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Construction of a passive sulfate treatment system

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Abstract

The paper reports on the third phase of constructing a passive sulfate reduction system with sulfur sequestering. The tiered approach included bench- and pilot-scale systems to prove the feasibility of using a passive treatment solution. This included the use of a biochemical reactor (BCR) with different proportions of wood chips, straw, manure, limestone, and biochar to culture sulfate-reducing bacteria. In addition, the concept of using a fixed-bed anaerobic bioreactor (FBAR), where alcohol was added to enhance the sulfate reducer activity, was also tested. In total, three BCRs and two FBARs were set up for this stage of the assessment. The resulting treated leachate was then passed through different media types to remove sulfur species generated by the bacteria, with an aerobic wetland used to polish the effluent. The success of the bench-scale (Tier 1) project led to a pilot-scale system (Tier 2) being constructed and monitored in spring 2020, the results of which confirmed the success of the bench-scale testing and provided useful insights into management of the system, particularly in winter months. The COVID crisis has had its impact, but the system has operated continuously and ran through 2021. This led to planning permission being awarded for the project, which enabled Tier 3 construction in late 2022/early 2023.

Keywords: *passive treatment, sulfate reduction, biochemical reactor, wetland, pilot plant*

1 Introduction

SLR Consulting (SLR) was appointed by British Gypsum (Saint-Gobain Construction Products UK Ltd trading as British Gypsum) to investigate options for the treatment of leachate emanating from an old landfill disposal site at their property in East Sussex. The options analysis undertaken by SLR highlighted that a passive treatment option for the removal of the sulfate, to below discharge standards, was a potential option but that it required treatability/feasibility testing. The concept involved the use of naturally occurring material containing sulfate-reducing bacteria to remove the sulfate, with the resulting dissolved sulfide in the water being 'scrubbed' by a filter. An aerobic wetland would then be used to polish any final effluent before it is discharged. Full details of the bench and pilot scale can be reviewed in a paper presented in 2021 (Robinson et al. 2021), although a summary is presented below.

Mine closure studies have shown that often elevated sulfur is present in water drainage from waste rock and/or tailings facilities. Therefore, it is considered this study will enable another tool to be developed to treat such sulfur concentrations, particularly in the absence of heavy metal ions.

2 The treatment process summary

The design of a treatment system should be based on the results of a 'staged process' of bench- and pilot-scale testing. Typically, flow rates of c.5 to 10 mL/min or less is a termed 'bench-scale' study, with a 'pilot-scale' study as one that would treat about 4 L/min or more. Bench-scale testing is an effective way to advance a project toward to full-scale implementation while gaining useful knowledge about appropriate media, reaction rates, and functionality that increase confidence and overall effectiveness. The typical passive biological treatment process for sulfate reduction utilises an anaerobic biochemical reactor or BCR. While BCRs receiving mining-impacted water may be configured as 'upflow' or 'downflow', experience has shown that upflow BCRs are better than downflow BCRs in treating sulfate-rich and metal-poor leachates.

The organic substrate comprises hard wood chips, limestone, straw and biochar in varying proportions. 0.1% animal manure is added to provide the naturally occurring sulfate-reducing bacteria inoculum. The bacteria consume the sulfate in the influent leachate and produce sulfide (Equation 1):

$$SO_4^{2-} + 2\ CH_2O = H_2S + 2\ HCO_3^- \quad (1)$$

The lack of suitable metals in the site discharge required a metal ion addition to passively sequester the sulfide generated through the sulfate reduction process. The dissolved sulfide will precipitate as an insoluble metal sulfide or potentially as free sulfur. At the site, iron was added at bench scale via a treatment substrate such that the following reaction (through precipitation of dissolved iron or on metal iron surfaces) in the substrate will occur, shown simplistically in Equation 2:

$$Fe^{2+} + S^{2-} \rightarrow FeS \quad (2)$$

This metal can be either in the zero-valent state, such as scrap iron, or as an oxide. However, care in media selection is warranted. The effluent is then directed to a passive oxidation wetland.

This aerobic polishing wetland (APW), a lined shallow pond filled with soil and locally harvested or cultivated vegetation, is used to re-aerate the anoxic effluent from the BCR.

