Design, construction and performance of the UK's first full-scale passive mine water treatment system for base metal mine drainage

Adam P Jarvis[1], Catherine J Gandy[1], Rachel Harris[2], John Malley[3], Arabella Moorhouse[2], and Hugh AB Potter[4]

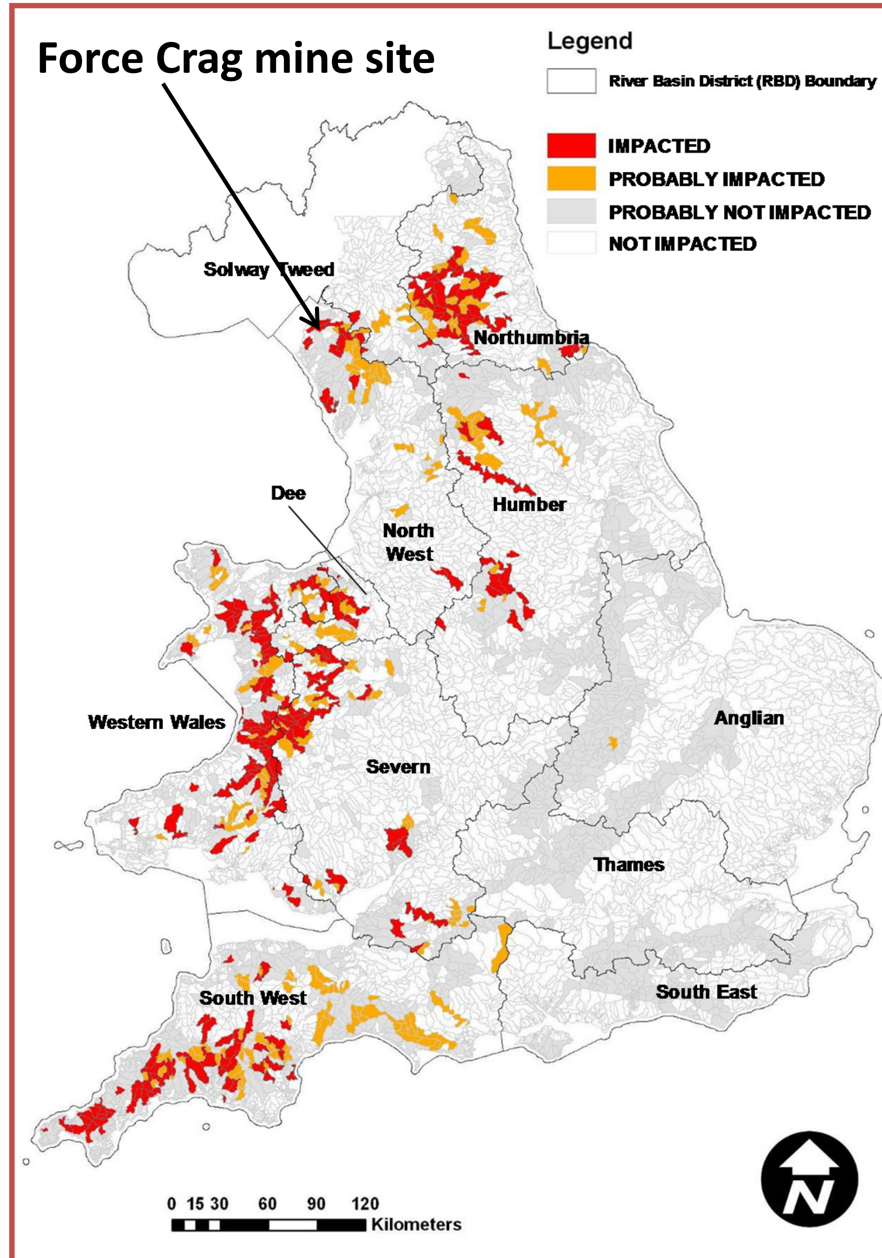
[1]Newcastle University, [2]Coal Authority, [3]National Trust, [4]Environment Agency

(adam.jarvis@newcastle.ac.uk)

Newcastle University
School of Civil Engineering & Geosciences

Background

- ~ 7% of freshwaters in England & Wales impacted by abandoned metal mine pollution
- Force Crag mine site, in Lake District national park, first site at which large-scale passive treatment system installed (commissioned April 2014)
- Construction possible as willing landowner – National Trust. Owns mine as last working mine in Lake District National Park
- Treatment system an initiative of Coal Authority, Environment Agency, National Trust and Newcastle University, funded by UK Department for Environment Food and Rural Affairs

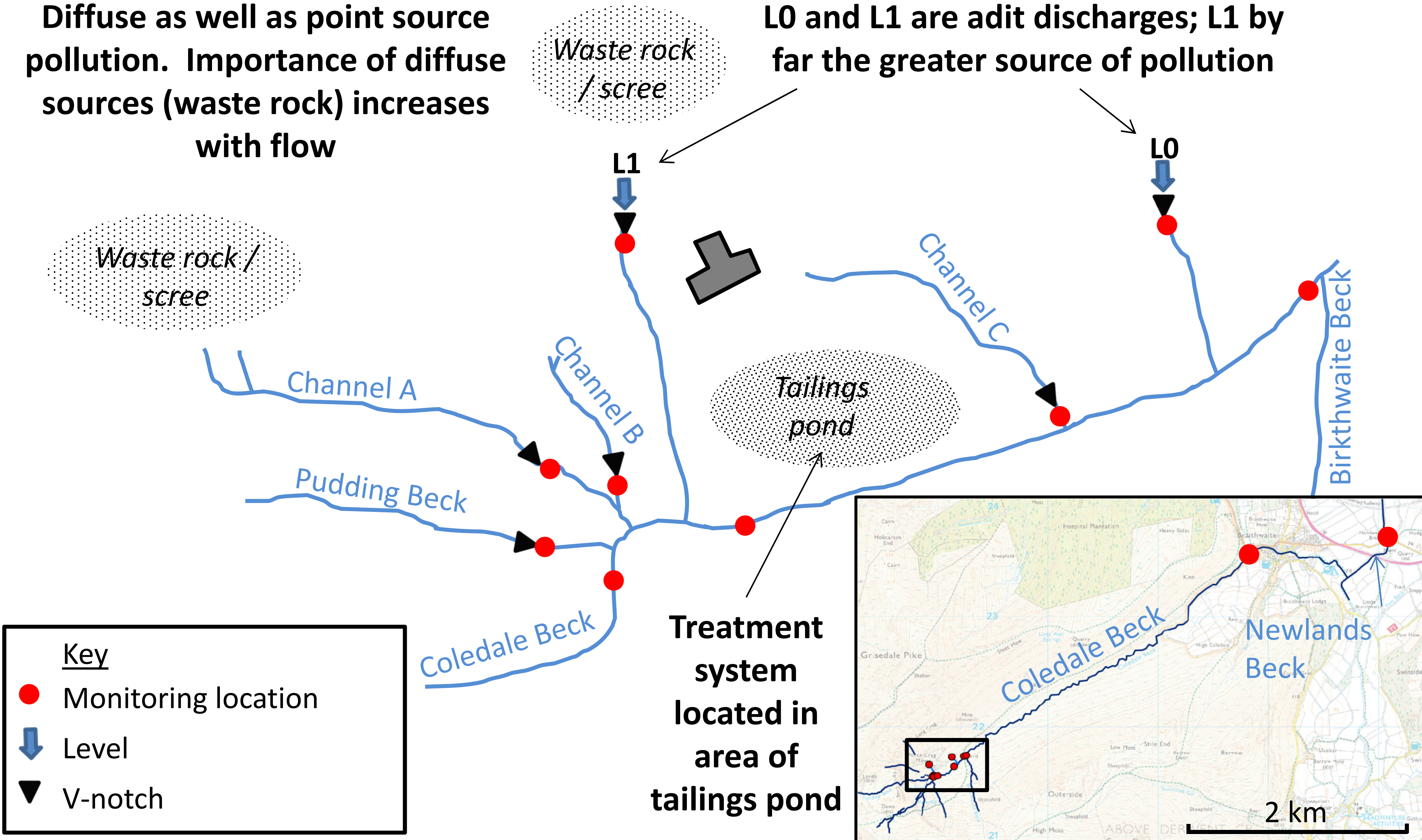


Force Crag mine site

- 10 km^2 watershed
- Upland location
- All drainage to Coledale Beck
- Zn main pollutant

