



Processes Controlling pH in Nyaruzinga Wetland Source and the Water Supply System in Bushenyi-Ishaka Municipality, Uganda

Christopher Kanyesigye^{1*}, Robinah N. Kulabako², Herbert M. Kalibbala², Charles B. Niwagaba², Mohammed Babu¹, Marisa Boller³ and Frank Kansiime⁴

¹National Water and Sewerage Corporation, Plot 3 Nakasero, P. O. Box 7053, Kampala, Uganda

²Makerere University, Department of Civil and Environmental Engineering, P. O. Box 7062, Kampala, Uganda

³Eawag, Swiss Federal Institute of Aquatic Science and Technology, Department of Sanitation, Water and Solid Waste for Development, Überlandstrasse 133, 8600 Dübendorf, Switzerland

⁴Makerere University, Department of Environmental Management, P. O. Box 7062, Kampala, Uganda

Abstract

This study investigated the processes responsible for perennial low pH in Nyaruzinga wetland water source in Western Uganda. Under anoxic conditions in wetlands, the redox potential and pH increase, thereby favouring dissolution of iron compounds, humic substances and release of copper, chromium, cobalt, nickel and lead. In situ temperature, pH, DO, EC and Eh were determined while the heavy metals, anions, cations, TOC, DOC and humic substances were analysed in the laboratory, for sediments, raw and treated water. The pH and DO increased from 70 cm deep in the wetland to the surface while the other parameters decreased. Copper (0.123-0.152 mg/L), chromium (0.002-0.299 mg/L), nickel (0.07-0.119 mg/L) and cobalt (0.006-0.081 mg/L) were determined at 70 cm deep, being trace (0.001-0.09 mg/L) at the wetland surface. High concentrations of TOC (14.7-28.3 mg/L) and DOC (0.03-0.71 mg/L) were measured in the wetland while traces of DOC (0.001-0.009 mg/L) and humic substances were determined in raw water but not in the treated water. The low pH in Nyaruzinga wetland is attributed to low molecular weight humic substances under perennial water logged conditions, and treatment processes should aim to remove them.

Keywords: Anaerobic conditions; Dissolved oxygen; Humic substances; Water source; Water logging; Wetlands.

INTRODUCTION

Wetlands act as natural water buffers by receiving and holding water during dry seasons and releasing it slowly into the surface and ground water bodies [1,2]. During prolonged saturated conditions, dying wetland vegetation experience slow decomposition leading to their accumulation. The prolonged saturation produces anoxic conditions in the sediment-root zone and soil layers [3]. The anoxic conditions lower the redox potential which results in pH increase that favors dissolution of elements like iron, phosphorus [4,5], and humic substances in colloidal form [6]. The rate of pH increase depends on the quantity of fresh organic matter that is decomposed by microorganisms [7]. Since this process is slow under anoxic conditions, the pH remains low for a relatively long period of time [8]. Additionally, the anoxic conditions favour the release of trace metals, mainly Copper (Cu), Chromium (Cr), Cobalt (Co), Nickel (Ni) and lead (Pb) and rare earth elements [6].

The pH in wetland sediments is controlled by the amounts of acidic and alkaline elements it contains. The elements are provided either by the soil parent material through groundwater influx, for alkaline cations

or precipitation and organic matter decomposition for acidic cations [9]. Wetlands that dominantly receive groundwater discharge tend to be less acidic than wetlands that receive most of their water through precipitation and surface water over flows [3]. The cation exchange capacity of most wetland soils is high, but the exchange complex is dominated by acidic cations and as a result the pH of most wetland soils is generally acidic [2]. Wetlands located in regions with limestone geology tend to have alkaline pH soils (pH > 8) rich in calcium, magnesium and sodium carbonates. Consequently, there is sequestration of calcium and magnesium by the wetland plants and uptake of carbon dioxide during photosynthesis [7]. Wetlands with acid sulphate soils containing substantial quantities of iron-sulphide minerals can have pH as low as 3 or less [10]. During the dry season when the acid sulphate soils are exposed, there is oxidation of the sulphides and subsequent formation of sulphuric acid accompanied by fast microbial decomposition of organic matter as their energy source [11]. During the wet season, water logging causes anoxic conditions, slowing down microbial decomposition of organic matter and the pH remains acidic [5]. Wetlands in the tropical African region receive a large fraction of their water from convectional rainfall directly over them and upstream run off, influenced by the tropical rain forests and the wetlands themselves [12].

This study investigated the processes controlling the pH in Nyaruzinga wetland water source and water distribution network in Bushenyi-Ishaka Municipality. A supplementary water supply source for the municipality, the Kitagata wetland was also included in the study for comparison purposes, particularly in terms of Total Organic Matter (TOC), Dissolved Organic Matter (DOC) and humic substances concentration. The specific objectives were: (i) to determine the pH, electrical conductivity (EC), redox potential (Eh), Dissolved Oxygen (DO), TOC, DOC, humic substances, total iron, iron III (Fe III) and iron II (Fe II); Manganese (Mn), Calcium (Ca), Magnesium (Mg), total alkalinity, sulphates, sulphides and heavy metals namely Cu, Cr, Co, Ni and Pb in the Nyaruzinga wetland, raw water (in the dam) and treated water (final and in the distribution system), and (ii) to establish the processes that lead to the transformation

Submitted: 02 November 2024 | **Accepted:** 27 November 2024 | **Published:** 29 November 2024

***Corresponding author:** Christopher Kanyesigye, National Water and Sewerage Corporation, Plot 3 Nakasero, P. O. Box 7053, Kampala-Uganda.

Copyright: © 2024 Kanyesigye C, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Citation: Kanyesigye C, Kulabako RN, Kalibbala HM, Niwagaba CB, Babu M, et al. (2024) Processes Controlling pH in Nyaruzinga Wetland Source and the Water Supply System in Bushenyi-Ishaka Municipality, Uganda. Ann Environ Sci Ecol 2: 11.



of compounds that are responsible for low pH in the Nyaruzinga wetland, raw water and treated water.

MATERIALS AND METHODS

Study area

Nyaruzinga wetland in South Western Uganda (Figure 1) is dominated by papyrus and experiences two distinct annual rainy seasons, March-May and September-November. The mean monthly rainfall for the wet season ranges from 106 mm to 412 mm, while for the dry seasons (December-February and June-August) ranges from 0 mm to 58 mm [13]. The average monthly relative humidity ranges between 68% and 84% during the two rainy seasons. The maximum monthly temperature is 30°C during the dry season months of June and July, which declines to 20°C during April and November, the peak rainy season months [14]. The pH of the raw water from Nyaruzinga wetland is acidic [15], ranging between 4.5-6.3, with an average pH of 5.5 ± 0.37 , requiring application of sodium carbonate (soda ash) for pH adjustment before coagulation and clarification [16]. After clarification (with aluminium based coagulants) and disinfection (with chlorine), the water remains acidic with a pH < 6.5, below the minimum requirement for drinking water supply according to the Uganda National Standard for Drinking Water Quality [17]. pH adjustment is done to the water leaving the treatment plant before it enters the distribution network. The annual cost of soda ash required for pre- and post- pH adjustment is on average US\$4,400 [18]. The low pH in the Nyaruzinga wetland could cause reducing conditions and release of heavy metals together with colloidal organic matter containing humic substances [19]. The constituents could reach toxic levels leading to negative health implications to humans. This could even be a bigger problem in Bushenyi-Ishaka municipality, where a fraction of the population uses untreated water for domestic purposes including drinking [13]. Additionally, application of aluminium-based coagulants and chlorine disinfection further lowers the pH, resulting in low pH in the distribution system in case pH adjustment is not adequately done. The acidic water supplied could potentially corrode metallic pipes and installations in the storage and distribution systems thereby increasing maintenance costs [21]. The water supplied from the Nyaruzinga source is not adequate to fully satisfy the demand of Bushenyi-Ishaka Municipality and the surrounding sub-counties. Hence another source of water, the Kitagata wetland source, was identified and in 2018, supplementary supply from this source started. The quality of the water from Kitagata differs from that of Nyaruzinga source especially in terms of pH. The pH of the Kitagata wetland source ranges from 6.5-7.1, and therefore does not need pH adjustment during treatment, hence complying with the National Standard for Drinking Water Quality [16] for this parameter, even before treatment. This fact prompted the idea of a comparative quality assessment of Kitagata wetland and Nyaruzinga wetland, aimed at understanding the constituents responsible for the difference in pH of the two sources [13-21].

