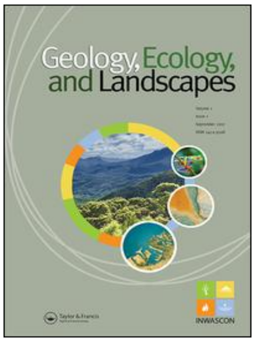

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RESEARCH ARTICLE

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# Assessment of water quality of lakes used for recreational purposes in abandoned mines of Linden, Guyana

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**ABSTRACT**

The open pit method is often the easiest and the most inexpensive form of mining. Bauxite mining, which commenced in 1916 in Linden, Guyana, has left many abandoned pits upon closure of mining activities; subsequently pit lakes have been formed. Globally, Acid Mine Drainage (AMD) is a common water quality problem for pit lakes. However, the pit lakes in Linden are used for recreational activities. In this study, the water quality of three lakes in Linden (NE Kara Kara, Kara Kara and Lucky Spot) were analysed for their physico-chemical characteristics. The morphological and aesthetic features were also examined. The study showed that all three lakes are acidic, with mean pH values of 3.4, 3.1 and 4.7, which are not within the allowable range for recreational waters. Mean concentrations of Al (23.06 mg/l), Fe (10.56 mg/l) and Mn (2.4 mg/l) exceeded acceptable limits; nevertheless, TDS levels measured were within the acceptable limits. In terms of aesthetic quality, NE Kara Kara and Kara Kara pit lakes were free from any form of waste and debris. For the pit lakes to be considered suitable for recreational purposes, treatment of the lakes' waters is recommended.

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**KEYWORDS**
Pit lake; chemical parameters; morphological parameters; aesthetic parameters; Acid Mine Drainage

## 1. Introduction

The environment serves as a viable source of food, shelter and clothing for humans. However, this dependence on natural resources by humans for survival has intensified conflicts between the natural environment and humans for decades, which has impacted geological and biochemical processes (Blanchette & Lund, 2016; Doyle & Runnells, 1997; El-Zeiny & El-Kafrawy, 2016; Søndergaard, Launridsen, Johansson, & Jeppesen, 2018). Perhaps, no natural resource is more altered by human activities than land (Betournay, 2016), with its over-the-years impacts on water resources as an example (Mollema & Antonellini, 2016; Muellegger, Weilhartner, Battin, & Hofmann, 2013). The mining operations for resources, such as bauxite, gold, coal, utilise the open pit method (Mossa & James, 2013; Oggeri, Fenoglio, Godio, & Vinai, 2019). While this method is considered the most common and inexpensive method for extraction of these resources, it causes serious environmental impacts which can take decades to correct (Bangian, Ataei, Sayadi, & Gholinejad, 2012; González, Olías, Macías, Cánovas, & de Villaránc, 2018; Robles-Arena & Candela, 2010; Younger, Banwart, & Hedin, 2002). To expose the ore for mining, it is necessary to excavate large quantities of waste materials (also called overburden) to gain direct access to the ore (González et al., 2018; Oggeri et al., 2019); the void created by the excavation is left opened for the full extent of the mine's life (Fourie & Dohm, Jr, 1992). The removed overburden may be later used in the backfilling process during mine closure rehabilitation (Betournay, 2016). However, if the restoration and rehabilitation activities are not conducted on the mined-out site, the excavated voids can over time develop into pit lakes (Boehrer, Yusta, Magin, & Sánchez España, 2016; Fabri, Carneiro, & Leite, 2013; Savage, Bird, & Ashley, 2000).

The development of pit lakes at abandoned mine sites is a common side effect of open pit mining (Blanchette & Lund, 2016; Chapman, 2002). Pit lakes, moreover, can lead to Acid Mine Drainage (ADM) with resultant effect in poor water quality (Castendyk, 2011; Castendyk, Balistrieri, Gammons, & Tucci, 2015; Castendyk & Webster-Brown, 2007; Koschorreck & Tittel, 2002; McCullough & Lund, 2006; McCullough, Marchant, Unseld, Robinson, & O'Grady, 2012; Mhlongo & Dacosta, 2014; Søndergaard et al., 2018). Nevertheless, pit lakes are regularly used for recreational activities (Doupe & Lymbery, 2005; Hinwood, Heyworth, Helen, & McCullough, 2012).

Bauxite mining in Linden, Guyana commenced in 1916 (Joaquin, 2017). However, upon closure of these mine fields, rehabilitation and restoration works were not considered as very important in the mine closure activity. This was due to the lack of operational and regulatory requirements at the time of closure.

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Therefore, there has been the abandonment of many open pit mine sites established in the early years of bauxite mining which has resulted in pit lakes. Data on these pit lakes is lacking due to limited scientific research. This lack of data and little focus on the chemical water quality of pit lakes can result in several unidentified environmental and social effects (Hinwood et al., 2012). Importantly, this lack of data has led to uninformed decisions by the public, as it relates to use of the lakes. The pit lakes in Linden, as it is common in other developing countries, are regularly used for recreational activities. The aim of this study therefore is to assess the water quality of three pit lakes regularly used for recreational purposes in Linden. The objectives in this study are: to assess the physico-chemical quality of the pit lakes; and to describe their morphological and aesthetic characteristics. This study is expected to contribute to the exiting pool of knowledge of pit lakes around the world. It can also pave the way for further scientific research on pit lakes derived from mining activities such as sand or gold mining and can aid in decision making regarding beneficial end use(s) for pit lakes.

## 2. Material and methods

### 2.1 Study area

Guyana is located on the northern coast of South America and is a member state of the Caribbean Community. The country is considered the third smallest independent nation on the continent, with only 215,000 square kilometres (83,000 square miles) of land (World Population Review, 2018). Linden is the second largest town in Guyana, located in the tenth administrative region (Upper Demerara – Upper Berbice) about 101 kilometres (63 miles) from the capital, Georgetown (Figure 1a). The town is divided into shores by the Demerara River – the Mackenzie and Wismar shores. According to the last conducted census in 2012, the town's population is approximately 30,000 inhabitants (Guyana Bureau of Statistics, 2012). The residents are engaged in small-scale farming, logging, gravel and bauxite mining (National Trust of Guyana, 2018).