- Major point source is ‘Level 1’ discharge
- Mined for Pb, Zn, Ba
- Extensive mine waste

Monitoring locations



Level 1 water quality and flow

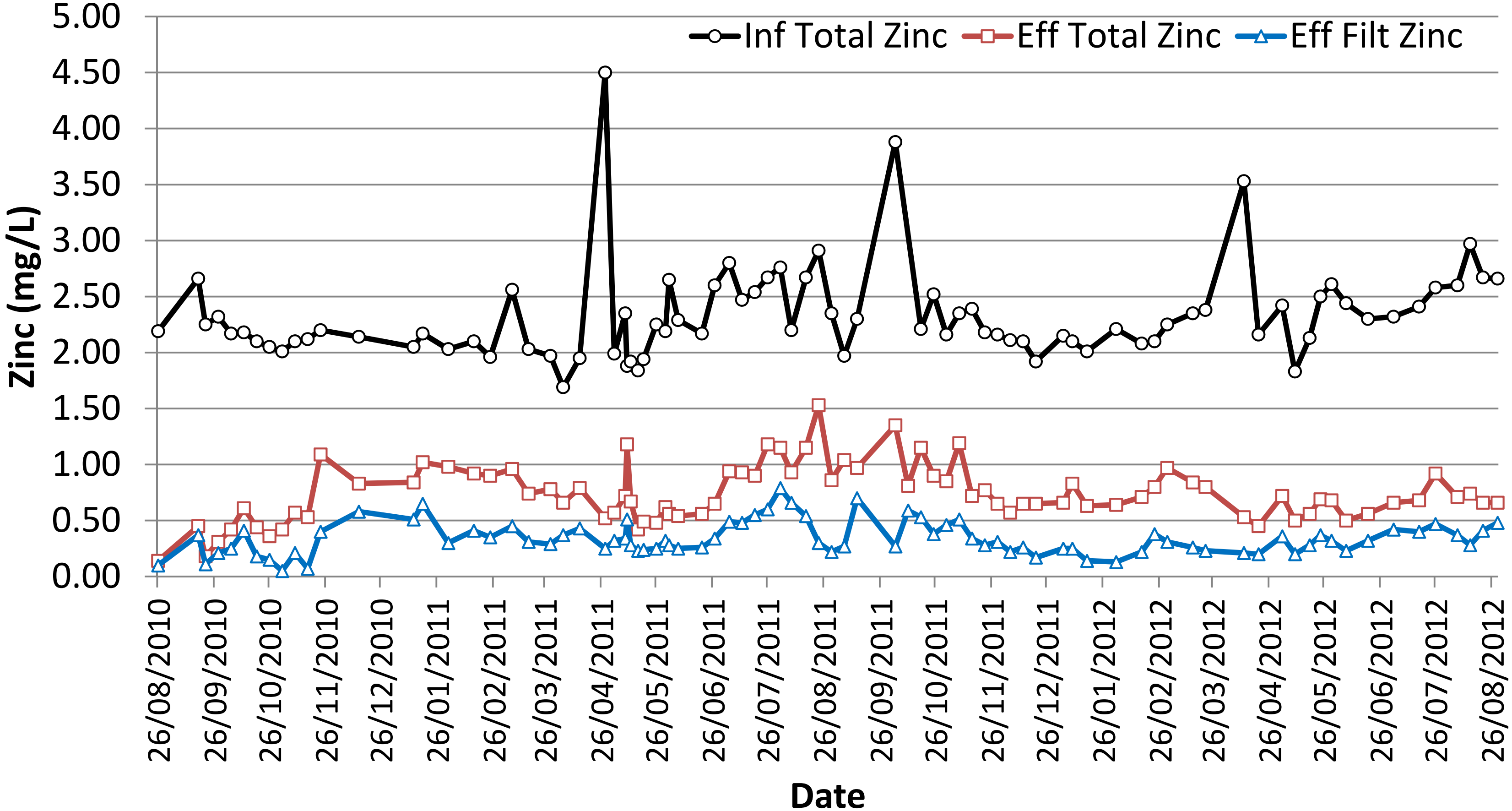
Variable	Range	Mean	n
Flow (L/s)	8.5 – 24.4	14.8	21
pH	5.6 – 7.7	6.8	25
HCO_3^- (mg/L)	8.5 – 26.8	16.7	28
Cl (mg/L)	4.7 – 7.6	5.7	28
SO_4 (mg/L)	16.0 – 39.5	26.6	28
Ca (mg/L)	5.1 – 14.5	9.5	28
Mg (mg/L)	1.95 – 5.00	3.30	28
Na (mg/L)	2.40 – 3.60	2.95	28
K (mg/L)	0.32 – 0.62	0.46	28
Fe (mg/L)	0.26 – 1.08	0.52	28
Mn (mg/L)	0.29 – 0.76	0.51	28
Al (mg/L)	0.05 – 0.20	0.08	28
Zn (total) (µg/L)	1 730 – 4 660	2 997	28
Zn (filt.) (µg/L)	1 710 – 4 550	2 950	28
Pb (µg/L)	25.0 – 87.9	43.6	28
Cd (µg/L)	5.00 – 20.00	14.24	28

Poorly mineralised discharge and stream; Zn is main pollutant; comparatively dilute waste stream, but typical of many UK metal mine waters

Treatment system design

- Same layout as a SAPS/RAPS i.e. downwards flow through compost into limestone layer overlying under-drainage pipe network
- But functionally different: objective is to immobilise divalent metals (primarily zinc); no requirement to generate alkalinity /elevate pH (limestone is purely for permeability over drainage pipes)
- Referred to as Vertical Flow Pond (VFP)
- Design informed by lab-scale and 2 year pilot-scale trials
- Large-scale Force Crag system still partly experimental, and therefore close flow control and good monitoring infrastructure key element of design

Treatment system design



- Pilot-scale treatment system performance: ~ 70% Zn removal
- Pilot-scale treatment system residence time: ~ 15 hours

https://www.gov.uk/government/publications/treatment-of-pollution-from-abandoned-metal-mines

