Constructed wetlands for the treatment of bauxite residue leachate: Long term field evidence and implications for management

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ABSTRACT

Alkaline leachate from bauxite residue disposal areas is likely to require treatment for post-closure. Traditional treatment methods are not attractive in the long-term due to management requirement, energy input and operational logistics and passive approaches offer an alternative approach. Constructed wetlands are widely cited as a potential treatment option but there is limited data on long term field-scale applications.

Treatment of alkaline residue leachate was assessed over a 52 month period and showed effective pH reductions from ca. pH 11.2 (inflow) to 7.2 (outflow). Trace element content measured during the 4th year of operation demonstrated effective reduction in trace element (Al 17,256 μg/l to 330 μg/l; V 140 μg/l to 13 μg/l) with no evidence of toxicity in test species Vibrio fischeri, Skeletonema costatum, Tisbe battagliai and Oncorhynchus mykiss in the wetland outflow. Sediment analysis found some increases in trace element content but no evidence of accumulation in Phragmites was found in vegetation sampling.

Longevity and management requirements for constructed wetland treating alkaline bauxite residue leachate are more likely to be impacted from increases in soil Na and pH. Increases are more evident in front sections of wetland but it is proposed that loading to wetlands can be decreased by incorporation of other passive technologies within the overall treatment approach and by feeding different sections of the wetlands on a cyclical basis.

1. Introduction

The environmental management of alkaline bauxite residue presents a growing challenge to the alumina industry. Globally, some 150 million tonnes are produced annually and add to the estimated stockpile of 3 billion tonnes (Di Carlo et al., 2019). The bulk of this residue is contained within bauxite residue disposal areas (BRDAs) and a number of residue management strategies have been developed to aid dewatering and partially neutralise the residue (e.g. Evans, 2016; Gomes et al., 2017; Zhu et al., 2016). However, leachates generated are typically alkaline (pH 9–13) and require treatment prior to discharge (Evans, 2016; Hua et al., 2015, 2019; Higgins et al., 2017, 2018).

High pH residue leachates can also contain elevated levels of soluble trace elements such as Al (500–1000 mg l⁻¹), As (3–5 mg l⁻¹) and V (5–10 mg l⁻¹) (Burke et al., 2013; Hua et al., 2015; Higgins et al., 2016). Contamination of soils with bauxite residue has resulted in increased levels of trace elements (Ruyters et al., 2011; Lehoux et al., 2013). The high pH associated with untreated residue leachate has been recognised as the primary concern with regard to potential ecological impacts (Brunori et al., 2005; Howe et al., 2011) and discharge of untreated residue (pH 12) to the marine environment has been associated with mortality in sea urchin larvae (Pagano et al., 2002). Neutralisation of residue leachate is viewed as a critical step in reducing the overall burden of alkalinity and soluble trace elements on the aqueous environment (Burke et al., 2013; Kong et al., 2017; Higgins et al., 2016).

Treatment by conventional methods, such as chemical neutralisation, is carried out during the operational lifespan of a refinery but is likely to become expensive following closure. The main drawback of such treatment approaches are the high cost for reagents, operation and maintenance (Chockalingam and Subramanian, 2006) and can produce large volumes of sludge. Passive treatment systems such as constructed wetlands are widely cited as suitable for treating acid mine drainage waters (Piramid Consortium, 2003) and metal removal in neutral mine waters (Batty and Younger, 2004) with the potential keep working with an almost negligible requirement for maintenance and supervision (Khan et al., 2020). The application of constructed wetlands to treating alkaline leachates, particularly as a component of closure planning, is therefore attractive, as continued generation of leachate and subsequent treatment may persist for many decades (Burke et al., 2013;
The potential of constructed wetlands for treating alkaline leachate was shown by a number of studies (Buckley et al., 2016; Higgins et al., 2016, 2017, 2018; Hua et al., 2015; Mayes et al., 2009; Gomes et al., 2019) but have been mainly confined to laboratory trials with limited data on long-term field application. Field results for wetlands treating alkaline industrial leachates have produced varied findings. In wetlands treating high pH steel slag leachate (pH 12.8), Gomes et al. (2019) reported median values above pH 9 in treated waters and elevated trace elements in sediments. Conversely, Higgins et al. (2018) reported pH reductions to < 9 in a wetland treating bauxite residue leachate (pH 9.7–11.3). The potential for wetlands to treat alkaline bauxite residue leachate is uncertain as Na⁺ is the main cation and most Na compounds are highly soluble (Hua et al., 2015). The successful 1 year operation reported by Higgins et al. (2017) used neat leachate diluted with water containing Ca (influent 20–60 mg l⁻¹) and calcite formation was found within the wetland system (Higgins et al., 2018). However, the Ca content of leachates for bauxite residue from closed or legacy sites is uncertain with some projections expecting minimal Ca content from diluting waters (Buckley et al., 2016). Consequently, the diluting waters were converted to deionised (DI) water in 2015 to investigate the potential of wetlands to treat Na dominated bauxite residue leachate.

