South African Journal of Chemical Engineering 37 (2021) 141–149

Contents lists available at ScienceDirect

South African Journal of Chemical Engineering

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

The challenge of improving the efficiency of drinking water treatment systems in rural areas facing changes in the raw water quality

Fernando García-Ávila [a,*], Alex Avilés-Añazco [a], Esteban Sánchez-Cordero [b], Lorgio Valdiviezo-Gonzáles [c], María D. Tonon Ordoñez [a]

[a] *Facultad de Ciencias Químicas, Universidad de Cuenca, Ecuador*
[b] *Facultad de Ingeniería, Universidad de Cuenca, Ecuador*
[c] *School of Environmental Engineering, Universidad César Vallejo, San Juan de Lurigancho, Lima, Perú*

ARTICLE INFO

Keywords:
Slow filtration
Rapid filtration
Water treatment plant modernization
Water quality

ABSTRACT

Safely managed drinking water for all is the United Nations Sustainable Development Goal 6.1. Achieving this goal is a challenge in rural areas. A strong partnership between users of a water treatment system was critical to the success of community-scale technological change. In this study, the efficiency of a water treatment system was evaluated after the implementation of a technological change in a rural area. This research was carried out in a community in Ecuador, which before the change in technology had a treatment system composed of gravel pre-filtration and slow filtration. This system did not guarantee adequate water quality, due to a notable increase in the color and turbidity levels of raw water; in addition to the growing demand for water in recent years. A new conventional treatment system was implemented consisting of: coagulation, flocculation, sedimentation, rapid filtration and disinfection. All the modernization works were carried out on the same infrastructure that had served as gravel pre-filters. Before modernization, samples of raw water and treated water were collected for six months. After the changes carried out, samples of raw and treated water were also collected for another six months. The parameters analyzed were: turbidity, color, pH, total dissolved solids, residual chlorine, nitrates, sulfates, phosphates, chlorides, alkalinity, total hardness and iron. The values of all the parameters analyzed improved after the modernization, indicating that the changes made in the treatment plant were successful. As a result, a conventional treatment to make water potable in rural areas has become a robust process that can operate within a wide range of water quality, improving the quality and quantity of drinking water.

1. Introduction

Water resources have recently been affected by climate change, population growth, and increased anthropogenic activities; posing great challenges to companies in charge of supplying drinking water, especially in developing countries (Hoslett et al., 2018; El-Alfy et al., 2019). The development level of a country is determined by the supply of drinking water for both domestic and industrial use (Majdi et al., 2019; Jakubaszek, 2019). Serious health problems related to the drinking water quality have focused interest on how to assess and improve water supplies (Guchi, 2015; Adesina et al., 2019). An efficient treatment technology should meet some criteria, such as: a. easy to install, operate and maintain, b. low investment, operation and maintenance cost, c. effective in improving water quality (Guchi, 2015; García-Ávila et al., 2019).

Sand filtration is a potable water purification method in which relatively large suspended particles are removed (García-Ávila et al., 2020). There are two main types of sand filters used for water treatment: rapid sand filters (RF) and slow sand filters (SF) (Arndt and Wagner, 2004). Slow sand filtration is an efficient alternative for developing countries (Clark et al., 2012). A feature of SF is the simplicity of operation and the ability of the process to remove potentially pathogenic organisms from the water (Chollom et al., 2017; Laghari et al., 2018). The disadvantages of SF are the difficulties associated with the filtration of appreciable turbid waters, the requirement for more space, and also the effects of algal blooms (Logsdon et al., 2002). In general, rapid filtration is preceded by a chemical pre-treatment of the water, generally coagulation-flocculation, decantation and a post-treatment (generally disinfection), together these processes are known as conventional treatment (Bar-Zeev et al., 2013; García-Ávila et al., 2021).

---

* Corresponding author.
E-mail address: fernando.garcia@ucuenca.edu.ec (F. García-Ávila).

https://doi.org/10.1016/j.sajce.2021.05.010
Received 25 December 2020; Received in revised form 3 May 2021; Accepted 26 May 2021

The disadvantage of SF is the low capacity to remove high turbidity peaks present in natural (raw) water that can enter the plant, the increase in turbidity clogs the slow filters. High turbidity is generally the product of a hydrological or climatic phenomenon, such as heavy rains, which makes it necessary to increase the frequency of maintenance of the filtration system (Ranjan and Prem, 2018). A slow filter loses functionality with turbidity greater than 20 or 30 NTU, which is very problematic, if it is necessary to work with peaks of 50 to 100 NTU (Logsdon et al., 2002b; Ellis and Wood, 2009; Gottinger et al., 2011). In contrast, rapid sand filtration allows treating high turbidity raw water and the effluent is of very good quality, complying with stricter specifications, allowing changes in turbidity and filtration rates (Al-Rawi, 2017).

When using SF it is essential to have a raw water supply that is not subject to prolonged periods of high turbidity (Liu et al., 2019). The high color in raw water is an additional disadvantage for SF; in contrast, RF allows working with high levels of color (Ellis and Wood, 2009). These same authors indicate that due to various factors that have caused an increase in the turbidity of the raw water for prolonged periods, it has been preferred to use rapid filtration, using a chemical pre-treatment will eliminate the turbidity to values below 1 NTU.

The use of RF allows satisfying the demand for effective water treatment, providing flexibility and reliability in the operation of the plant, especially when the raw water quality is variable, with high levels of color and suspended solids. At the end of the filtration, turbidity of less than 0.5 NTU can be obtained (EPA, 1995).

In the country of Ecuador there is a water treatment plant managed by the "Bayas" Potable Water Administration Board (BPWAB), which is a non-profit social organization whose purpose is to provide drinking water service in the community. The directors of this organization decided to change the SF treatment technology to a conventional treatment system. This decision was made due to the fact that the raw water that entered said plant presented high levels of turbidity and color, caused by the erosion that exists in areas adjacent to the catchment sources, making it difficult to treat raw water in a SF system. The increase in the concentration of color and turbidity affected the operating conditions of the plant, especially the slow filters, causing a rapid degree of clogging of the sand. This in turn causes a decrease in the flow of treated water and therefore a supply deficit, causing greater maintenance on slow filters. A granulometric analysis of the sand from the slow filters showed that the sand had reached its useful life, requiring its replacement with a new sand. Considering the aforementioned problems and the increase in the population of the Bayas community, the community leaders made the decision to change the SF treatment system for an RF treatment plant, which guarantees the drinking water quality.