Treatment system layout

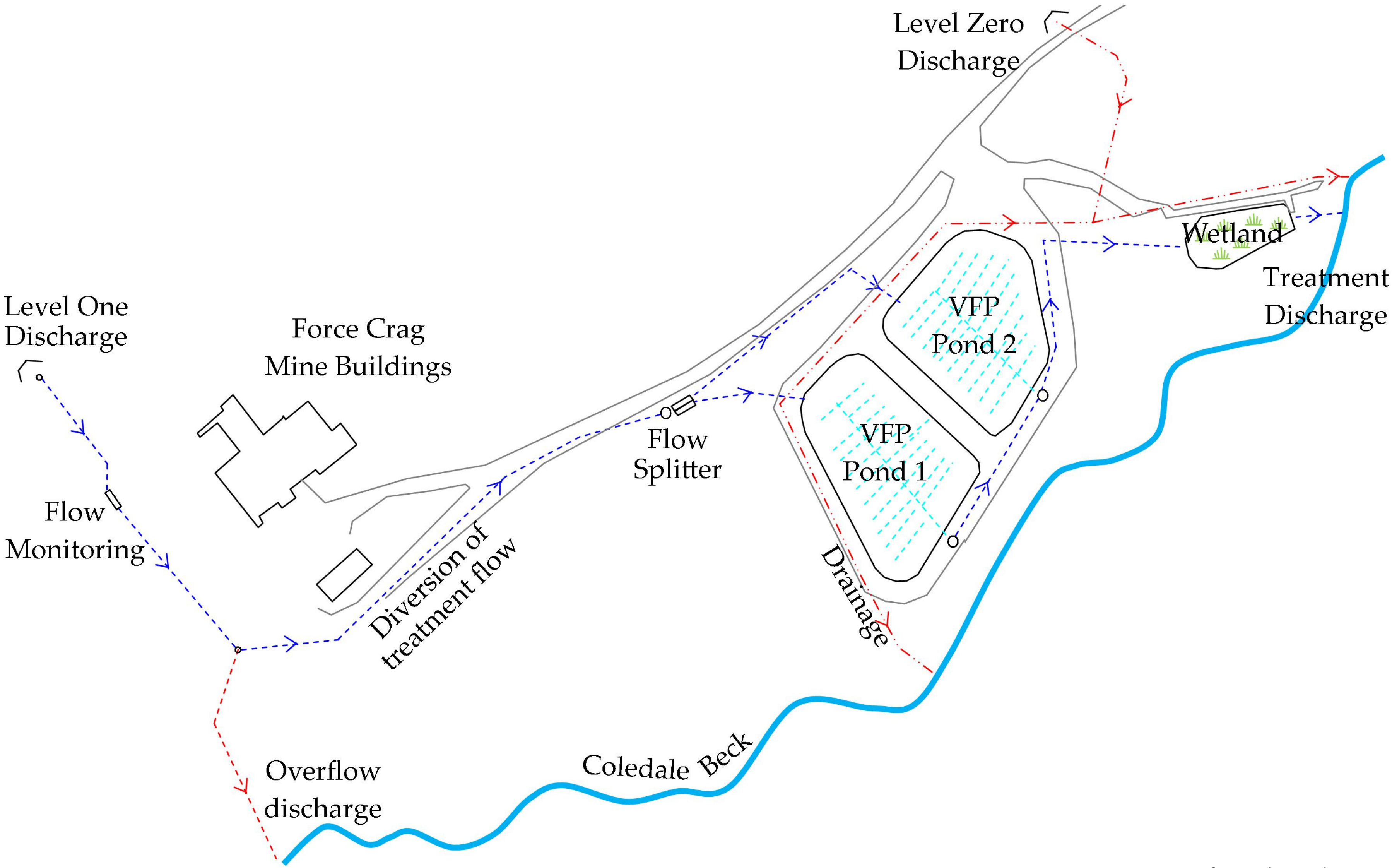
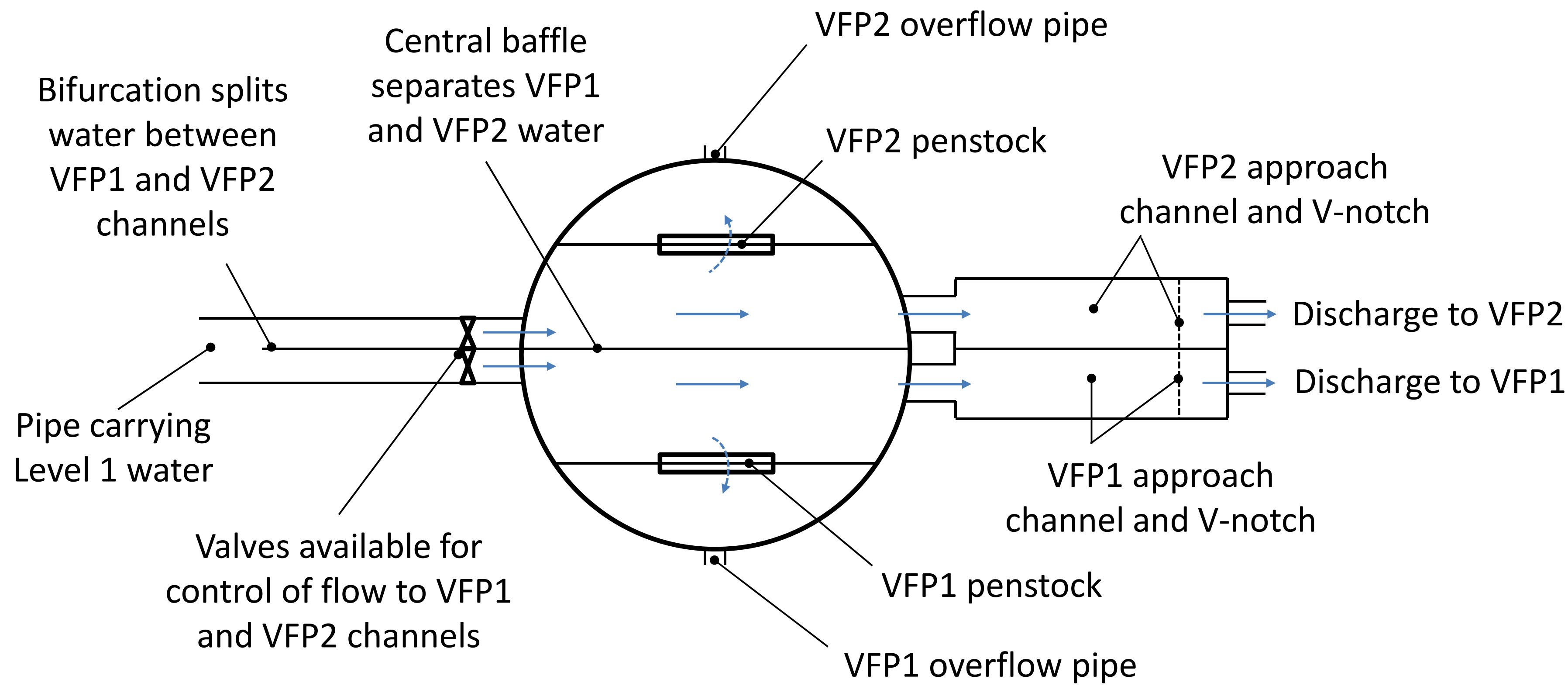


