Water Practice & Technology

 Water Practice & Technology Vol 18 No 12, 2989 doi: 10.2166/wpt.2023.193

Assessment of risks to the quality of water supplied in Bushenyi-Uganda using the water safety plan approach

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ABSTRACT

This study assessed the effects of environmental and operational hazardous events on the Bushenyi water supply system over the period 2017–2020. Monthly secondary water quality data for the period July 2013–December 2017 were analyzed together with data from field samples collected monthly from January 2018 to November 2020. The parameters analyzed were pH, turbidity, total iron, free chlorine and faecal coliforms. Hazardous events and risks affecting the water supply at the source, treatment and distribution system were identified and assessed during the field visits. Control measures were determined during water safety plan development effective July 2017 and implemented effective August 2018. Quality of water in the distribution system met the national standards for turbidity (93%), total iron (99%), residual free chlorine (90%) and faecal coliforms (96%). pH in the storage and distribution system was below the national standard (annual mean range, 5.5–6.7). Water quality was negatively influenced by extreme seasonal weather variations at the source, source protection gaps, treatment deficiencies related to clarifier, filter and chemical dose management as well as distribution management and maintenance gaps. Improved source protection, treatment and distribution network management and maintenance are recommended for sustainable system and water quality standards.

Key words: control measures, hazardous events, water quality parameters, water safety plans, water supply risks, water treatment

HIGHLIGHTS

- Water supplied to Bushenyi is abstracted from a wetland.
- The water supply system is faced with risks that affect the source, treatment, and distribution.
- The study assessed the risks and applied control measures using the water safety plan approach.
- Water quality analysis showed that control measures resulted in meeting standards.
- The study recommends investment in risk control measures for safe water supply.

1. INTRODUCTION

Sustainable Development Goal (SDG) Target 6.1 aims at achieving universal and equitable access to safe and affordable drinking water for all by 2030 (United Nations 2015). To achieve this target, drinking water supply systems for both rural and urban populations should be properly sited, operated, and maintained at all times. Recent studies showed that this is not always the case (Kigsirisin *et al.* 2016; Kanyesigye *et al.* 2019; String *et al.* 2020). In 2012, the Joint Monitoring Programme (JMP) estimated that at least 1.8 billion people globally used a source of drinking water that was contaminated with faecal matter (WHO/UNICEF 2021). According to the JMP report of 2021, about 26% of the global population was still lacking access to safely managed drinking water services, and only 30% in sub-Saharan Africa had access to safely managed drinking water services (WHO/UNICEF 2021). The aforementioned suggests that a great proportion of the population was still exposed to the risks of contaminated drinking water sources. Consequently, JMP recommended that monitoring of water safety should include both water quality testing and risk management which is in line with the WHO recommendation for the adoption and use of water safety plans (WSPs) (WHO/UNICEF 2021). WSPs are the most effective means of consistently ensuring the safety of drinking water supply through the use of a comprehensive risk assessment and management approach that encompasses all steps in water supply from catchment to consumer (World Health Organization 2017).

Systematic preventive management of water sources, water treatment and distribution systems is the key to sustained safe drinking water supply instead of relying solely on end-product testing (Serio *et al.* 2021). Preparedness planning against the major natural hazards for which water supply systems worldwide are vulnerable is critical to ensure sustained safe water supply. Such natural hazards include floods, avalanches and extreme dry weather. These may impact reservoirs, lakes, pools and water towers which are relied upon as surface raw water sources. Disaster preparedness plans that rely on geographical information systems, reliability analysis tools and database queries have to be put in place by water utility managers and reviewed periodically. For water supply networks, pressure management programmes such as pressure zoning, night operation analysis and pressure regulation aimed at water and energy saving have to be put in place (Tsakiris *et al.* 2011). Preventive management employs appropriate control measures that are designed to reduce, eliminate or prevent the risk of contamination of the water supply (Memon *et al.* 2023). When such preventive management is adopted, monitoring can focus on a few simple parameters that can be determined *in situ* or in the laboratory (Pal *et al.* 2018). The reasons for testing are aimed at rapidly identifying where control is compromised, so as to identify actions to be taken immediately to rectify the system before contaminated water is distributed and consumed (Tsitsifli & Kanakoudis 2020). Application of preventive management as prescribed under WSPs has been carried out in several Ugandan urban centres managed by National Water and Sewerage Corporation (NWSC), the Uganda national urban water utility agency, including the Bushenyi-Ishaka area. The water supply risks in the Bushenyi-Ishaka area include seasonal quality and quantity changes at the raw water source, infrastructure, and Operational and Maintenance (O&M) deficiencies of the treatment and distribution system (Muhangane *et al.* 2017). In response to these identified risks, appropriate control measures have been progressively put in place to improve water production and quality in the distribution system (NWSC 2019).

This study was carried out to assess the effects of environmental and operational hazardous events on the water quality at all the stages of water supply management, i.e. source, treatment, storage and distribution system and the risk control measures taken in Bushenyi-Ishaka Municipality. The specific objectives were to: (i) identify the hazardous events and risks affecting the water treatment and distribution system and the risk control measures taken between July 2017 and November 2020; (ii) establish the water quality status and its historic trends from July 2013 to November 2020 and (iii) determine the relationship between the identified risks, their control measures and water quality status.

2. MATERIALS AND METHODS

2.1. Study area

Bushenyi-Ishaka Municipality is the main urban area of Bushenyi District in South Western Uganda (Figure 1). The municipality is at an average altitude of 1,432 m above sea level, with two distinct annual rainy seasons from April to May and August to December (Marks *et al.* 2020). The municipality has a population of 42,800 (Uganda Bureau of Statistics 2019) and about 79% of the population is supplied with piped water from NWSC (NWSC 2019). Until July 2018, all piped water to the municipality was from the Nyaruzinga wetland (Figure 2), located within the municipality (Safari *et al.* 2012; Muhangane *et al.* 2017). The Nyaruzinga water treatment plant has a design production capacity of 4,000 m^3/day, but currently supplies 1,400 m^3/day due to system limitations. The rest of the municipality's piped water supply is from the Kitagata water treatment plant, which contributes 4,300 m^3/day, which is 80% of the total municipality supply. The Kitagata water treatment plant is located about 25 km southeast of the municipality. The Nyaruzinga plant is a conventional water treatment system consisting of pre-settlement, screening, aeration, pH adjustment using soda ash, clarification using polyaluminium chlorides (PAC) and aluminium sulphate (Alum), rapid sand filtration and disinfection (using chlorine). The treated water is pumped to the Katungu reservoir with a capacity of 360 m^3 for distribution under gravity. By June 2019, Bushenyi-Ishaka Municipality had a water distribution network length of 442 km, supplying 73 public standpipes, 2,585 domestic connections, 161 institutional connections and 907 commercial connections (NWSC 2019).

