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Comparative Studies on the Performance Evaluation of Slow and Rapid Sand Filters in Potable Water Purification and Production- A Case Study of Chanchaga Water Works

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Abstract

Water is one of the most vital ingredients for life and can easily become deleterious when contaminated with foreign materials. This research paper focused on the comparative studies on the systems performance assessments for the slow sand filtration (SSF) and rapid sand filtration (RSF) in the water treatment and purification plant (WTPP). The raw water was sourced from Tagwai Dam and utilized as the essential material. The performance indicators employed in the evaluation studies are total hardness, turbidity, total alkalinity, presence of chloride ions, pH, electrical conductivity, and bacterial removal. It was found that the performance indicators for the slow and rapid sand filters are as follows: total hardness of 60 mg/L and 58 mg/L, turbidity of 1.5 NTU and 3 NTU, total alkalinity of 62 mg/L and 40 mg/L, presence of chloride ion to be 11 mg/L and 10 mg/L, pH of 7.4 and 7.2, electrical conductivity of 85 and 72, and bacterial removal of 98% and 86%, respectively. The result of the studies is in conformity with the national standards of Nigerian Standard Drinking Water Quality (NSDWQ) and World Health Organization (WHO), which discloses the slow sand filters are more efficient in getting rid of bacteria and turbidity than the rapid sand filters. However, the rapid sand filter appears to be more efficient in the removal of total hardness, alkalinity, presence of chloride ions, pH adjustment towards neutrality, and electrical conductivity.

Keywords: Turbidity, pH level, bacterial removal, total hardness, total alkalinity, presence of chloride ions, electrical conductivity.

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1. Introduction

Slow sand filtration (SSF) is referred as the biological filtration (BF) process due to the dominant effect of microbial activity within the sand bed resulting in very high removal efficiency of total coliform bacteria and other microorganisms [1,2]. It is one of the oldest valuable technologies deployed in filtration units of the water treatment plants (WTPs) due to its simple design, ease of operation, maintenance, inexpensiveness, capability, reliability, and efficiency of the process in getting rid of the unwanted materials and contaminants ranging from suspended solids, heavy metals, protozoa, parasites, bacteria, cysts, to viruses, etc, in most of the developing nations. According to Younus and Grady [3], the evidence for the usage of the man-made filtration system in Senegal, West Africa, where pits were dug into the sand and allowed to filter the river water, collect, and store the filtered water, was reported in 1776. An account for the first developed and commissioned SSF and supply of treated water not through the pipeline distribution systems but the use of horses and carts to an entire municipality households took place in 1804, at Paisley, Scotland as stated by Baker [4]. The system unit consists of a tank made from reinforced concrete, ferrocement, bricks or stones, plastics, a metal basin for keeping the supernatant layer of the raw water, a bed of fine sands, a system of underdrains, an inlet and outlet streams, and systems of level and flow control devices comprising of sensors and control valves [1,5-6]. The gravel layer base material varies from 3 to 65 mm gravel size with a depth from 30 to 75 cm, particle size of the bed of fine sands ranges from 0.15 to 0.3 mm effective size with coefficient of uniformity from 2 to 3, and a bed depth of 105 cm. The outer surface of the sand bed forms a vital layer called schmutzdecke when the filter is ripened. This layer is referred as zoological or biological layer, which is considered as the heart of SSF capable of adsorbing the organic matter, coliforms, Escherichia coli, Cryptosporidium sp., Giardia sp., cysts, among other microorganisms, oxidizing the ammonical nitrogen to nitrates, and thereby making the filtered water free from microorganisms [1-2,7].