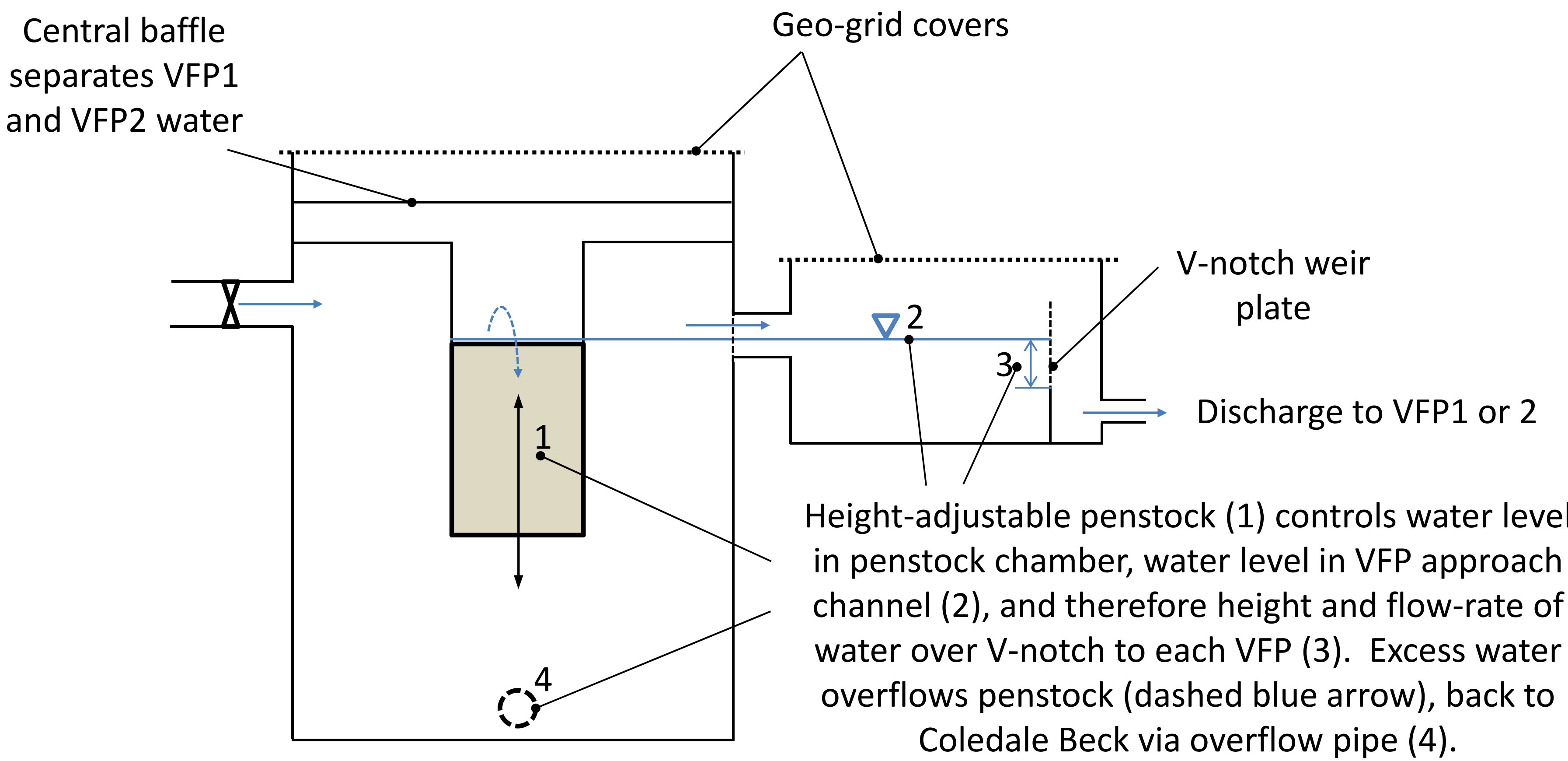
Figure courtesy of Coal Authority

Treatment system layout

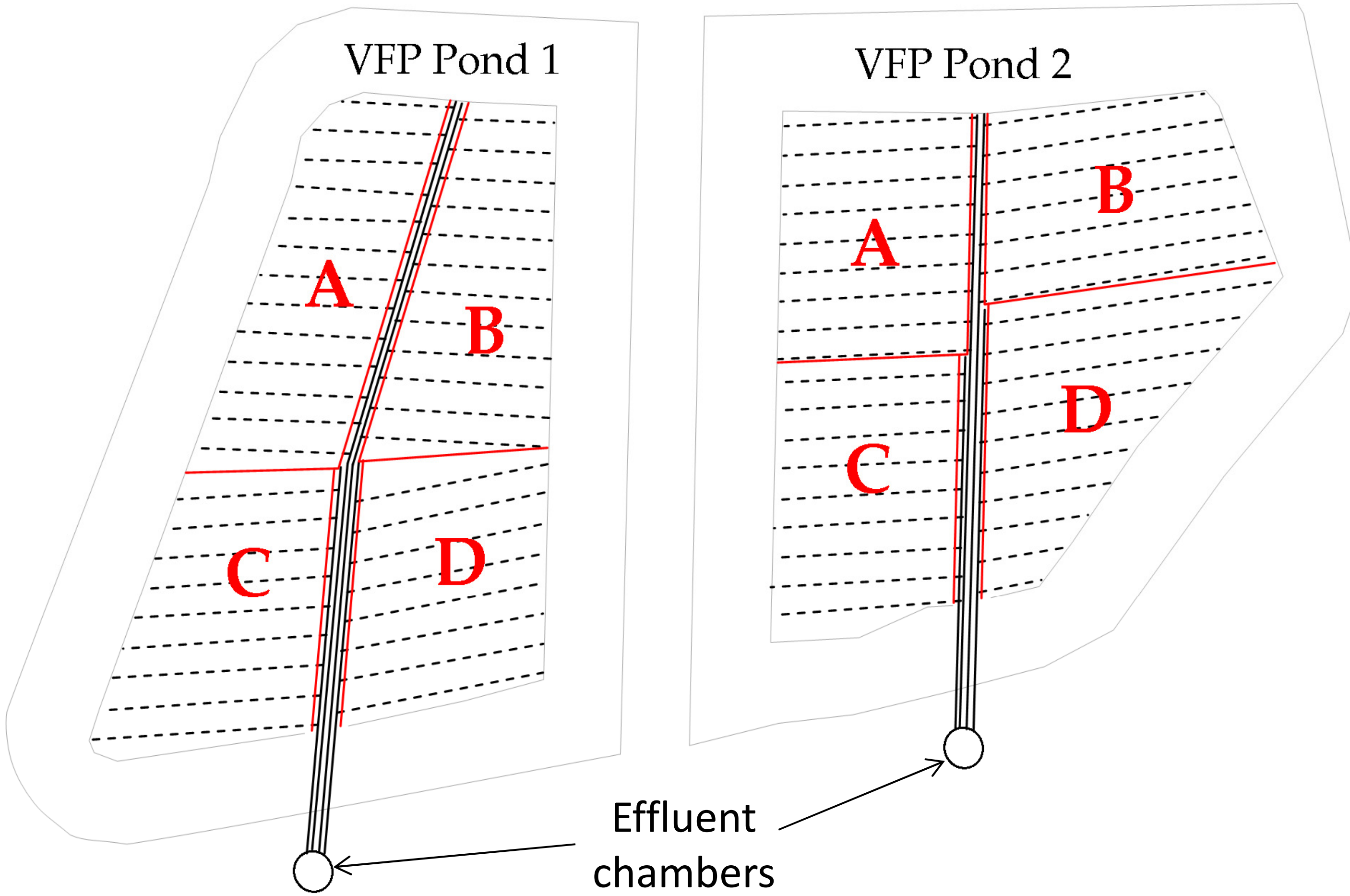


- Gravity fed system
- Close flow control to ensure consistency of flow
- Open channel flow control system for ease of maintenance