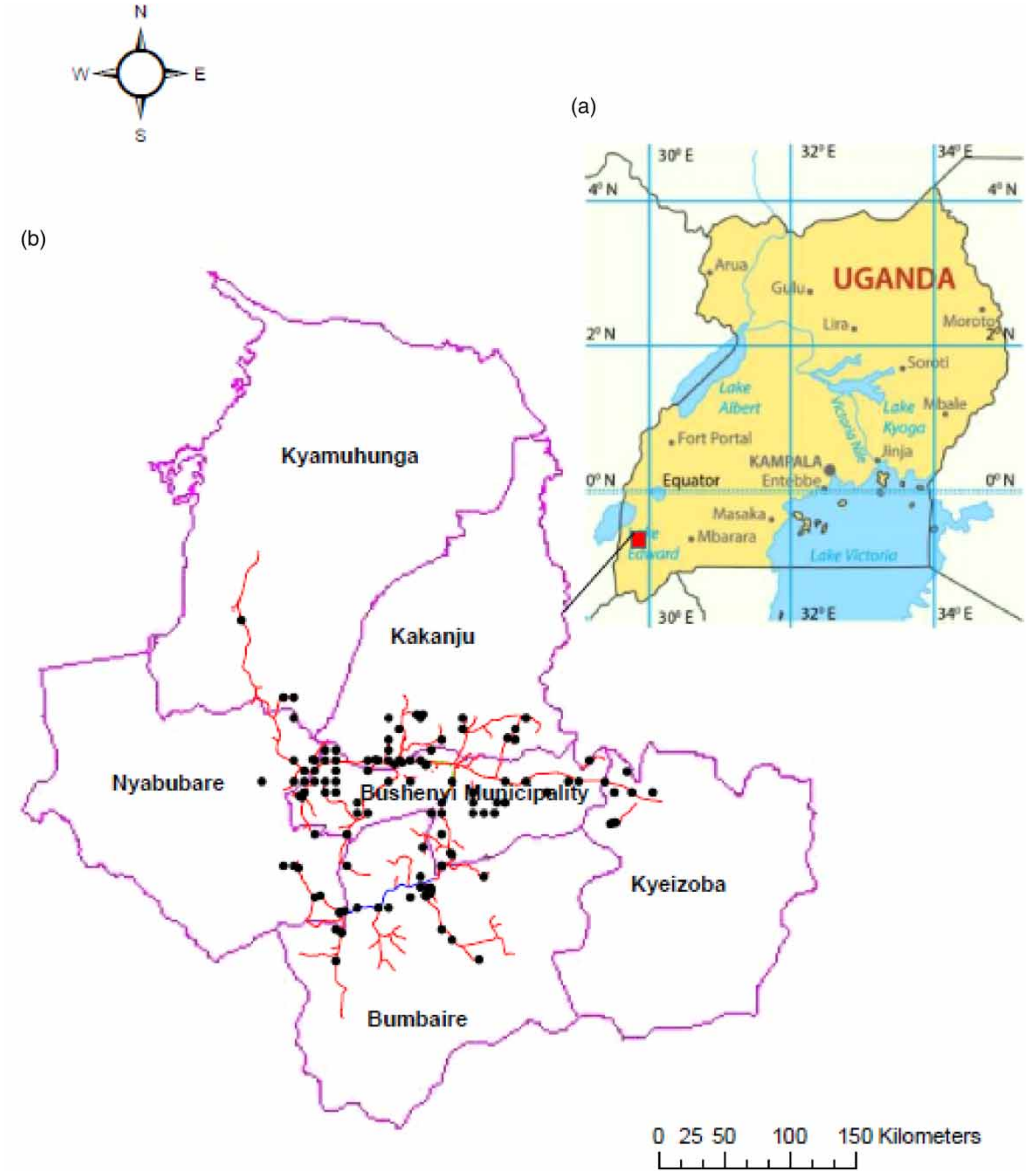

Figure 1 | (a) Map of Uganda and (b) Bushenyi-Ishaka Municipality, with sub-county boundaries shown by red lines and NWSC routine sampling points shown by black dots.

2.2. Data collection

In order to assess the water quality trends throughout the water supply system and the associated risks, secondary data for the period July 2013–December 2017 were obtained. The secondary data were obtained from daily and weekly reports from the NWSC Bushenyi-Ishaka Area laboratory, monthly reports from NWSC Mbarara Regional Laboratory and NWSC Central Laboratory at Bugolobi, Kampala. The secondary data comprised of the following parameters: pH, turbidity (NTU), total iron (mg/L), free residual chlorine (mg/L) and faecal coliforms (CFU/100 mL). Water quality monitoring was carried out by sampling and laboratory analysis on a monthly basis during the period from January 2018 to November 2020. The water quality parameters considered for sampling and analysis in this study were pH, turbidity, total iron, free residual chlorine and faecal coliforms. pH and free residual chlorine were measured *in situ* while the rest were analyzed at the NWSC Mbarara Regional water laboratory. Sampling was done between 8:00 am and 12:00 noon for each of the sampling days, using pre-washed and dried plastic screw-caped 1-l bottles for physicochemical parameters. The ambient temperature in the field during sampling ranged between 21 and 23 °C. For microbiological faecal coliform samples, pre-washed, sterilized half-liter glass bottles were used. After sampling, the samples were packed in clean-dry sample carriers containing frozen ice parks to maintain cool temperatures (below 8 °C) and transported to the laboratory within

Figure 2 | Intake works, Nyaruzinga water treatment plant.

2 h, and analysis commenced immediately. The temperature in the laboratory during analysis ranged between 22 and 23 °C. Regarding hazardous events and risks, data were generated through field assessments of the catchment and source, treatment, distribution network, consumer premises and through review of operational and maintenance reports for the water treatment and distribution processes. The hazardous events, risks and control measures data were generated by the NWSC Bushenyi-Ishaka area WSP team as part of the WSP development from July 2017 to July 2018 and WSP implementation, which was started in August 2018. The control measures and their monitoring schedules were progressively passed on to the management for implementation through training and the provision of revised procedures and work instructions.