The use of appropriate filtration systems improves the drinking water quality. Design modifications increase treatment efficiency and broaden the applicable quality range of raw water (Lenart-Boroń et al., 2019; Jakubaszek, 2019). The objective of this study was to determine the effectiveness in removing turbidity and color in the water treatment plant in Bayas (Ecuador) after modernization. The effectiveness of the water treatment was evaluated based on the degree of removal for which of the physicochemical parameters.

2. Materials and methods

2.1. Study area

The study area is located in the south of Ecuador, city of Azogues, Bayas community. The area is characterized by an urban-marginal and rural infrastructure. The population of the Bayas parish is served only by a drinking water treatment plant. The plant was built in 1998 and consisted of a slow filtration system with a gravel filtration pretreatment. After modernization, the plant is currently made up of a conventional system: coagulation, flocculation, sedimentation, rapid filtration and disinfection, with a treatment capacity of 20 L/s, currently producing 15 L/s. The distribution is by gravity, covering an approximate population of 6000 inhabitants.

2.2. Modernization of the technological water treatment system

The technology change consisted of replacing the SF system with an RF system (conventional treatment). The design of each treatment unit considered the guidelines proposed by the Pan American Center for Sanitary Engineering (CEPIS, 2004), contained in Manual II: Design of appropriate technology plants. Treatment of water for human consumption. Rapid filtration plants.

2.2.1. Sizing and construction of the conventional treatment plant

The rapid mixing consisted of a rectangular weir, in free fall with a mixing gradient$>$ 1000 s^{-1}, with a mixing time $\langle$1 s and a Froude number 4.5 $<$NF$\rangle$ 9, which guarantees that the hydraulic jump that is formed is stable, properly promoting the mixture of water with coagulant and a water speed at the mixing point$>$ 2 m/s.

Two vertical flow hydraulic flocculators with baffles were designed and built for a flow rate of 10 L/s each, retention time of 20 min, speed of 0.15 m/s, depth of 2.6 m and velocity gradients that varied between 70 and 20 s^{-1}.

Likewise, two high-rate decanters were designed and built, each 1.30 m wide, 7.0 m long and 2.60 m deep. These decanters were built with asbestos-cement plates, 1.20 m wide and 1.3 m long, with a spacing between plates of 0.05 m, 8 mm thick plates and an inclination of 60°, with a design flow for each decanter of 10 L/s and a sedimentation rate of 120 m^3/m^2d. Asbestos-cement is no longer allowed in many countries, which is why community leaders have committed to changing asbestos-cement plates to tube settler modules of Acrylonitrile Butadiene Styrene (ABS).

A self-cleaning and declining rate filtration system was built, made up of four filters. This allows at least three units to be operational, while the fourth unit is cleaned. The filter bed implemented is sand with an effective size TE= 0.55 mm, a uniformity coefficient CU= 1.60 and a porosity of 0.42. For the design and construction of the filters system, the following phases were completed: a) the filtration area and the number of filters in the filter system that guarantees the washing flow were determined, b) definition of the characteristics of the filter medium, c) the filtration rate was chosen considering the characteristics of the influent, medium filter, method of operation and hydraulic load, d) calculation of head losses during the washing of a filter and location of the outlet weir e) calculation of the hydraulic head required by the filter system to operate at a decreasing rate. Each filter was built 1.2 m wide, 1.6 m long and 4.2 m deep with a filtration rate of 250 m^3/m^2d.

2.3. Sampling and analysis of water

The studies were conducted for six months before modernization (March-August) and for six months after modernization (February-July). The modernization works were carried out from September to December. Raw water and treated water samples were collected from the SF system and the conventional plant after the changes made. That is, before and after modernization. The parameters analyzed were turbidity (Tur), color (Col), pH, total dissolved solids (TDS), nitrates (NO_3), sulfates (SO_4), phosphates (PO_4), chlorides (Cl^-), alkalinity (Alk), hardness total (TH) and iron (Fe). The samples were collected in a volume of 1000 ml in sterile polypropylene bottles, with a fortnightly frequency, which resulted in a collection of 13 samples for each sampling site and for each monitoring time, giving a total of 52 samples. The laboratory analysis allowed determination of the changes in the water quality during the six months before and during the six after the modernization.

The tests in all water samples were analyzed according to the Standard Methods for the examination of water and wastewater. Turbidity was measured using a HACH 2100P turbidimeter. Color was measured using a HACH DR.... 890 colorimeter. The TH and Alk were measured by the titration method; the pH, TDS were measured with the Hach Multiparameter HQ 40d The parameters NO_3, SO4, Cl^-, PO4 and Fe were determined with the HACH DR.... 2500 spectrophotometer; and compared with national standards.

2.4. Robustness index based on turbidity

Huck and Coffey (2004) in their study evaluated a simple easily implementable filtration robustness concept for use based on an index that explains the mean and variance. They called this index the turbidity robustness index (TRI) (Eq. (1)). This same turbidity robustness index (TRI) for both coagulation / flocculation / sedimentation and filtration was used by Li and Huck (2008) and Zhang et al. (2012).

$$TRI_{95} = \frac{1}{2}\left(\frac{T_{95}}{T_{50}} + \frac{T_{50}}{T_{goal}}\right) \tag{1}$$

Where TRI_{95} is the turbidity index using the 95th percentile, T_{50} and T_{95} are 50th and 95th percentiles (NTU), respectively, Tgoal (NTU) is the filter turbidity goal. The first term T_{95}/T_{50} represents uniformity, the second term T_{50}/T_{goal} represents the overall performance of the filter against the target; the closer the value is to 1, the more robust the system will be (Li and Huck, 2008; Hartshorn et al., 2015).

2.5. Statistical analysis

To verify whether there are statistically significant differences in the physical and chemical parameters of water quality between the periods before and after modernization, the ANOVA analysis of variance was used. Data normality was determined by the Shapiro-Wilk Test. The p values ≤ 0.05 were considered significant.

