Passive treatment of mine drainage: Options, challenges, and possible future developments

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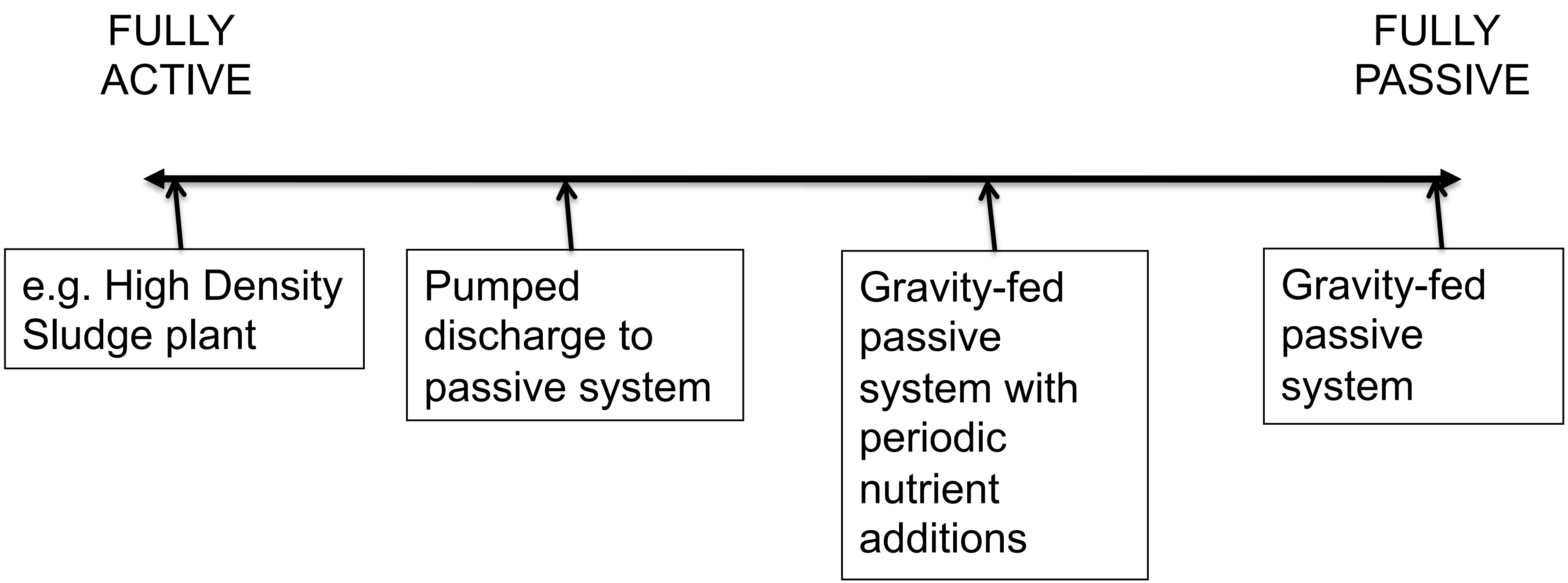
Definitions

- **Active Treatment** is the improvement of water quality by methods which require ongoing inputs of artificial energy and / or (bio)chemical reagents (long-established methods)

- **Passive Treatment** is the improvement of water quality using only naturally-available energy sources (eg gravity, microbial metabolic energy, photosynthesis) in systems which require only infrequent (albeit regular) maintenance