2.3. Water quality analysis methods

The water quality analysis was done using standard methods for the examination of water and wastewater (APHA, AWWA and WEF 2012). For pH, analysis was done *in situ* by applying test method ISO 10523:2008 (Water quality-Determination of pH), using a glass electrode (SensION HACH Model, USA). For turbidity, analysis was done in the laboratory using the ISO 7027 method that elaborates on the measurement of diffuse radiation for water of low turbidity. The analysis was done using an electronic turbidity meter (2100Q HACH model, USA). The turbidity meter was pre-calibrated using a formazin standard solution each time a sample was inserted and the displayed reading was taken in NTU units. For total iron, analysis was done in the laboratory using a direct reading spectrophotometer DR6000-HACH model, USA (Spectrophotometric determination of iron in water). The procedure involved measuring the blank of which deionized water was used. This was followed by preparing a calibration curve by measuring iron standards and then the iron sample itself, reporting results in mg/L. For chlorine (free residual), analysis was done *in situ* by applying the colourimetric test method (International StandardISO 7393-2), using the portable SMART3 colourimeter (LaMotte Model, USA). The procedure involved the addition of DPD tablets into a vial of the sampled water, causing a colour change to pink, then inserting the vial into the meter, reading the intensity of the colour change (by emitting a wavelength of light) and automatically determining and displaying the colour intensity (free residual chlorine) digitally in mg/L. For faecal coliform determination, the membrane filtration method using membrane lauryl sulphate broth was used for colony enumeration −8074, incubating for 18–20 h at 44.5 °C. An isotherm forced convection laboratory incubator (ESCO, Malaysia) was used and the results were quantified as colony-forming units in 100 mL (CFU/100 mL).

2.4. Data analysis

Water quality data, both secondary and primary, were analyzed to ascertain the central tendency and temporal trends for the raw, final and distribution system sampling points in Bushenyi-Ishaka Municipality from July 2013 to November 2020. The data were checked for format uniformity and completeness. Preliminary data analysis was done using Microsoft Excel 2016, and further analysis using SPSS Version 23 (IBM SPSS Statistics, USA). Regarding hazardous events and risks, qualitative description of both was recorded and tabulated according to how they applied to the water supply system stages of the source, treatment and distribution chain including a combination of these unit operations and processes: clarification, filtration, disinfection, storage and the distribution network. For each water quality parameter, the mean and standard deviation were calculated. One-way ANOVA tests were run to determine the effect of monthly changes on water quality (refer to supplementary information). Bivariate comparisons of raw and final water pH at the Nyaruzinga treatment plant were done using the student's t-test, while for the comparison of faecal coliform concentrations between 2013–2014 and 2015–2020, the Mann–Whitney U test was used.

3. RESULTS

3.1. Hazardous events, risks and corresponding control measures implemented in the catchment, treatment plant and distribution system

During the WSP development (July 2017–July 2018) and implementation (effective August 2018), hazardous events were identified, corresponding risks assessed, and control measures were determined and implemented in the immediate catchment and source, treatment and distribution system of Bushenyi-Ishaka Municipality. These are presented in Table 1.

3.2. Status of water quality in Bushenyi-Ishaka municipality during the period July 2013–November 2020

3.2.1. Monthly water quality variation

There was a significant monthly effect on the faecal coliforms concentration ($F(11,77) = 2.38$, $p = 0.014$) at the Nyaruzinga raw water source, but no significant monthly effect on the total iron concentration, turbidity and pH values. For the final treated water, there was no significant monthly variation for all the parameters (pH, total iron, turbidity, free residual chlorine and faecal coliforms). Similarly, for the Katungu reservoir, there was no significant monthly variation in terms of the mentioned parameters. Apart from total iron concentration ($F(11,77) = 2.16$), $p = 0.025$) at Bumbeire PSP, there was no significant monthly variation of pH, turbidity, free residual chlorine and faecal coliforms at all the distribution points sampled during the study period.

3.2.2. Annual water quality variation

There was a significant annual variation in turbidity, residual free chlorine and pH, but no significant variation in total iron and faecal coliforms at the final water sampling point. The annual variation at Katungu tank was significant in terms of turbidity, residual free chlorine and total iron but not significant in terms of faecal coliforms and pH. At Kyeitembe P/S, there was a significant annual variation in turbidity, total iron, residual free chlorine and pH, but not in terms of faecal coliforms. At Rwentuha PSP, Bumbeire PSP and Market PSP-Bushenyi, there was a significant annual variation in turbidity, total iron, residual free chlorine and pH, but not in terms of faecal coliforms. At Kizinda PSP, Market PSP-Ishaka and Kashenyi TC, there was a significant annual variation in turbidity, residual free chlorine and pH, but not in terms of total iron and faecal coliforms. At Basajjabalala SS, there was a significant annual variation in turbidity, residual free chlorine and total iron but not in terms of pH and faecal coliforms. The levels of significance are given under each of the parameters in subsections from 3.2.4 to 3.2.8.

3.2.3. Water quality variation between sampling points

There was a significant variation in water quality between all the sampling points in terms of turbidity, total iron, residual free chlorine and pH apart from faecal coliforms. The significant differences are given under each of the following parameters.

3.2.4. pH

The pH of the raw water at Nyaruzinga water treatment plant was generally low, ranging between 4.7 and 6.5, with an average of 5.7 ± 0.4, ($n = 89$). The final water from the treatment plant exhibited lower pH values which were significantly more acidic than for raw water ($t(88) = 3.11$, $p = 0.003$), ranging from 3.6 to 6.9, with an average of 5.6 ± 0.6 ($n = 89$), compared to National Standards for treated drinking water quality range, i.e. 6.5–8.5 (UNBS 2015). The pH of the final water was above the lower limit of the national standard, i.e. 6.5 on only two occasions between July 2013 and November 2020. Consequently, in a majority of the cases, the pH values were below the stipulated National Standard for treated drinking water (UNBS 2015). Hence water in the reservoir (Katungu tank) and the distribution system from 2013 to 2018 exhibited pH <6.5, with an

Table 1 | Hazardous events identified, risks, existing control measures and their improved implementation in the immediate catchment, treatment and distribution system during July 2017–November 2020