Guyana lies south of the Caribbean and its climate is influenced by the northeast trade winds. The tropical climate is almost uniform in terms of temperatures and humidity. However, seasonal variations in temperature are slight and are experienced, particularly along the coast (Merrill, 1993). The climate in Linden is classified as *Af*, which indicates a tropical rainforest climate. The climate is generally characterised by two (2) wet and 2 dry seasons – December to February and May to July are the wet seasons, while mid-February to April and August to November are the dry seasons. Rainfall mean is 2350 mm annually. March is considered the driest month with 116 mm of rainfall. The highest amount of precipitation occurs in June, with a mean of 312 mm. The mean annual temperature is 26.5 °C with the warmest month being in October (mean temperature 27.4 °C) and the coolest being in January (mean temperature 25.7 °C) (Climate Data, URL).

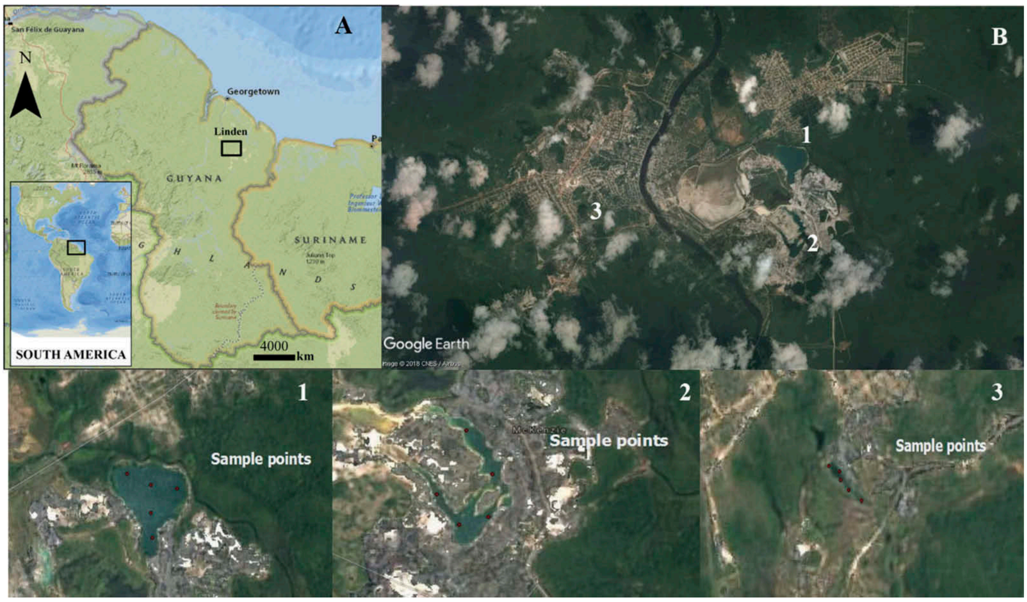


Figure 1. (a) Location of the study area (Inset: South America showing the location of Guyana and Map of Guyana showing Linden where the Lakes are located) (b) Google map of Linden and the three (3) Pit Lakes studied. 1 – North East (NE) Kara Kara mine, 2 – Kara Kara mine and 3 – Luck spot mine, showing sampling points. Data Sources: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp. Credit: Content may not reflect National Geographic's current map policy. Imagery Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

This study targets three (3) pit lake sites in Linden. Pit Lakes 1 and 2 are located on the Mackenzie shore and Pit Lake 3 is located on the Wismar shore (Figure 1b). The sites were chosen based on the local knowledge of its recreational use and accessibility. Pit Lake 1 is called North East (NE) Kara Kara mine while Pit Lake 2 and Pit Lake 3 are called Kara Kara mine and Lucky Spot mine, respectively. The soil type for the study site is generally defined as fine to medium sand (grey, black, brown or white); and soft grey and dark brown clay (GGMC & Linmine, 1995).

### 2.2 Data collection and analysis

A multi-parameter metre (HACH HQ40d) was used to measure surface water quality at each of the pit lake sites for pH, temperature, total dissolved solids (TDS) and total dissolved oxygen (TDO). Clarity was measured using a Secchi disk, and turbidity was measured using a HACH 2100P turbidimeter. Five (5) water samples were taken from each of the three sample sites at random points; spatial locations of which were marked using a Garmin Series 62 GPS-MAP system during the fieldwork of February 2018. Samples from each of the sites were stored in 125 millilitre (ml) sterile containers for laboratory analyses. One sample from each lake was collected for the testing of faecal coliform to determine the concentration of coliform bacteria associated with the possible presence of disease-causing organisms. The concentrations of the elements aluminium, manganese, chromium, iron, arsenic, lead, copper, cadmium, zinc were determined using the Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) and faecal coliform was tested using the Most Probable Number (MPN) method. The methods of data collection and analysis used in this study are well documented in literature, for example McCullough (2015), and Søndergaard et al. (2018).

The physical and chemical water quality results were compared with two recreational water quality guidelines: (1) *Guidelines for Canadian Recreational Water Quality* (Health Canada, 2012); and, (2) *Guidelines for recreational water quality and aesthetics* in *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZECC& ARMCANZ, 2000) in the absence of in-country guidelines. Additionally, the former standard was used to identify the parameters which were examined for the aesthetic characteristics. Similar to De Lange, Genthe, Hill, and Oberholster (2018), the physical characteristics examined in this study also considered selected morphological characteristics of the pit lakes.

The physical characteristics assessed in the field were mean depth, sediment type, hydroperiod, surrounding land use and presence of aquatic plants. Mean depth was measured using the 20 metre (m) length of the rope of a Secchi disk, which was submerged into the lake at three points and the mean of the three points was then calculated. In cases where the entire (20 m) length of the rope was submerged, that point was considered greater than 20 m. Lake area, shape, type of pit lake, and prior mining activity were also evaluated and considered. Water samples collected from the pit lakes were analysed in the laboratory. The aesthetic considerations discussed in this study were from the on-the-field observation. Presence or absence of materials like broken glass or other sharp objects, large rocks, litter, floating debris, medical wastes, seaweed or algae on shore line are some of the things looked out for on the sites, in addition to the consideration of access to the sites via automobiles, boats or on foot (after Health Canada, 2012).