Sampling strategy

Sediment and water sampling was done during both wet and dry seasons. Sampling for the wet season was done in April-May and August-September 2022 while for the dry season, sampling was done in June-July 2022. Further sampling of sediment and raw water from both Nyaruzinga and Kitagata sources was done in June 2023 specifically for confirmation of humic substances. Sediment samples were collected at 70 cm deep in the wetland where there is minimal air exchange with the atmosphere and at the wetland surface. The depth of 70 cm was considered most appropriate after preliminary in situ tests pH, EC, DO and Eh gave similar results for 60 cm to 100 cm, while less than 60 cm depth gave unreliable results due to open air interaction. The sediment samples were taken using a sediment sampler (Beeker sediment core sampler, Royal Eijkkelkamp, The Netherlands, Model 04 23 SA) and kept in polypropylene bottles under refrigeration temperatures (<4°C) during

transport and storage and analysis done 8 hours. The sampling bottles were washed with dilute hydrochloric acid and kept dry before sampling. Sampling of treated (final water and water in the distribution network) was done using half-litre polypropylene bottles the same day of sediment and water sampling. Nyaruzinga raw water samples were taken from the dam while distribution system sampling was done from Katungu tank and Bumbeire Public Stand Pipe (PSP), which were receiving water from only Nyaruzinga water treatment plant. Additionally, water samples were taken from Kikuba tank and Bushenyi Market PSP which were receiving water only from Kitagata water treatment plant. Sampling from the Kitagata wetland, at 70 cm deep and surface, and raw water source was also done for comparison purposes.

A laboratory bench experiment was carried out to determine the effect of progressive increase of Dissolved Oxygen (DO) on concentration of Dissolved Organic Carbon (DOC) in Nyaruzinga and Kitagata wetlands and raw water samples. The aim of this experiment was to establish the comparative DO concentrations of Nyaruzinga and Kitagata wetland sources and whether presence of DOC persists up to DO saturation. The initial concentration of DO and DOC was determined, thereafter the samples were aerated for two hours. Analysis of DOC was done and the aeration of the samples was continued for another two hours after which DOC analysis was done. During the aeration process, continuous analysis of DO was carried out. Further aeration was done for another two hours and again DOC analysis was carried out. The aeration process ended having noted that towards the sixth hour, the DO concentration remained unchanged implying that it had reached saturation.

Laboratory analysis

The physico-chemical parameters namely pH, DO (mg/L), EC ($\mu\text{S}/\text{cm}$) and Eh (mV) were measured *in situ* using a multi-parameter (SensION HACH Model, USA). Total alkalinity (mg/L CaCO_3) was determined using the titrimetric method based on standard methods [22]. Sediment samples were prepared for analysis by drying and grinding with an agate pestle and mortar. Analysis of heavy metals i.e. Cr, Cu, Co, Ni and Pb was done using an Atomic Absorption Spectrophotometer (novAA® 400 P, Germany) after microwave digestion. A 10 mL volume of a mixture of HNO_3 and H_2O were added to 100 mg of the sample. Quality control was performed by analysis of certified reference materials of estuarine sediments (LGC 6137). Analysis of Fe III, FeII, Mn, Ca, Mg, sulphates and sulphides was done using the spectrophotometric method, UV-VIS (721 Model, USA). Analysis of TOC and DOC was done using the High Temperature Combustion Method, with a TOC analyser [22]. Fractionation of Natural Organic Matter (NOM) was done at Eawag, Swiss Federal Institute of Aquatic Science and Technology laboratories by the Size Exclusion Chromatography (SEC) method, using the Liquid Chromatography-Organic Carbon-Organic Nitrogen Detector (LC-OCD-OND) at Ultraviolet (UV) absorbance of 254 nm. The SEC-OCD design based on the Gräntzel thin-film reactor (S-100, Knauer, Berlin, Germany) was used [23].

Data analysis

Water quality data sets were analyzed to ascertain the central tendency and temporal and spatial trends for the wetland, raw water, final water and the distribution system sampling points. The data was checked for format uniformity and completeness. Preliminary statistical data analysis was done using Microsoft Excel 2016 and further analysis using SPSS Version 23 (IBM SPSS Statistics, USA). Analysis was done to ascertain whether there was a significant seasonal and spatial variation of the parameters tested in terms of their concentrations. The data obtained from sampling of both seasonal and spatial variations in the wetland, raw water in the dam and treated water were compared using the non-parametric Wilcoxon Signed-Rank test. The Wilcoxon Signed-Rank test is best suited for comparison of means of continuous data of two dependent sets that do not satisfy conditions of normality, which was the case in this study.

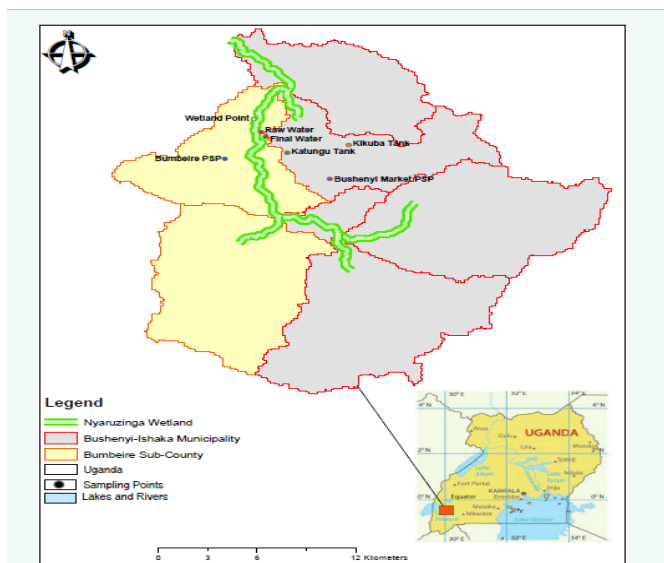


Figure 1: Map showing location of Bushenyi-Ishaka Municipality in Uganda, and the sampling points.

RESULTS

pH

The pH at the depth of 70 cm was slightly lower than at the surface in Nyaruzinga wetland, which was significantly higher ($p = 0.037$) in the raw water dam than at the surface (Figure 2a). The average pH in the wetland, 70 cm deep during the wet season was 5.24 ± 0.73 while for the dry season it was 5.56 ± 0.14 . On the wetland surface, the average pH during the wet season was 5.31 ± 0.88 while during the dry season it was 5.68 ± 0.13 . There was no significant difference between the average pH of the water at the wetland surface and at a depth of 70 cm. There was also no significant difference between the average pH during the wet and dry seasons both on the wetland surface and at a depth of 70 cm. The average pH in the raw water dam was significantly higher ($p = 0.036$) than that for the final water while that of Kikuba tank was also significantly higher ($p = 0.05$) than that of Katungu tank (Figure 2a).

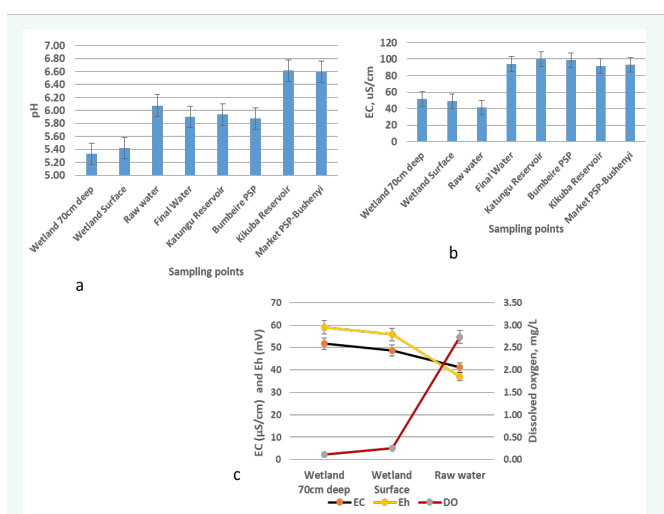


Figure 2: a). Average pH in Nyaruzinga wetland, raw water (dam) and treated water and b). Average EC in the wetland, raw and treated water, c). Average EC, Eh and DO in the wetland and raw water dam; $n = 80$, bars represent mean values \pm SE.