Treatment system layout



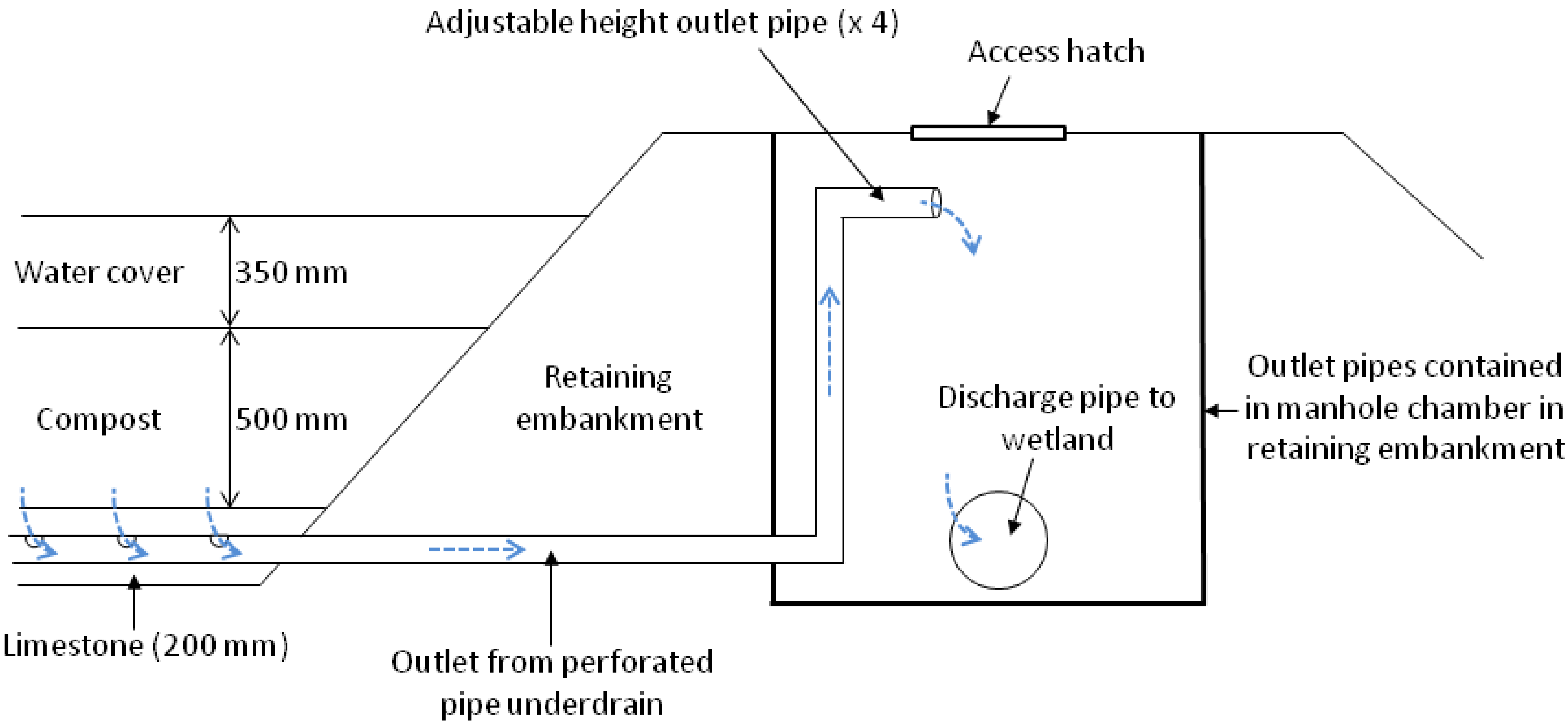
Treatment system layout



•Within each VFP have 4 independent perforated pipe drainage networks of equal area

Figure courtesy of Coal Authority

Treatment system layout



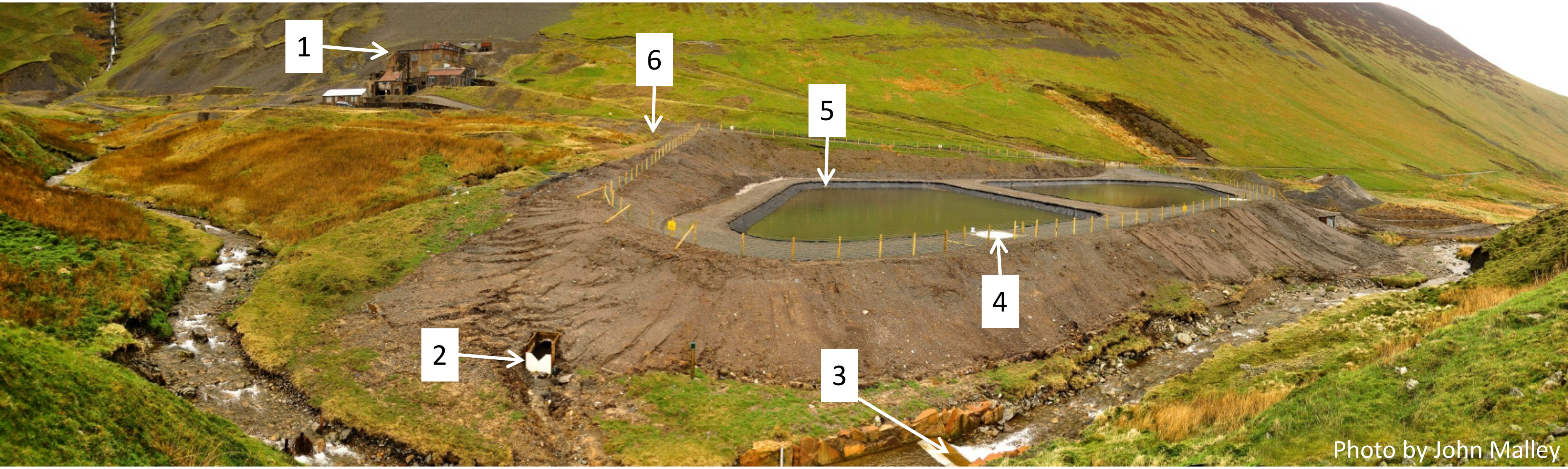
Compost: 45% BSI PAS 100 compost
45% wood chips
10% municipal WWTP activated sludge

Treatment system layout

A. Under drainage perforated pipe

B. Limestone (200 mm) and compost (500 mm) being placed over drainage

Treatment system layout



1. Location of Level 1 discharge
2. Subsurface drain diverts groundwater around treatment system
3. One of two flat V weirs for flow measurement in the Coledale Beck
4. Outlet chamber, VFP1
5. Inlet pipe to VFP1
6. Location of flow splitter

Vital statistics

Each VFP:

Surface area (top of compost)	760 m^2
Volume of compost	400 m^3
Volume of limestone	110 m^3
Design flow-rate	3 L/s
Nominal residence time in compost	18.5 hours

- Short residence time particular important given UK land constraints (actual HRT being checked with tracer tests)

- Combined design flow of 6 L/s (less than total flow of Level 1 discharge due to restriction on land area available)

Treatment principles

•As elsewhere, key process is bacterial sulfate reduction (BSR):