Spearman's Rank Correlation statistical test for the results were undertaken using the Paleontological Statistics (PAST) software (after Hammer, Harper, & Ryan, 2001; Oyedotun, 2016), to determine the connection and variances between the parameters and sites.

## 3. Results

### 3.1 Chemical and microbiological parameters

The chemical characteristics in this study focused on the fourteen (14) determinants: pH, TDO, TDS, manganese, arsenic, cadmium, chromium, lead, aluminium, copper, iron, zinc, silicon, titanium, and one microbiological parameter (faecal coliform) which are critical for determining the water quality of the pit lakes.

#### 3.1.1. pH, total dissolved solids (TDS) and total dissolved oxygen (TDO)

The mean pH of all the samples collected was 3.7. Specifically, the mean pH values for NE Kara Kara, Kara Kara and Lucky Spot were 3.4, 3.1 and 4.7, respectively (Figure 2). The results were not within the ANZECC & ARMCANZ (2000) and Health Canada (2012) range of 5.0–9.0. The results for TDS indicated that all the samples collected were within the acceptable limit of 1,000 mg/l specified by ANZECC & ARMCANZ (2000). In this study, Pit Lake 2 had the highest TDS concentration (Figure 2). The mean TDS values were as follows: NE Kara Kara 306.6 mg/l, Kara Kara 443.0 mg/l and Lucky Spot 5.2 mg/l. Total Dissolved Oxygen (TDO) is considered as one of the best indicators of the health of any aquatic ecosystem (Muigai, Shiundu, Mwaura, & Kamau, 2010). The mean TDO for the samples was 8.1 mg/l, which is in accordance with the standard of > 6.5 mg/l stipulated by ANZECC & ARMCANZ (2000). NE Kara Kara had the highest concentration of 8.2 mg/l, followed by Kara Kara with a TDO of 8.1 mg/l and Lucky Spot with a TDO of 8.0 mg/l.

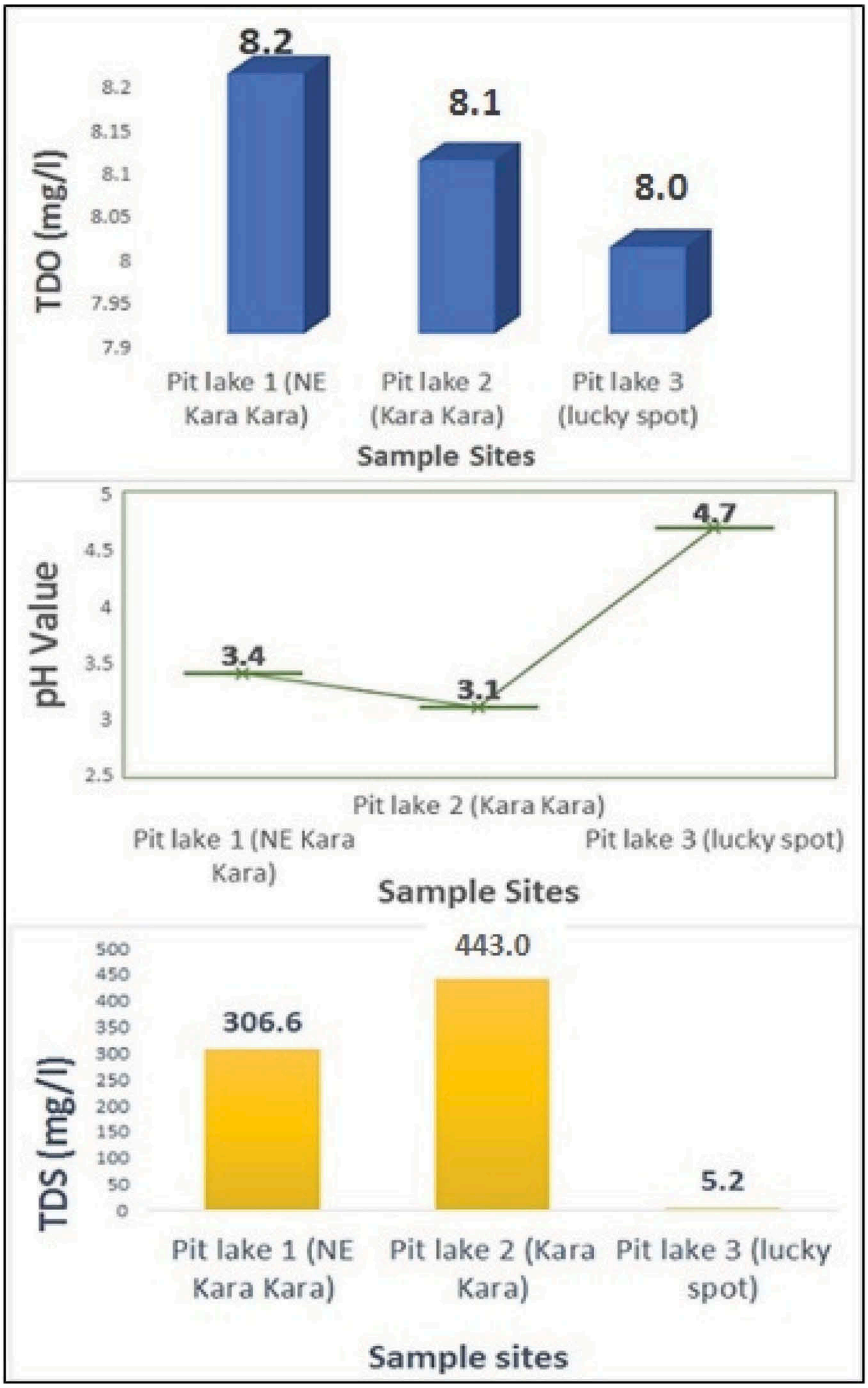


**Figure 2.** Mean pH, TDS and TDO for the three Pit Lake sample sites.

### *3.1.2. Aluminium, titanium and silicon*

Aluminium, titanium and silicon were analysed because of the high-quality composition of these chemicals in bauxite ore, which was the main material previously being mined in the study area. The extremely high levels of the composition of these materials can be dangerous (Eccarius, 1998; Fabri et al., 2013), therefore the need for their consideration in the analyses. The results for aluminium indicated that the samples collected from Pit Lakes 1 and 2 were not within the acceptable limit of 0.2 mg/l as specified by ANZECC & ARMCANZ (2000); the recorded values were 9.02 mg/l and 23.06 mg/l respectively. Pit Lake 3, on the other hand, had the lowest concentration of aluminium and it was within the ANZECC & ARMCANZ (2000) guideline (Figure 3). The mean titanium concentration for NE Kara Kara, Kara Kara and Lucky Spot sample sites was 10 µg/l. Results for silicon revealed that the mean was 4.2 mg/l. Specifically to the sites, Kara Kara had the highest concentration of 7.1 mg/l, followed by NE Kara Kara with a value of 5.1 mg/l, and Lucky Spot with a concentration of 0.4 mg/l (Figure 3). However, neither titanium nor silicon are included in the two recreation water quality guidelines as elements of concern.