The objective of the current study was to determine the effectiveness of the wetland to buffer pH over a 52 month monitoring period. During the 4th year of operation trace element content (inflow and outflow) was determined and the potential toxicity assessed on multi-trophic acute end-points. Accumulation of elements in wetland sediments and plants was examined over two sampling campaigns and data used to make recommendations on implications for wetlands as a long-term leachate treatment option for alkaline bauxite residue leachate.

2. Methodology

A pilot-scale horizontal surface flow constructed wetland was constructed at a Bauxite Residue Disposal Area (BRDA) in Europe. The constructed wetland was approximately 44 m² (4 × 11 m) with of 200 mm soil depth and vegetation type was dominated by Phragmites australis. The wetland operated over a one-year period treating high pH residue leachate (pH 13) diluted with tap water to ca. pH 10.3 (Higgins et al., 2017). Due to the formation of calcite crusts within the mixing and dosing system which compromised its efficiency, and to investigate the potential of constructed wetlands for treating residue leachate with negligible Ca content, the mixing system was converted to dilute neat leachate with deionised (DI) water.

Prior to receiving the DI diluted leachate feed, the wetland underwent a lag phase of approximately 9 months during which time the only water ingress was precipitation. Neat residue leachate (pH 12–13) was collected and stored within a 1 m³ IBC tank. A programmable logic computer (PLC) mixing system was used to mix the leachate with the DI water to prepare a residue leachate runoff that could manifest from a closed BRDA (Higgins et al., 2017). The diluted leachate was then pumped to the constructed wetland at a pre-set pH (ca. pH 11) and flow rate of 10–30 l/h (winter months) and 45–55 l/h (summer months). The diluted bauxite residue leachate discharge to the wetland commenced in May 2015 and the wetland subsequently received residue leachate for 52 months (May 2015–August 2019).

Inflow and outflow pH and electrical conductivity (EC) were determined daily by field probe (monthly averages reported) over the 52 month period. During the period June 2018 to June 2019 wetland inflow and outflow samples were taken on a monthly basis for elemental analysis and filtered (with 0.45-μm cellulose nitrate filters) prior to analysis. Al, Ca, Cr, Mg, Na and V content was determined by inductively coupled plasma (ICP-MS).

2.1. Effluent chronic toxicity

Inflow and outflow (treated) waters from June 2019 was assessed for ecotoxicological endpoints (Aquatic Toxicity Testing Service - City Analysts), across the multi-trophic freshwater species: bacterium (Vibrio fischeri) (ISO 11348: 2007, unicellular green alga (Skeletomena costatum) (ISO 10253:2006); copepod (Tisbe battagliai) (ISO 14669: 1999; and rainbow trout gudgeon (Onchorhyncus mykiss) (OECD 1992). Toxic units were used to represent the ratio between the concentration of leachate mixture and its toxicological chronic endpoint. The toxic unit was calculated by dividing 100 by the calculated EC 50 (EPA, 1998).