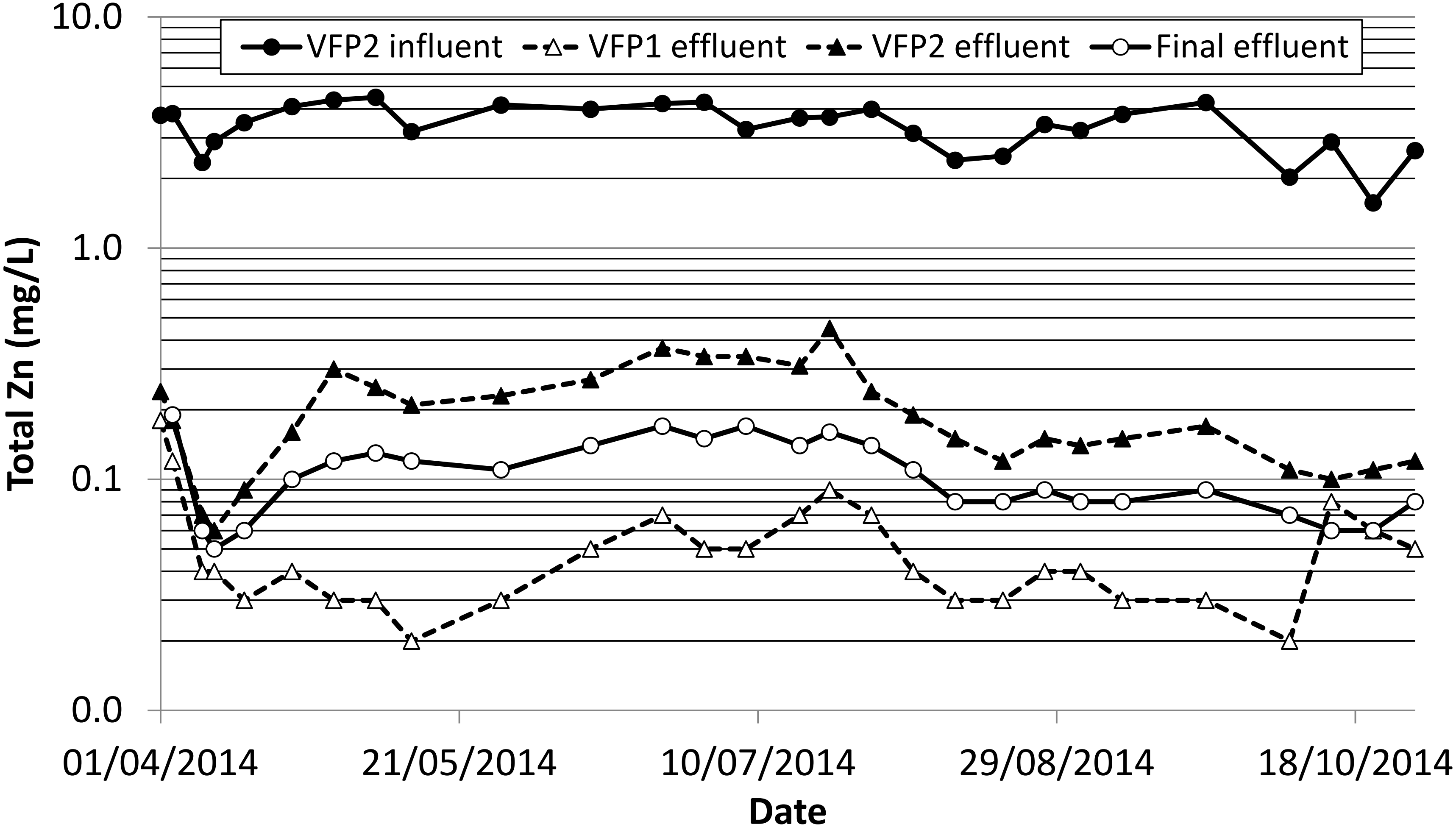
$$2CH_2O + SO_4^{2-} \rightarrow H_2S + 2HCO_3^-$$
$$H_2S + Zn^{2+} + 2HCO_3^- \rightarrow ZnS(s) + 2H_2O + 2CO_2$$

•System design based on a pilot-scale system that operated for 2 years (different site, but very similar water)

•Level 1 mine water is not acidic (mean pH = 6.8), and therefore sole objective to immobilise Zn as sulfide

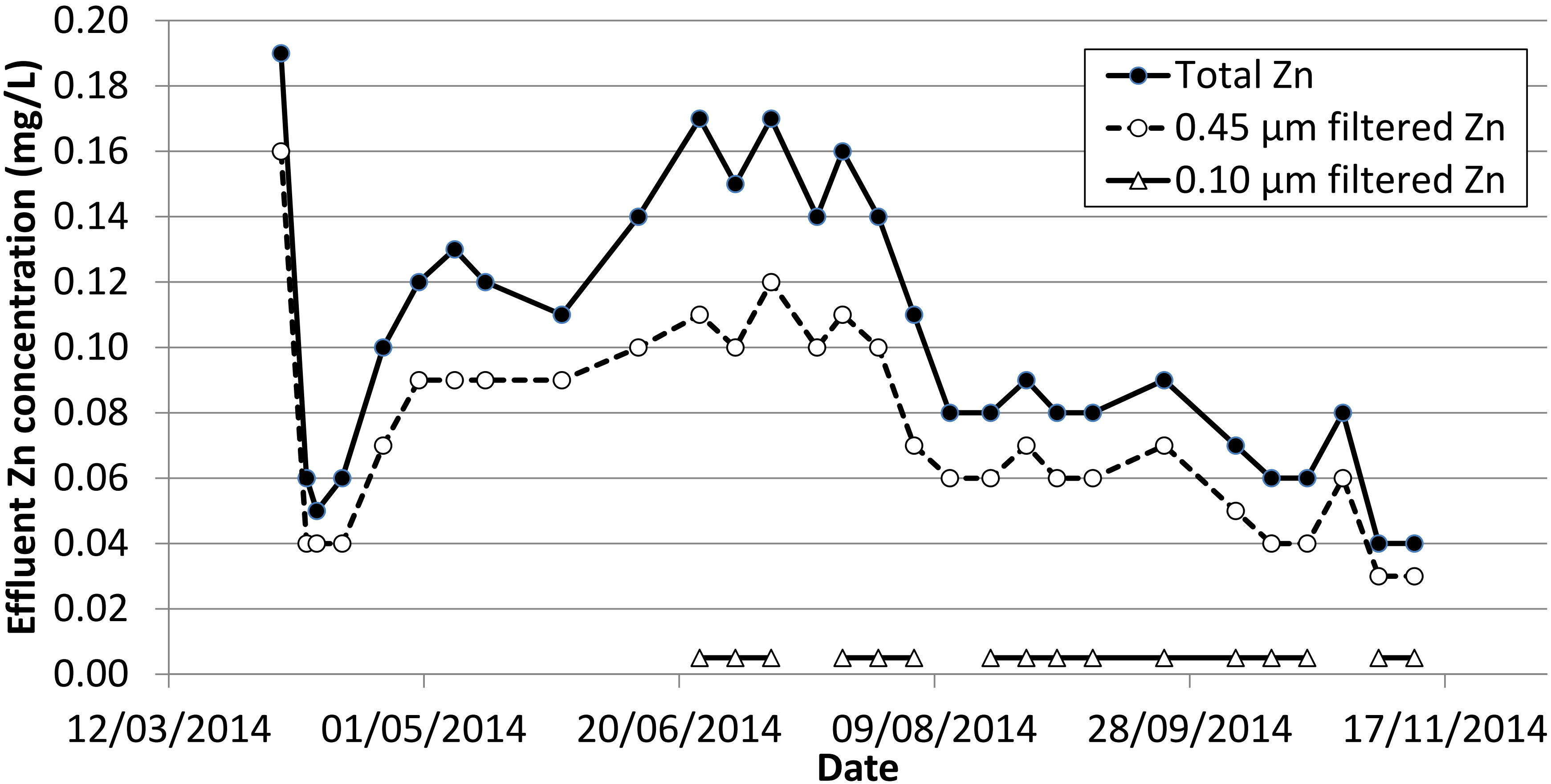
•Sulfate concentrations in Level 1 water relatively low (16.0 – 39.5 mg/L), and therefore lab tests to ensure sulfate reduction would occur