3. Results and discussion

3.1. Implementation of the conventional treatment system

The modernization made it possible to implement rapid mixing in the water inlet channel to the treatment plant. Flocculators and decanters were installed in the existing gravel pre-filters, while the new RF filter system was built on a new site. The slow filters were not removed but remained out of commission and separate to the new system (Fig. 1).

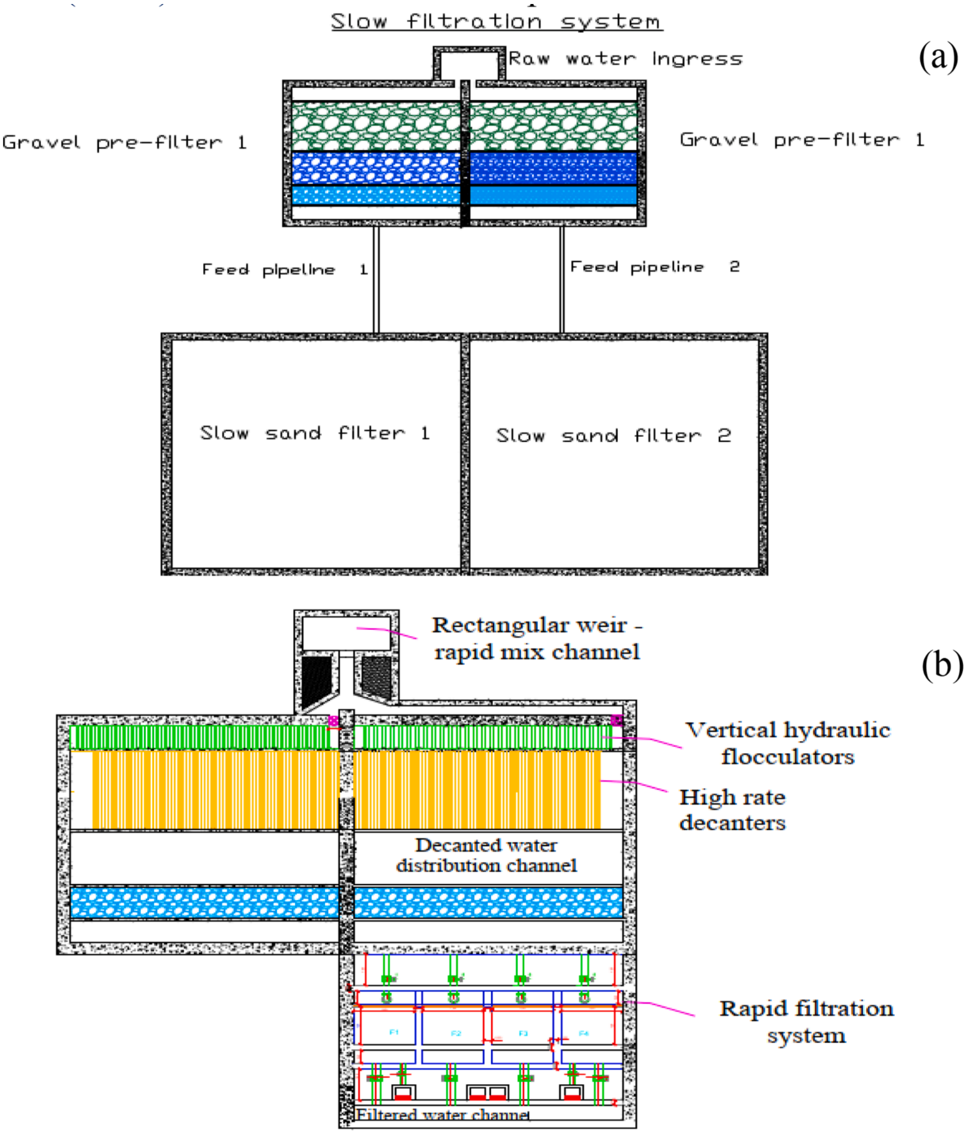

Fig 1. (a) Treatment plant before modernization. (b) Treatment plant after modernization.

3.2. Physicochemical characteristics of raw water and treated water

Table 1 shows the average concentrations of the physical and chemical parameters of raw and treated water analyzed before modernization. In other words, all these data were obtained from the SF system. Turbity and color in the treated water were lower compared to raw water, with a significant removal of these parameters. The parameters pH, TDS, TH, Alk did not show a notable variation between raw and treated water. Sulfates, nitrates and phosphates increased in the plant effluent, which agrees with Ellis and Wood (2009); Ranjan and Prem(2018) who indicate that these parameters increase with slow filtration.

The results presented in Table 1 indicate that the new treatment system has a high efficiency to remove turbidity (98.76%), color (99.82%), chlorides (59.12%), nitrates (64.89%), phosphates (69.23%), iron (94.03%). Allowing the treatment system to be sustained over time, due to the potential capacity to face future deterioration in raw water quality. Confirming that there is greater removal of turbidity and color, as well as other parameters after the raw water is subjected to coagulation, flocculation, sedimentation and filtration.

Table 2 shows the average concentrations of the physical and chemical parameters of raw and treated water analyzed after modernization. In other words, all these data were obtained from the conventional treatment system that includes rapid filtration. The turbidity, color and Fe in the treated water were much lower compared to raw water, with very significant removal of these parameters. The parameters pH, TDS, TH, Alk did not show a notable variation between raw and treated water. Chlorides, nitrates, phosphates were also removed in a considerable quantity. In contrast, sulfates increased, this is due to the fact that, in the conventional treatment process, aluminum sulfate was used as a coagulant, which is why sulfates increased in the plant effluent.

3.3. Compliance of treated water with regulations

Table 3 analyzes the compliance of treated water with Ecuadorian regulations before modernization, as well as after modernization. As can be seen before the modernization, the treated water did not comply with the limits established by local regulations in three parameters: turbidity, color and phosphates. After modernization, however, all the parameters complied with the regulations.