Soil samples were taken from the wetland during the Summer (June) for both 2018 and 2019 and followed the method of Higgins et al. (2017). Briefly, along its length the wetland was divided into a front section, middle section and bottom section. At each point and across the wetland width three soil samples (0-10 cm) were retrieved by digging with a spade. Samples were air-dried and sieved (< 2 mm) samples prior to analysis. Samples were analysed for pH and EC (1:5) and total elements were determined following digestion (HNO₃). Earlier studies on bauxite residue leachate have indicated that formation of sodium carbonate contributes to alkalinity removal, and increases in soluble and exchangeable fractions of these elements occurs in the soil (Higgins et al., 2017, 2018). Thus, soil samples were also analysed for soluble, exchangeable (1 M NH₄OAc, pH 7) and carbonate bound (1 M NH₄HCO₃ adjusted to pH 5) sodium. Total organic carbon (TOC) and inorganic carbon (TIC) content was measured using a Thermo FlashEA 1112 Elemental Analyser.

During the summer 2019 sampling vegetation (Phragmites australis) were also taken. Three samples of aerial biomass were taken at each of the sampling points (front, middle and bottom) were harvested. Samples were subsequently rinsed thoroughly with DI water, oven dried & milled, acid digested in HNO₃, and elemental content determined by ICP-MS. The Biological Accumulation Factor (BAF) for target metals was calculated as the heavy metal concentration of aboveground part divided by the same metal content in soil.

3. Results

Wetland leachate feed (inflow) monthly mean pH varied between 9.23 and 12.17 (mean 11.23) over the 48 months of operation, with treated leachate (outflow) ranging from 6.6 to 8.27 (mean of 7.21) (Fig. 1) with a consistent reduction to below the target value (pH 9).

Electrical conductivity showed high variability in the inflow with a range of 64–1120 μS cm⁻¹ (mean 480) whilst outflow ranged from 205 to 859 μS cm⁻¹ (mean 449) over the 48 month period (See Fig. 2).

Cr in both inflow and outflow were below detection limits. There were marked decreases in various concentration of trace elements Al and V between leachate feed and wetland outflow samples over the course of the 1 year of monitoring. Reductions in Al content was observed with mean Al content in wetland inflow of 17,256 μg/l (median 11,670) with treated water (outflow) mean recorded of 330 μg/l (Fig. 3). Similarly, mean V content in wetland inflow was 140 μg/l with treated water (outflow) mean of 13 μg/l.

The dominant soluble cation in the leachate inflow was Na⁺ with a median concentration of 70 mg/l. Much lower values for were recorded for Ca²⁺ (Fig. 4), which is typical of bauxite residue leachates. Mg concentration in the inflow was below detection limit and K in the range of 1–2 mg/l (data not shown). Na content in inflow and outflow were similar but the Ca content increased significantly (ca 5 fold) in the outflow samples.

3.1. Toxicity units

The Emission Limit Value (ELV) defined by the regulator is 5 Toxic Units (TU) and all test species produced results in excess of this when
exposed to the alkaline wetland inflow water. Conversely, when exposed to the wetland outflow samples the TU recorded was within the permitted guidelines for all four test species and therefore qualify as suitable for discharge (Table 1).

3.2. Soil

Wetland soil pH, EC content varied significantly both temporally and spatially over the 2 monitoring campaigns. Increases in soil pH and EC were most evident in the front and middle sections of the wetland. Increases in soil pH from the baseline pH 6.7 to pH 8.47 in Summer 2018 and pH 9.01 for Summer 2019 in the wetland front section, and up to pH 8.21 (8.46) in middle section and pH 6.5 (6.6) for lower end of wetland (Fig. 5).