Electrical conductivity

The average EC at the depth of 70 cm was slightly higher than at the surface in Nyaruzinga wetland, and it was significantly higher ($p = 0.005$) than in the raw water dam (Figures 2b,c). The average EC of raw water was significantly lower ($p = 0.005$) than that of the final water (Figure 2b).

Dissolved oxygen

The average DO at Nyaruzinga wetland surface was significantly higher ($p = 0.005$) than at the depth of 70 cm and it was significantly higher ($p = 0.005$) in the raw water dam (Figure 2c). The average DO in the wetland, at 70 cm depth during the wet season and dry season was 0.12 ± 0.03 mg/L. At the wetland surface, the average DO during the wet season was 0.27 ± 0.09 mg/L while during the dry season it was 0.21 ± 0.33 mg/L. The average DO concentration at the wetland surface during the wet season was significantly higher ($p = 0.027$) than at the depth of 70 cm. However, this was not so during the dry season (Figure 2c).

Redox potential

The Eh at the depth of 70 cm in Nyaruzinga wetland was slightly higher than at the surface, which further decreased in the raw water dam (Figure 2c). The average redox potential in the wetland at the depth of 70 cm during the wet season and dry season was 67.9 ± 16.3 mV and 38.1 ± 8.8 mV respectively. On the wetland surface, the average redox potential during the wet season and dry season was 63.6 ± 13.7 mV and 37.7 ± 16 mV respectively. There was no significant difference between the average redox potential in the wetland at the depth of 70 cm and the surface, during both the wet and dry season.

Iron concentration

Iron III: The average iron III concentration at the depth of 70 cm in Nyaruzinga wetland was higher than at the surface, which further decreased in the raw water dam (Figure 3). The average iron III concentration in the wetland at a depth of 70 cm during the wet season and dry season was 30.6 ± 19.8 mg/L and 19.0 ± 7.4 mg/L respectively. On the wetland surface, the average iron III concentration during the wet and dry season was 17.7 ± 10.3 mg/L and 16.3 ± 4.6 mg/L respectively (Figure 4a). In the raw water dam, the average iron III concentration during the wet and dry season was 1.72 ± 0.95 mg/L and 1.54 ± 0.17 mg/L respectively (Figure 4c). There was no significant difference between the average iron III concentration in the wetland at the depth of 70 cm, surface and in the raw water dam, during both the wet and dry season.

Iron II: The average iron II concentration at the depth of 70 cm in Nyaruzinga wetland was lower than at the surface, which significantly decreased ($p = 0.003$) in the raw water dam (Figure 3). The average iron II concentration in the wetland, at the depth of 70 cm during the wet season and dry season was 9.9 ± 0.5 mg/L and 8.7 ± 0.7 mg/L respectively. On the wetland surface, the average iron II during the wet and dry season was 13.0 ± 5.6 mg/L and 7.3 ± 4.9 mg/L respectively (Figure 4b). In the raw water dam, the average iron II concentration during the wet and dry season was 2.67 ± 1.37 mg/L and 1.97 ± 0.52 mg/L respectively (Figure 5c). There was no significant difference between the average iron II concentration in the wetland, at 70 cm depth, surface and in the raw water dam, during both the wet and dry seasons.

The difference in concentration of iron III at the wetland surface and at a depth of 70 cm decreased as the dry season approached but it still remained high (Figure 4a). Iron II concentrations during the wet season was higher at the wetland surface than at a depth 70 cm and decreased during the dry season. In the raw water dam, the concentration of iron II remained higher than that of iron III irrespective of season (Figure 4c).

Total iron: The raw water dam of Nyaruzinga wetland had an average total iron concentration which was significantly higher ($p = 0.05$) than

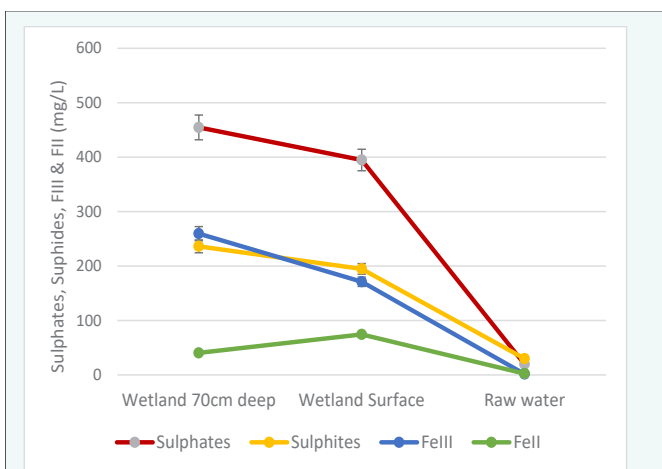


Figure 3: Average sulphates, sulphides, iron-III and iron II concentration in Nyaruzinga wetland and raw water dam. $n = 80$, bars represent mean values \pm SE.

that of the treated water (Figure 4d).

Sulphates and sulphides concentration

Sulphates: The average sulphates concentration in Nyaruzinga wetland was higher at the depth of 70 cm compared to the surface, and it significantly decreased ($p = 0.05$) from the wetland surface to the raw water dam (Figure 3). The wet season concentrations of sulphates were higher compared to the dry season at the depth of 70cm (Figure 5a). On the wetland surface however, sulphates concentration in the dry season was higher than that during the wet season (Figure 5a). There was no significant difference between the average sulphates concentration at the wetland surface and at 70 cm deep irrespective of season. Likewise, there was no significant difference between the average sulphates concentration in the raw water and final water.

5.6.2. Sulphides: The average sulphides concentration in Nyaruzinga wetland was significantly higher ($p = 0.05$) at the depth of 70 cm than the surface, and it was still significantly higher ($p = 0.003$) at the wetland surface than in the raw water dam (Figure 3). The average sulphides concentration in the wetland, both at 70 cm deep and at the surface during the wet season was higher than during the dry season (Figure 5b). The average concentration of sulphides at the wetland surface was significantly higher ($p = 0.05$) than at 70 cm depth during the wet season