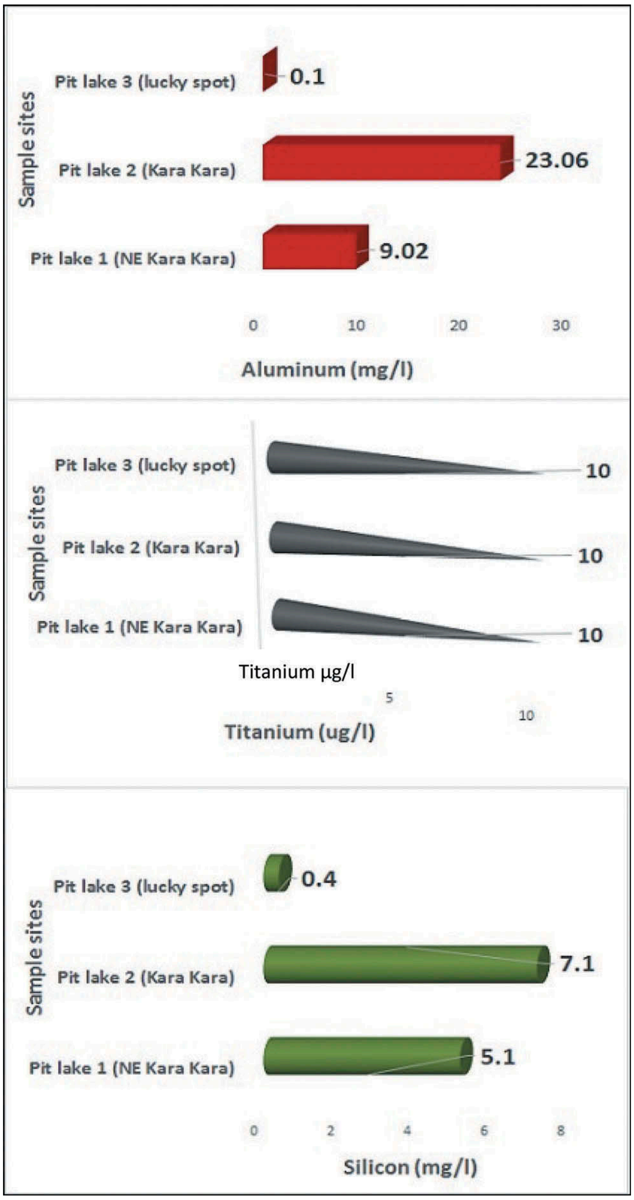


Figure 3. Mean concentrations of aluminium, titanium and silicon in the lakes.

### 3.1.3. Chromium, manganese and arsenic

The mean concentration of chromium for Pit Lakes 1, 2 and 3 was 20 µg/l. All results obtained were within the limit of 50 µg/l (ANZECC & ARMCANZ, 2000). The mean concentration of manganese was 1.58 mg/l. The mean manganese concentration for NE Kara Kara was 2.40 mg/l, for Kara Kara it was 2.14 mg/l, and for Lucky Spot, it was the lowest at 0.20 mg/l (Figure 4). These values exceeded the ANZECC & ARMCANZ (2000) acceptable limit of 0.1 mg/l. However, the mean arsenic concentration was within the acceptable limit of 50 µg/l (ANZECC & ARMCANZ, 2000). The mean concentration of arsenic at all three sites was 30 µg/l (Figure 4).

### 3.1.4 Lead, copper and cadmium

The mean concentration of lead for all the samples indicated that they were all within the limit of 50 µg/l as specified by ANZECC & ARMCANZ (2000). The mean for NE Kara Kara was 10 µg/l, Kara Kara was 15 µg/l and Lucky Spot was 10 µg/l. Regarding the copper levels, Pit Lake 2 (Kara Kara) had the highest concentration (Figure 5), while Pit Lakes NE Kara Kara and Lucky Spot had a value of 2 µg/l each. All values obtained were below or within the recommended limit of 1000 µg/l. Additionally, the mean concentration of cadmium for the three pit lakes was 2 µg/l (Figure 5), which was within the limit of 5 µg/l (ANZECC & ARMCANZ, 2000).

### 3.1.5 Zinc, iron and faecal coliform

The mean concentration of zinc in the samples from Kara Kara was 498.4 µg/l, which was the highest concentration compared to the other pit lakes. Pit Lakes 1 and 3 recorded zinc values of 103.4 µg/l and 9.75 µg/l, respectively (Table 1). However, these results do not exceed the limit of 5000 µg/l recommended by ANZECC & ARMCANZ (2000). The mean result for the iron of all the samples was