Water supply stage	Hazardous event	Existing (or non-existent) control measures	Risk and basis for its rating	New control measures implemented
Catchment and raw water source	Diminishing raw water quantity due to extreme dry seasons	Before July 2017, the Nyaruzinga treatment plant only produced 1,400 m^3/day, inadequate to meet the demand	High: Failure to produce and meet the targeted water distribution demand	Introduction of two alternative sources namely; (1) raw water from the neighbouring PIBID company and (2) treated water from the Kitagata treatment plant in July 2018
	Faecal contamination of the water source due to cattle keeping and grazing close to the source	Before July 2017, cattle grazing still went on despite this being unacceptable in reference to the municipal by-laws	High: Failure to produce water that meets water quality standards	Sensitization meetings held with the farmers and local authorities, agreed that cows are restricted away from the drinking water source effective July 2017
	Contamination of raw water due to wetland encroachment activities close to the source such as farming and brick laying	Wetland encroachment activities close to the source such as farming and brick laying still went on despite this being unacceptable to the municipal by-laws	High: Failure to produce water that meets water quality standards	Brick laying and illegal farming activities stopped, alternative livelihood activities discussed and encouraged with the communities effective July 2017
	Contamination of raw water due to silting of the wetland channels	Cleaning of wetland channels done as and when possible but not following a schedule	Medium: Failure to produce water that meets water quality standards	Cleaning schedule for wetland channel introduced and followed effective July 2017
Intake works	Poor raw water quality in the dam due to development of algal blooms	Slashing and cleaning of the dam banks and bar screens done but not on schedule	Low: Failure to produce water that meets water quality standards	Schedule for clearing and cleaning of the dam banks and bar screens introduced and followed effective July 2017
	Insufficient water production due to frequent pump breakdown	Existing pumps operated and maintained but under performing	High: Failure to produce and meet the targeted water distribution demand	New high capacity pumps purchased and installed in August 2018
	Interrupted water treatment due to inconsistent power supply	Existing power generator operated but broke down frequently	Medium: Failure to produce and meet the targeted water distribution demand	Replacement of faulty standby power generator in October 2018
Clarification	Poor quality of clarified water due to sludge accumulation in the clarifiers	Cleaning of clarifiers done but dirt remains due to non-functional valves	High: Potential increase of suspended solids, microorganisms and chemicals in the treated water	Clarifier channels modified and new valves fixed in November 2018
	Poor quality of clarified water due to insufficient stock of pre-treatment and coagulant chemicals	Chemicals used for treatment but sometimes low doses applied due to insufficient stocks	High: Failure to produce water that meets water quality standards	Budget and stocking of water treatment chemicals improved through introduction of the e-procurement system since March 2017

(*Continued.*)

Table 1 | Continued

Water supply stage	Hazardous event	Existing (or non-existent) control measures	Risk and basis for its rating	New control measures implemented
	Poor aesthetic water quality due to improper mixing of coagulants especially aluminium sulphate (Alum)	Manual mixing of coagulants done	High: Inadequate clarification leading to supply of water with poor aesthetic, chemical and microbial quality	Proper chemical mixers for Alum and Soda ash purchased and installed in September 2018
	Poor quality of clarified water due to improper type of polymer coagulants	Treatment carried out with available coagulant brands	High: Failure to produce water that meets water quality standards	Research into appropriate coagulant polymer types and dose determination carried out and implemented effective August 2018
	Poor water quality due to improper alum and chlorine chemical dozers	Chemical dosing done with old gravity dozers, at times manually operated	High: Overdosing or underdosing of treatment chemicals (alum and chlorine), hence failure to produce water that meets aesthetic, chemical and microbiological standards	New chemical dozers purchased and installed in August 2018
Filtration	Poor treated water quality due to insufficient sand media	Filtration done with insufficient sand levels in the rapid gravity filters	High: Failure to produce water that meets water quality standards	Resanding gradually done for all the four filters effective December 2018
	Turbidity and microorganisms break through due to loss of fine sand media	Filtration done with insufficient top fine sand levels in the rapid gravity filters	Medium: Breakthrough of finer suspended solids and possibly pathogenic microorganisms in filtered water	Fine sand media top-up done for all the four filters in December 2018
	High plant water losses due to short filter runs (due to poor quality of clarified water)	Reduction in raw water pump hours to reduce intake of poor quality raw water	Medium: Failure to produce and meet the targeted water distribution demand and increased production costs	pH correction coupled with seasonal pre-chlorination done to achieve improved quality of clarified water effective March 2017
	Poor microbial quality arising from blockage of some air scour nozzles for backwashing	Backwashing of the filters done without sufficient air scouring	Medium: Failure to produce water that meets water quality standards	Filter bed repairs and nozzle replacement done, proper backwashing done effective November 2018
	Poor quality filtered water due to collapse of filter bed during 2017 and 2018	Filtration done insufficiently since air scour and backwash could not be effectively achieved	High: Increase in suspended solids and probably pathogenic microorganisms in filtered water	Filter bed repairs done in November 2018
	Poor quality due to failure of filter inlet and wash out valves during 2017 and 2018	Uncontrolled inflow of clarified water into the filters leading to uneven flow through the media	High: Potential increase of suspended solids and pathogenic microorganisms in the filtered water	Filter repairs done and all valves replaced in November 2018
Disinfection	Poor microbial quality due to improper chlorine dossers	Chemical dosing done with old gravity dozers	High: Overdosing or underdosing of chlorine for disinfection, hence failure to produce water	New chlorine dozers purchased, installed and calibrated in August 2018

(*Continued.*)