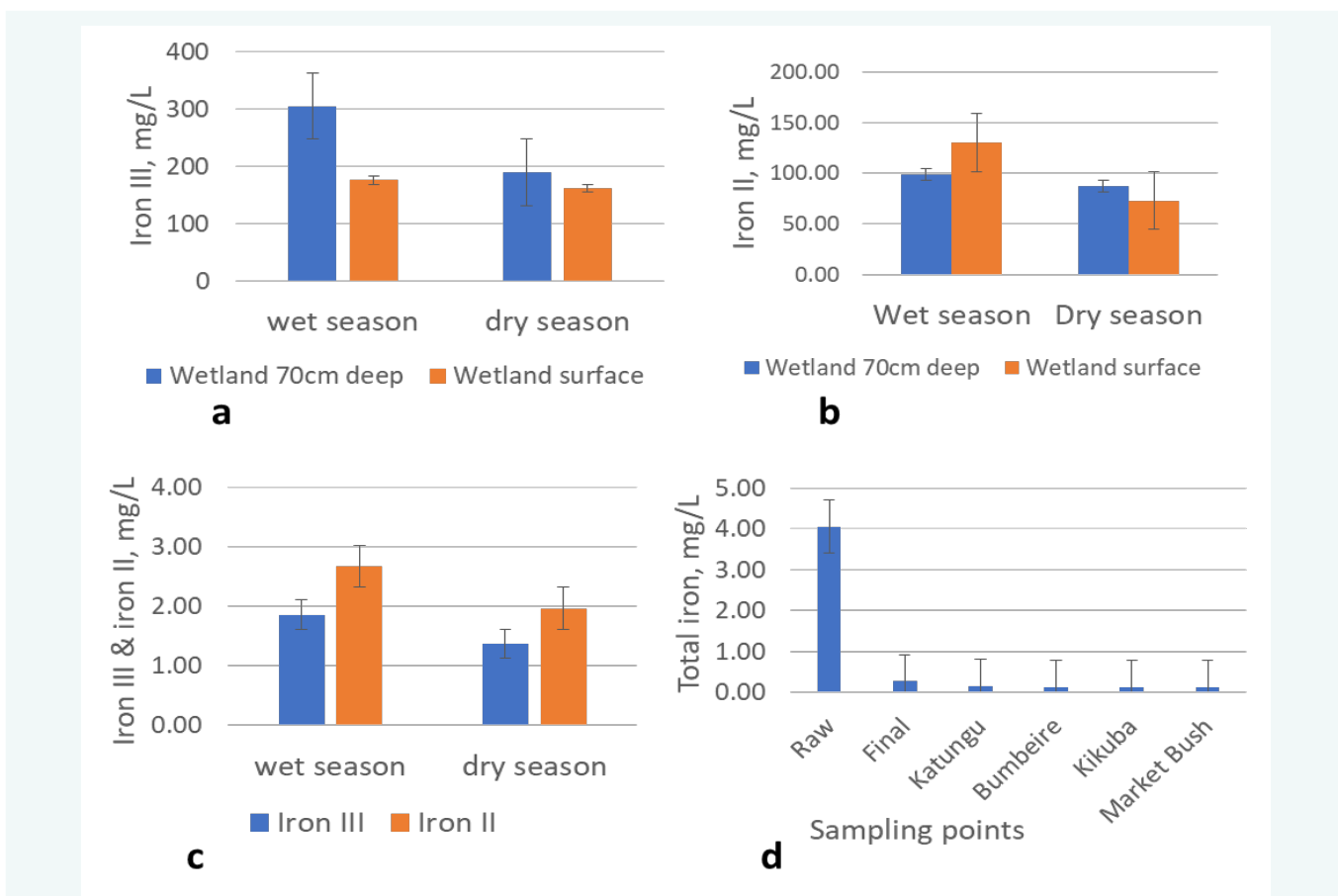


Figure 4: a). Average Iron-III concentration in Nyaruzinga wetland, b). Average Iron-II concentration in the wetland, c). Average iron-II and iron III concentration in Nyaruzinga raw water dam and d). Average total iron concentration in the raw and treated water. $n = 80$, bars represent mean values \pm SE.



but not during the dry season. In the raw water dam, the average sulphide concentration during the wet season was lower than during the dry season (Figure 5c).

The difference in concentration of sulphates during the wet season at the wetland surface and at 70 cm deep decreased as the dry season approached (Figure 5a), while for sulphides, the concentration during the wet season remained higher than during the dry season at both 70 cm deep and at the wetland surface (Figure 5b). In the raw water dam, there was higher concentration of sulphides than sulphates and the difference increased during the dry season (Figure 5c).

Total alkalinity

The total alkalinity in Nyaruzinga wetland was significantly higher ($p = 0.012$) at a depth of 70 cm compared to the surface but it was significantly lower ($p = 0.008$) in the raw water dam compared to the surface (Figures 6a). The average total alkalinity both at the surface and at 70 cm depth was higher during the dry season compared to the wet season (Figure 5a). There was no significant difference between the average total alkalinity at the wetland surface and 70 cm depth irrespective of seasons. The average total alkalinity in final water and in the distribution network ranged between 2.0 mg/L (CaCO_3) and 17.2 mg/L (CaCO_3), with an average of 8.1 ± 4.1 mg/L (CaCO_3) (Figure 6b). The average total alkalinity of raw water was significantly higher ($p = 0.012$) than for the final water.

Manganese

The average Mn concentration in Nyaruzinga wetland at the depth of 70 cm during the wet season and dry season was 29.5 ± 8.4 mg/L and 38.4 ± 7.7 mg/L respectively. On the wetland surface, the concentration during the wet and dry season was 23.7 ± 7.2 mg/L and 29.4 ± 6.8 mg/L respectively. In the raw water dam, the average Mn concentration during the wet and dry season was 0.35 ± 0.53 mg/L and 0.08 ± 0.03 mg/L respectively. The average Mn concentration was significantly higher ($p = 0.007$) at a depth of 70 cm compared to the surface during the entire sampling period, being more significant in the wet season ($p=0.028$). The average Mn concentration in the raw water dam was significantly higher ($p = 0.014$) than in the final water. The average Mn concentration in final water and the distribution network ranged between 0.05 ± 0.03 mg/L and 0.06 ± 0.03 mg/L.

Calcium

The average Ca concentration in Nyaruzinga wetland was significantly higher ($p = 0.022$) at a depth of 70 cm compared to the surface and it was still significantly higher ($p=0.05$) at the surface compared to the raw water dam. The average calcium concentration in the wetland 70 cm deep during the wet season was 68.0 ± 16 mg/L while for the dry season was 52.5 ± 26 mg/L. On the wetland surface, the average calcium concentration during the wet season was 50.5 ± 8.6 mg/L while during the dry season it was 47.0 ± 30 mg/L. In the raw water dam, the average calcium concentration during the wet season was 9.1 ± 5.1 mg/L while during the dry season it was 4.5 ± 0.5 mg/L. The average concentration of Ca at the wetland surface was significant higher ($p = 0.028$) than at 70 cm deep during the wet season but not during the dry season. The average calcium concentration in final water and the distribution network ranged between 4.6 ± 2.3 mg/L and 5.2 ± 3.2 mg/L.

Magnesium

The average Mg concentration in Nyaruzinga wetland was higher at a depth of 70 cm compared to the surface, and it was significantly higher ($p = 0.05$) at the wetland surface than in the raw water dam. The average Mg concentration in the wetland at 70 cm deep during the wet season was 21.2 ± 9.6 mg/L while for the dry season it was 17.7 ± 9.9 mg/L. On the wetland surface, during the wet season it was 23.1 ± 9.8 mg/L while during the dry season it was 12.2 ± 6.5 mg/L. In the raw water dam, the average Mg concentration during the wet season was 5.5 ± 0.23 mg/L while during the dry season it was 0.9 ± 0.4 mg/L. There was also no significant difference between the average Mg concentration in the raw water and final water. The average Mg concentration in final water and the distribution network ranged between 4.2 ± 2.4 mg/L to 5.7 ± 3.0 mg/L.

Heavy metals, total organic carbon and dissolved organic carbon

The concentration of heavy metals and DOC in Nyaruzinga wetland, raw water dam, final water and the distribution network is given in table 1. Apart from lead, the concentration of the heavy metals *i.e.*, Cu, Cr, Co and Ni was higher at the depth of 70 cm in the wetland compared to the surface. TOC and DOC concentration was higher at 70 cm below the wetland surface compared to the surface at all the sampling times.