3 Bench-scale set-up

To test the theory of a passive wetland treatment solution, a bench-scale system was set up at the site to run for 20 weeks. The bench-scale system was constructed in a shipping container as shown in Figure 1 and comprised:

- 3 No. BCRs – pump fed, each filled with a different test mixture comprising different proportions of manure, wood chips, hay, limestone, and biochar.
- 3 No. sulfide scrubbers (SCR), each filled with a different test mixture comprising magnetite, hematite, and iron filings.
- 3 No. APW cells planted with wetland plants from the site.
- 2 No. fixed-bed anaerobic bioreactors (FBAR) with 2 No. SCR, aeration tub and settlement tub.

As part of the treatability, it was also decided to consider the use of a hybrid-passive approach, which involves the addition of a soluble form of hydrocarbon, in the form of alcohol, to increase the metabolic rate of the bacteria. To enable this, an FBAR was used where small quantities of ethanol are added to a small system to provide a food source for the bacteria. The reasoning being that with a more soluble food source the bacteria will consume more of the sulfate and hence less area will be needed for the treatment at pilot and full scale.

(a) (b) (c)

Figure 1 Bench-scale test set-up. (a) Biochemical reactors and sulfide scrubbers (SCR) 1–3; (b) Fixed bed anaerobic bioreactor, SCRs and aeration; (c) Aerobic polishing wetland

4 Monitoring and results

The system was monitored for a variety of analytes along with the flows throughout the system. Weekly field-based monitoring of pH, redox and conductivity was undertaken along with sulfate, sulfide, nitrate, calcium and magnesium. At monthly intervals, phosphate, alkalinity, hardness, iron, nickel, zinc and total organic carbon (TOC) were analysed. The flows through the reactor were typically 6 L/d for the BCRs and 25 L/d for the FBARs. The latter was also reduced at the end of the treatment to be closer to the BCR flow rate to act as a comparison. The monitoring of the system was undertaken at weekly intervals where the redox and pH of the various components coupled with the flow rates were recorded. Samples were analysed at an offsite UKAS-accredited laboratory for sulfate and other constituents. The results of the treatability study are shown below in Figures 2 to 5 (where PWT = feed water tank and IBC = flow-balancing tank).