Changes in soil EC were increased significantly in both front and middle sections of the wetland with marked increases in 2019 with values of 800 uS/cm recorded in the front section of the wetland. Soil analyses (Fig. 6) shows elemental content varied significantly both temporally and spatially in the two sampling campaigns when compared with baseline values. Aluminium content in baseline soil ranged from 12,920–14,350 mg/kg and with slight increases in Summer 2018 where a maximum value of 16,970 was recorded in the bottom section of the wetland. Slight increases were recorded for Summer 2019 with an overall trend of higher Al in bottom sections. While V content increased from 49 mg/kg in the baseline soil to a maximum of 73 mg/kg in the bottom section of the wetland during the Summer 2019 sampling. Cr content in baseline soil was 32 mg/kg with a range of 29–38 mg/kg in Summer 2018, this was slight increases to 34–41 in Summer 2019.

Distinct trends were observed for both Ca and Na where values increased incrementally from baseline to Summer 2018 and again for Summer 2019. For each sampling campaign the highest values for each cation was in the order of Front section > Middle section > Bottom section.

Conversely, significant increases in all sodium content was observed over time with elevated content in the front and middle sections of wetland. Results of sequential extractions for sodium are shown in Fig. 7. Significant increases in all sodium soil fractions were observed over time with particular loading to front and middle sections. Water-soluble Na accounted for 28% in baseline soil with the amounts for Summer 2018 of 74% in the front section of the wetland and 56% in the middle and bottom. In the same time period, the carbonate bound Na increased from non-detectable levels in baseline soil to 5% in front and middle sections with the lower end increased to ~0.5%. Exchangeable fraction represented 31% of Na in the baseline soil with decreases to < 20% in summer 2018.
Total carbon (inorganic and carbon) was 3.9% in baseline soil with inorganic fraction content negligible (< 0.2%) (see Fig. 8). Subsequent samples displayed significant increases in total carbon content with significant contributions from inorganic carbon which is used to infer carbonate content. This increase in inorganic carbon was most noticeable in the front (ca. 4%) and middle sections (ca. 2.5%) of the wetland soils.

Baseline values for trace elements and nutrient content in aerial portions of *P. australis* were taken during the summer months prior to leachate dosing commenced (2013). Slightly lower values for N and Ca content were observed while P, K and Mg were slightly higher than baseline values. Na was not detected in baseline samples and increase to 0.04 g/100 g. Trace element (Al and V) also displayed higher numbers than those recorded for baseline samples (Table 2).

Bioaccumulation Factor (BAF) values of 1 or greater indicate bioaccumulation and there was no evidence for accumulation of trace elements in the aboveground biomass across the three wetland sections (Table 3). Values for Ca and Na increased incrementally across the wetland. Conversely, Na BAF was highest in the front and middle sections of the wetland with lowest values for the bottom section.

4. Discussion

Constructed wetlands are regularly proposed as a suitable option for the treatment of leachate from mine waste facilities, particularly as part of a closure planning. However, most studies have focused on the suitability of substrate media for removal efficiency and there are few studies with data from medium to long term field data. Anticipated or reported data can be for up to several decades (e.g. Beining and Otte, 1996) yet many studies only report data over several months. The data in the current study is encouraging as it demonstrates sustained efficiency over 4 years in target parameters (e.g. pH) associated with bauxite residue leachate. Suggested mechanisms for pH reduction in wetlands treating alkaline leachates is microbial respiration and associated CO₂ as well as production of organic acids through decomposition and root exudates (Higgins et al., 2017; Mayes et al., 2009). Certainly, carbonation has been demonstrated as effective at lab level (Higgins et al., 2018) and shorter term field trials (Higgins et al., 2017; Mayes et al., 2009; Gomes et al., 2019). The current work demonstrates that this process continues over several years, with treated leachate several units below discharge pH 9 guidelines.

Previously, Higgins et al. (2018) reported satisfactory pH reduction for leachate treatment over a 12 month period. When the current study and that of Higgins et al. is combined it demonstrates effective pH buffering for 5 years. Conversely, Gomes et al. (2019) reported a wetland receiving pH 12.3 treating effluent to over pH 9, while the starting effluent is higher than current study the authors also highlight sparse vegetation cover as a possibility. Findings suggest that pH > 12 may be beyond the limit of wetland treatment but also the need to sustain adequate stands of vegetation and hydraulic regimes throughout wetland lifespan.