Treatment system performance: Zn



- Mean Zn removal (03/04/2014 – 18/10/2014) = **96.8%** (*n* = 27)
- VFPs 1 and 2 perform rather differently, despite same size, flow-rate and treatment media

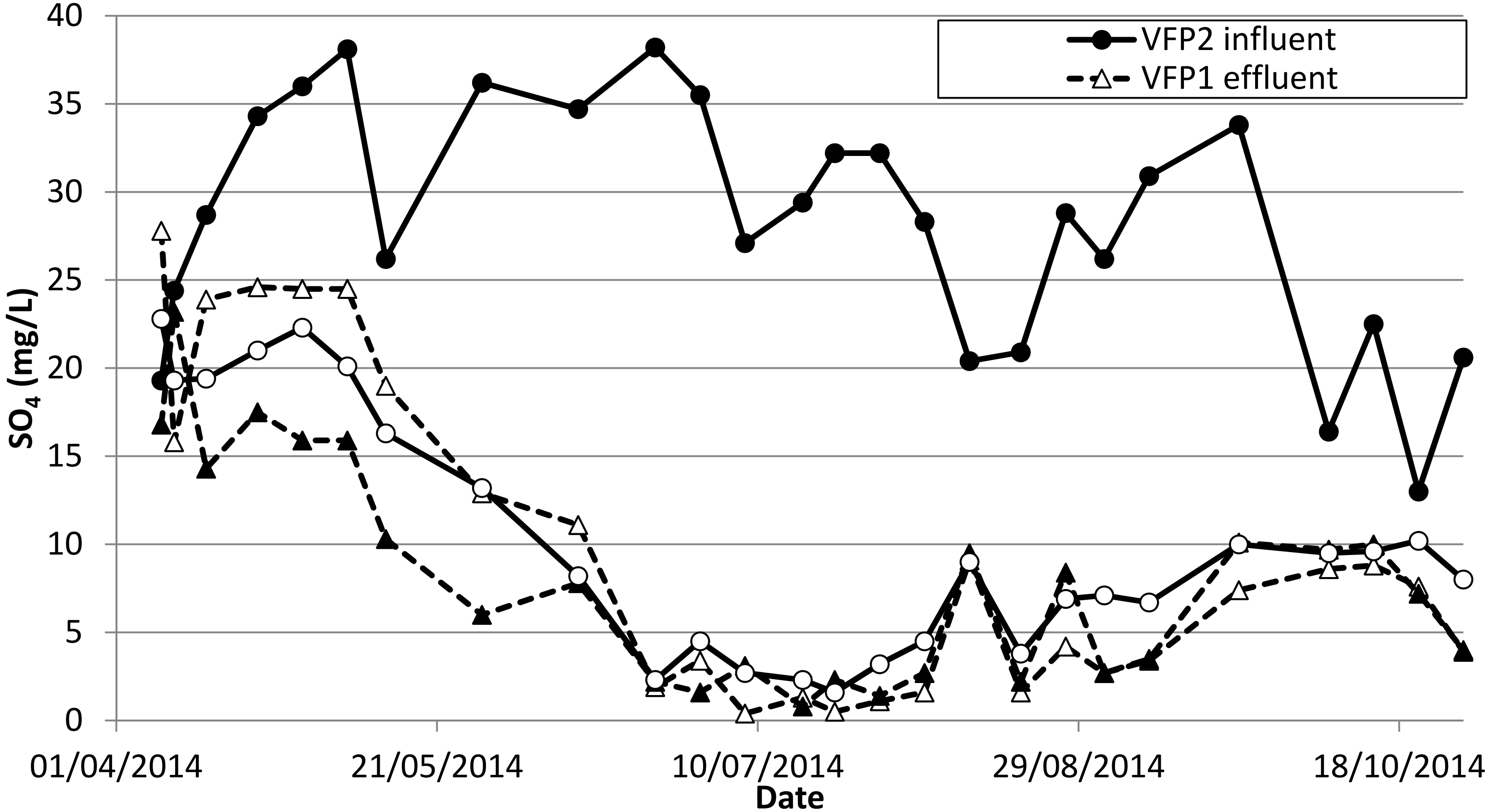
Treatment system performance: Zn



- Filtering effluent samples through 0.45 and 0.10 µm filters shows Zn in effluent is in colloidal form (ZnS?)

Note: 0.10 µm filtered sample concentrations consistently below detection limit of 0.01 mg/L, and therefore reported here as 0.005 mg/L

Treatment system performance: SO_4



- Substantial attenuation of sulfate in treatment system, despite low influent concentration. Strong odours of H_2S.
- Rate of sulfate reduction appears as though it may be influenced by temperature i.e. higher rate during warmer temperatures