Selecting passive treatment options

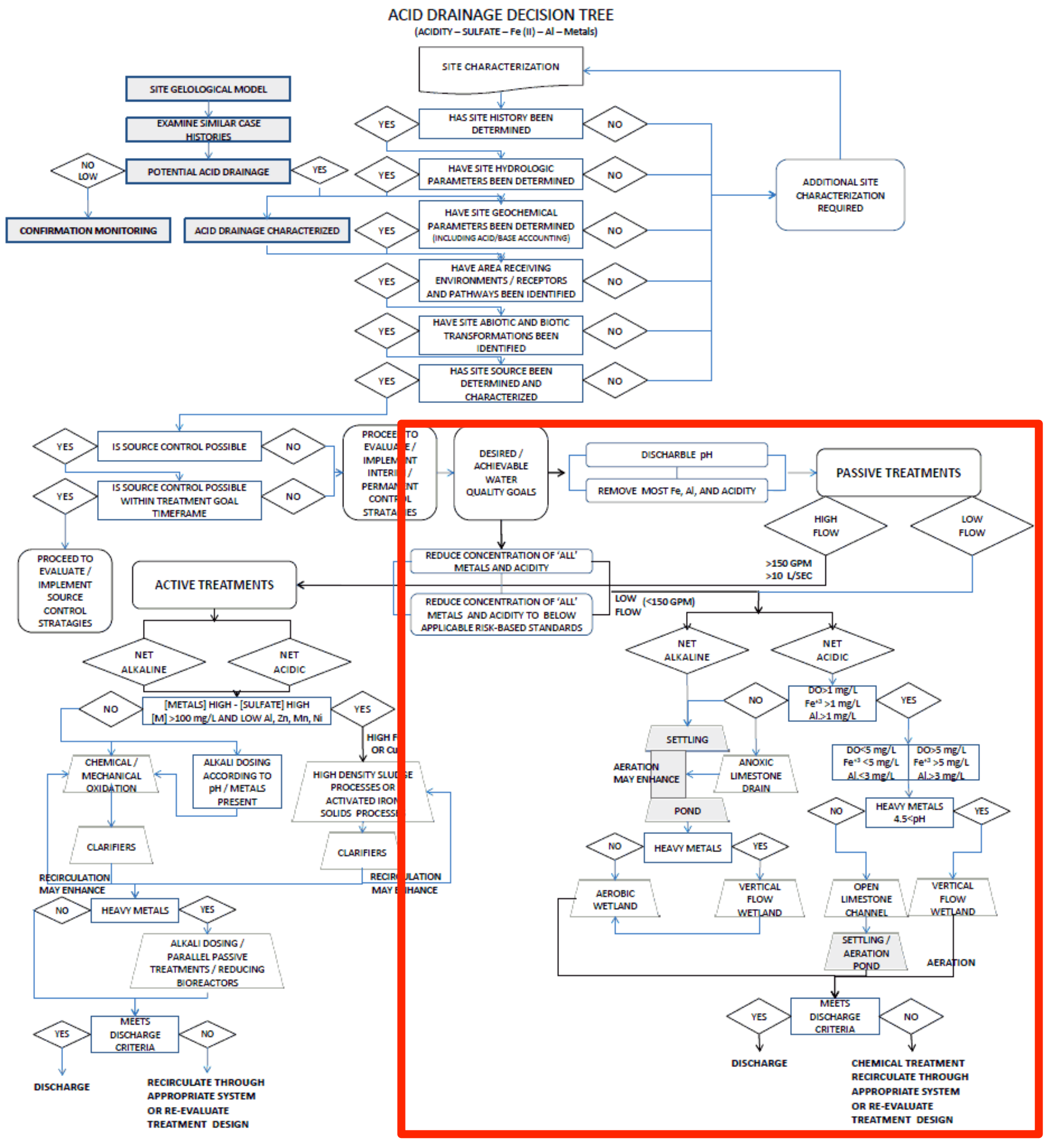
- ‘fully active’ and ‘fully passive’ either end of a sliding scale e.g.