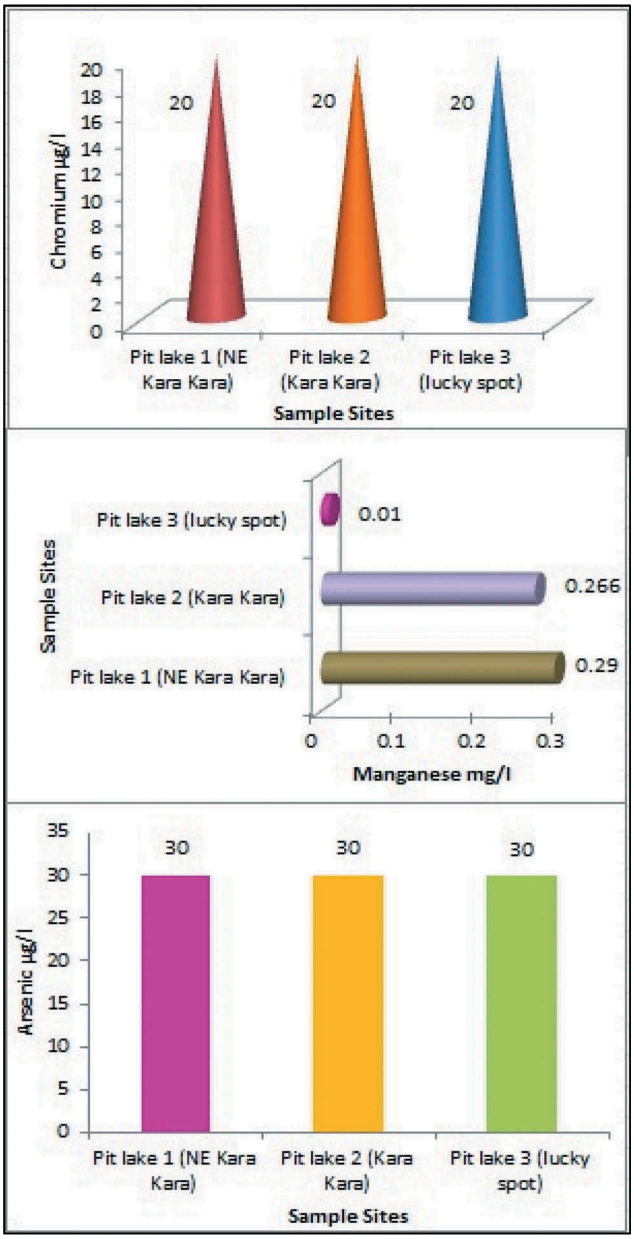


Figure 4. Mean concentrations of manganese, chromium and arsenic in the sampled pit lakes.

4.85 mg/l while for each individual site the mean levels of iron were: for NE Kara Kara it was 3.96 mg/l, for Kara Kara it was 10.56 mg/l and for Lucky Spot it was 0.032 mg/l. Pit Lakes 1 and 2 were above the ANZECC & ARMCANZ (2000) limit of 0.3 mg/l. The results for faecal coliform indicated that all the samples collected were within the acceptable limit of 150 MPN/100 ml recommended by ANZECC & ARMCANZ (2000). Pit Lake 1, 2 and 3 all had faecal coliform levels of 0 MPN/10 ml (Table 1).

## 3.2 Physical characteristics

### 3.2.1 Morphological characteristics

The surface areas of the pit lakes varied from 16,790 $m^2$ to 478,293 $m^2$ and the mean depths varied from 16.3 m to > 20 m (Table 2). The mean depths in Pit Lakes 1 and 2 were greater than 20 m; they were deeper than Pit Lake 3 with a mean depth of 16.5 m (Table 2). All the pit lakes were sandy with permanent waterlogged hydroperiods. All lakes were acidic with pH values below 5 and a mean pH of 2.28 (Figure 2). Bauxite mining was the prior mining activity at all sample sites. In terms of shape, Pit Lakes 1 and 2 can be considered as irregular while Pit Lake 3 is linear. Pit lakes 1 and 2 had aquatic plants which were submerged and attached to the sediments in the littoral zone while there were no aquatic plants in Pit Lake 3. Regarding possible water pollution source and the directional flow of it, Pit Lake 1 was the only lake with a possible pollution source (Kara Kara Creek) which flows west of the lake and is separated by a dam. The Kara Kara Creek runs through the Kara Kara community and drains into the Demerara River.