Table 1 | Continued

Water supply stage	Hazardous event	Existing (or non-existent) control measures	Risk and basis for its rating	New control measures implemented
			that meets microbial standards	
Final water storage	Deteriorating final water quality due to sludge accumulation in the clear water tank	Cleaning of the clear well tank done but not on schedule hence accumulation of dirt	High: Failure to supply water that meets water quality standards	Schedule for cleaning of the clear well tank made and followed effective July 2017
	Poor microbial quality in distribution system due to inadequate chlorine contact time in the clear water tank	Settlement of filtered water in the clear well tank allowed but for less than 30 min	High: Failure to supply water that meets microbial quality standards	Supplementary water supply from Kitagata plant in August 2018 helped to meet the demand hence provision for adequate contact time at Nyaruzinga plant was achieved
	Deteriorating final water quality due to ingress of contaminants in the contact tank through unprotected vents	Vent outlets on the roof of the clear well tank got old and torn possibly allowing entry of foreign matter	Medium: Failure to supply water that meets water quality standards	The vent outlets were covered with a plastic mess in July 2017
Reservoirs	Recontamination of water in the distribution network due to on-site solid waste disposal in the vicinity of Katungu reservoir	Solid wastes collected but kept to accumulate in the tank compound	Low: Possible contamination of water in the tank or tank outlets leading to supply of water that does not meet water quality standards	An appropriate waste disposal point was identified and used for all solid wastes effective July 2017
	Recontamination of water in Katungu reservoir due to delayed and incomplete cleaning	Tank cleaning done but not on schedule hence accumulation of dirt	Medium: Supply of water that does not meet water quality standards	A network and tanks cleaning schedule was prepared and followed effective July 2017
Distribution network	Ingress of contaminants in the pipe system due to frequently bursting aged and corroded pipes especially asbestos cement pipes	Old pipe replacement done but not exhaustively due to inadequate budget	High: Supply of water that does not meet water quality standards, failure to meet supply demand and non-revenue water targets	A schedule for network pipe replacement was prepared based on budget, and gradual process of replacement followed, effective July 2017
	Recontamination of water in the distribution system due to drop in residual chlorine	Network flushing especially dead ends and valley points done but not on schedule	High: Failure to supply water that meets microbial quality standards	A schedule for network flushing to reduce turbidity, especially dead ends and valley points was prepared and followed effective July 2017
	Recontamination of water in the distribution system due to improper sizing of pipes that are prone to leaks and bursts	Identification and replacement of undersized pipes done but not on schedule	High: Supply of water that does not meet water quality standards, failure to meet supply demand and non-revenue water targets	As part of network management, systematic replacement of small size pipes done effective November 2017
	Recontamination of water in the distribution system due to delay to repair leaks and bursts	Repair of leaks and bursts done but occasionally delayed	High: Supply of water that does not meet water quality standards and failure to meet supply	Effective July 2017, the following was done: • Public sensitization for reporting of bursts and leaks done;

(*Continued.*)

Table 1 | Continued

Water supply stage	Hazardous event	Existing (or non-existent) control measures	Risk and basis for its rating	New control measures implemented
			demand and non-revenue water targets	• fittings and materials for repair of bursts and leaks stocked; • transport of plumbers enhanced with motorcycles
	Recontamination of water in the distribution system due to low pressure resulting in back syphonage	Occasional low network pressure experienced according to demand	High: Supply of water that does not meet water quality standards	Water supply quantity and pressure enhanced by treating more water supplied from PIBID Company, and introducing treated water from Kitagata plant in August 2018
	Recontamination of water in the distribution network due to delayed flushing of dead ends	Network flushing especially dead ends and valley points done but not on schedule	High: Supply of water that does not meet water quality standards	A schedule for network flushing especially dead ends and valley points was prepared and followed effective July 2017
	Recontamination of supplied water due to uncleaned and uncovered customer tanks	Some customer reserve tanks left uncleaned posing a risk of recontamination of received clean water	High: Supply of water that does not meet water quality standards	Customer awareness and training done for maintenance of reserve tanks in their premises effective July 2017

annual mean range of 5.5 ± 1.0–6.1 ± 0.6 (Figure 3). It was however observed that afterwards, during 2019 and 2020, the pH in the distribution system rose above 6.5, with an annual mean range of 6.1 ± 0.7–6.7 ± 0.04 (Figure 3). The pH range for final water, Katungu reservoir and Bumbeire PSP, however, remained below 6.5 during 2019 and 2020 (Figure 3). There was no significant monthly variation in pH at all the sampling points during the assessment. There was however a significant variation among the sampling points ($n = 890$, $p < 0.0001$) during the assessment period (2013–2020).

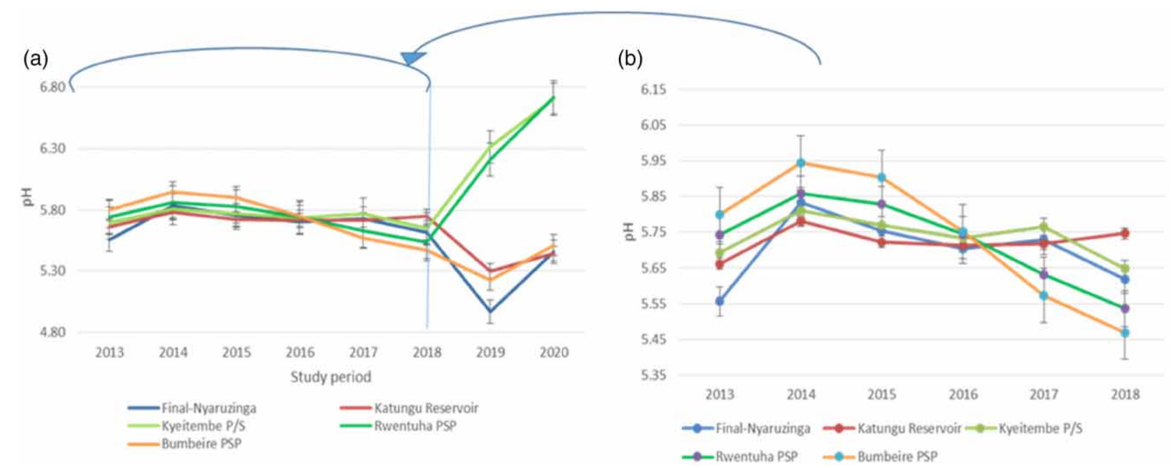

Figure 3 | (a) Annual mean pH of final water, Katungu reservoir and in the distribution system at Kyeitembe P/S, Rwentuha PSP and Bumbeire PSP, for the period 2013–2020. Mean = 5.7 ± 2.6, $N = 445$. (b) Represents data of 2013–2018 to enable clarity of the line graphs; sample size $N = 89$; in both figures (a) and (b), bars represent mean values ± standard error. For field, laboratory, and environmental conditions, refer to subsection 2.2.

3.2.5. Turbidity

The turbidity for raw water generally decreased over the period 2013–2020 with an annual mean of 113.5 ± 50.4 NTU and 14.6 ± 3.2 NTU in 2013 and 2020, respectively (Figure 4). The annual mean turbidity for the entire period was 49.6 ± 39 NTU.