Selecting passive treatment options

- Various decision-making flow charts available for selecting appropriate passive treatment option
- Selection is based around one, or a combination of, flow-rate, acidity and (which) metals present
- Historically, many such flow charts (and remediation initiatives) focussed on passive treatment of coal mine drainage (acidity, Fe, Mn, Al)
- In UK, now more of a focus on design criteria for passive base metal mine drainage systems (Zn, Cd, Pb, Cu)

Decision-making flow chart



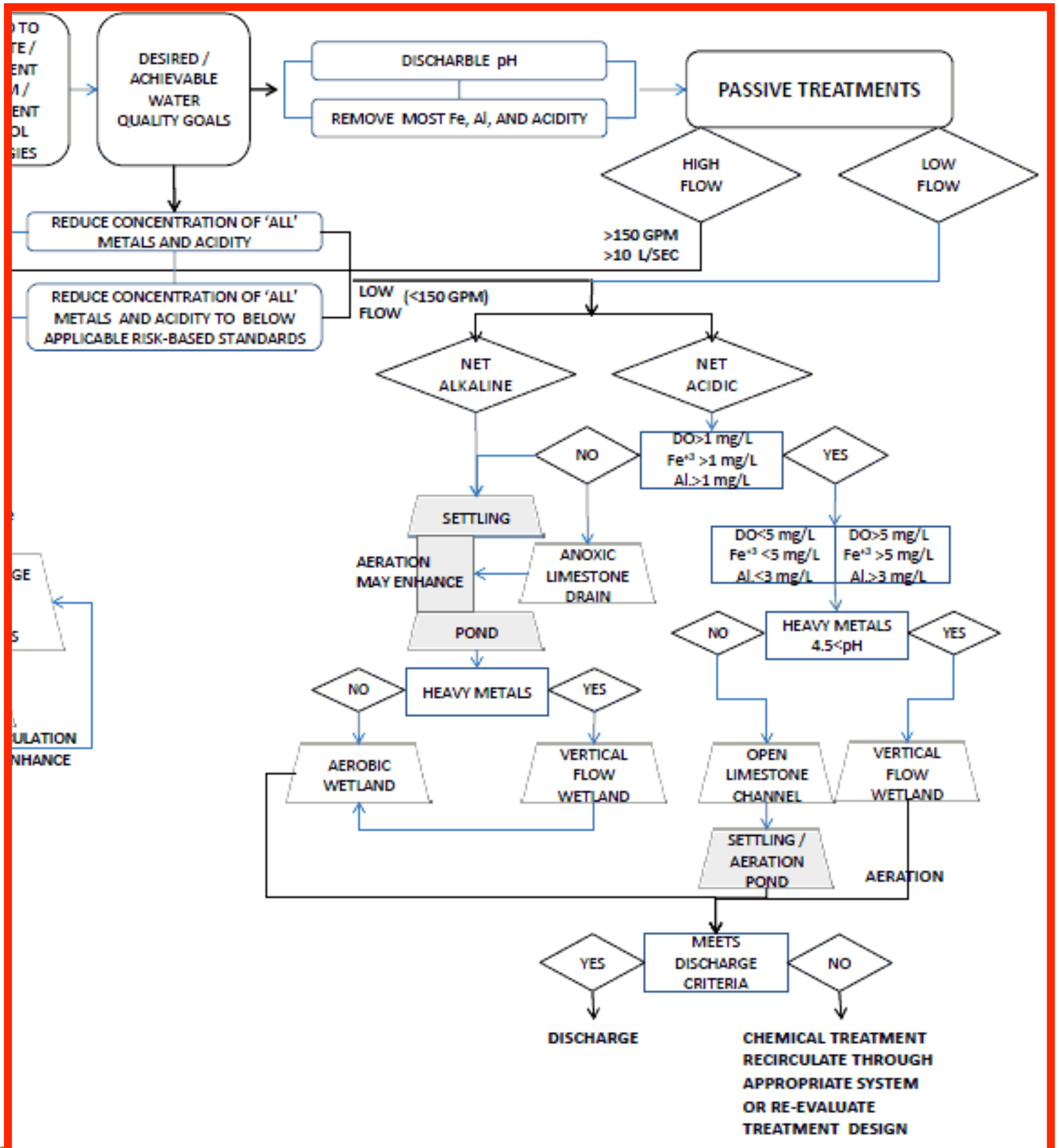
From GARD Guide:

(http://www.gardguide.com/index.php?title=Chapter_7)

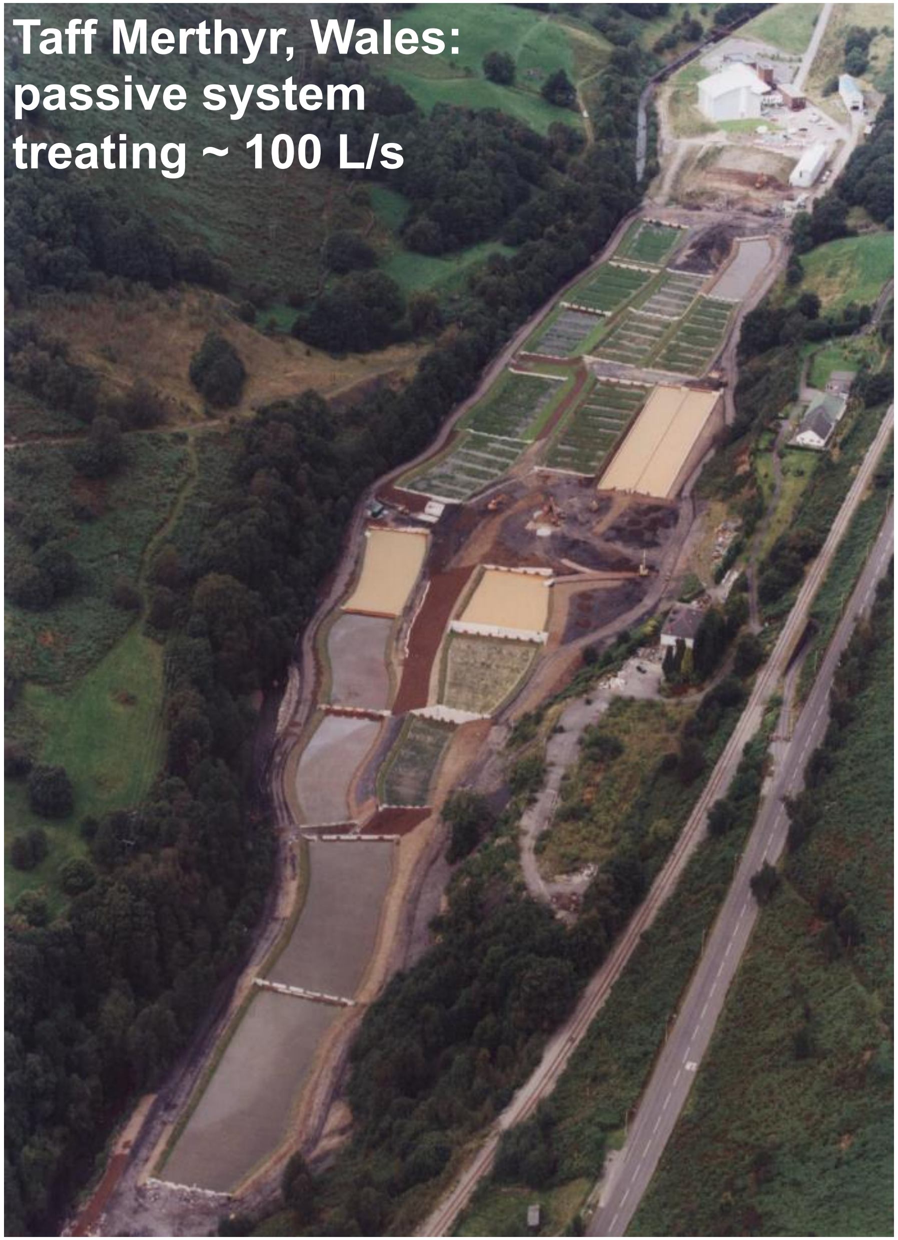
Passive treatment options:

Discharge flow-rate as key decision-making variable

Decision-making flow chart



- Discharge flow-rate < 10 L/s (150 GPM) = passive treatment feasible
- Next decision-making step: net-alkaline or net-acidic?
- And then: what is the target solid phase in which to immobilise metals – hydroxide, sulfide, carbonate



The risks of generic decision-making flow charts:

- There are often exceptions to the rule
- Site-specificity
- False sense of security / confidence: superficially 'simple' systems are actually rather complex

Passive treatment options

1. **Settlement lagoons**: for net-alkaline, metal-rich (iron) discharges
2. **Aerobic wetland**: as above

Common approach for net-alkaline, Fe-rich water in UK: ~ 70 systems

3. **Compost wetland**: for net-acidic, metal-rich discharges
4. **Anoxic Limestone Drains** (**ALDs**): for net-acidic discharges with low metals and dissolved oxygen
5. **Oxic Limestone Drains** (**OLDs**): for net-acidic discharges with moderate-high metals and dissolved oxygen
6. **Reducing and Alkalinity Producing Systems** (**RAPS**) and **Vertical Flow Ponds** (**VFPs**): for net-acidic and / or metal-rich discharges where hydraulic head available
7. **Permeable Reactive Barriers** (**PRBs**): for subsurface flows of net-acidic, metal-rich waters

Currently favoured for base metal mine drainage in UK

Passive treatment options

Settlement lagoon

Compost wetland

Anoxic limestone drain

Aerobic wetland

RAPS

Permeable Reactive Barrier

Passive treatment system design

- Typically empirical design
  - Optimum **Hydraulic Residence Time** (HRT) e.g. 14 hour contact time with limestone for optimum alkalinity generation (RAPS, ALDs)
  - **Area-adjusted removal rates** (US Bureau of Mines, 1994)
    - e.g. Aerobic wetland

$$A = \frac{Q_d\,(C_i - C_t)}{R_A}$$

- R_A value of 10 g/m^2/d for **Fe removal** still used in UK, more than 20 years after it was proposed by US Bureau of Mines

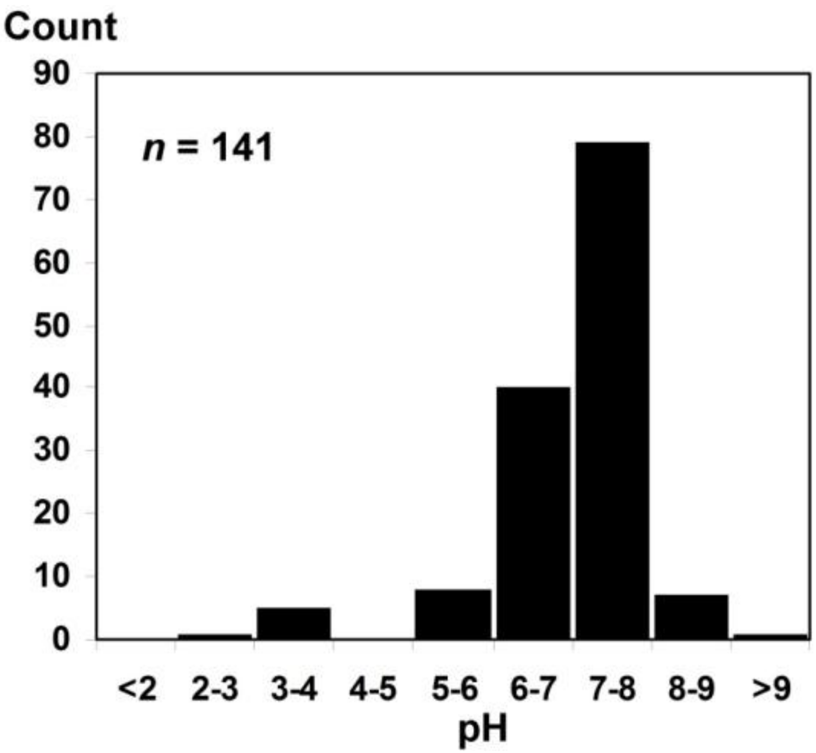
where:
A = wetland area required (m^2)
Q_d = Mean flow rate (m^3/d)
C_i= Inlet iron concentration (mg/L)
C_t= Target iron concentration (mg/L)
R_A= Area-adjusted removal rate (g/m^2/d)