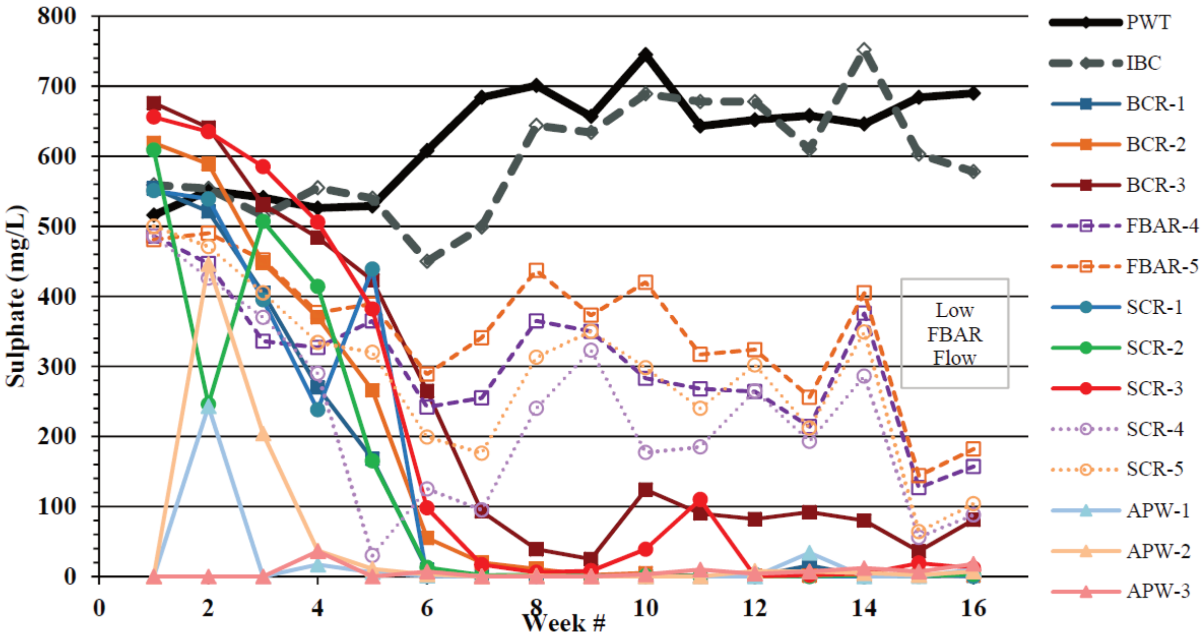

Figure 2 Sulfate concentrations

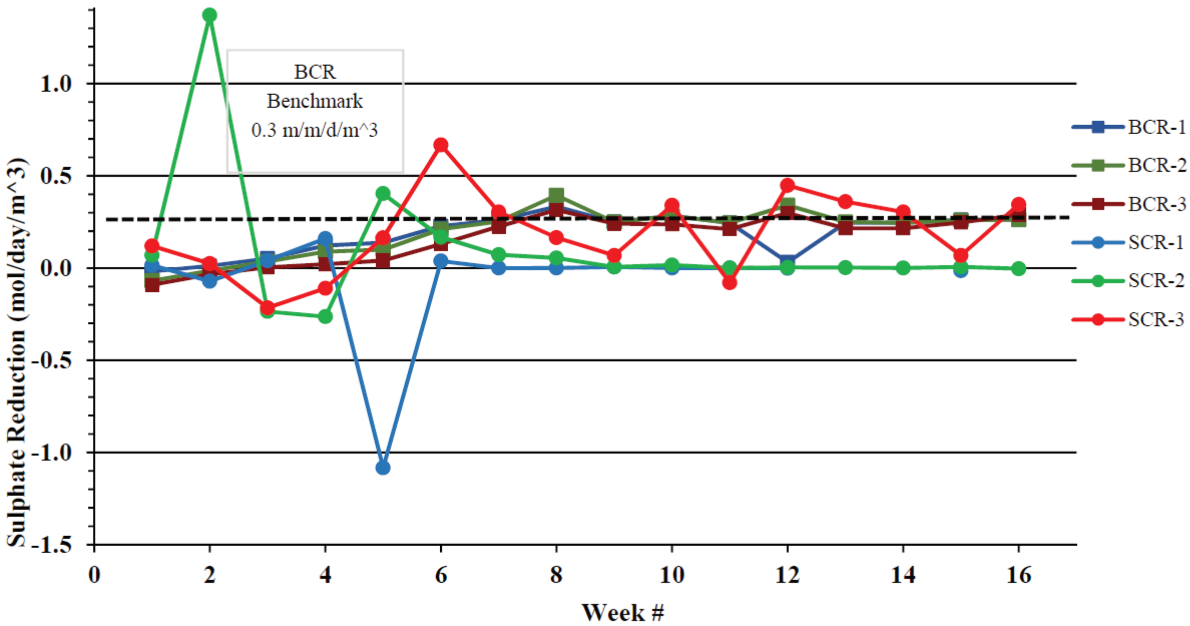

Figure 3 Biochemical reactors sulfate reduction rate

