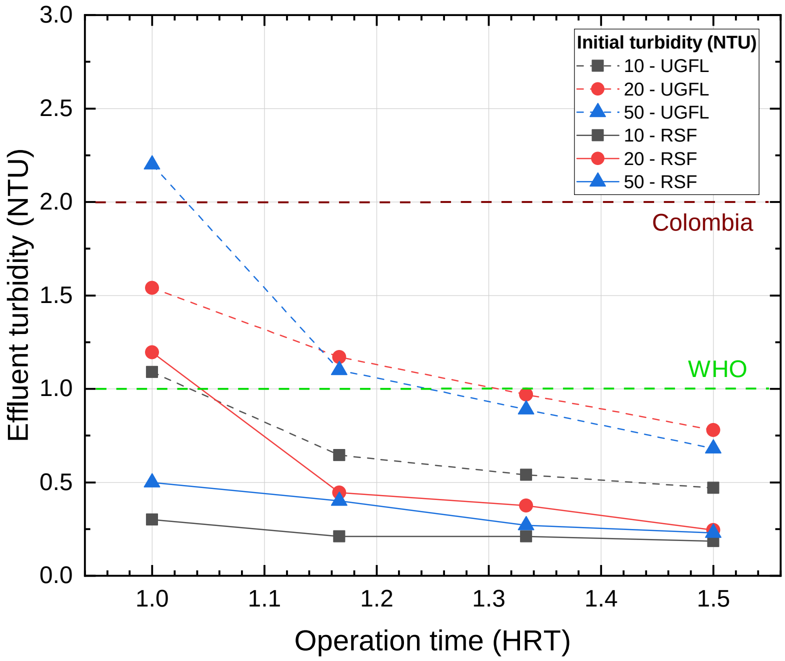

Figure 12. Results for the assessment of the increase in influent turbidity (PACl and 1.0 m^3/d).

4. Conclusions

The UGFL and the RSF that are part of the SDWTS presented a predominance of piston flow, without short circuits and dead zones, for the operating flows of 0.5 and 1.0 m^3/d. These hydraulic conditions favoured flocculation and sedimentation processes in the UGFL and particle transport and adhesion mechanisms in the RSF.

The treatment of raw water with turbidity levels of 10 and 20 NTU using the SDWTS generated treated water that complies with the maximum permissible limits for water for human consumption in Colombia in terms of turbidity, apparent colour, pH, electrical conductivity and residual coagulant (Al or Fe), from an operating time corresponding to 1 HRT. In the SDWTS, the improvement of water clarification was evidenced by the incorporation of the coagulation stage prior to the double filtration system, achieving turbidity levels in the treated water lower than those recommended by the WHO (1.0 NTU).

The highest turbidity removals in the SDWTS occurred with PACl coagulant, with the water type II (turbidity: 20 NTU) and operating flow of 1.0 m^3/d. Under these conditions, the SDWTS achieved complete inactivation of total coliforms and *E. coli* after an operating time of 3 HRT.

The SDWTS showed a good response in removing turbidity and apparent colour to significant changes in flow (up to 3.0 m^3/d), allowing a higher drinking water production than the one defined in its design (1.0 m^3/d). Similarly, when faced with increases in raw water turbidity (up to 50 NTU), which have a high probability of occurring due to climatic variations or high intensity rainfalls, the SDWTS was able to continue producing drinking water.

This research shows that the evaluated SDWTS can be an efficient and innovative alternative for water treatment in rural or small communities. SDWTS combines the benefits of a centralised system: good performance in pollutant removal and elimination of pathogenic microorganisms, with the advantages of decentralised systems (low construction costs and energy consumption, operational and maintenance simplicity). The SDWTS contributes to universal and equitable access to safe and affordable drinking water for all, as established in the Sustainable Development Goals.

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