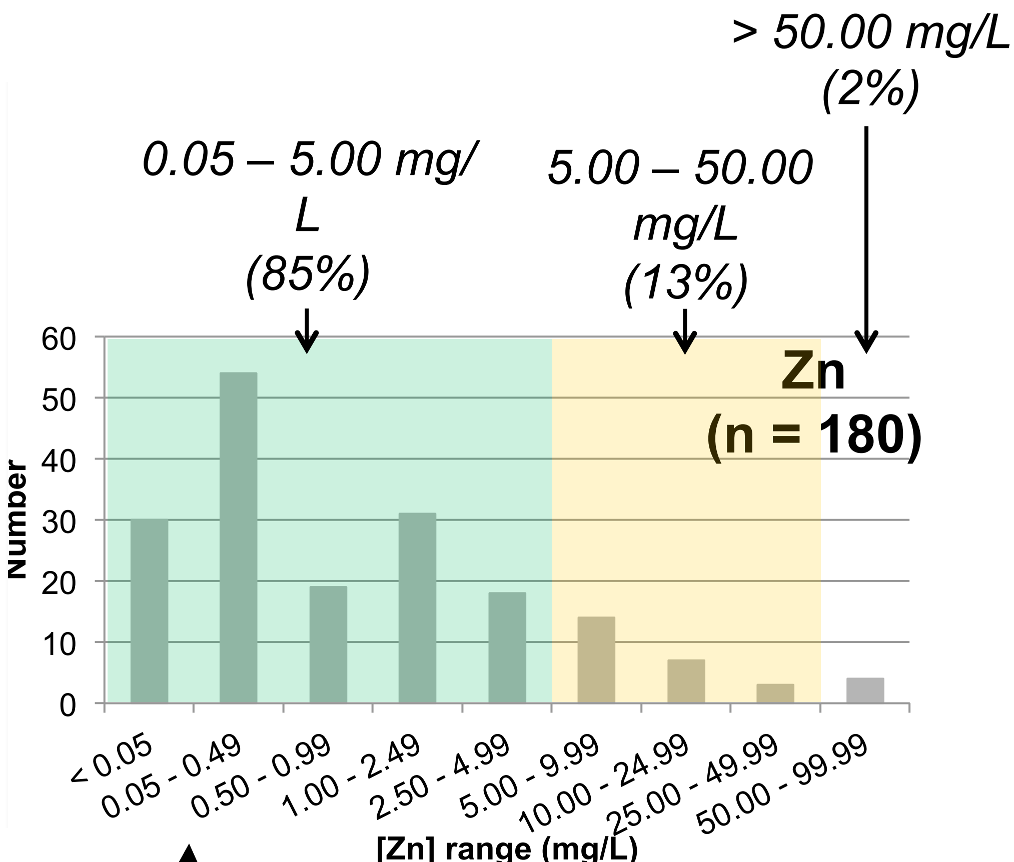
$$Fe^{2+} + \tfrac{1}{4}O_2 + H^+ \rightarrow Fe^{3+} + \tfrac{1}{2}H_2O$$
$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3\downarrow + 3H^+$$

Passive treatment system design

- Such empirical guidelines less well defined for divalent metals such as Zn and Cd
- Trivalent metals, or metals that can be readily oxidised to trivalent state (Fe), can be removed as their hydroxides in aerobic passive treatment systems (mainly *abiotic*)
- The solubility of divalent metal hydroxides is such that a high pH required for quantitative removal from solution – higher than feasible in passive treatment units
- Therefore aim to remove Zn, Cd, Ni etc as sulphides in compost-based systems (mainly *biotic*)