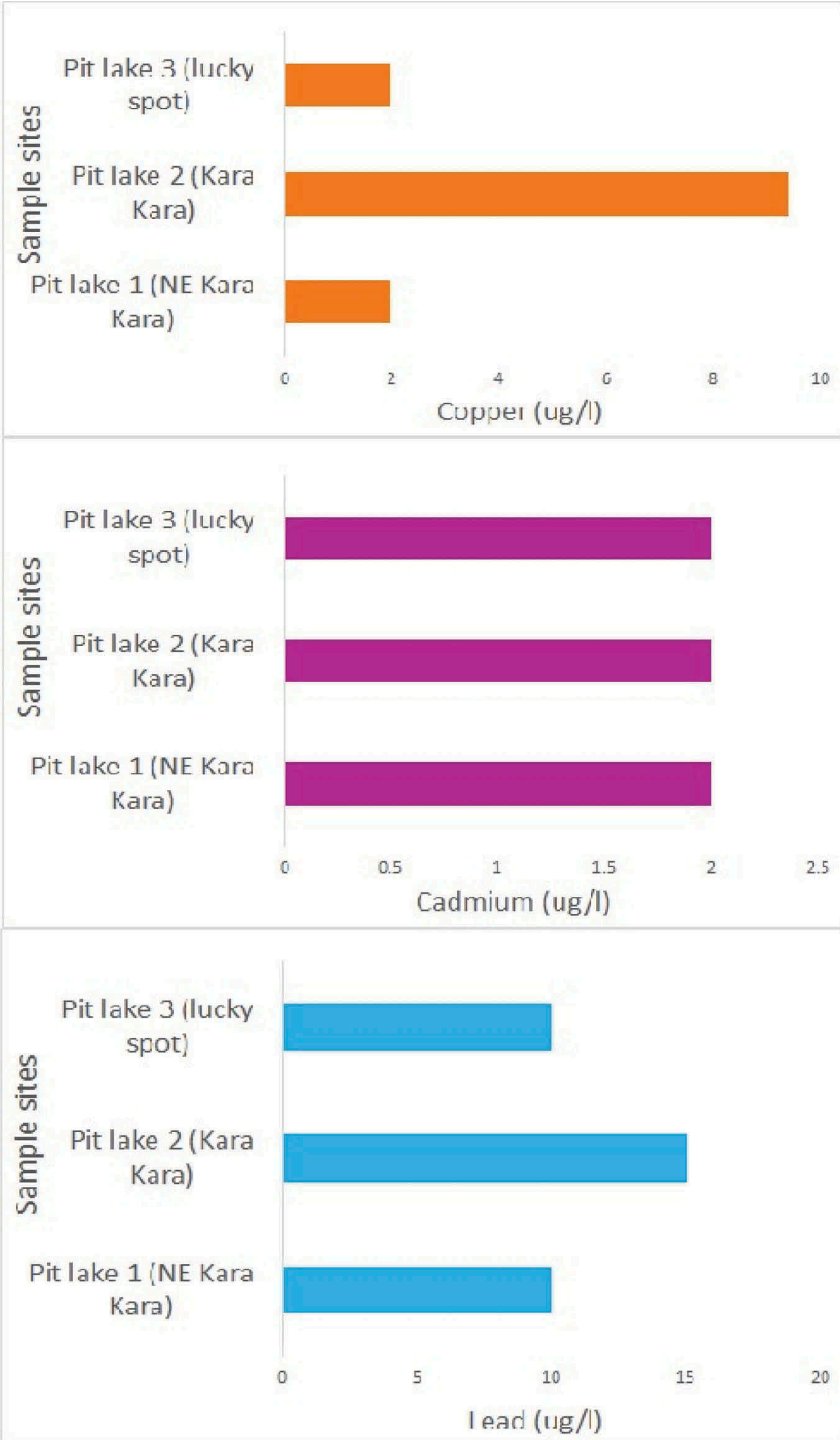


**Figure 5.** Mean concentrations of lead, copper and cadmium in pit lakes' waters.

**Table 1.** Mean concentration of Zinc, Iron and Faecal coliform.

| Parameters | Pit lake 1 (NE Kara Kara) | Pit lake 2 (Kara Kara) | Pit lake 3 (Lucky Spot) |
|---|---|---|---|
| Iron (mg/l) | 3.96 | 10.56 | 0.032 |
| Zinc (µg/l) | 103.4 | 498.4 | 9.75 |
| Faecal coliform (MPN/10 ml) | 0 | 0 | 0 |

### *3.2.2 Clarity, turbidity and water temperature*

Mean water temperature for Lucky Spot was 32.0 °C which was the highest when compared to the other pit lakes. Pit lakes 1 and 3 recorded mean temperatures of 31.4 °C and 31.5 °C, respectively (Figure 6). The results were within the allowable limit of 33 °C (ANZECC & ARMCANZ, 2000). The mean turbidity of all the samples collected was 0.83 nephelometric

Table 2. Physical variables and the results obtained for each pit lake.

| Variables | Pit Lake 1 | Pit Lake 2 | Pit Lake 3 |
|---|---|---|---|
| Hydroperiod | Permanent | Permanent | Permanent |
| Pit lake shape | Irregular | Irregular | Linear |
| Pit lake type | Acidic | Acidic | Acidic |
| Previous mining activity | Bauxite | Bauxite | Bauxite |
| Possible Pollution source (PPS) | Creek | None | None |
| Directional flow of PPS | West | None | None |
| Conservation area | No | No | No |
| Surface area ($m^2$) | 478,293 | 318,187 | 16,790 |
| Mean depth (m) | > 20 | > 20 | 16.5 |
| Sediment type | Sand | Sand | Sand |
| Aquatic plants | Submerged (below water, roots attached) | Submerged (below water, roots attached) | No aquatic plants |

turbidity units (NTU). The mean turbidity for NE Kara Kara and Lucky spot were both 0.7 NTU, while the turbidity in Kara Kara was 1.1 NTU. The turbidity levels of all pit lakes were below the acceptable limit of 50 NTU (ANZECC & ARMCANZ, 2000). The results for clarity indicate that all the pit lakes were within the limit of 1.6 m specified by ANZECC & ARMCANZ (2000) and 1.2 m specified by Health Canada (2012). Pit Lake 1 had a clarity reading of 5.9 m, Pit Lake 2 had a value of 4 m and Pit Lake 3 a reading of 2.6 m (Figure 6).

### 3.2.3 Aesthetic considerations

Pit Lakes 1, 2 and 3 were free from any form of floating debris on the lake water. Additionally, there were no broken glass or sharp objects, nor large rocks, seaweed, algae, medical waste on the shoreline of any of the pit lakes. However, only Pit Lakes 1 and 2 were completely free from litter. As it relates to access to the lakes, only Pit Lake 1 could be accessed via vehicular transport and on foot (Table 3).

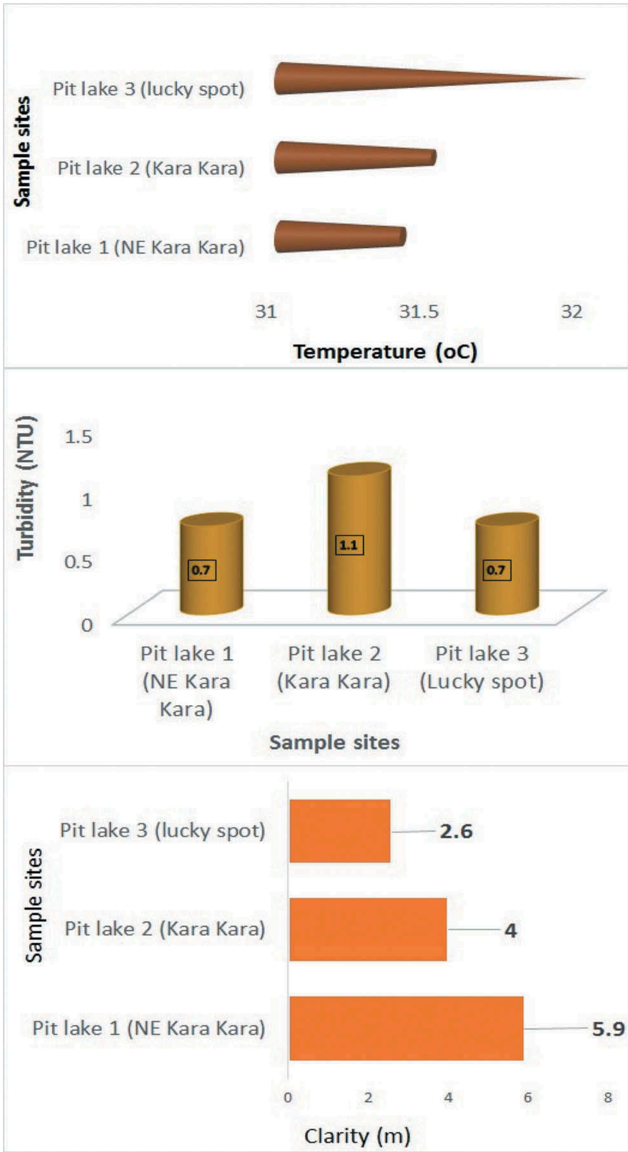


Figure 6. Mean clarity, turbidity and temperature of water in sampled pit lakes.