On the other hand, rapid sand filter (RSF) which is also known as the mechanical filtration (MF) process in the sense that auxiliary equipment such as pumps and air compressors are required to execute some specific operations of the system. RSF was developed almost 9 decades after the commissioning of SSF [4,8]. The increased demand of more potable water for drinking purposes necessitates the process development of RSF with higher filtration rates to address some of the demerits and bottlenecks of the SSF. It is somehow like the SSF where bed of sands is used as the filter media. However, in contrast to SSF, the gravels in RSF are placed in from 4 to 5 layers, each from 10 to 15 cm in depth with base material ranges from 3 to 45 mm gravel size with a depth from 60 to 90 cm, particle size of the bed of sands varies from 0.35 to 0.55 mm effective size with coefficient of uniformity from 1.2 to 1.8, and a bed depth of 75 cm. There have been several reported research for the process improvements, intensifications, and performance evaluations of SSFs [9-18] and RSFs [19-22,33] since after their invention and commissioning in the water treatment and purification plants (WTPPs) [19-20,23-32,]. In a nutshell, the SSF and RSF essentially differs in the following features: the filtration rates, the characteristics of the particulate material(s) in the water used for filtration, the grain sizes of the sand for the bed, the techniques employed for cleaning the filter, and the sand stratification [33]. SSF was used to be seen and assumed as an old-fashioned technique of WTPP in comparison with RSF and other high-rate filtration technologies. Nevertheless, this conception would be checked and viewed fairly in this paper by comparing the SSF and RSF through comprehensive performance assessments.

2. Materials and methods

The materials and techniques that were used in the studies are explained under this section and subsections. The step procedures are divided into two (2) categories. The first part compared the design features of slow and rapid sand filters as well as the different outcomes of their process operations. The method for assessing the quality and safety of drinking water through the following performance indicators: turbidity, total hardness, total alkalinity, presence of chloride ions, pH, electrical conductivity, and bacterial removal are presented in the second part of the studies.

2.1. Comparison of slow and rapid sand filters

Sand filtration systems have been in operation for centuries. Basically, there are two main types of sand filters. These are the slow and rapid sand filters that are successfully found in operations. They are somehow similar in function for the treatment and purification of raw water but distinctly differed in their throughputs, designs, operations, performances, and the quality of the treated water as well as their maintenance for longevity and subsequent length of filter run cycle time. The summary of the comparisons for the main features of the two (2) different filters would be presented and discussed under the succeeding sections.

2.2. Performance indicators of the water quality parameters

For a functional and successful performance operation of water treatment and purification plant (WTPP), a standard operating procedure is needed for achieving optimal performance in the quality control assurance of the raw water, potable water production, reduction in the cost of consumables such as chemicals, and minimization of wastes. This is in line with the bigger picture of any responsible management operational visions of a WTPP to keep producing excellent qualitative potable water at the full capacity of the plant regardless of the changes in quality of the raw water sources. Consequently, standard methods are required in estimating the quantity of the quality performance indicators of the treated water. These techniques are presented in the following subsections.

2.2.1 Water sampling

The samples of treated water for the analysis of quality performance indicators of the treated water were collected from the units of the slow and rapid sand filters of Chanchaga water treatment and purification plants (CWTPP) for four (4) consecutive days. The primary source of the raw water used in CWTPP is from one of the greatest valleys, the Tagwai dam, and not the Shiroro or Kainji dams. The other two (2) dams are principally used for hydroelectric power generations. Figures 1 and 2 are the maps of our studies areas, the CWTPP and Tagwai dam, respectively.