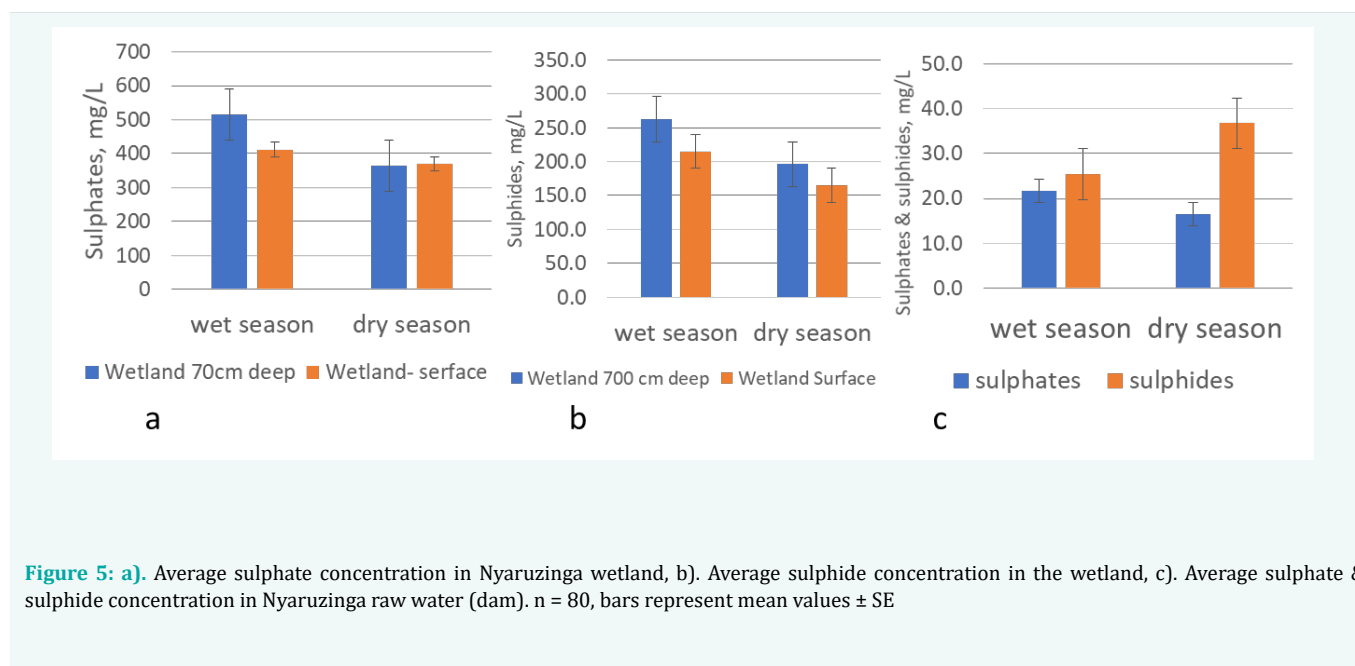


Figure 5: a). Average sulphate concentration in Nyaruzinga wetland, b). Average sulphide concentration in the wetland, c). Average sulphate & sulphide concentration in Nyaruzinga raw water (dam). n = 80, bars represent mean values \pm SE



Table 1: Concentration of heavy metals (mg/L), TOC (mg/L) and DOC (mg/L) in Nyaruzinga wetland, raw water and water in the distribution system.

Sample Description	May.24 th	Jun.3 rd	Jun.16 th	Jul.12 th	Jul.31 st	Aug.31 st	Sept.16 th
Cu-Wetland 70 cm deep	0.123	0.152	0.151	0.141	0.139	0.125	0.132
Cu-Wetland Surface	0.042	0.021	0.016	0.031	0.09	0.022	0.015
Cr-Wetland 70 cm deep	0.064	0.154	0.02	0.102	0.056	0.299	0.106
Cr-Wetland Surface	nd	nd	0.006	0.007	nd	nd	0.091
Cr-Raw water	nd	nd	0.018	nd	nd	nd	nd
Cr-Final Water	nd	0.009	0.009	nd	nd	nd	nd
Cr-Kikuba Reservoir	nd	nd	nd	nd	0.002	nd	nd
Ni-Wetland 70 cm deep	0.092	0.104	0.082	0.095	0.07	0.119	0.106
Ni-Wetland Surface	nd	nd	nd	nd	0.079	nd	nd
Ni-Raw water	nd	nd	0.013	nd	nd	nd	nd
Ni-Final Water	nd	nd	0.003	nd	nd	nd	nd
Co-Wetland 70 cm deep	0.052	0.041	0.067	0.046	0.006	0.05	0.081
Co-Wetland Surface	0.001	nd	nd	0.008	0.014	nd	0.001
Co-Raw water	nd	nd	nd	nd	0.001	0.007	nd
Co-Final Water	nd	nd	nd	nd	nd	0.007	nd
Co-Bumbeire PSP	nd	nd	nd	nd	nd	0.005	nd
Pb-Wetland 70 cm deep	nd	nd	nd	nd	0.004	nd	nd
Pb-Wetland Surface	nd	nd	nd	nd	0.008	nd	nd
Pb-Raw water	nd	nd	nd	nd	0.003	nd	nd
Pb-Final Water	nd	nd	0.002	nd	0.004	0.008	0.004
Pb-Katungu Reservoir	nd	nd	0.002	nd	0.007	0.003	0.001
Pb-Bumbeire PSP	nd	nd	nd	nd	0.001	0.004	0.002
DOC-Wetland 70 cm deep	0.58	0.64	0.45	0.31	0.71	2.84	2.75
DOC-Wetland Surface	0.19	0.11	0.08	0.03	0.06	1.37	1.21
DOC-Raw water	0.004	0.003	0.002	0.001	0.005	0.008	0.009
TOC-Wetland 70 cm deep	21.4	19.6	17.8	16.5	25.2	28.35	28
TOC-Wetland Surface	18.1	16.2	15.8	14.7	19.1	21.2	24.9
TOC-Raw water	3.1	2.5	2.1	2.1	3.2	3.3	3.6

Note: The parameters were only detected at the points & dates indicated; **nd:** not detected, detection limit is 0.001 mg/L.

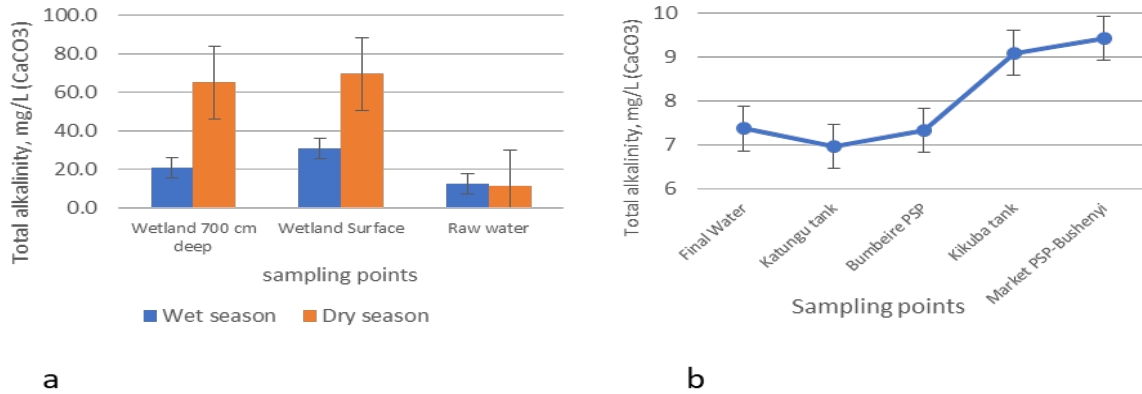


Figure 6: a). Average total alkalinity in Nyaruzinga wetland and raw water dam during the wet and dry season, b). Average total alkalinity for final water and water in the distribution network. n = 80, bars represent mean values ± SE.