### 3.2.4 Correlations

The parameters TDO and clarity achieved the strongest positive correlation with an R-value of 0.69. Conversely, the strongest negative correlation was between parameters TDS and pH, with a correlation value of −0.93. Table 5 shows the correlation between the different parameters tested during the field assessment; the analysis was done using the Spearman's rank correlation statistic.

## 4. Discussion

### 4.1 Chemical characteristics

Analysis of the results reveals that water from the NE Kara Kara, Kara Kara and Lucky Spot pit lakes were acidic with pH values which did not achieve the allowable recreational water quality range of 5.0–9.0 units (Figure 2, Table 4). The recorded mean pH was 3.7. It has been established that pit lakes affected by ADM have pH values between 2–4 units (Castendyk et al., 2015; Castendyk & Eary, 2009; Castendyk, Eary, & Balistrieri, 2014; Koschorreck & Tittel, 2002; Kumar, McCullough, Lund, & Larranãga, 2011). A common characteristic of low pH waters is high concentration of metals which would subsequently increase TDS values (Mhlongo & Dacosta, 2014). Nevertheless, concentrations of arsenic, cadmium, chromium, lead, copper and zinc were found to be well within the limits specified by the two guidelines for recreational water quality (ANZECC & ARMCANZ, 2000; Health Canada, 2012) (Table 4). Aluminium, silicon, titanium and iron were major elements found in the soil at the pit lakes, with mean concentrations ranging from 2–70% (GGMC & Linmine, 1995). Although silicon and titanium were not elements of concern in the recreational water quality standards, the mean concentrations were 4.2 mg/l and 10 µg/l respectively. Aluminium and iron concentrations, however, were found to be above the acceptable limit with mean readings of 10.72 mg/l and 4.85 mg/l, respectively. Individual readings for iron and aluminium show that samples taken from the Lucky Spot pit lake were below specified limits (Table 4). Reduced concentration of metals in Pit Lake 3 may be attributed to the neutralisation process which slowly increases the pH level and hence metals become more insoluble, as similarly observed by Islam et al. (2017), Blanchette and Lund (2017), Elwira and Michal (2016). Additionally, concentrations of manganese were found to be above the allowable limit in all three of the pit lakes. TDS refer to total amount of inorganic salts and organic matter present in solution in water. As TDS increases, the pH decreases and vice versa, which demonstrates an inverse relationship (Islam et al., 2017). This rule of thumb was observed and confirmed in this study where a strong negative correlation between pH and TDS, that is, a value of −0.93 was determined (Table 5). The TDS values for the three pit lakes were within the acceptable limit. The TDO values for the three pit lakes were found to be adequate for the survival of biological life (Castendyk et al., 2014; Muigai, et al., 2010; Santofimia & López-Pamo, 2013) with values averaging 8.2 mg/l, 8.1 mg/l and 8.0 mg/l respectively. However, little to no visible aquatic life at the lakes studied suggests that the other conditions may be needed for conducive biological growth (Emmrich, Schälicke, Hühn, Lewin, & Arlinghaus, 2014; Linton &

Table 3. Aesthetic parameters for each pit lake.

| Parameters | Pit Lake 1 | Pit Lake 2 | Pit Lake 3 |
|---|---|---|---|
| Large rocks | Absent | Absent | Absent |
| Litter on shore | None | None | Low |
| Floating Debris | None | None | None |
| Broken Glass or other sharp objects | None | None | None |
| Medical Waste | None | None | None |
| Seaweed or Algae on the shoreline | None | None | None |
| Access to pit lake | Automobiles & on foot | On foot | On foot |

Table 4. Comparison between recreational water quality limits and results.

| Parameter | ANZECC & ARMCANZ (2000) | Health Canada (2012) | Pit Lake 1 | Pit Lake 2 | Pit Lake 3 |
|---|---|---|---|---|---|
| Arsenic (µg/l) | 50 | - | 30 | 30 | 30 |
| pH | 5.0–9.0 | 5.0–9.0 | 3.4 | 3.1 | 4.7 |
| Cadmium (µg/l) | 5 | - | 2 | 2 | 2 |
| Chromium (µg/l) | 50 | - | 20 | 20 | 20 |
| Clarity (m) | 1.6 | 1.2 | 5.9 | 4 | 2.6 |
| Lead (µg/l) | 50 | - | 10 | 15 | 10 |
| Aluminium (mg/l) | 0.2 | - | 9.02 | 23.06 | 0.1 |
| Turbidity (NTU) | - | 50 | 0.7 | 1.1 | 0.7 |
| Copper (µg/l) | 1,000 | - | 2 | 9.4 | 2 |
| Dissolved Oxygen (mg/l) | 6.5 | - | 8.2 | 8.1 | 8 |
| Iron (mg/l) | 0.3 | - | 3.96 | 10.56 | 0.032 |
| Manganese (mg/l) | 0.1 | - | 2.4 | 2.14 | 0.2 |
| Zinc (µg/l) | 5,000 | - | 103.4 | 498.4 | 9.75 |
| Total dissolved Solids (mg/l) | 1,000 | - | 306.6 | 443.0 | 5.2 |
| Temperature (°C) | 33 | - | 31.4 | 31.5 | 32.0 |
| Faecal coliform (MPN/100 ml) | 150 | - | 0 | 0 | 0 |
| Silicon (mg/l) | - | - | 5.1 | 7.1 | 0.4 |
| Titanium (µg/l) | - | - | 10 | 10 | 10 |

Table 5. Correlation coefficient between different parameters measured on site.

| | Temperature | Turbidity | TDS | pH | TDO | Clarity |
|---|---|---|---|---|---|---|
| Temperature | | 0.048963 | −0.46,968 | 0.47,331 | −0.55,103 | −0.34,401 |
| Turbidity | 0.048963 | | 0.57,143 | −0.54,286 | −0.26,727 | 0.052254 |
| TDS | −0.46,968 | 0.57,143 | | −0.93,571 | −0.69,956 | 0.16,397 |
| pH | 0.47,331 | −0.54,286 | −0.93,571 | | 0.07175 | −0.099103 |
| TDO | −0.55,103 | −0.26,727 | −0.069956 | 0.07175 | | 0.69,322 |
| Clarity | −0.34,401 | 0.052254 | 0.16,397 | −0.099103 | 0.69,322 | |

Goulder, 2000; Mollema & Antonellini, 2016; Williams, Whitfield, & Biggs, 2008).