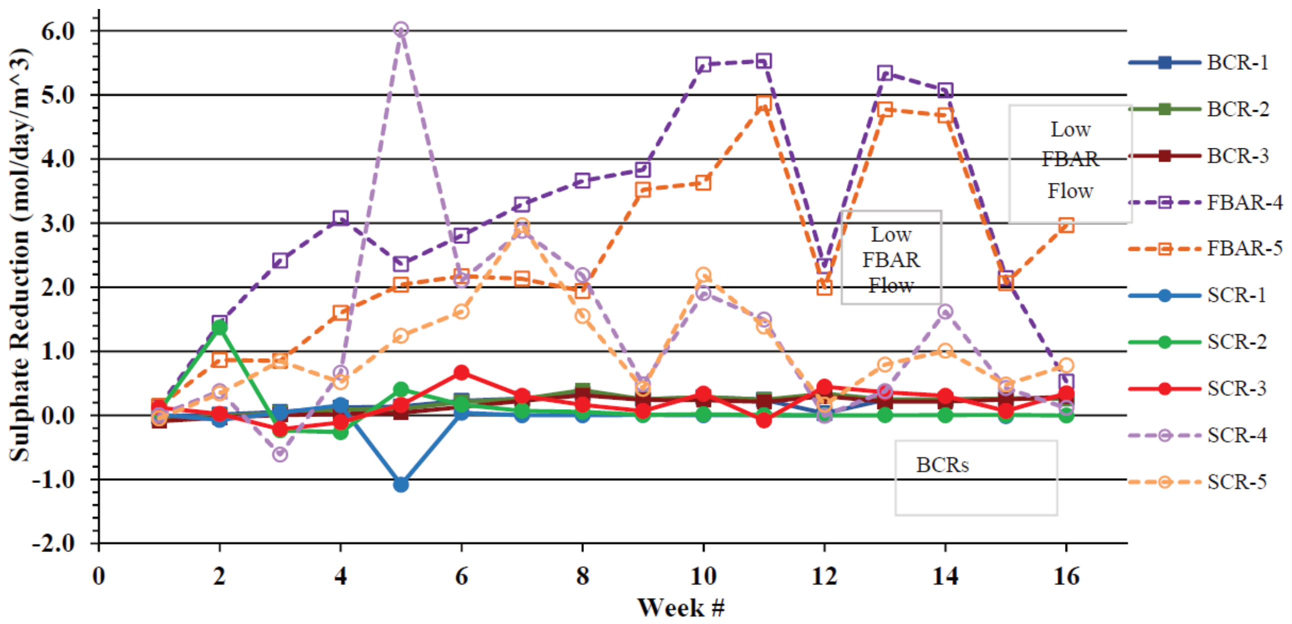

Figure 4 Fixed bed anaerobic bioreactor and biochemical reactors sulfate reduction rate