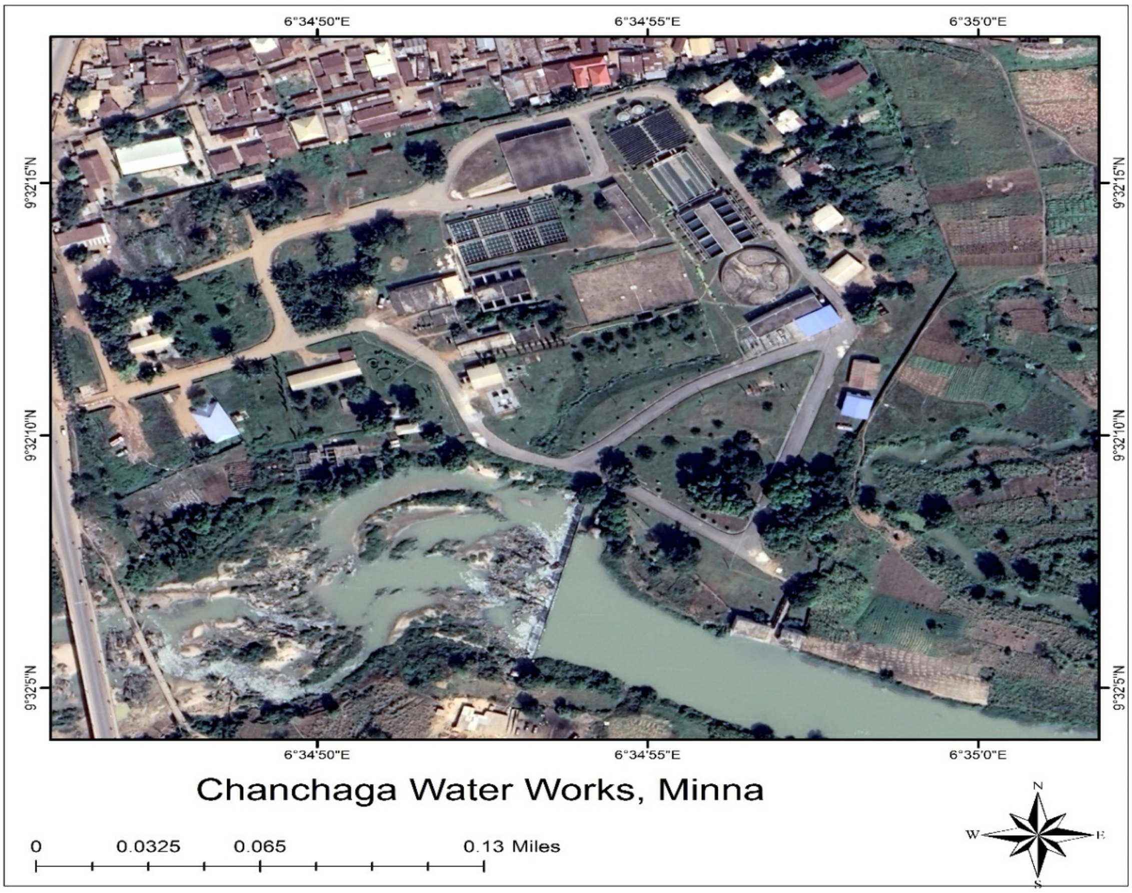

Figure 1. Map of Chanchaga Water Treatment and Purification Plant, Minna, Nigeria