Trace element content in untreated alkaline residues and associate leachates may be at concentrations which exceed recommended values (Gomes et al., 2019). Gomes et al. (2019) reported V levels of ca. 0.12 mg/l entering wetland but slightly elevated 0.15 in the treated effluent. Sufficiently lowered pH was not achieved in that study and removal efficiency of V from residue leachate is dependent on pH and filter media characteristics (Hua et al., 2015). Hua et al. (2015) proposed that for bauxite residue-derived leachates, a pH of 6.0–7.0 is required for effective removal of trace elements. Burke et al. (2013) reported removal rates of 70% in neutralised residue leachate and the presence of additional sorption sites helps to reduce aqueous V concentration (Telfeyan et al., 2015). The sustained removal rates of ca.
90% observed during the 5th year of operation in the current study are above rates of 0–48% previously reported (Kröpfelová et al., 2009). V concentrations in the wetland outflow were lower than reported for other alkaline leachate wetlands (Gomes et al., 2019) and fell well below reported toxicity values. Nedrich et al. (2018) reported a LC50 of 400 μg L⁻¹ for *Hyalella azteca* and *Daphnia magna* and values for acute and chronic hazardous concentrations for 5% of freshwater test species were estimated as 0.64 and 0.05 mg V/L (Schiffer and Liber, 2017).

Although elevated Al is cited as an important ecological concern in residue leachate, significant removal rates are reported when leachate is partially neutralised to pH 8 (Burke et al., 2013; Hua et al., 2015) causing Al precipitation. Similarly, effective removal rates are reported for wetlands (e.g. Kröpfelová et al., 2009) and for wetlands treating alkaline leachates (Higgins et al., 2017; Gomes et al., 2019) due to formation of insoluble compounds through hydrolysis and/or oxidation which leads to the formation of a variety of oxides, oxyhydroxides and hydroxides. Sustained removal rates over 5 years of operation highlight the potential for wetland technology to treat alkaline bauxite residue leachate.

### 4.1. Toxicity

High pH and associated elevated levels of trace elements is associated with toxicity in residue leachate. Pagano et al. (2002) attributed 100% embryonic mortality in sea urchins to hyperalkalinity (pH 12) and elevated Al. Conversely, using Microtox® test, microalgae toxicity test and sea urchin embryo end point Brunori et al. (2005) found no evidence of toxicity in neutralised (seawater) red mud. Howe et al. (2011) studied the freshwater *Ceriodaphnia dubia* and marine *Paracalliope australis* in residue leachate both untreated and treated (sulfuric acid, carbon dioxide, seawater and a mixture of the last two), and attributed the toxic effects in partially neutralised (pH 7.9–8.3) to osmotic shock, high EC, alkalinity (primarily bicarbonates), sulfate and Na concentrations remaining. Absence of toxicity in the current study suggest that wetlands may be preferable treatment to the non-passive technologies used by Howe et al. as pH reduction alone may not be suitable treatment for ecological discharge. Indeed, Hua et al. (2015) suggests the use of wetland treatment for seawater neutralised leachate due to remaining levels of trace elements.

### 4.2. Soils

Increases in soil pH and salinity have been previously reported following additions of both residue and residue leachate to soil (Ruyters et al., 2011; Higgins et al., 2016; Higgins et al., 2017). Supernatant water in the wetland typically displays pH 10+ within the first 3 m and decreases to pH ca. 8 within 6 m, with pH < 7.5 thereafter (unpublished data) and supports the decreasing trend of alkalinity through the wetland. The trend of higher soil pH in front sections of the wetland observed in the current study was also reported by Higgins et al. (2017) and values are higher than those reported previously which highlights the potential for front loading within the wetland system. Salinity remains lower than the values previously reported for wetland soils treating residue leachate (Higgins et al., 2017) and are not considered excessively saline.