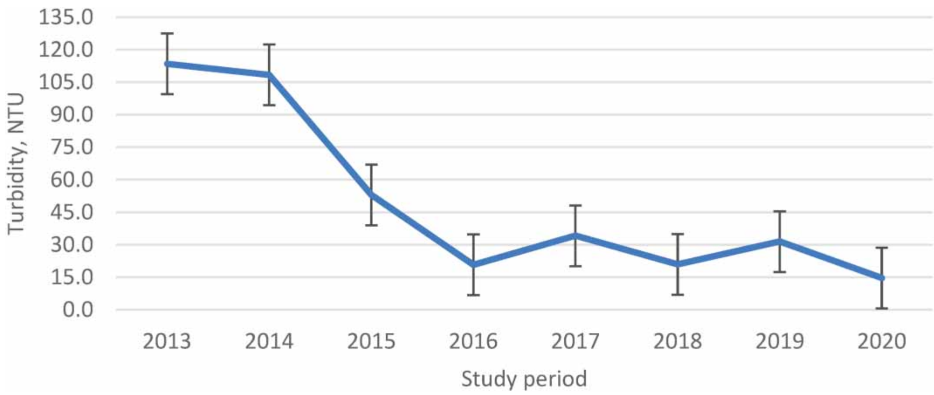

Figure 4 | Annual mean turbidity of raw water for the period 2013–2020; sample size $n = 89$, bars represent mean values ± standard error. For field, laboratory, and environmental conditions, refer to subsection 2.2.

The raw water turbidity was lowest in July 2016 (9.2 NTU) and highest in December 2013 (203 NTU), with an average of 45.7 ± 44 NTU. Turbidity for the final water and water in the distribution system largely complied with the National Standards for treated drinking water (≤5 NTU) (UNBS 2015). The percentage of samples that had turbidity complying with the national standard for treated drinking water was 93.1% (827/888). High turbidity for final water was observed in in March 2018 and March 2019 (18.0 NTU) and at Kashenyi Trading Centre in April 2018 (14.8 NTU). There was a significant annual improvement in turbidity for the sampled locations namely, Nyaruzinga final water ($F(7,81) = 2.80$, $p = 0.012$), Katungu reservoir ($F(7,81) = 2.13$, $p = 0.049$), Market PSP-Bushenyi ($F(7,80) = 3.19$, $p = 0.005$), Kyeitembe P/S ($F(7,81) = 4.65$, $p < 0.001$), Bumbeire PSP ($F(7,81) = 3.22$, $p = 0.005$), Rwentuha PSP ($F(7,81) = 4.30$, $p < 0.001$), Kashenyi PSP ($F(7,81) = 2.29$, $p = 0.035$), Market PSP-Ishaka ($F(7,80) = 4.04$, $p < 0.001$), Basajjabalaba SS ($F(7,81) = 6.37$, $p < 0.001$) and Kizinda kiosk ($F(7,81) = 3.35$, $p = 0.004$). There was no significant monthly variation in turbidity at all the sampling points during the assessment. There was however a significant difference among the sampling points ($n = 890$, $p = 0.012$) during the assessment period (2013–2020).

3.2.6. Total iron

The annual mean total iron concentration for raw water was lowest in 2018 (4.8 ± 1.9 mg/L) and highest in 2015 (10.3 ± 2.6 mg/L) (Figure 5). The total iron concentration in the raw water was lowest at 2.5 mg/L in February 2018 and at 14.0 mg/L in May 2014 with an average of 7.8 ± 3.0 mg/L .

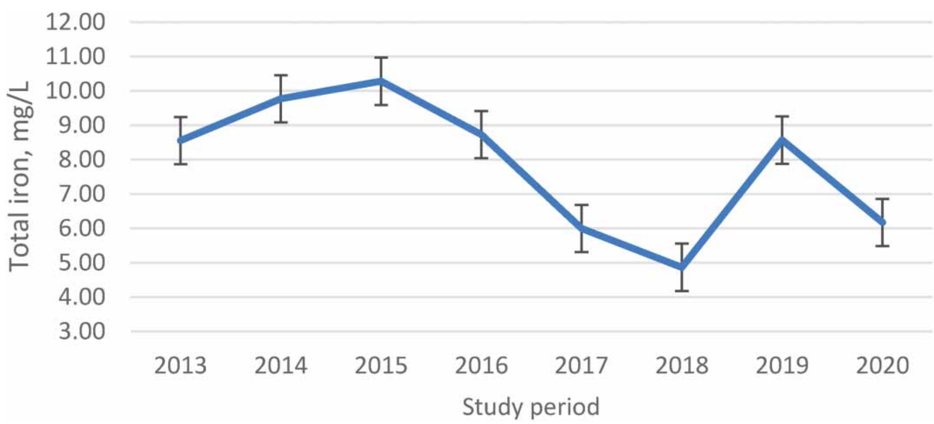

Figure 5 | Annual mean total iron concentration for raw water for the period July 2013–November 2020, sample size $n = 89$; bars represent mean values ± standard error. For field, laboratory, and environmental conditions, refer to subsection 2.2.

The total iron concentration in the final water and water in the distribution system was largely compliant with the national standards for treated drinking water, i.e. ≤0.3 mg/L (UNBS 2015). Only 27 out of 890 samples (0.03%) from the final water and all the sampled distribution points did not meet the standard. There was no significant annual change in total iron concentration for the final water during the study period. There was however, a significant annual change at Katungu reservoir ($F(7,81) = 6.00$, $p < 0.0001$), Market PSP-Bushenyi ($F(7,81) = 4.36$, $p = 0.0004$), Kyetembe P/S ($F(7,81) = 2.30$, $p = 0.034$), Bumbeire PSP ($F(7,81) = 3.19$, $p = 0.004$), Rwentuha PSP ($F(7,81) = 2.72$, $p = 0.014$) and Basajjabalaba SS ($F(7,81) = 4.63$, $p = 0.0002$). The annual change in total iron concentration was however not significant at Market PSP-Ishaka, Kashenyi PSP and Kizinda kiosk. There was no significant monthly variation in total iron concentration at all the sampling points during the assessment. There was however a significant difference among the sampling points ($n = 890$, $p < 0.0001$) during the assessment period (2013–2020).