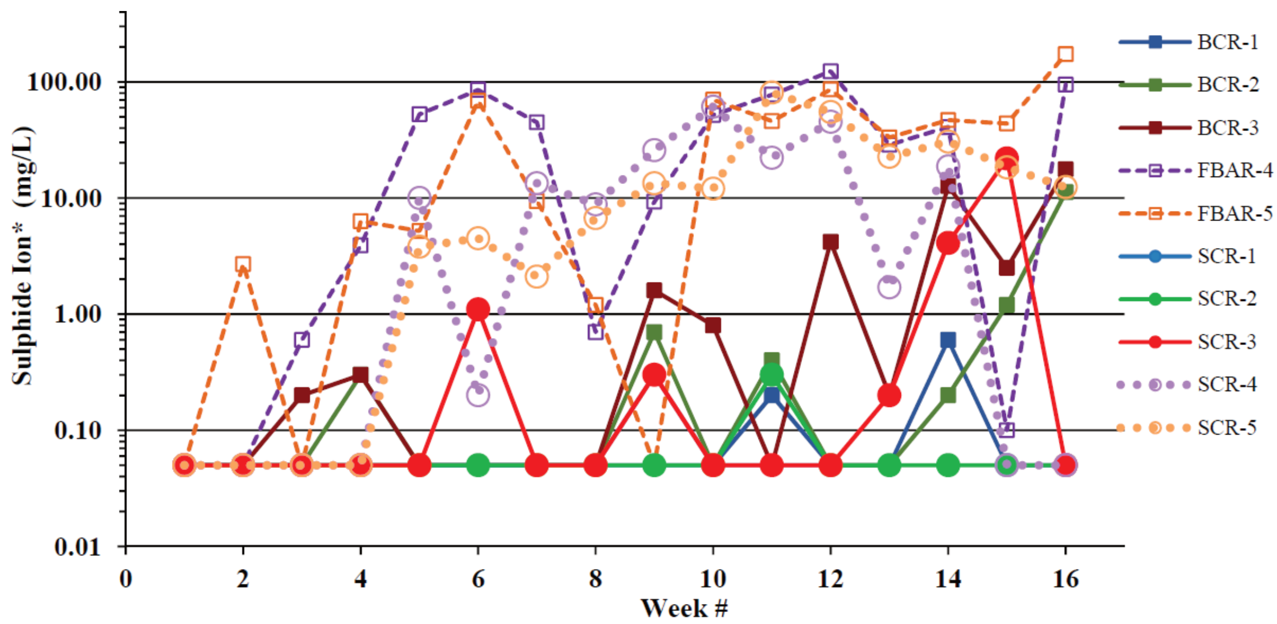

Figure 5 Sulfide concentrations

The bench-scale test results indicated that both BCRs and FBAR treatment will produce an effluent that would meet a 250 mg/L sulfate discharge limit. In mine water treatment systems, sulfate reduction rates typically range from 0.1 to 0.3 moles/m^3 substrate/day. The rates for this study are shown to be at the upper end of this range. In addition, the FBAR rate of sulfate reduction was c.15 times that of the BCR reduction rate. Consequently, the media volume required to accomplish this with a BCR will be c.15 times greater than for the media volume for an FBAR with an identical treatment capacity. The land area footprint required for an FBAR treatment unit would therefore also be 15 times smaller than that required for a BCR. However, the FBAR process will require the delivery of a steady and reliable supply of food, such as alcohol, as a microbial nutrient.

The passive BCR process does not require the addition of nutrient, such as alcohol, and therefore is seen as a more practical solution at the site. The scrubbers appeared to sequester sulfide ion present in the BCR and FBAR effluents, although it was also clear that free sulfur was precipitated in the outfall from the anaerobic systems. The bench scrubbers that received the FBAR effluents proved to be undersized. The aerobic wetland system was effective in removing the iron leached from the scrubbers and did have a positive impact on the organic carbon that came through the system. The results of the bench-scale testing were very encouraging. This has led to the design and development of a pilot-scale system at the site.

5 Pilot-scale testing

The success of the bench-scale trials led to the design and installation of a pilot-scale system in spring 2020 on the site. The purpose of the system was to confirm the success of the bench-scale study by using the sulfate removal coefficients and preferred media option. The latter comprised mixing of wood chips, biochar, limestone, wheat straw, bench-scale organic material and goat manure inoculum.

The desired flow being introduced into the system was 0.5 L/min and above, and there was no addition of alcohol as a nutrient. Review of the bench-scale testing showed that free sulfur precipitation dominated and hence the iron scrubbers were not required, although sand filters were included. The pilot-scale system had the original orientation of sequential treatment, although three BCRs were established such that variety in flow rate and other parameters can be used to test the system. To construct the pilot plant, shipping containers were used for the three BCRs. These were lined with insulation on the base and sides, which also prevented leaks and reinforced such that they could hold the substrate and the water.

Sampling ports were established such that different horizons in the units could be analysed if required. The aerobic polishing reed beds for the removal of BOD/TOC were designed with baffles to lengthen the flow path in the wetland. The piping allows for later addition of an iron-based sulfide sequestering unit should monitoring indicate that sulfide is leaving the system at concentrations that were unsustainable from an environmental perspective.

The pilot system was commissioned in spring 2020 before the COVID emergency, and monitoring has been undertaken by a skeleton staff onsite since. Sampling points included redox zone depth measurement in the anaerobic material, along with the treatment zones at various locations along the system.

The results of the ongoing monitoring indicate good sulfate removal with no sulfide detectable in the effluent. Free sulfur, which has the potential to oxidise and release stored sulfur as sulfate, was identified in the system, although during the summer/spring there was no evidence this has occurred.

Elemental sulfur may be the primary product of sulfate reduction in the BCRs. Evidence includes the white cloudiness in the BCR effluents, white deposits in the wetland influent zones, and the purple tinge (likely the bacteria *Chromatium sp.* and *Chlorobium sp.*) in the final pond influent zone (Figure 6). Purple sulfur bacteria produce elemental sulfur as part of their lifecycle. Thus far, the pilot cell is confirming the results of the bench-scale testing with latest influent sulfate of c.800 mg/L reduced to c.100 mg/L in the effluent, thus providing robust design data for the full-scale system.

Figure 6 Passive treatment pilot plant from right to left (feed tank; BCR 1, 2, 3, 4; reed bed (aerobic polishing wetland) 1, 2, discharge holding pond showing purple/white bacteria)

In the winter months, the treatment efficiency decreased as a consequence of lower ambient temperatures and potential free sulfur re-oxidation in the filters. This temperature dependency is a well-known phenomenon with passive systems, with sulfate reduction rates improving in spring and summer months. This aspect of the pilot scheme has been very useful in guiding potential management changes, which may need to be included in winter months to maintain the same reduction in sulfate.