Concentrations of chemical constituents which were above the specified limits could have harmful consequences. For example, aluminium, manganese and iron were not within the acceptable limits. Prolonged exposure to such waters can cause itchy and runny eyes, short-term skin rashes/infections, infections of the mucus membrane in the nasal cavity, and sore eyes (ANZECC& ARMCANZ, 2000; Hinwood et al., 2012; Schmid-Wendtner & Korting, 2006).

### 4.2 Physical characteristics

Historically, the creation of pit lakes has impacted the landscape and environment in many ways. Additionally, these lakes have the potential to contaminate groundwater resources and the wider catchment area (Boehrer et al., 2016; Davis and Ashenberg, 1989; González et al., 2018; Robles-Arena & Candela, 2010; Sarmiento, Nieto, Olías, & Cánovas, 2009; Savage et al., 2000; Søndergaard et al., 2018; Younger et al., 2002). Pit lakes have differing physical characteristics when compared to natural lakes. An assessment of the results obtained revealed that parameters hydroperiod, pit lake type, prior mining activity, conservation practices and sediment type were similar for all the pit lakes. Hydroperiod is the period in which a soil area is waterlogged, which for the pit lakes is in a permanent state. This therefore means that the water in the lakes remains for all year round. Pit Lakes 1 and 2 had aquatic plants which were submerged and attached to the sediments in the littoral zone (Figures 5 and 6). Although, turbidity and clarity values were low and well within the allowable limit for recreational use (Table 4), the depths of Pit Lakes 1 and 2 (> 20 m) increase the risk for recreational activities such as swimming or diving (Hinwood et al., 2012). The shape of Pit Lakes 1 and 2 are irregular (Table 3), while Pit Lake 3 was more linear and had a mean depth 16.5 m, which is considerably lower when compared to Pit Lakes 1 and 2. This depth maybe as a result of continuous in-filling of sediments from the surrounding areas as common with other pit lakes that have been studied elsewhere (e.g. Bangian et al., 2012; Castendyk et al., 2015, 2014). The surface area for the pit lakes ranged from approximately 16,700 to 480,000 $m^2$, with Pit Lake 1 having the greatest surface area of 478,293 $m^2$. As it relates to possible pollution source and its directional flow, Pit Lake 1 was the only lake with a possible pollution source (Kara Kara Creek) (Table 2) which flows west of the lake and is separated by a dam. Physical examination of the dam suggests that the water level of the dam is significantly higher than that of the lakes, as a result the dam overtops during the rainy season contaminating the creek water that flows into the lake.

### 4.3 Aesthetic characteristics

Waters used for recreational purposes should be free from substances or objects that impair its aesthetic quality (ANZECC & ARMCANZ, 2000). An evaluation of the pit lakes studied indicated that they were generally free from unpleasant substances and objects. The exception, however, was Pit Lake 3 which had a small amount of litter on the shore (e.g. Figure 7). This is an indication that the lake is frequently visited and used for recreational and other purposes by the public. The lakes were, however, free from other dangerous and hazardous materials such as broken glasses, sharp objects, medical wastes and algae. The accessibility to the lakes is restricted due to the left-over heaps of sediments which were left around the lakes because of the previous mining excavation and activities. The only access to Pit Lakes 2 and 3 is via foot, while Pit Lake 1 can be accessed both on foot and by use of automobiles.

Figure 7. Example of litter observed at Pit Lake 3 (Lucky Spot lake).

## 5. Conclusion and recommendation

This study investigated the water quality, morphological and aesthetic characteristics of three pit lakes located in abandoned mine areas in Linden, Guyana. Pit Lakes 1 and 2 (NE Kara Kara and Kara Kara) were found to have the highest levels of contaminants present. Pit Lakes 1 and 2 both had mean pH values below 4 units and TDS levels ranging from 306.6 mg/L – 443 mg/L indicating a positive correlation with the high concentrations of metals, including Al (9.02 mg/l and 23.06 mg/l) and Fe (3.96 mg/l and 10.56 mg/l), both of which exceeded the specified limits for recreational use. Of the sixteen (16) chemical, microbiological and physical parameters analysed, a total of twelve (12) parameters for each of the Pit Lakes 1 and 2 was within the acceptable limits and four (4) parameters were not. These parameters are pH, Al, Fe and Mn. For Pit Lake 3, only two (2) of the sixteen water quality parameters did not achieve the allowable limits, they are pH and Mn. Therefore, the results point to the need to consider treatment of the pit lakes' water before the lakes are used for intensive recreational activities; the treatment would neutralise the water and remove aluminium, manganese and iron. Alternatively, rehabilitation of the pit lakes for other uses could be considered.

This study also revealed that the three pit lakes had similar morphological features, namely the sediment type, hydro-period, shape and type although there were differences in the surface areas, depths and presence of aquatic plants. Notwithstanding the fact that aesthetic quality is difficult to measure due to individual preferences, it can be concluded from this study that the lakes were aesthetically pleasing, attributed primarily to the absence of floating debris, seaweed and other hazardous materials.

The results presented in this study highlight the need for further studies, including conducting a human health risk assessment for the heavy metals that exceed the recreational guidelines and undertaking a correlation study between the quality of the sediment/surrounding soil and water quality. Further investigations along these suggested lines of research are hereby recommended prior to the lakes being promoted for use for recreational activities.

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No potential conflict of interest was reported by the authors.

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