3.4. Variation of the physical and chemical parameters of the treated water: before modernization and after modernization

To analyze whether the effluent characteristics improved after modernization, Fig. 2 is presented. In this figure turbidity, color, nitrates, phosphates and iron were significantly reduced after modernization.. In the case of the other physicochemical parameters, no significant changes were found (Fig. 2). Only sulfates increased in the effluent after modernization, which is due, as previously stated, to the use of aluminum sulfate as a coagulant, the treatment leaves a residual sulfate; however, as observed in Table 3, the sulfate level is well below the maximum limit established in the regulations. As a result of the modernization implemented in the drinking water treatment plant, the quality of the effluent showed a significant improvement after the changes made to the infrastructure.

The slow sand filtration system (before modernization) proved to be efficient in removing many physico-chemical impurities contained in raw water. However, there were impurities that were removed more effectively with the conventional treatment system (after modernization). According to Table 2 and Fig. 2, the average turbidity of the treated water before modernization was 5.45 NTU and after modernization it was 0.45 NTU. The average color of the treated water before modernization was 44.92 CU Pt-Co and after modernization it was 0.62 CU Pt-Co. This shows that the treated water quality improved notably with the changes implemented in the treatment plant. In the SF there was a reduction in turbidity by 88.69%, while in the conventional plant the removal of turbidity was 98.75%, which corroborates what was reported by Al-Rawi (2017); Laghari et al. (2018). The color was reduced by 90.33% in the SF, coinciding with what was mentioned by certain authors, who indicate that the color is not as removed as efficiently in slow filters (Logsdon et al., 2002b; Gottinger et al., 2011). In contrast, the removal of color in the conventional system was 99.82%.

The average pH of the treated water before modernization was 7.34 and after modernization it was 7.32. The average TDS of treated water before modernization was 69.13 mg/L and after modernization it was 68.63 mg/L; therefore, there was no significant change in these parameters as expected, since these treatment systems do not eliminate dissolved solids.

The average TH of treated water before modernization was 55.69 mg/L $CaCO_3$ and after modernization it was 45.69 mg/L $CaCO_3$, the use of coagulants was an aid for this softening process (Ordóñez et al., 2012). The average alkalinity of the treated water before modernization was 56.31 mg/L $CaCO_3$ and after modernization it was 37.77 mg/L $CaCO_3$. The conventional treatment system presented a lower level of alkalinity, this due to the fact that in coagulation alkalinity is consumed by reacting the coagulant with alkalinity (García-Ávila et al., 2018).

The average nitrate values of the treated water before modernization was 4.18 mg/L and after modernization it was 0.79 mg/L. The average values of phosphates in the treated water before modernization was 0.42 mg/L and after modernization it was 0.08 mg/L. The conventional treatment system presented a better elimination of these pollutants. Which confirms that there are chemical impurities that are not removed effectively with SF, such as sulfates, nitrates, phosphates (Ellis and Wood 2009; Gottinger et al., 2011; Ranjan and Prem, 2018). The average sulfate before modernization was 3.02 mg/L and after the changes it was 17.85 mg/L. It increased due to aluminum sulfate, which leaves a residual sulfate in the water; but this value was very below the permissible limit in drinking water (Gabelich et al., 2002). The average value of iron in the treated water before modernization was 0.1 mg/L and after the changes it was 0.04 mg/L; it was removed by a considerable in slow filtration as determined by Gottinger et al. (2011) and Guchi (2015), but

Table 1
Characteristics of the physical and chemical parameters of the quality of raw and treated water before modernization.

Parameter	Unit	Raw water				Treated water			
		Mean	Min	Max	CV	Mean	Min	Max	CV
Turbidity	NTU	48.21	9.88	125.3	70.77	5.45	1.8	10.5	50.55
Color	UC	465	99	1160	67.84	44.92	9	94	64.03
pH	7.58	7.18	7.85	3.19	7.34	7.12	7.65		
TDS	mg/L	65.85	58.8	75.6	7.83	69.13	56.4	84.1	9.5
Total hardness	mg/L as $CaCO_3$	53.38	42	65	13.5	55.69	48	71	11.03
Alkalinity	mg/L as $CaCO_3$	52.15	46	62	9.29	56.31	52	69	8.62
Sulfates	mg/L	2.06	1.2	3.1	23.97	3.02	1.9	3.8	15.29
Chlorides	mg/L	15.11	10.2	17.2	13.46	8.24	5.24	9.85	16.06
Nitrates	mg/L	2.81	1.4	5.1	43.92	4.18	2.2	6.3	35.57
Phosphates	mg/L	0.32	0.16	0.56	36.7	0.42	0.26	0.57	25.03
Iron	mg/L	0.8	0.51	1.24	30.09	0.1	0.06	0.18	34.38

Table 2
Characteristics of the physical and chemical parameters of the quality of raw and treated water after modernization.

Parameter	Unit	Raw water				Treated water			
		Mean	Min	Max	CV	Mean	Min	Max	CV
Turbidity	NTU	36.29	9.78	112.3	80.97	0.45	0.28	0.71	26.05
Color	UC	347.4	101	1004	76.2	0.62	0	2	124.79
pH		7.58	7.57	7.21	7.98	2.8	7.32	6.98	7.71
TDS	mg/L	74.22	64.5	88.6	9.61	68.63	59.2	82	10.71
T. Hardness	mg/L as $CaCO_3$	49.92	41	61	13.32	45.69	34	56	13.82
Alkalinity	mg/L as $CaCO_3$	50.31	42	59	9.27	37.77	24	49	20.91
Sulfates	mg/L	1.99	1.1	3.8	36.45	17.85	8	33	46.26
Chlorides	mg/L	15.19	12.4	17.6	10.43	6.21	2.6	8.3	29.15
Nitrates	mg/L	2.25	0.98	4.4	38.55	0.79	0.48	1.6	38.82
Phosphates	mg/L	0.26	0.11	0.44	37.17	0.08	0.04	0.14	34.74
Iron	mg/L	0.8	0.51	1.24	43.69	0.04	0.01	0.08	58.91

Table 3
Characteristics of the physical and chemical parameters of the quality of raw and treated water before modernization.