3.2.7. Residual free chlorine

During the study period, the majority of the samples (719 out of 801 = 89.8%) taken from the storage and distribution systems had free residual chlorine complying with the national standards for treated drinking water (0.2–0.5 mg/L) (UNBS 2015). There was a significant drop in the concentration of the free residual chlorine from the final water to the Katungu reservoir ($F(9,880) = 118.39$, $p < 0.0001$) and the sampled distribution points). There was no detectable free residual chlorine (<0.01 mg/L) at Ishaka Market PSP in February 2018, Rwentuha PSP in February 2018, Kyeitembe P/S in May 2018, Bumbeire PSP in January 2019, Kizinda Kiosk in May 2019 and, Kashenyi PSP in March 2019. At these sampling points, free residual chlorine was well below the national standard for drinking water of 0.2–0.5 mg/L (UNBS 2015). Conversely, the free residual chlorine concentration was above the upper limit of the national standard (0.5 mg/L) once at Kizinda Kiosk (0.6 mg/L) in August 2014. Similarly, 19 out of the 89 samples (21.3%) from the Katungu reservoir had free residual chlorine above the upper limit of the national standard of 0.5 mg/L. There was a significant annual change in free residual chlorine at all the sampling points during the assessment period, as follows: Final water ($F(7,81) = 12.85$, $p < 0.0001$), Katungu reservoir ($F(7,81) = 2.46$, $p = 0.0245$), Market PSP-Bushenyi ($F(7,81) = 2.66$, $p = 0.0158$), Kyetembe P/S ($F(7,81) = 6.34$, $p < 0.0001$), Bumbeire PSP ($F(7,81) = 2.97$, $p = 0.008$), Rwentuha PSP ($F(7,81) = 5.15$, $p = 0.0001$) and Basajjabalaba SS ($F(7,81) = 5.83$, $p = 0.0002$), Kizinda PSP ($F(7,81) = 3.38$, $p = 0.0033$, Market PSP-Ishaka ($F(7,81) = 3.64$, $p = 0.0018$, Kashenyi PSP ($F(7,81) = 4.87$, $p = 0.0001$). There was no significant monthly variation in free residual chlorine among all the sampling points during the assessment. There was however a significant difference among the sampling points ($n = 890$, $p < 0.0001$) during the assessment period (2013–2020).

3.2.8. Faecal coliforms

The faecal coliform counts in the raw water samples taken during the study period ranged from 30 CFU/100 mL in December 2013 to 1,700 CFU/100 mL in April 2014 (Figure 6). There was a significant difference in annual mean faecal coliform concentration for raw water ($F(11,77) = 2.14$, $p = 0.0174$). The annual mean and median

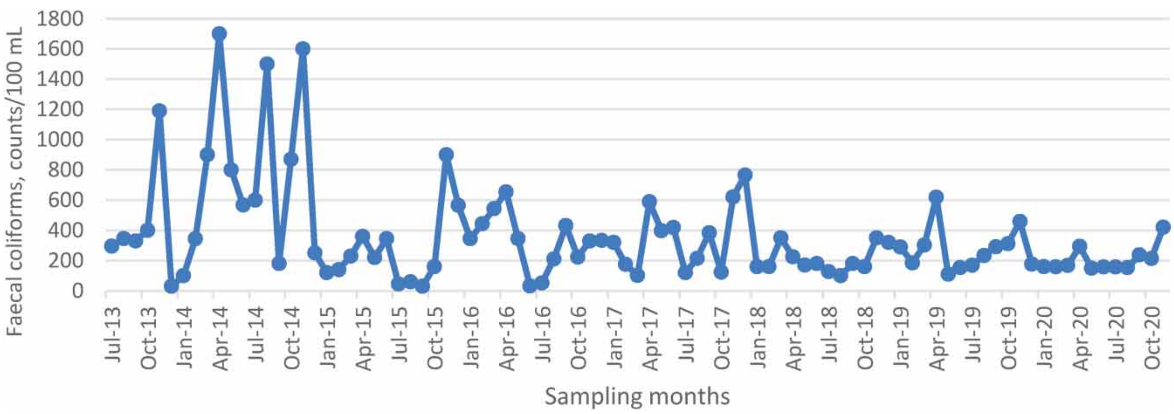

Figure 6 | Faecal coliforms for raw water for the period July 2013–November 2020 on a monthly basis, sample size $n = 89$. For field, laboratory, and environmental conditions, refer to subsection 2.2.

faecal coliform concentration increased during the period 2013–2014 and significantly decreased between the period 2015 and 2020 ($U = 323.50$, $p = 0.001$, (Figure 6). The median faecal coliform concentration for the period 2013–2014 was 484 CFU/100 mL ($n = 18$) and ranged from 30 to 1,700 CFU/100 mL while for the period 2015–2020, the median faecal coliform concentration was 220 CFU/100 mL ($n = 71$) and ranged from 30 to 900 CFU/100 mL.

For final water and water in the distribution, out of 890 samples collected, 857 samples (96.3%) complied with the national standard for treated drinking water (<1 CFU/100 mL), while 33 did not. Of the 33 samples that did not comply, most (61%) had a concentration of 1 CFU/100 mL. All but one of the remainder violations (15 CFU/100 mL at Kizinda Kiosk in December 2019) were in the range of 2–10 CFU/100 mL taking place 1–3 times per year from 2014 to 2020. The water quality in the distribution system therefore met the bacteriological national standard for drinking water that is, being absent in 95% of yearly samples (UNBS 2015).

4. DISCUSSION

4.1. Status of water quality

4.1.1. pH

The pH of raw water was low as reported by previous studies (NEMA 2019; Twesigye 2021). The pH of the treated water was significantly lower than that of raw water likely followed by the reactions of the chemical inputs utilized in the treatment processes that is, the aluminium-based coagulants and chlorine disinfectant (Saritha *et al.* 2020). The increase in pH in the distribution system apart from Katungu reservoir and Bumbeire PSP resulted from the introduction of supplementary supply of water from the Kitagata treatment plant that produces water, which exhibits a relatively higher pH (6.5–6.9).

4.1.2. Turbidity

The declining (improving) raw water turbidity trend (Figure 4) during the entire study period could be due to progressive adherence to environmental regulations particularly reduced wetland encroachment which is attributed to law enforcement by local authorities (Muhame 2019), as encouraged through the WSP control measures (Table 1). Turbidity in the distribution system largely complied with the national standards, which is important for ensuring that the concentration of pathogenic microbial organisms, whose survival tends to be proportional to the level of turbidity, is kept as low as possible (World Health Organization 2017). The annual reduction of turbidity in the final water and water in the distribution system was observed to occur with improved operation and maintenance of the treatment plant and the network over the years, during the development and implementation of WSP, as indicated in Table 1. The control measures included preparing a schedule for network pipe replacement which was gradually followed according to budget, and preparing and following a schedule for network flushing, especially for dead ends and valley points.