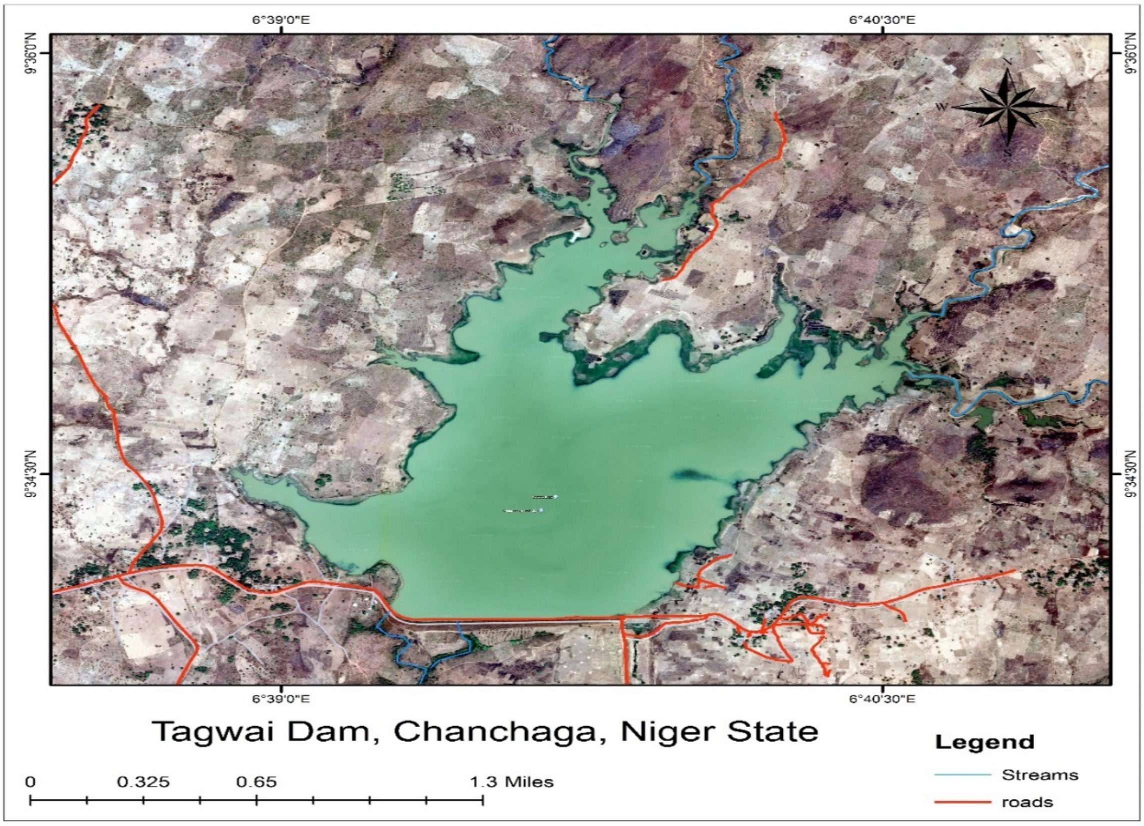

Figure 2. Map of Tagwai Dam, Niger State, Nigeria

2.2.2 Chemicals and Reagents

All the chemicals, reagents, and other consumables used in the analysis of water quality performance indicators of the treated water are of analytical grades.

Turbidity measurement

The samples of the treated water were put into the test tubes, and the turbidity was determined using turbidity meter according to the standard method such as comprehensive performance evaluation (CPE) and analytical hierarchy process (AHP) techniques.

pH level measurement

The measurement of pH level for the samples of treated water were conducted, and the results were observed and recorded according to the standard method such as comprehensive performance evaluation (CPE) and analytical hierarchy process (AHP) techniques.

Bacterial removal

The analysis of the bacterial removal for the samples of treated water were conducted, and the results were observed and recorded according to the standard method such as comprehensive performance evaluation (CPE) and analytical hierarchy process (AHP) techniques.

Determination of total hardness

The analysis for total hardness of the samples of treated water were carried out, the results were observed and recorded according to the standard method such as comprehensive performance evaluation (CPE) and analytical hierarchy process (AHP) techniques.

Determination of total alkalinity

The determination for total alkalinity of the samples of treated water were carried out, the results were observed and recorded according to the standard method such as comprehensive performance evaluation (CPE) and analytical hierarchy process (AHP) techniques.

Determination of chloride ions

The analysis for the estimation for chloride ions of the samples of treated water were conducted, the results were observed and recorded according to the standard method such as comprehensive performance evaluation (CPE) and analytical hierarchy process (AHP) techniques.

Electrical conductivity

The measurement of electrical conductivity of the samples of treated water were carried out, and the results were observed and recorded according to the standard method such as comprehensive performance evaluation (CPE) and analytical hierarchy process (AHP) techniques.

3. Results and discussion

3.1 Comparison for the basic features of slow and rapid sand filters

Table 1 compares the fundamental features of the slow and rapid sand filters based on their capacities and throughputs, designs, ease of operations, the quality of the treated water, maintenance for longevity and preparation for the next length of filter run. One of the basic key differences between SSF and RSF is in the capacities and throughputs of the two (2) processes. It can be observed from Table 1 that the applied hydraulic filtration rates for all the SSFs only fall within the range from 100 to 200 L/hr.

m^2, which is much less than that of RSFs, falling with the ranges from 3000 to 6000 L/hr. m^2. However, the SSFs have an excellent feature for getting the rid of bacteria, parasites, and other microorganisms related to the raw water such as *Giardia*, and *Cryptosporidium cysts* than the RSF. This is due to the formation of a vital layer, referred as the zoological layer, and called *schmutzdecke*, that has the capability of adsorbing any kind of microorganisms. For instance, the removal efficiency of the bacteria is from 98 to 100 % and 80 to 90% for slow and rapid sand filters, respectively.