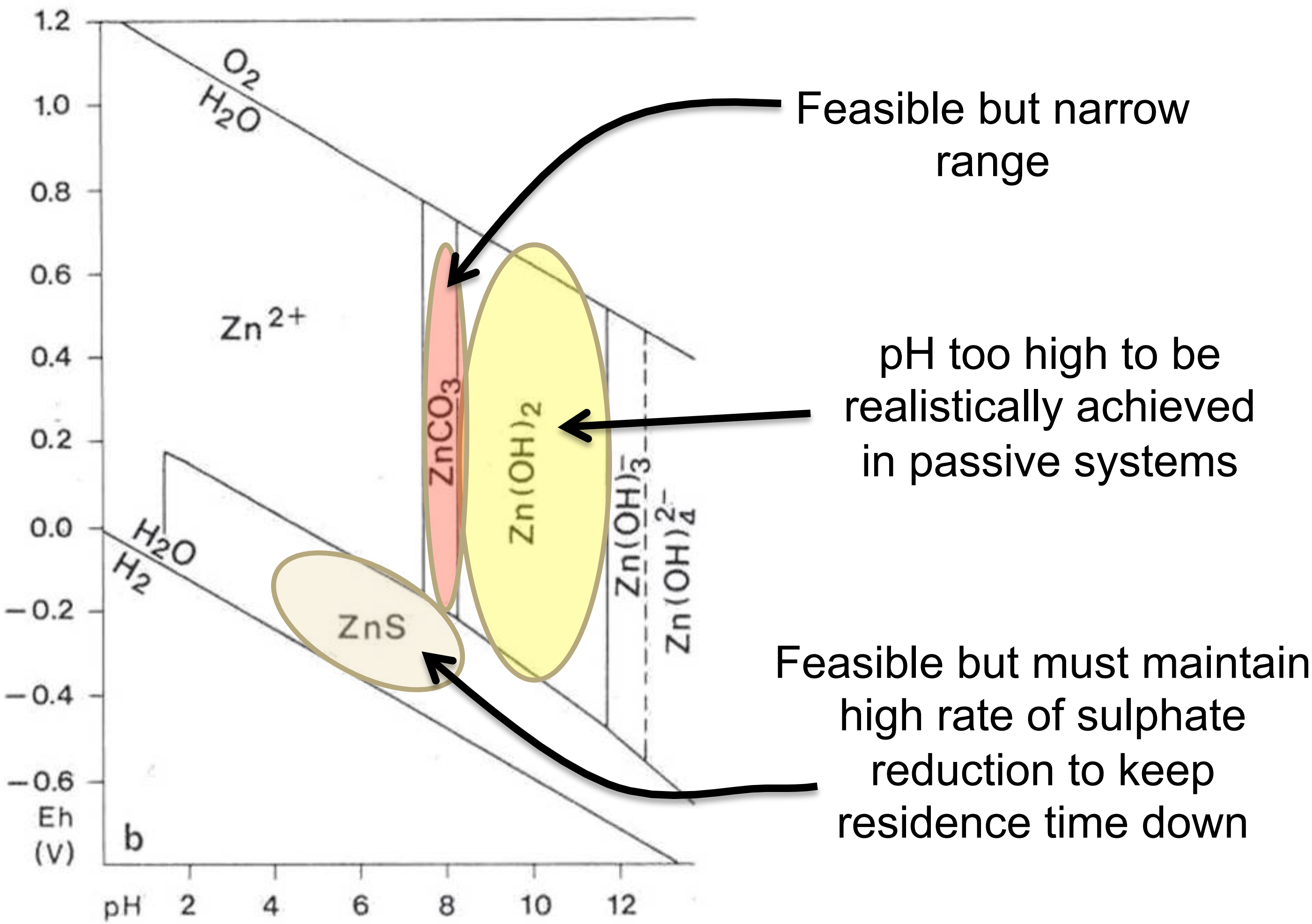
UK metal mine water characteristics





But collectively discharge > 250 tonnes / year Zn to freshwaters of England and Wales