Paremeter	Unit	Maximum limit allowed according to regulations	Average value before modernization	Compliance with Regulations (yes/ No)	Average value after modernization	Compliance with Regulations (yes/ No)
Turbidity	NTU	5	5.45	N	0.45	Y
Color	UC	15	44.92	N	0.62	Y
pH		6.5–8.5	7.34	Y	7.32	Y
TDS	mg/L	1000	69.13	Y	68.63	Y
Total hardness	mg/L $CaCO_3$	300	55.69	Y	45.69	Y
Alkalinity	mg/L $CaCO_3$	250	56.31	Y	37.77	Y
Sulfate	mg/L	200	3.02	Y	17.85	Y
Chloride	mg/L	250	8.24	Y	6.21	Y
Nitrate	mg/L	50	4.18	Y	0.79	Y
Phosphate	mg/L	0.1	0.42	N	0.08	Y
Iron	mg/L	0.3	0.1	Y	0.04	Y

the highest removal was presented by the conventional system.

After determining the normality of the data, it was found that all the data sets presented normality (with 95% confidence). There were significant differences in the monitoring carried out before and after the modernization ($p < 0.05$). Table 4 presents the importance of the differences in the examined physicochemical parameters of the treated water before and after modernization.

Only the pH and TDS did not present a significant difference, the other nine physicochemical parameters did present a significant difference. Therefore it can be said that if there is a difference in the water quality after the improvements implemented in the treatment plant, therefore the modernization was effective.

3.5. Robustness index based on turbidity

Table 5 shows percentile turbidity and TRI95 values, calculated for periods before and after modernization. It is clear that TRI95 was better after retrofit, as it has substantially better average performance and is closer to the turbidity target (Zhang et al., 2012; Hartshorn et al., 2015). A clear difference is obtained between the two periods analyzed.

The target for turbidity to ensure disinfection effectiveness should not be higher than 1 NTU and preferably much lower. Large and well-managed municipal supplies must be able to reach less than 0.5 NTU (WHO, 2011), that is, T_{goal}= 0.5 NTU in Eq. (1). The calculated values TRI95 are presented in Table 5.

3.6. Microbiological comparison between rapid filtration and slow filtration

The microbiological comparison was made with the raw water samples and with the water at the outlet of the rapid and slow filters. The results are presented in Table 6, a notable decrease can be observed, both in total coliforms and fecal coliforms in the rapid filter and also in the slow filter. There was a removal of fecal coliforms of 98.91% in the rapid filtration system (conventional treatment) and 99.09% in the slow filtration system. The results indicate that total coliforms and fecal coliforms were removed in a high proportion after the raw water was subjected to coagulation, flocculation, sedimentation and filtration. After disinfection with calcium hypochlorite solution, these microbiological parameters were not present.

A conventional treatment plant was implemented, consisting of a rectangular weir, vertical flow hydraulic flocculator, high-rate decanter and a filters system. This system replaced a system composed of gravel pre-filters and slow filters. This alternative was selected because the conditions of a conventional treatment allow treatment of waters with high levels of turbidity and color, the new system implemented significantly improved the characteristics of drinking water.

The companies in charge of supplying drinking water must establish the objective of supplying drinking water with <1 NTU, must continually strive to improve the performance of the purification processes. At turbidity> 1 NTU, higher doses of disinfectant or longer contact times will be required to ensure efficient disinfection. This implies improvements in the operations, design, administration, and maintenance of a water system. That is, modernizing the infrastructure that allows operating personnel to handle future challenges, such as unforeseen changes in the raw water quality (Makungo et al., 2011).

The integration of the community and other stakeholders in projects to implement new drinking water treatment systems is essential for the results to be appropriate to local circumstances and to be sustainable in the long term (Mac Mahon and Gill, 2018). This experience demonstrated that communities organized into local boards can be innovative and proactive in improving the drinking water quality. However, it must be emphasized that in this type of project it is essential to provide support to the community in the medium and long term, executing training for the personnel who operate this type of plants. Likewise, the monitoring and evaluation of the physical facilities must be carried out.