Treatment system performance

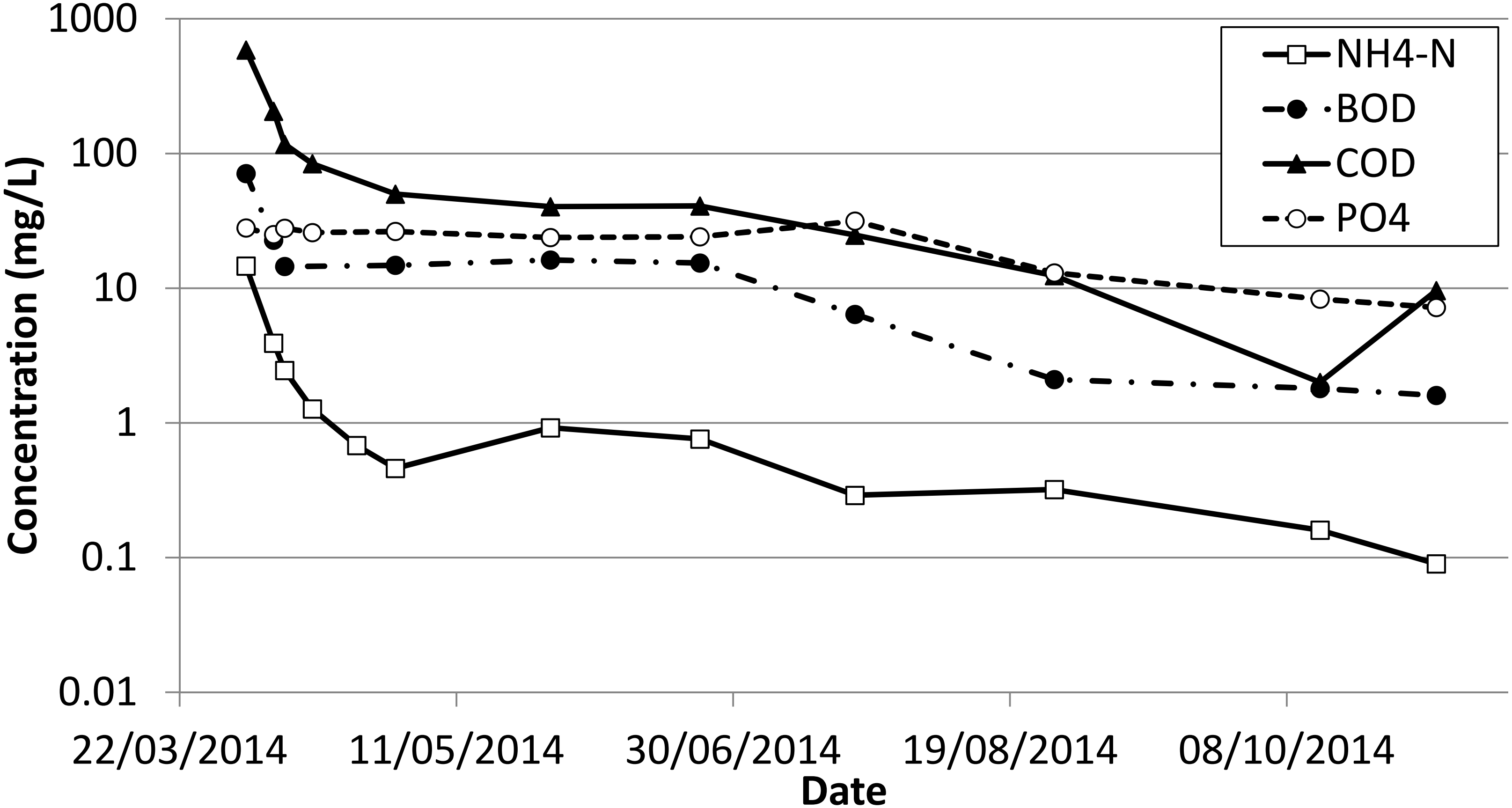
•Mean Zn removal to date (96.8%) substantially better than predicted from pilot-scale system (68%)

•On average, 3.35 mg/L Zn in Level 1 water, and 18.5 mg/L SO_4 removed during treatment. Equates to 51.5 mmol/L x 10^{-3} Zn^{2+} and 64.0 mmol/L x 10^{-3} S^{2-}

•According to chemical reactions for the precipitation of ZnS(s) via BSR, 1 mole of Zn will be immobilised as ZnS for every 1 mole of S^{2-} liberated from SO_4^{2-}. Therefore appears as though sufficient BSR to immobilise all of Zn in mine water.

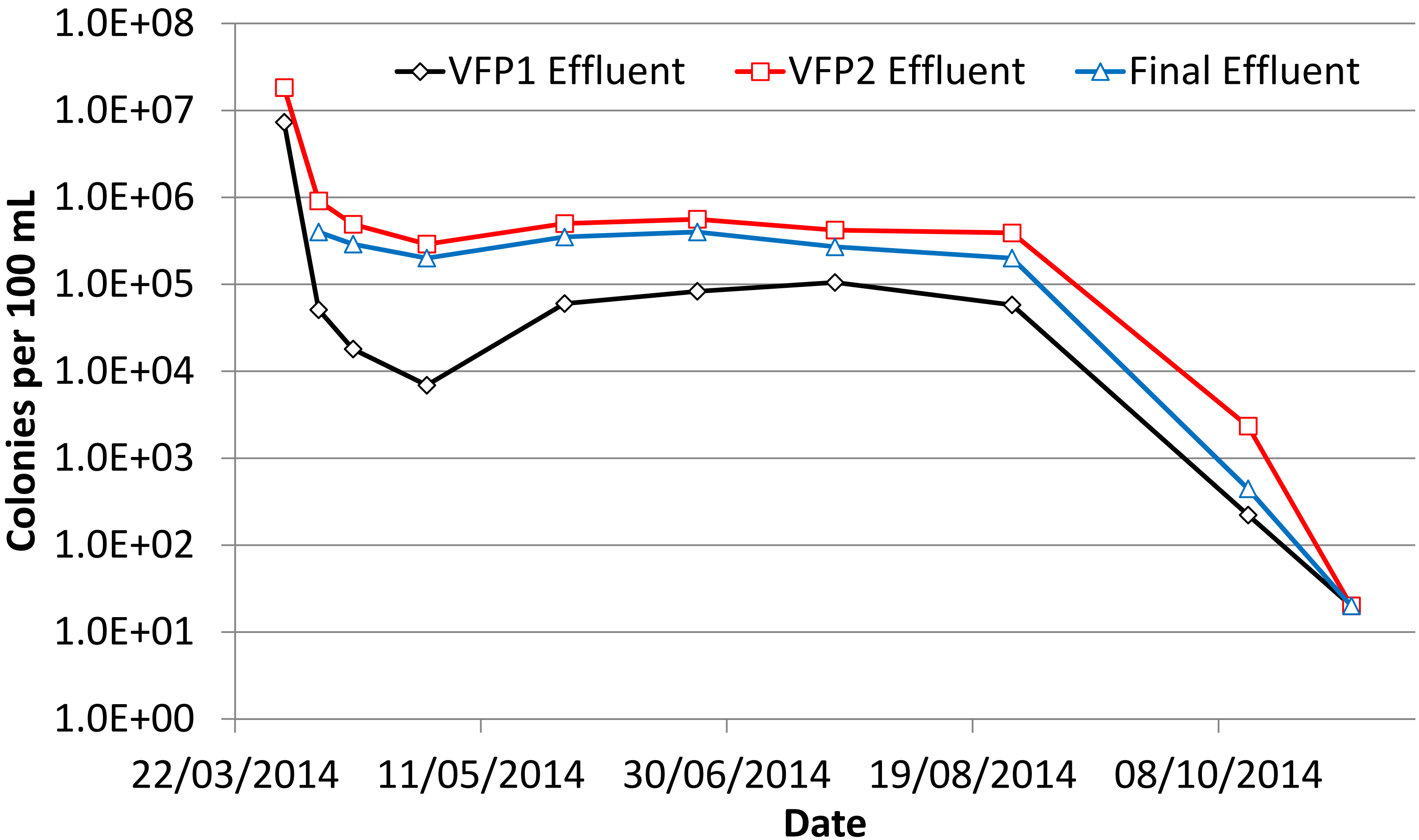
•Appears possible that all Zn is precipitated, but a small proportion physically entrained from treatment system in colloidal form

Treatment system performance



- Initially elevated concentrations of BOD, COD, NH_4-N and PO_4, but decreased rapidly
- Not an issue at this site, but could be at others (e.g. abstractions)

Treatment system performance



- Faecal coliform counts suddenly and dramatically decreased

Conclusions

•First 7 months of operation show very successful performance, although short-term secondary pollution due to organics

•But true success will be long-term attenuation of zinc

•Possible limitations to long-term successful operation an ongoing area of work:

- o Carbon limitation
- o S^{2-} toxicity / inhibition of sulfate reducing bacteria
- o Physical compaction of substrate / short-circuiting

•Management of metal-rich compost at end of life an important issue, and likely a key determinant of full life cycle costs (subject of ongoing PhD study at Newcastle)

Photo by John Malley