The reduction in, the performance of, the BCRs over the winter months was investigated, as shown in Figure 7. The monitoring showed some interesting changes in redox and TOC in the leachate entering the treatment system. It was postulated that while the influent leachate TOC 'food' (that is 'digestible') will sustain the BCR performance, when this food is reduced quickly, however, in the influent leachate, the whole biosystem in the BCRs is essentially put on starvation mode, with knock-on lower sulfate reduction rates. This provided very useful information, as it might suggest soluble organic matter amendment (as used in the bench-scale testing) may be required during the winter months if the sulfate treatment is shown to fall below established permit conditions.

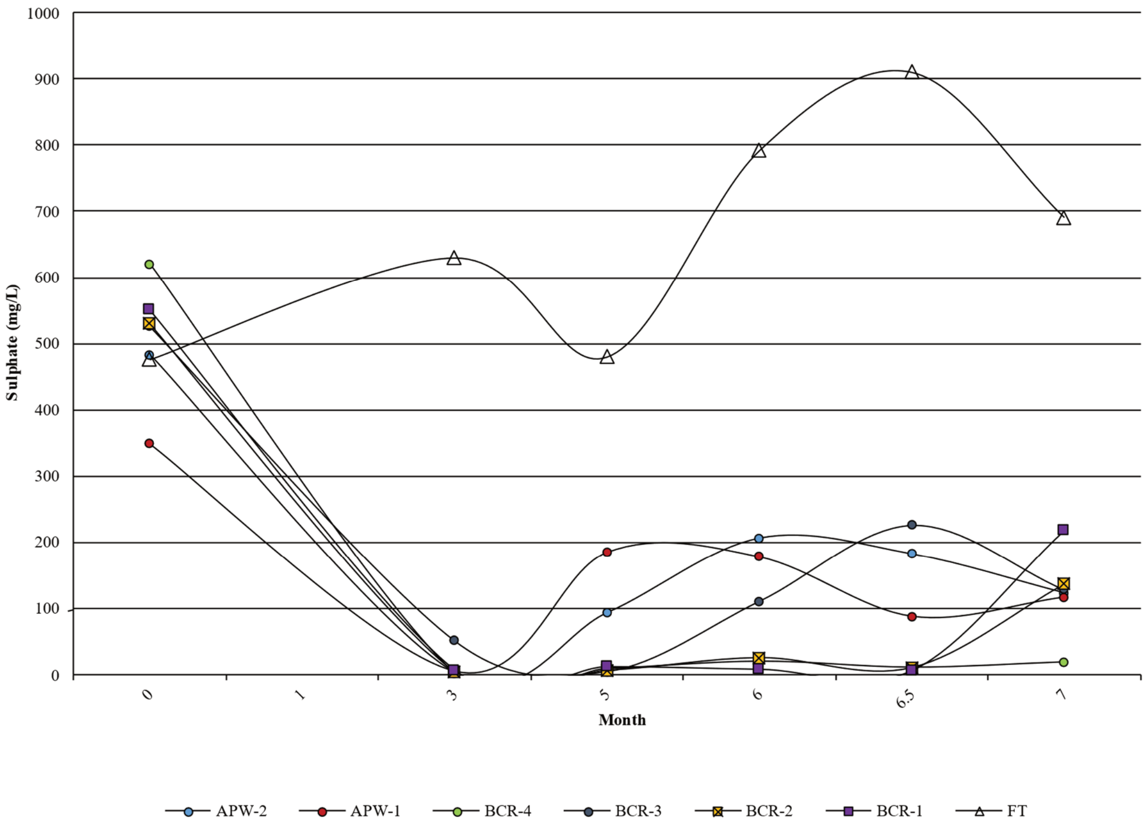

Figure 7 Example of sulfate treatment from the pilot plant operation

The pilot system operated until January 2022, and planning permission for the full-scale system was received in late 2021. The design layout of the full-scale system is shown in Figure 8.