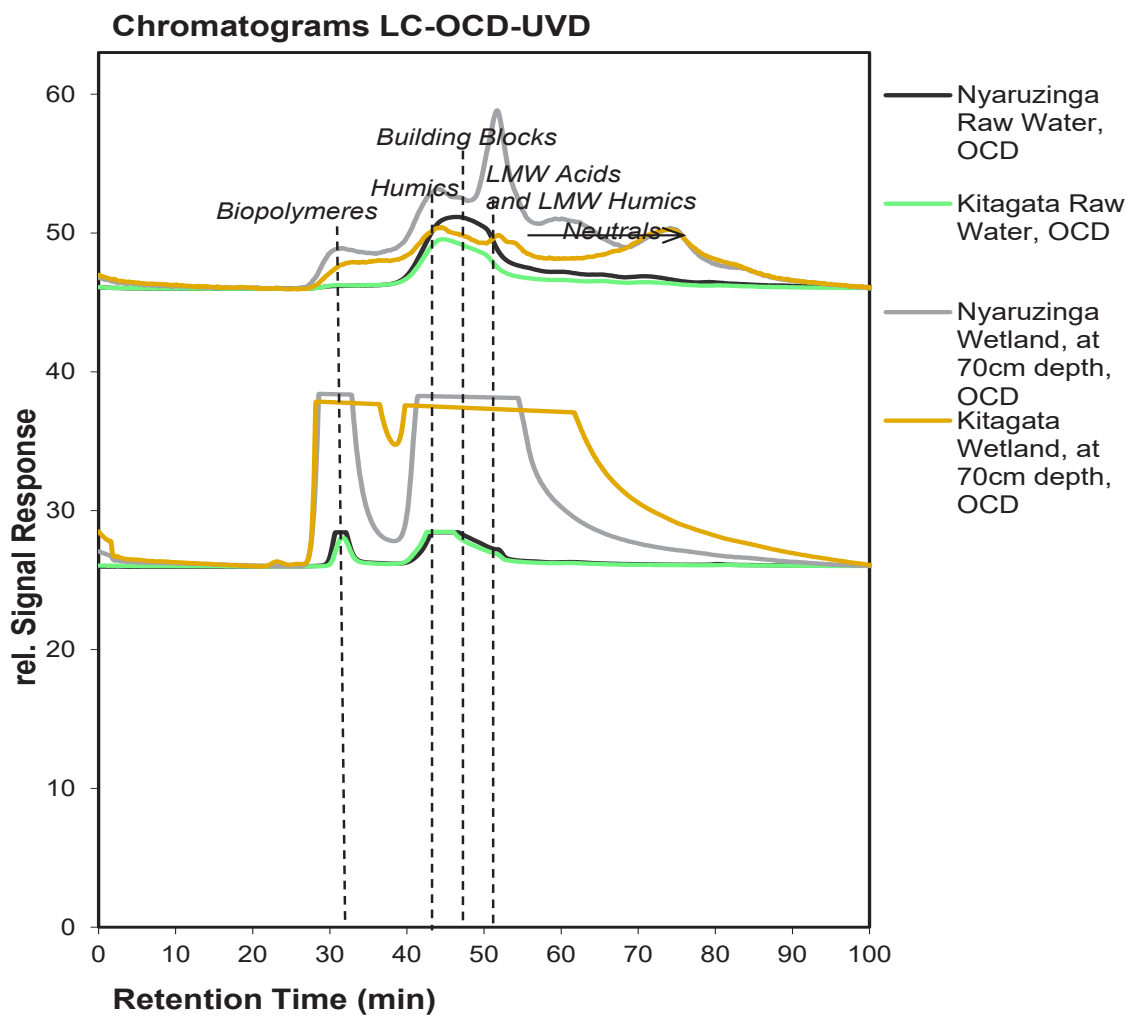


Figure 7: Chromatograms obtained from organic matter fractionation of Nyaruzinga and Kitagata wetland and raw water samples using the LC-OCD-UVD.



DOC was detected in raw water but not in the final water and distribution network. All the heavy metals apart from copper were detected in the raw and final water. In the distribution network, there was detectable concentrations of chromium (at Kikuba tank), cobalt (at Bumbeire PSP) and lead (at Katungu tank and Bumbeire PSP).

Humic substances

Wetland sediment and raw water sample analysis was done using the Size Exclusion (SE) Liquid Chromatography-Organic Carbon-Organic Nitrogen Detector (LC-OCD-OND) with fixed wave length UltraViolet Detection at 254 nm (UVD). Results showed that Nyaruzinga wetland had higher concentration of TOC, DOC, Humic Substances (HS) and building blocks (breakdown products of HS) and Low Molecular Weight (LMW) acids compared to Kitagata wetland (Figure 8). Likewise, a similar trend was observed for the two raw water source samples much as these had no detectable LMW acids. Conversely, Kitagata wetland had over four times higher concentration of Dissolved Organic Nitrogen (DON) compared to Nyaruzinga wetland, which was more than double for Kitagata than Nyaruzinga raw water samples.

Correlation between pH and Eh, alkalinity, sulphates and iron III in the wetland

The redox potential and pH levels in Nyaruzinga wetland at the depth of 70 cm were inversely correlated such that at all the times of sampling, increase of pH corresponded to decrease in Eh and vice versa. A similar trend applied to alkalinity. Conversely, there was a fairly strong positive correlation between sulphates and pH, and iron III and pH in the wetland at the depth of 70 cm (Figure 8).

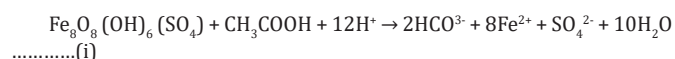
Effect of increase in DO on concentration of DOC

An experiment was performed to determine the effect of progressive increase of DO on concentration of DOC in Nyaruzinga and Katagata wetland and raw water samples. From the aeration (oxygenation) experiment, it was noted that upon aeration, even up to six hours when

the DO concentration reached saturation, there was DOC in both wetland samples but with more of it in Nyaruzinga wetland (Figure 9). Both raw water samples had traces of DOC which diminished to undetectable levels upon aeration for two hours and beyond (Figures 9c,d).

DISCUSSION

As shown in the results, the pH and alkalinity in Nyaruzinga wetland remained low throughout the sampling period, especially at 70 cm below the wetland surface. The pH remaining within the acidic range (pH < 5.33), and the low alkalinity (Alk. < 38.6 mg/L), is mainly attributed to prolonged water logging that inhibited dissolved oxygen diffusion. As a result of the latter, anaerobic conditions prevailed resulting in spatial decomposition of organic matter and its subsequent accumulation [24]. The organic matter then served as the energy source for facultative and obligate anaerobic microorganisms that further enhanced the development of reducing conditions [2,25]. As the reducing conditions prevailed, the action of iron reducing bacteria resulted in increase of alkalinity, due to bicarbonate ions, as indicated in equation (i):



Furthermore, anaerobic conditions enhanced the growth of sulphate reducing bacteria that thrive at pH just above 5, generating bicarbonates, promoting substantial alkalinity increase, as indicated in equation (ii):



Abundance of fresh organic matter as measured in terms of TOC during the sampling period however, could have provided the needed substrate as the electron donor for microbial respiration during periods of flooding with limited dissolved oxygen. This could have limited the extent of bacterial iron and sulphate reduction, hence controlling the increase of alkalinity and maintaining low pH [10,11].