4.1.3. Iron

The treatment process namely aeration and clarification was able to remove iron to levels within the treated national standard (Podgórni & Rząsa 2014). The challenge of significant annual variation in iron concentration across sampling points in the distribution system may be attributed to deficiencies in operation and maintenance effort, staff capacity and availability of resources (Muinamia 2015).

4.1.4. Free residual chlorine

The presented results show that the distribution system was adequately protected against regrowth or recontamination with pathogenic microorganisms, as evidenced by 89.8% of the samples meeting the national standard for free residual chlorine (World Health Organisation 2017). That this is the case may be attributed to the development and implementation of WSP, particularly the risk control measures (Table 1) namely; following a schedule for network flushing, tanks cleaning, and scheduled replacement of old pipes and undersized pipes that are prone to bursts and leaks. The significant drop in the concentration of free residual chlorine from the final water to the storage and distribution points is expected owing to chlorine decay following from reaction with organic and inorganic matter (mainly presented as turbidity) in the pipes over time (Karikari & Ampofo 2013). The incidental lack of free residual chlorine at several points in the distribution system could have led to exposure to pathogenic regrowth or recontamination through back syphoning during times of low pressure in the network (Karikari & Ampofo 2013).

4.1.5. Faecal coliforms

The presented results show that there was a significant decrease in annual median faecal coliform concentration in raw water from 2015 to 2020. The observed reduction likely follows from progressive adherence to environmental regulations, particularly reduced wetland encroachment. This is due to law enforcement campaigns by local authorities (Muhame 2019). Additionally, the decrease in faecal coliform concentration may be due to wetland restoration through community engagement and training on alternative livelihood options (UNDP 2019). The community engagement and training were partly done under the WSP development and implementation effectively starting in July 2017 as indicated in Table 1. We also observed that most of the water samples collected (96.3% over the 7 years of the study) in the distribution system met the national standard for faecal coliform concentration. That this is the case is likely as a result of the effectiveness of treatment, adequacy of free residual chlorine in the distribution network and good maintenance of the pipe network, particularly timely response to bursts and leaks (Tsitsifli & Kanakoudis 2020). The effectiveness in treatment and network management was part of the control measures instituted during the development and implementation of WSP as indicated in Table 1.

4.2. Annual and monthly variation of water quality

This study shows that there were significant monthly changes in faecal coliform concentration in the Nyaruzinga raw water. That this is the case could be attributed to soil erosion during the rainy seasons from agricultural activities around and alongside the wetland (NEMA 2019). Municipal wastes and domestic sewage disposal into the wetland may also have led to faecal contamination, especially during the rainy seasons (Safari *et al.* 2012). As noted in Figure 6, the escalating faecal coliform trend observed from 2013 to 2014 did not recur thereafter. This is likely attributable to the WSP control measures (Table 1), that were put in place, particularly holding sensitization meetings with farmers and local authorities that discouraged illegal farming activities, cattle grazing and bricklaying in the wetland and close to the raw water source and recommended alternative livelihood activities.

For treated water (final and distribution system), there was no monthly variation, apart from a few incidences, owing to the fact that the treatment process and network management maintained the water quality within the national standards. The significant annual water quality variation at all the sampling points could be attributed to the various control measures instituted by management to improve the quality and quantity of supply (Serio *et al.* 2021). The apparent significant water quality variation among the sampling points in the distribution system could be due to hazardous events that applied differently to the sampling point locations. For example, bursts and leaks could happen at one location in the network affecting the water quality in the local area. The same applies to inadequate pressure in the network, delayed repairs, delayed cleaning and flushing of dead ends (Tsitsifli & Kanakoudis 2020; Karikari & Ampofo 2013).

5. CONCLUSION, RECOMMENDATIONS AND FUTURE RESEARCH

5.1. Conclusion

- The main hazardous events and risks affecting the quality of water supplied in Bushenyi-Ishaka Municipality include extreme seasonal weather variations, source protection gaps, treatment deficiencies and distribution management gaps.
- Management of the water treatment and distribution system was sound, largely supplying water that was in compliance with the national standards for treated drinking water as follows: turbidity (93%), total iron (99%), free residual chlorine (90%) and faecal coliforms (96%). However, the pH of the treated water in the distribution system, range of 5.5 ± 1.0–6.1 ± 0.06, was below the national standard (6.5–8.5) from July 2013 to July 2018 until supplementary supply from the Kitagata water treatment plant was introduced in August 2018, attaining a range of 6.1 ± 0.07–6.7 ± 0.07.
- The quality of water in the distribution system largely complying with the national standards is attributed to adherence to control measures that were instituted against the risks in the treatment plant and the distribution network.

5.2. Recommendations

- For sustained system and quality assurance, it is recommended that stakeholder engagement is intensified to minimize activities leading to soil erosion and faecal contamination from the catchment.
- Efforts to improve treatment processes need to be emphasized, particularly clarifier and filter performance and chemical dose optimization. Provision of appropriate coagulant types, optimum dose determination and application is recommended. Regular resanding and periodic top-up of fine sand media is recommended for sustained treated water quality improvement.
- There is a need for additional investment in network management, particularly old pipe replacement, scheduled cleaning and timely response to bursts and leaks.

5.3. Future research

Further research is ongoing to evaluate the overall performance of the WSP of Bushenyi-Ishaka Municipality in terms of outcomes and short-term impacts.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of the following who contributed towards the planning, data collection, data analysis and manuscript preparation. Eng. Francis Kateeba, General Manager, NWSC Mbarara, who by then was the Area Manager, NWC Busheyi, and rallied his section heads to carry out WSP development and implementation. Also acknowledged is Deo Mugume, Senior Quality Control Officer at NWSC Bushenyi, who helped with sampling and in situ analysis; John Owona, Philbert Bankunda, Deo Mugume and Dora Kukundakwe who were members of the Area WSP team that spearheaded the field exercise of hazard identification, risk assessment and determination of control measures. Acknowledgement also goes to Profilio Tebandeke, Principal Quality Control Officer at NWSC, Mbarara and head of the Regional water quality laboratory at Ruharo, together with Naboth Mwebaze and Rita Kamiti, who helped carry out some water quality analysis. The authors also acknowledge the contribution of Fred Muwanika who helped with statistical data analysis.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 9 January 2023; accepted in revised form 29 October 2023. Available online 9 November 2023