The accumulated amounts of inorganic C (carbonates) and carbonate-bound Na in wetland soils illustrate the findings of (Mayes et al., 2006; Mayes et al., 2009) and Higgins et al. (2017, 2018) in the role of carbonate in removing alkalinity. Increases in soluble and exchangeable sodium were also observed by Higgins et al. (2017) and result in plant available forms. Examining the effects of bauxite residue additions to soils, Ruyters et al. (2011) concluded that elevated Na content was the most significant factor for soil and vegetation quality. Although enhanced BCF (transfer) is noted in the current study, values recorded in plants are not at levels considered phytotoxic.

Increased levels of trace elements in soils and freshwater sediments have also been observed following addition of residue leachate and other alkaline effluents. Immobilisation and attenuation of V as extractable oxides and carbonate phases in sediments and wetland soils were reported previously (Mayes et al., 2011; Higgins et al., 2017). Levels of Al and V observed are lower than those reported for wetland sediments in wetlands treating alkaline leachates (Higgins et al., 2017; Gomes et al., 2019) are within normal concentrations for Irish soils (Fay et al., 2007).

Phragmites rhizomes were not included in the current study due to the destructive sampling necessary to remove sufficient biomass from the wetland sediments. However, monitoring of aerial portions has been proposed as a potential bioindicator of Al content in wetlands (Bonanno, 2011). Metal concentrations in the current study are all within levels recorded in other wetlands (Vymazal et al., 2009;...
Fig. 6. Wetland soil elemental content (0-10 cm) for wetland sampling sections over two sampling campaigns (n = 3).

Fig. 7. Sodium fractionation in wetland soils for baseline and Summer 2018 sampling (n = 3).

Fig. 8. Organic and inorganic carbon in baseline wetland soils and spatial sections for two sampling campaigns (n = 3).
Table 1
Concentration of plant nutrients and trace elements in Phragmites growing in the constructed wetland.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Mg</th>
<th>Na</th>
<th>Cr</th>
<th>Al</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>4.02</td>
<td>0.21</td>
<td>1.2</td>
<td>0.56</td>
<td>0.1</td>
<td>n.d</td>
<td>0.6</td>
<td>48</td>
</tr>
<tr>
<td>Top</td>
<td>3.6 ± 0.13</td>
<td>0.24 ± 0.01</td>
<td>1.5 ± 0.08</td>
<td>0.46 ± −0.01</td>
<td>0.23 ± 0.01</td>
<td>0.04</td>
<td>38</td>
<td>0.19</td>
</tr>
<tr>
<td>Middle</td>
<td>3.6 ± 0.03</td>
<td>0.24 ± 0.01</td>
<td>1.6 ± 0.04</td>
<td>0.34 ± 0.04</td>
<td>0.14 ± 0.01</td>
<td>0.03</td>
<td>44</td>
<td>0.51</td>
</tr>
<tr>
<td>Bottom</td>
<td>3.5 ± 0.1</td>
<td>0.24 ± 0.01</td>
<td>1.7 ± 0.02</td>
<td>0.33 ± 0.02</td>
<td>0.14 ± 0.005</td>
<td>0.03</td>
<td>60</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 2
Bioaccumulation factors for trace elements and cations in Phragmites growing in constructed wetland.

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>V</th>
<th>Ca</th>
<th>Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>0.09</td>
<td>0.37</td>
</tr>
<tr>
<td>Middle</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>0.12</td>
<td>0.61</td>
</tr>
<tr>
<td>Bottom</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>1.32</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Bonanno, Gomes et al., 2019) and much lower than the reported range for phytotoxic levels of 1000–3000 for AL and 5–10 mg/kg for V (Kabata-Pendias, 2000). Bioavailability of trace elements Al, Cr and V remain low after 5-years operation and are further supported by findings of Mayes et al. (2011) and Higgins et al. (2017) who reported that abundance of trace element residue-affected sediments appeared to be associated mainly with recalcitrant residual phases that are relatively immobile.