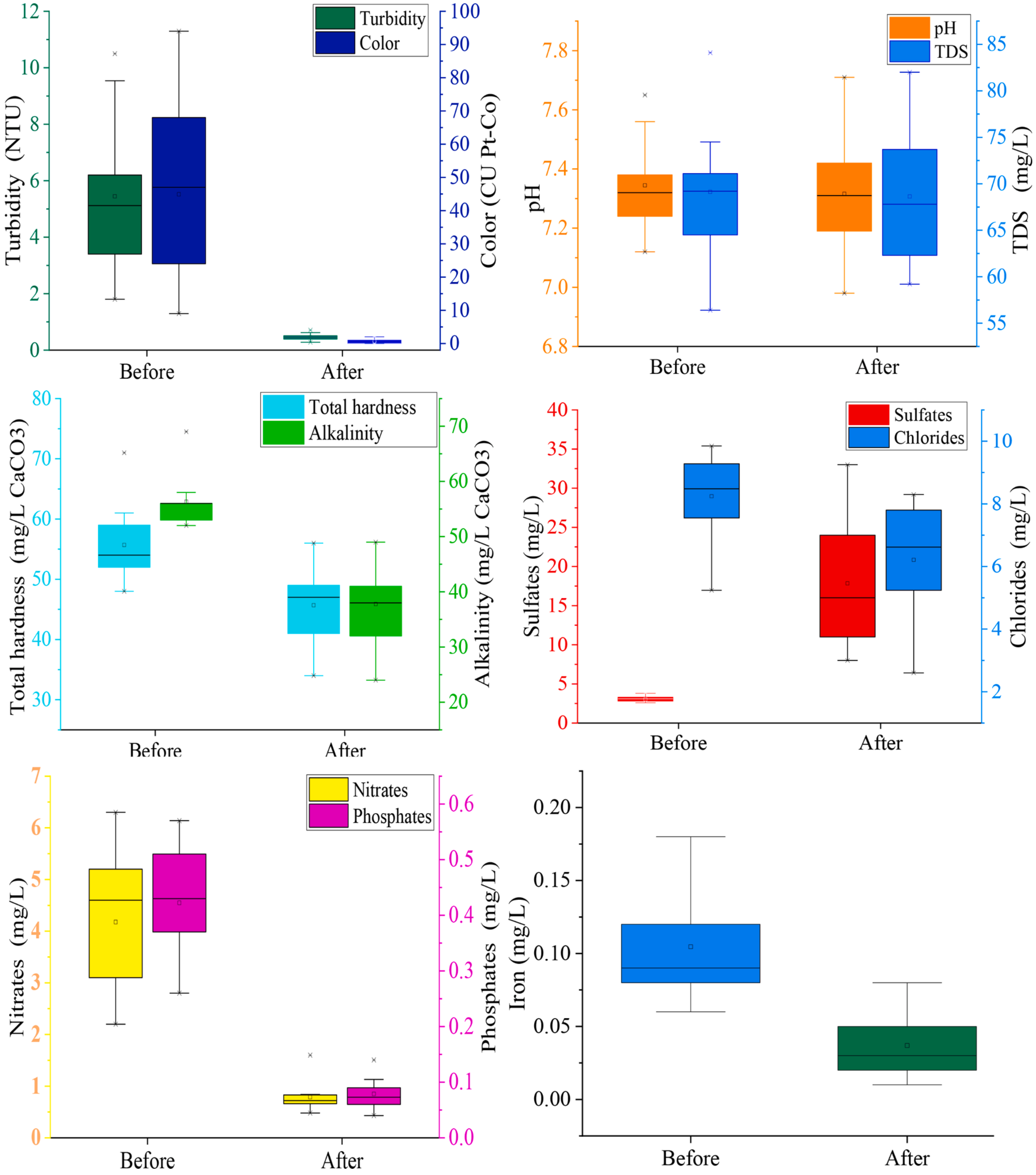

Fig. 2. Variation of the physical and chemical parameters of the treated water: before modernization and after modernization.

This modernization project implemented in a community in Ecuador tries to show how a change in water treatment technology can provide a system to improve the drinking water quality. This could be applied in a rural context but could also apply in a peri-urban context. This modernization allows treating raw water that is being affected by climate change (e.g., increased rainfall and subsequently runoff increment, increased erosion and water quality degradation) and the change in land use due to the expansion of the agricultural frontier that contributes to the increase in surface water with high turbidity and color. Besides, this new system helpful face future quality water troubles due to an increase of surface flow by changes in climate and land use and land cover in watersheds.

It should be noted that challenges arise during the transition of new water treatment technology, mainly due to lack of financial resources to implement. These issues can be resolved by persuading community managers to try a new approach to water treatment, so financial collaboration from users is essential.

The challenge is great for leaders and users of the BPWAB, considering that surface water sources are being affected by the continuous process of deforestation and erosion, and by the effects of climate variability. The consequences of this situation require that the purification system cope with higher loads of suspended solids and bacteriological contamination. This new treatment system is more efficient, allowing it to provide good quality drinking water to its users.

Table 4
Differences in the results of the physicochemical parameters that determine the treated water quality before and after implementing the improvements.

Parameter	Results
Turbidity	Significant Difference (p <0.0001)
Color	Significant Difference (p <0.0001)
pH	No Significant Difference (p = 0.7013)
TDS	No Significant Difference (p = 0.8564)
Total hardness	Significant Difference (p = 0.0004)
Alkalinity	Significant Difference (p <0.0001)
Sulfate	Significant Difference (p <0.0001)
Chlorides	Significant Difference (p = 0.0033)
Nitrates	Significant Difference (p <0.0001)
Phosphates	Significant Difference (p <0.0001)
Iron	Significant Difference (p <0.0001)

Table 5
50th to 95th percentile turbidity and TRI_{95} values for before and after of the treatment plant modernization.

Data period	T_{50}	T_{95}	T_{goal}	TRI_{95}
Before Modernization	5.12	10.5	0.5	6.15
After Modernization	0.45	0.71	0.5	1.24

Table 6
Microbiological content after the rapid and slow filtration.

	Raw water	Rapid filtration	Slow filtration
Total coliforms (MPN/100 ml)	295.8 ± 115.0	2.6 ± 2.5	2.2 ± 2.9
Fecal coliforms (MPN/100 ml)	110 ± 103.9	1.2 ± 1.5	1.0 ± 1.3

Table 7
Challenges to ensure the sustainability of drinking water in the BPWAB.

Components	Challenges overcome	Challenges to overcome
Environmental		Propose a maintenance and conservation plan for surface water sources that supply the treatment plant. To face the problems in the efficient use and saving of water and integral management of the water resource in the face of climatic variability.
Technical	Technological solutions that can be sustained in these contexts, guaranteeing community participation. Designation of operators in the plant treatment.	Maintain an efficient treatment system to face changes in raw water quality in the face of climatic variability. Continuous training for operators.
Financial	Investment for the implementation of a new treatment system.	Secure grants to community organizations to balance total costs with income via fees.
Investment for the operation and maintenance of the treatment system.		
	Investment resources in harmony with the context, facilitating the participatory process of the community.	
Social	Guarantee community participation in all phases of the project.	Flexibility in the payment of rates to users with limited economic resources. Strengthening of the BPWAB in administration, operation and maintenance, regulatory and legal processes.
Institutional	Guarantee technical support for administration, operation and maintenance, through support from universities.	Integrate work with local government institutions with new conceptual frameworks. Guarantee an effective information system for users when the service is suspended due to the maintenance of the treatment units.

The challenges for a sustainable treatment of drinking water in the Bayas community must be faced by the leaders of the BPWAB, addressing the problems with a comprehensive vision and directing their efforts to balance the technological and non-technological components. All this framed in a process of community participation with full responsibility, authority, autonomy and control in the monitoring, evaluation and decision-making in the different phases of the project. The challenges to ensure the sustainability of drinking water in the BPWAB are presented in Table 7.

In Table 8 a comparison has been made between the operation and maintenance requirements, as well as the costs necessary for said operation and maintenance of the old and new treatment system. The costs are higher in the new system (1845.94 USD/month) compared to the old system (768.80 USD/month). To cover these additional costs, the general assembly of users agreed that once the new system was built, the basic rate would increase by 0.5 USD per user. In addition, it was agreed to charge an additional rate for users with consumption greater than 10 m^3/month. With the aforementioned, it has been possible to have an average additional income of 2599 USD per month, thus allowing to cover the costs of operation and maintenance, including a balance of 753.06 USD/month, which is used for other maintenance expenses of the network of distribution.