Much as there was a significant increase ($p = 0.005$) in DO from 70

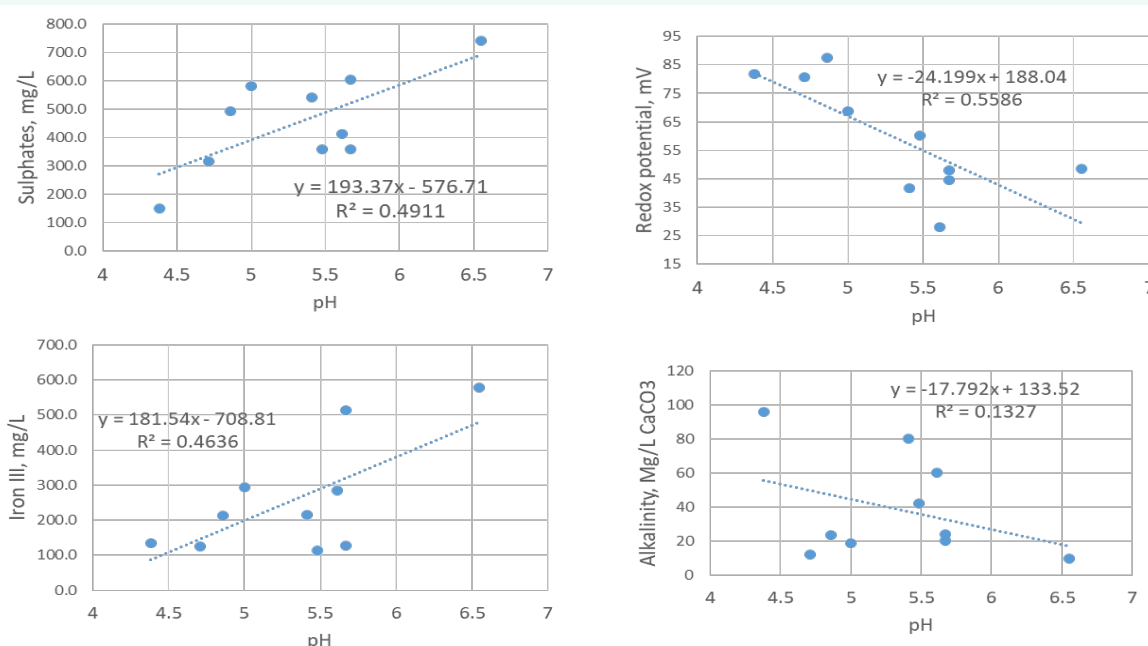


Figure 8: Relationship between sulphates and pH, redox potential and pH, iron III and pH and alkalinity and pH in Nyaruzinga wetland (70 cm deep) from April to Sept. 2022.

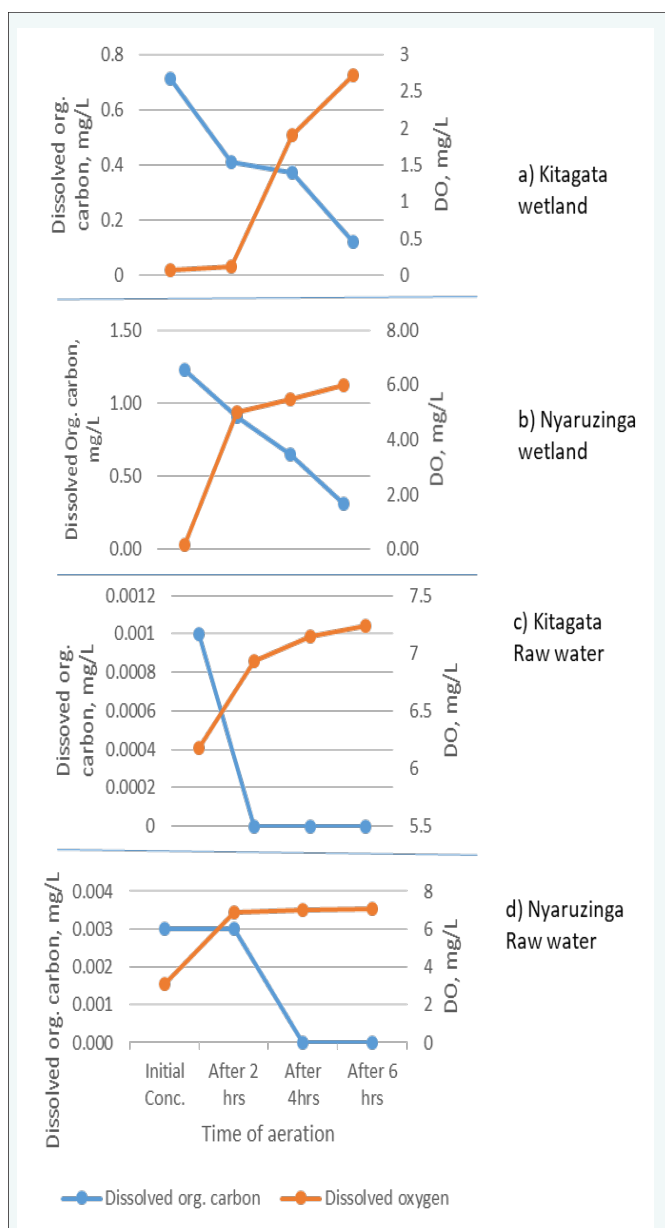


Figure 9: Effect of progressive increased dissolved oxygen (aeration) on dissolved organic carbon in Nyaruzinga and Kitagata wetlands (at 70 cm deep) and raw water a). Kitagata wetlands at 70 cm deep, b). Nyaruzinga wetland at 70 cm deep c). Kitagata raw water (dam) and d). Nyaruzinga raw water.

cm deep to the surface, the DO levels do not seem to have been adequate enough to cause F^{2+} oxidation to F^{3+} since there was corresponding increase in F^{2+} concentration. The results instead showed a decrease in F^{3+} , sulphides, sulphates and a significant decrease ($p = 0.007$) in manganese. The results suggest that the main driver inhibiting oxidation of iron II, sulphides and manganese could have been abundance of organic matter with limited dissolved oxygen causing anaerobic conditions. The anaerobic conditions likely favoured microbial organic matter decomposition as the electron donor for their respiratory survival [2,26]. Additionally, the anaerobic conditions favoured the action of iron reducing bacteria and sulphate reducing bacteria, hence the declining concentration of F^{3+} and sulphates [27]. The fairly strong positive

correlation between sulphates and pH in the wetland at 70 cm below the surface while there appeared to be no correlation at the wetland surface could be as a result of the action of sulphate reducing bacteria under anaerobic conditions resulting in a slight pH increase [11]. The pH increase however did not rise above acidic conditions (maximum pH 6.5) due to abundance of organic matter and prevailing anaerobic conditions [7,11]. The results also showed a significant increase in DO ($p = 0.005$) from the wetland to the raw water dam, together with significant decrease in calcium ($p = 0.05$), magnesium ($p = 0.05$) and alkalinity ($p = 0.008$). There was also corresponding significant decrease in sulphates ($p = 0.05$) and sulphides ($p = 0.003$) and some marked decrease in iron III and manganese concentrations. The significant increase ($p = 0.005$) in DO from the wetland surface to the raw water dam which corresponded with decrease in Eh implies that abundance of organic matter could be a primary determining factor for oxidation-reduction (Eh) and pH levels in the wetland (both at the surface and 70 cm deep) than DO [7]. Dissolved oxygen concentration being significantly higher ($p = 0.005$) at the wetland surface than at 70 cm deep particularly during the wet season implies that the increased flooding during the rainy season diminished the possibility of DO penetration in the wetland sediments at least up to 70 cm deep [28]. The prevalence of anaerobic conditions and slow microbial mineralization of organic matter released DOC together with heavy metal elements, particularly Cu, Cr, Co, Ni and Pb [29]. The mineralization of organic matter could further be responsible for the fairly negative correlation between sulphates and sulphides both at the wetland surface and 70 cm deep during prolonged flooding with lowering of dissolved oxygen. The organic matter mineralization also resulted in release of redox sensitive metals particularly Fe and Mn through reduction of their sulphates and oxyhydroxides to sulphides. The concomitant release of DOC including humic substances together with not only reduced Fe and Mn compounds but also trace metals particularly Cu, Cr, Co, Ni and Pb have been reported [6,29]. Formation of humic substances, particularly the low molecular weight humic substances, is likely to be the major contributor to maintaining the acidity in Nyaruzinga wetland and the raw water (dam) [30]. The Nyaruzinga wetland having higher concentration of humic substances and building blocks (breakdown products of humic substances) and low molecular weight acids compared to Kitagata wetland could be the reason for lower pH of Nyaruzinga wetland.

The raw water pH being significantly higher than for treated water (final and distribution network) was because of application of coagulants and chlorine for clarification and disinfection both of which react by lowering the pH [21]. Much as soda ash (sodium carbonate) was applied for raising the pH in the distribution network, the extent of pH correction was not adequate enough to raise it above the raw water pH level. The average EC of treated and supplied water being significantly higher ($p = 0.005$) than in the wetland and raw water, could similarly be explained by the application of coagulants, chlorine and soda ash all of which introduce more ionic compounds in the water [21]. The pH in the distribution system at Katungu tank and Bumbeire PSP was significantly lower than that in the Kikuba tank and Market PSP-Bushenyi, since the latter two sampling points received water from Kitagata plant which releases treated water that exhibits relatively higher pH (6.5-7.1). There was no detectable DOC in treated water, likely due to coagulation, flocculation and sedimentation processes.