3.2 Analysis of water quality performance indicators

A total of seven (7) water quality parameters, namely turbidity, pH, bacterial removal, total hardness, total alkalinity, presence of chloride ions, and electrical conductivity of the treated water from the slow and rapid sand filters of Chanchaga water treatment and purification plant (CWTPP) were examined. The results obtained from the comparison studies between the slow and rapid sand filters for are shown from Tables 2 to 5. Table 2 presents the result obtained on the 1st day's experiment. The values of the turbidity and pH levels for the treated water of the slow and rapid sand filters were observed to be 1.9 NTU and 4 NTU, and 6.9 and 7, respectively. The efficiency of getting rid of bacteria were found to be 97.5% and 89% for the slow and rapid sand filters, respectively. The total hardness and alkalinity of slow sand filter for the slow and rapid sand filters were observed to be 46 mg/L and 24 mg/L, and 16mg/L and 14 mg/L, respectively. Likewise, the presence of chloride ions and electrical conductivity for the slow and rapid sand filters were determined to be 23 mg/L and 14 mg/L, and 110 and 80, respectively. Table 3 presents the result obtained on the 2nd day's experiments. The values of the turbidity and pH levels for the treated water of the slow and rapid sand filters were observed to be 1.5 NTU and 3 NTU, and 7.4 and 7.2, respectively. The efficiency of getting rid of bacteria was found to be 98% and 86% for the slow and rapid sand filters, respectively. The total hardness and alkalinity of slow sand filter for the slow and rapid sand filters were observed to be 60 mg/L and 58 mg/L, and 62 mg/L and 40 mg/L, respectively.

Similarly, the presence of chloride ions and electrical conductivity for the slow and rapid sand filters were determined to be 11 mg/L and 10 mg/L, and 85 and 72, respectively. The results obtained on the 3rd day's experiments are shown in Table 4. The turbidity and pH levels of the treated water for the slow and rapid sand filters were observed to be 0 NTU and 2.1 NTU, and 7.2 and 7.6, respectively. The percentage removal of bacteria from the treated water was determined to be 99% and 90% for the slow and rapid sand filters, respectively.

Table 1. Comparison for the fundamental features of slow and rapid sand filters

S/No.	Parameter	Slow sand filter (SSF)	Rapid sand filter (RSF)
1.	Capacity and throughputs:		
	○ Filtration rates	(100 – 200) L/hr. m^2	(3000 – 6000) L/hr. m^2
2.	Design		
	○ Filter media		
	– Effective grain size, D_{10}	D_{10} – (0.15 – 0.30) mm	D_{10} – (0.35 – 0.55) mm
	– Coefficient of uniformity, C_u	C_u – (2 – 3)	C_u – (1.2 – 1.8)
	○ Filter bed size	(100 – 2000) m^2	(10 – 90) m^2
	○ Gravel layer		
	– Gravel size	(3 – 65) mm	(3 – 45) mm
	– Gravel depth	(30 – 75) cm	(60 – 90) cm
	○ Drainage system	Pipes connections are done openly, while the drains are covered with perforated blocks.	Perforated pipes are discharging filtered water laterally into the main header.
3.	Operation		
	○ Mode of operation		
	– Gravity flow through:		
	Continu. pumping of raw water	Continuous	Continuous
	Constant rate filtration	Continuous	Continuous
	Declining rate filtration	Continuous	Continuous
	○ Controllability	Less trendy	More sophisticated
	○ Flexibility	Less flexible	More flexible
	○ Pre-treatments	Not required	Highly essential
4.	Performance		
	○ Removal efficiency		
	– Bacterial removal	(98 – 100) %	(80 – 90) %
	– Parasite removal	(99 – 100) %	(83 – 93) %
	– Turbidity	≤ 1NTU	≤ 1NTU
	– pH level	6.5–8.5	6.5–8.5
5.	Maintenance		
	○ Cleaning	Scrapping	Backwashing
	○ Frequency of cleaning	(1 – 3) months	(24 – 48) hours
	○ Cost	Higher initial costs with low operating and maintenance costs.	Relatively lower initial costs, with high operating and maintenance costs.
	○ Supervision	Skilled personnel are not needed.	Skilled personnel are required.