The BPWAB guarantees the sustainability of drinking water in harmony with the community management capacity, for which, it has not only assumed the administration, operation and maintenance of the systems but also assumed control, authority, responsibility and projection of the provision of the service. The BPWAB has demonstrated the capacity to operate this conventional treatment system, the data is better organized, determining that the community organizations that operate the drinking water treatment plant have higher levels of performance regarding sustainability, possibly because the implementation phase was accompanied by technical-business advice. Additionally, a longer operating time makes it easier to improve management, learned from its experience, allowing it to comply with regulatory and legal frameworks. Since the start-up of the treatment plant, there are operators who cover the three shifts of the day, from 06:00 to 14:00, from 14:00 to 22:00 and from 22:00 to 06:00, which guarantees an efficient operation of the treatment system.

The leadership that manages the drinking water system of this community has demonstrated its management capacity; with their own resources from the Potable Water Board and contributions from the users, they were able to raise the economic funds necessary to carry out the modernization of the plant; as well as to be able to keep the system working efficiently.

Therefore, ensuring the participation of the entire community from the planning to the implementation of this type of projects is crucial to maximize the sustainability and acceptability of the project, in such a way that a community ownership of the new system takes place.

Table 8
Operation and maintenance requirements of the old (slow filtration) and new treatment system (conventional treatment).

System	Slow filtration	Conventional treatment
Operation requirements	Sodium hypochlorite dosing by electrolysis.	Gravity dosing of coagulants and flocculants. Gravity dosing of calcium hypochlorite.
Maintenance requirements	Monthly cleaning of the gravel pre-filters.	Monthly cleaning of the flocculators Weekly cleaning of the settlers.
	*Monthly cleaning of the sand filter bed.	Daily filter washing
Operation and maintenance cost (USD/month)	768.80	1845.94

* The maintenance of the slow filtration was carried out monthly when it no longer operated efficiently, even reaching biweekly maintenance.

4. Conclusions

This document presents evidence that the modernization of a treatment plant improves the quality of drinking water, thus, in this study, when replacing a slow filtration system with a conventional treatment system that includes rapid filtration, the quality of the treated water improved markedly. A conventional treatment allows treating raw water with high levels of turbidity and color, something that cannot be easily removed using slow filters. From the results of the analysis of the physicochemical parameters, it was observed that nine of the eleven parameters analyzed did show a significant difference, therefore it can be said that there is a difference in the quality of the water after the improvements implemented in the treatment plant therefore the modernization was effective. Turbidity and color improved significantly after modernization. Also, nitrates, phosphates and iron were successfully removed. Applying the turbidity robustness index TRI_{95}, it was found that this index was less after the modernization, confirming the effectiveness of the changes implemented in the modernization of the treatment plant. The results highlight the need for a constant evaluation of the performance of the purification processes. This study allows us to conclude that the first step to purify water is to determine the initial quality of the water in the supply source, which will allow us to choose the best design to treat that raw water. Due to the deterioration in the quality of raw water, it is currently necessary to implement new treatment technologies to improve the quality of drinking water. The experience of this modernization study showed the need to know the behavior of surface water, given the increasingly unpredictable changes in the quality of raw water due to changes in climate and land use, that is necessary to have sufficiently robust treatment systems to face future hazards that could harm the population.

Declaration of Competing Interest

None.

Acknowledgments

The authors wish to thank the Dirección de Investigación de la Universidad de Cuenca (DIUC) for funding the research through the project "Transferencia de nuevas tecnologías sostenibles de bajo costo para el tratamiento de agua potable en comunidades en desarrollo".

References

Adesina, O.A., Abdulkareem, F., Yusuff, A.S., Lala, M., Okewale, A., 2019. Response surface methodology approach to optimization of process parameter for coagulation process of surface water using Moringa oleifera seed. S. Afr J. Chem. Eng. 28, 46–51. https://doi.org/10.1016/j.sajce.2019.02.002.

Al-Rawi, S.M., 2017. Introducing sand filter capping for turbidity removal for potable water treatment plants of Mosul /Iraq. Afr. J. Water Conservation Sustainability 5 (1), 167–175.

Arndt, R., Wagner, E., 2004. Rapid and slow sand filtration techniques and their efficacy at filtering triactinomyxons of myxobolus cerebralis from contaminated water. N Am J Aquac 66 (4), 261–270. https://doi.org/10.1577/a04-004.1.

Bar-Zeev, E., Belkin, N., Liberman, B., Berman-Frank, I., Berman, T., 2013. Bioflocculation: chemical free, pre-treatment technology for the desalination industry. Water Res. 47, 3093–3102. https://doi.org/10.1016/j.watres.2013.03.013.

CEPIS, 2004. Centro Panamericano de Ingeniería Sanitaria y Ciencias del Ambiente. Manual II: Diseño de plantas de tecnología adecuada.

Chollom, M.N., Pikwa, K., Rathilal, S., Pillay, V.L., 2017. Fouling mitigation on a woven fibre microfiltration membrane for the treatment of raw water. S. Afr. J. Chem. Eng. 23, 1–9. https://doi.org/10.1016/j.sajce.2016.12.003.

Clark, P.A., Pinedo, C.A., Fadus, M., Capuzzi, S., 2012. Slow-sand water filter: design, implementation, accessibility and sustainability in developing countries. Med. Sci. Monitor 18 (7), 105–117. https://doi.org/10.12659/MSM.883200.

El-Alfy, M.A., Hasballah, A.F., El-Hamid, H.T., El-Zeiny, A.M., 2019. Toxicity assessment of heavy metals and organochlorine pesticides in freshwater and marine environments, Rosetta area, Egypt using multiple approaches. Sustain. Environ. Res. 29, 1–12. https://doi.org/10.1186/s42834-019-0020-9.

Ellis, K.V., Wood, W.E., 2009. Slow sand filtration. Crit. Rev. Environ. Control 15 (4), 315–354.

EPA. 1995. Water treatment. Manuals Filtration. Ireland.

Gabelich, C.J., Yun, T.I., Coffey, B.M., Suffet, I.H.M., 2002. Effects of aluminum sulfate and ferric chloride coagulant residuals on polyamide membrane performance. Desalination 150, 15–30. https://doi.org/10.1016/S0011-9164(02)00926-8.