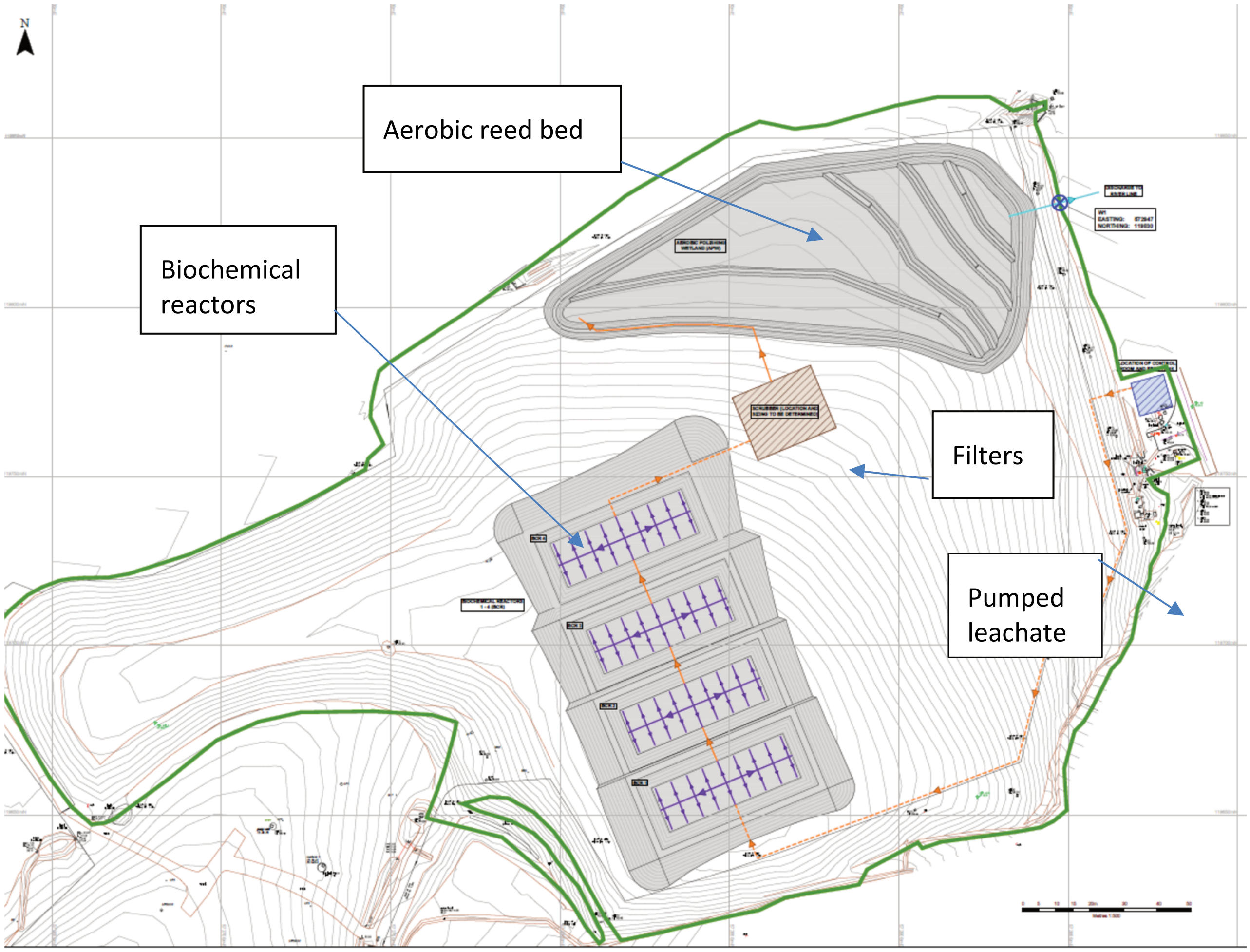

Figure 8 Proposed layout of full-scale system

It was decided to construct the system atop an old landfill at the site and therefore additional geotechnical assessments were made regarding the stability of the ground and the potential impact on leachate generation from the additional loading. Given this was an innovative system, the Environment Agency (UK regulatory) required additional information regarding the design and longevity of such systems. Construction of the system is planned for the summer, and the result of the initial work will be presented at the conference.

Acknowledgement

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