The total hardness and total alkalinity were estimated to be 58 mg/L and 50 mg/L, and 68 mg/L and 56 mg/L, respectively. The presence of chloride ions and electrical conductivity for the slow and rapid sand filters were determined to be 10 mg/L and 8 mg/L, and 120 and 50, respectively. On the 4th day's experiments, the results for the turbidity and pH levels of the treated water for the slow and rapid sand filters were observed to be 3 NTU and 4.2 NTU, and 7.1 and 7.2, respectively as shown in Table 5.

Table 2. Comparison between water quality performance indicators from the slow and rapid sand filters of Chanchaga water treatment and purification plant for Day 1.

Parameters	Slow sand filters	Rapid sand filters	NSDWQ
Turbidity (NTU)	1.9	4	≤5
pH	6.9	7	6.5-8.5
Bacterial removal (%)	97.5	89	100
Total hardness (mg/L)	46	24	150
Total alkalinity(mg/L)	16	14	NS
Chloride ion (mg/L)	23	14	250
Electrical conductivity	110	80	1000

Table 3. Comparison between water quality performance indicators from the slow and rapid sand filters of Chanchaga water treatment and purification plant for Day 2.

Parameters	Slow sand filters	Rapid sand filters	NSDWQ
Turbidity (NTU)	1.5	3	≤5
pH	7.4	7.2	6.5-8.5
Bacterial removal (%)	98	86	100
Total hardness (mg/L)	60	58	150
Total alkalinity(mg/L)	62	40	NS
Chloride ion (mg/L)	11	10	250
Electrical conductivity	85	72	1000

Table 4. Comparison between water quality performance indicators from the slow and rapid sand filters of Chanchaga water treatment and purification plant for Day 3.

Parameters	Slow sand filters	Rapid sand filters	NSDWQ
Turbidity (NTU)	0	2.1	≤5
pH	7.2	7.6	6.5-8.5
Bacterial removal (%)	99	90	100
Total hardness (mg/L)	58	50	150
Total alkalinity(mg/L)	68	56	NS
Chloride ion (mg/L)	10	8	250
Electrical conductivity	120	50	1000

Likewise, the efficiency of the bacterial removal from the treated water was found to be 96% and 85.7% for the slow and rapid sand filters, respectively. The total hardness and total alkalinity were determined to be 53 mg/L and 45 mg/L, and 48 mg/L and 12 mg/L, respectively, while the presence of chloride ions and electrical conductivity to be 11 mg/L and 11 mg/L, and 70 and 50, respectively for the slow and rapid sand filters as shown in Table 5.

Table 5. Comparison between water quality performance indicators from slow and rapid sand filters of Chanchaga water treatment and purification plant for Day 4.

Parameters	Slow sand filters	Rapid sand filters	NSDWQ
Turbidity (NTU)	3	4.2	≤5
pH	7.1	7.2	6.5-8.5
Bacterial removal (%)	96	85.7	100
Total hardness (mg/L)	53	45	150
Total alkalinity(mg/L)	48	12	NS
Chloride ion (mg/L)	11	11	250
Electrical conductivity	70	50	1000

It was observed from the water quality performance indicators analysis that none the results of the treated water samples had any objectionable appearance of odour, colour, or taste. All the values of the results are found within the limits, and in agreements with the standards of NSDWQ for turbidity of ≤5 and pH levels between 6.5 and 8.5 assigned by EPA (2002). The presence of high content of chloride ions can facilitate the corrosion rates of the process vessels, metallic pipes, harming the growing plants and animals (WHO, 2003). The recommended limit of chloride ions set by EPA should not be more than 250 mg/L.

4. Conclusion

Based on the research findings from the investigations, it can be concluded that the comparative studies on the performance assessment of slow and rapid sand filters (SSF and RSF) have been successfully conducted. It was observed that none of the quality performance indicators for the treated water exceeded the standard limits of the Nigerian Standard Drinking Water Quality (NSDWQ) and that of the World Health Organization (WHO). The result of the studies discloses the slow sand filter as the more efficient and effective filter than the rapid sand filters in getting rid of the bacteria and turbidity removal, which is in conformity with the fundamental features of SSF when compared to RSF. However, the SSF appeared to have lesser efficiencies than the RSF in the removal of total hardness, total alkalinity, the presence of chloride ions and electrical conductivity.

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Conflict of Interest

The authors declare that there is no known conflict of interest in this research paper.

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