García-Ávila, F., Ramos-Fernández, L., Zhindón-Arévalo, C., 2018. Estimation of corrosive and scaling trend in drinking water systems in the city of Azogues, Ecuador. Revista Ambiente e Agua 13 (5). https://doi.org/10.4136/ambi-agua.2237.

García-Ávila, F., Avilés-Añazco, A., Ordoñez-Jara, J., Guanuchi-Quezada, C., Flores del Pino, L., Ramos-Fernández, L., 2019. Pressure management for leakage reduction using pressure reducing valves. Case study in an Andean city. Alexandria Eng. J. 58, 1313–1326. https://doi.org/10.1016/j.aej.2019.11.003.

García-Ávila, F., Zhindón-Arévalo, C., Álvarez- Ochoa, R., Donoso-Moscoso, S., Tonon-Ordoñez, M.D., Flores del Pino, L., 2020. Optimization of water use in a rapid filtration system: a case study. Water-Energy Nexus 3, 1–10. https://doi.org/10.1016/j.wen.2020.03.005.

García-Ávila, F., Avilés-Añazco, A., Ordoñez-Jara, J., et al., 2021. Modeling of residual chlorine in a drinking water network in times of pandemic of the SARS-CoV-2 (COVID-19). Sustain Environ. Res 31 (12). https://doi.org/10.1186/s42834-021-00084-w.

Gottinger, A.M., McMartin, D.W., Price, D., Hanson, B., 2011. The effectiveness of slow sand filters to treat Canadian rural prairie water. Canadian J. Civil Eng. 38, 455–463. https://doi.org/10.1139/l11-018.

Guchi, E., 2015. Review on slow sand filtration in removing microbial contamination and particles from drinking water. Am. J. Food Nutr. 3 (2), 47–55. https://doi.org/10.12691/ajfn-3-2-3.

Hartshorn, A.J., Prpich, G., Upton, A., Macadam, J., Jefferson, B., Jarvis, P., 2015. Assessing filter robustness at drinking water treatment plants. Water Environ. J. 29, 16–26. https://doi.org/10.1111/wej.12094.

Hoslett, J., Massara, T.M., Malamis, S., Ahmad, D., van den Boogaert, I., Katsou, E., Ahmad, B., Ghazal, H., Simons, S., Wrobel, L., Jouhara, H., 2018. Surface water filtration using granular media and membranes: a review. Sci. Total Environ. 639, 1268–1282. https://doi.org/10.1016/j.scitotenv.2018.05.247.

Huck, P.M., Coffey, B.M., 2004. The importance of robustness in drinking-water systems. J. Toxicol. Environ. Health - Part A 67 (20–22), 1581–1590. https://doi.org/10.1080/15287390490491891.

Jakubaszek, A., 2019. Water quality assessment after modernization of the technological system in the water treatment plant in Drzenin (Poland). Civil and Environ. Eng. Rep. 29 (4), 257–266. https://doi.org/10.2478/ceer-2019-0059.

Laghari, A.N., Walasai, G.D., Jatoi, A.R., 2018. Performance analysis of water filtration units for reduction of pH, turbidity, solids and electricity conductivity. Eng., Technol. Appl. Sci. Res. 8 (4), 3209–3212.

Lenart-Boroń, A., Bojarczuk, A., Jelonkiewicz, Ł., Żelazny, M., 2019. The effect of a Sewage Treatment Plant modernization on changes in the microbiological and physicochemical quality of water in the receiver. Arch. Environ. Prot. 45 (2), 37–49. https://doi.org/10.24425/aep.2019.127979.

Li, T., Huck, P.M., 2008. Improving the evaluation of filtration robustness. J. Environ. Eng. Sci. 7, 29–37. https://doi.org/10.1139/S07-032.

Liu, L., Fu, Y., Wei, Q., Liu, Q., Wu, L., Wu, J., Huo, W., 2019. Applying bio-slow sand filtration for water treatment. Polish J. Environ. Stud. 28 (4), 2243–2251. https://doi.org/10.15244/pjoes/89544.

Logsdon, G.S., Hess, A.F., Chipps, M.J., Rachwal, A.J., 2002. Filter Maintenance and Operations Guidance Manual. USA.

Logsdon, G.S., Kohne, R., Abel, S., LaBonde, S., 2002b. Slow sand filtration for small water systems. J. Environ. Eng. Sci. 1, 339–348. https://doi.org/10.1139/S02-025.

Mac Mahon, J., Gill, L., 2018. Sustainability of novel water treatment technologies in developing countries : lessons learned from research trials on a pilot continuous fl ow solar water disinfection system in rural Kenya. Dev Eng. 3, 47–59. https://doi.org/10.1016/j.deveng.2018.01.003.

Majdi, H.S., Jaafar, M.S., Abed, A.M., 2019. Using KDF material to improve the performance of multi-layers filters in the reduction of chemical and biological pollutants in surface water treatment. S. Afr. J. Chem. Eng. 28, 39–45. https://doi.org/10.1016/j.sajce.2019.01.003.

Makungo, R., Odiyo, J.O., Tshidzumba, N., 2011. Performance of small water treatment plants: the case study of Mutshedzi Water Treatment Plant. Phys. Chem. Earth 36, 1151–1158. https://doi.org/10.1016/j.pce.2011.07.073.

Ordóñez, R., Moral, A., Hermosilla, D., Blanco, A., 2012. Combining coagulation, softening and flocculation to dispose reverse osmosis retentates. J. Ind. Eng. Chem. 18, 926–933. https://doi.org/10.1016/j.jiec.2011.08.004.

Ranjan, P., Prem, M., 2018. Schmutzdecke- A Filtration Layer of Slow Sand Filter. Int J Curr Microbiol Appl Sci 7 (07), 637–645. https://doi.org/10.20546/ijcmas.2018.707.077.

WHO, 2011. Guidelines for Drinking-water Quality. World Health Organization, Geneva, pp. 303–304.

Zhang, K., Achari, G., Sadiq, R., Langford, C.H., Dore, M., 2012. An integrated performance assessment framework for water treatment plants. Water Res. 46, 1673–1683. https://doi.org/10.1016/j.watres.2011.12.006.