While Na levels have increased from baseline values and yield BCF close to 1 in some cases, the values are not considered excessive. Bragato et al. (2006) reported Na levels of 660–1580 mg/kg in Phragmites within wetlands. Elevated Na associated with bauxite residue may result in nutrient deficiencies (Ruyters et al., 2011). Gomes et al. (2019) also indicated that nutrient deficiency rather than toxicity is more likely to limit the long-term use of wetlands for treating alkaline leachate. Nutrient values in the current study are broadly similar to baseline samples and do not pose deficiency.

5. Longevity

Investigations on wetland suitability for treating industrial and mine waste waters have focused mainly on the assessment of wetland treatment efficiency, and much fewer papers have been published on the issue of reliability of such systems over a longer time of operation (Jóźwiakowski et al., 2017). Operational lifetimes of wetlands for treating mine waters are highly variable and will depend on wetland dimensions and wetland type as well as on influent water quality (Brown-P; Palmer et al., 2015). Typical lifetimes for wetlands are predicted in the region of 20–30 years (Piramid Consortium, 2003; Sheoran and Sheoran, 2006) although some estimates of 100+ years have been predicted at historic sites (Beining and Otte, 1996; Eger and Wagner, 2002).

In order to calculate the potential lifetime for a specific wetland and a number of factors need to be assessed including of the ability of the wetland soil/ sediment to retain contaminants.

Sudden changes in the wetland hydraulic regime, such as storm events, may bring about changes in element mobility, and waters rich in anions can exchange with adsorbed elements (Khan et al., 2019; Khan et al., 2020). Conversely, V in sediments may be remobilized during long dry periods through oxidation of V(III) to labile V(V) (Nedrich et al., 2018). Particularly mobile metals such as Ni or Zn, can be leached more readily than Cu from wetland soils (Niineminen et al., 2002; Palmer et al., 2015). The number of active adsorptive sites can increase or decrease over time, depending e.g., on the quality of influent (Ronkanen and Kløve, 2009; Palmer et al., 2015) and removal efficiencies may decrease if the retention capacity of the wetland is exceeded. Removal efficiency of both alkalinity and trace elements within the current wetland remain high with values recorded in the effluent consistently below the target guideline values.

Accumulation of metals within wetland sediment typically necessitates intervention and management. Considering the soil threshold guideline values set by regulators the wetland longevity may be assessed. Palmer et al. (2015) determined metal levels in wetland soils and comparing against lower guideline values predicted exceedance for As and Ni within 1 and 11 years, while using higher guideline values for As, Sb, and Ni predicted exceedance within 6, 10, and 18 years respectively. Similarly, sediment from wetlands used to treated steel slag leachate exceeded TEL (threshold effect level) for As, Cd, Cr, Cu, Ni and Zn and PEL (predicted effect level) is exceeded for As, Cr and Ni (Gomes et al., 2019). However, it was also determined that TEL would exceed in reference sites.

Due to prolonged contaminant loading, some wetland soils may be classified as a contaminated soil, which limits reuse and disposal options. While the soils in the current study did not exceed guideline values there was evidence of front loading within the wetland with significant increases in pH and sodium. The increase in sodium were also associated with the soluble, exchangeable and carbonate bound forms. It is proposed that the lifetime of such wetlands treating alkaline leachate may be enhanced by incorporation of other passive technologies within the overall treatment system. Integrated passive treatment, including wetlands, have been employed for other industrial-derived leachates and include sedimentation tanks, and variations of wetland types, e.g. anaerobic, aerobic, RAPS (Piramid Consortium). Implementation of cascade systems such as those reported by Gomes et al. (2017) can reduce pH in alkaline leachate by 1–1.5 pH units and offer a potential additional treatment to the wider passive technology approach (Gomes et al., 2018). Carbonation of bauxite residue leachate can consume alkalinity through precipitation of carbonates and generating conditions conducive to (contaminant) metal co-precipitation (Higgins et al., 2018). Constructed wetland treatment offers long-term treatment options for bauxite residue leachate and the longevity of such approaches may be enhanced through implementation of a wider passive treatment approach.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References