CONCLUSION:

- The low pH and alkalinity of water in Nyaruzinga wetland is attributed to prolonged water logging that inhibits dissolved oxygen diffusion, causing anaerobic conditions, and leading to organic matter accumulation.
- Significant dissolved oxygen increase in the raw water dam compared to the wetland does not cause increase in sulphates, iron III, manganese and electrical conductivity, implying that the prevailing accumulation of organic matter in the water-logged wetland under



anoxic conditions is likely the primary determining factor for rising redox potential and lowering pH levels than dissolved oxygen.

- Perennial anaerobic conditions at the depth of 70 cm in Nyaruzinga wetland favoring microbial organic matter mineralization leads to release of redox sensitive minerals, particularly iron and manganese with DOC, mainly in the form of low molecular weight humic substances and their building blocks responsible for prevailing low pH. There is concurrent release of trace heavy metal elements, particularly copper, chromium, cobalt, nickel, and lead that are bound to DOC.

ACKNOWLEDGMENT

The authors are grateful for the support from fellow staff at the National Water and Sewerage Corporation (NWSC) Bushenyi-Ishaka Area and Central Laboratory, Kampala for the support during sampling and laboratory analysis.

REFERENCES

1. Lee S, McCarty GW, Moglen GE, Lang MW, Jones CN, Palmer M, et al. Seasonal drivers of geographically isolated wetland hydrology in a low-gradient, coastal plain landscape. *Journal of Hydrology*. 2020; 583: 124608.
2. Jackson R, Thompson J, Kolka R. Wetland soils, hydrology, and geomorphology. In: Batzer, D., Sharitz, R. (Eds.) *Ecology of freshwater and estuarine wetlands*. Berkeley. 2014.
3. Knorr KH. DOC-dynamics in a small headwater catchment as driven by redox fluctuations and hydrological flow paths—are DOC exports mediated by iron reduction/oxidation cycles? *Biogeosciences*. 2013; 10: 891-904.
4. Gu S, Gruau G, Dupas R, Petitjean P, Li Q, Pinay G. Respective roles of Fe-oxyhydroxide dissolution, pH changes and sediment inputs in dissolved phosphorus release from wetland soils under anoxic conditions. *Geoderma*. 2019; 338: 365-374.
5. Barbosa MV, Fernandes TA, Siqueira GB, de Siqueira FL, de Moraes PB. Spatial variability of the physicochemical properties of soils from seasonally flooded forest fragments on a tropical plain. *Applied and Environmental Soil Science*. 2019; 2019: 1814937.
6. Davranche M, Grybos M, Gruau G, Pédrot M, Dia A, Marsac R. Rare earth element patterns: A tool for identifying trace metal sources during wetland soil reduction. *Chemical Geology*. 2011; 284: 127-137.
7. Reid RJ, Mosley LM. Comparative contributions of solution geochemistry, microbial metabolism and aquatic photosynthesis to the development of high pH in ephemeral wetlands in South East Australia. *Science of the Total Environment*. 2016; 542: 334-343.
8. Boulogne I, Ozier-Lafontaine H, Merciris P, Vaillant J, Labonte L, Loranger-Merciris G. Soil chemical and biological characteristics influence mineralization processes in different stands of a tropical wetland. *Soil Use and Management*. 2016; 32: 269-278.
9. Köhler SJ, Lidman F, Laudon H. Landscape types and pH control organic matter mediated mobilization of Al, Fe, U and La in boreal catchments. *Geochimica et Cosmochimica Acta*. 2014; 135: 190-202.
10. Husson O. Redox potential (Eh) and pH as drivers of soil/plant/microorganism systems: A transdisciplinary overview pointing to integrative opportunities for agronomy. *Plant and soil*. 2013; 362: 389-417.
11. Jayalath N, Mosley LM, Fitzpatrick RW, Marschner P. Addition of organic matter influences pH changes in reduced and oxidised acid sulfate soils. *Geoderma*. 2016 ;262:125-132.
12. Taylor CM, Prigent C, Dadson SJ. Mesoscale rainfall patterns observed around wetlands in Sub-Saharan Africa. *Quarterly Journal of the Royal Meteorological Society*. 2018; 144: 2118-2132.
13. Marks SJ, Clair-Caliot G, Taing L, Bamwenda JT, Kanyesigye C, Rwendeire NE, et al. Water supply and sanitation services in small towns in rural-urban transition zones: The case of Bushenyi-Ishaka Municipality, Uganda. *NPJ Clean Water*. 2020; 3: 21.
14. Safari D, Mulongo G, Tumwesigye W, Byarugaba D. Impact of human activities on the quality of water in nyaruzinga wetland of bushenyi district-Uganda. *International Science Congress Association*. 2012.
15. Muhangane L, Nkurunungi JB, Yatuha J, Andama M. Suitability of drinking water sources from Nyaruzinga Wetland for domestic use in Bushenyi Municipality, Uganda. *Journal of Water Resource and Protection*, 2017; 9: 1587-1611. Twesigye I. Assessment of Bushenyi-Ishaka water treatment and supply system using the water safety planning approach. MSc thesis, Makerere University, Kampala, Uganda. 2021. UNBS, 2015. Potable Water-Specification, US EAS 12: 2014.
16. NWSC. National Water and Sewerage Corporation, Uganda, Annual Report 2018-2019.
17. Davranche M, Gruau G, Dia A, Marsac R, Pédrot M, Pourret O. Biogeochemical factors affecting rare earth element distribution in shallow wetland groundwater. *Aquatic Geochemistry*. 2015; 21: 197-215.
18. Paul, R. Water governance in small towns at the rural-urban intersection: The case of bushenyi-ishaka, uganda. Masters Thesis, IHE Delft-Institute for Water Education, Delft, the Netherlands. 2018.
19. Katrivesis FK, Karela AD, Papadakis VG, Paraskeva CA. Revisiting of coagulation-flocculation processes in the production of potable water. *Journal of Water Process Engineering*. 2019; 27: 193-204.
20. APHA, AWWA, WEF. Standard Methods for Examination of Water and Wastewater. 22nd ed. Washington: American Public Health Association. 2012; 1360.
21. Huber SA, Balz A, Abert M, Pronk W. Characterisation of aquatic humic and non-humic matter with size-exclusion chromatography-organic carbon detection--organic nitrogen detection (lc-ocd-ond). *Water Res*. 2011; 45: 879-885.
22. Nascimento DC, Berbert CP, Ribeiro BT. Electrochemical attributes of water from cerrado wetlands (veredas), triângulo mineiro region, Brazil. *Revista Ciência Agronômica*. 2018; 49: 11-21.
23. Zhang Z, Furman A. Soil redox dynamics under dynamic hydrologic regimes - A review. *Sci Total Environ*. 2021; 763: 143026.
24. Karimian N, Johnston SG, Burton ED. Iron and sulfur cycling in acid sulfate soil wetlands under dynamic redox conditions: A review. *Chemosphere*. 2018; 197: 803-816.
25. Seo DC, DeLaune RD. Effect of redox conditions on bacterial and fungal biomass and carbon dioxide production in Louisiana coastal swamp forest sediment. *Sci Total Environ*. 2010; 408: 3623-3631.



26. Tokarz E, Urban D. Soil redox potential and its impact on microorganisms and plants of wetlands. *Journal of Ecological Engineering*. 2015; 16: 20-30.
27. Grybos M, Davranche M, Gruau G, Petitjean P. Is trace metal release in wetland soils controlled by organic matter mobility or Fe-oxyhydroxides reduction? *Journal of colloid and interface science*. 2007; 314: 490-501.
28. Watanabe A, Moroi K, Sato H, Tsutsuki K, Maie N, Melling L, et al. Contributions of humic substances to the dissolved organic carbon pool in wetlands from different climates. *Chemosphere*. 2012; 88: 1265-1268.