Passive treatment for divalent metals



Pourbaix diagram for the Zn-O-H-S-C system at 25ºC and 1 atm (from Salomans, W. and Förstner, U. (1984) *Metals in the Hydrocycle*. Springer-Verlag, Berlin, Germany. 349pp). Possibilities for solid phases that might be retained in a passive system are indicated

Passive treatment for divalent metals

- Reducing and Alkalinity Producing Systems (RAPS): originally developed for generation of alkalinity in acidic waters with high metals (iron) content
- Compost over limestone: anaerobic conditions generated in compost to prevent 'armouring' of limestone below, which therefore generates alkalinity. Fe removal in subsequent units.
- Arrangement of Vertical Flow Ponds (VFPs) is same, but main objective (in UK) is to immobilise divalent metals as sulphides, via bacterial sulphate reduction, in compost layer

$$2CH_2O + SO_4^{2-} \rightarrow H_2S + 2HCO_3^{-}$$
$$\mathbf{M}^{2+} + H_2S + 2HCO_3^{-} \rightarrow \mathbf{MS} + 2H_2O + 2CO_2$$

Passive treatment for divalent metals

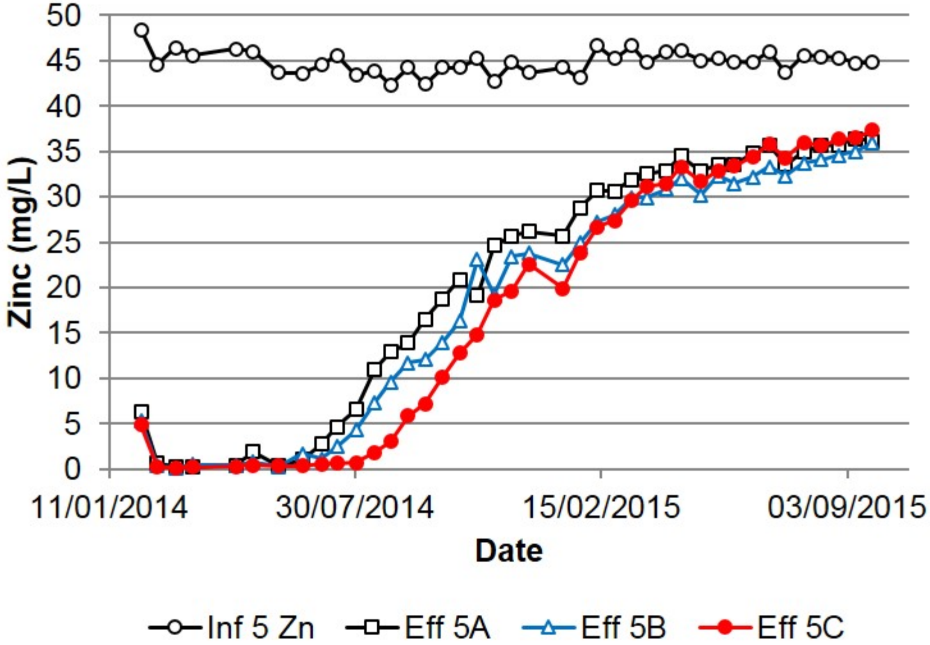
- Very effective removal of Zn and Cd, from neutral mine drainage, in a VFP system in Lake District National Park, UK: > 95% Zn removal over 2.5 years operation (C_i ~ 4 mg Zn/L)

- Key questions about longevity; require understanding of optimal physical (HRT), biological and chemical conditions, and their evolution i.e. process-based understanding

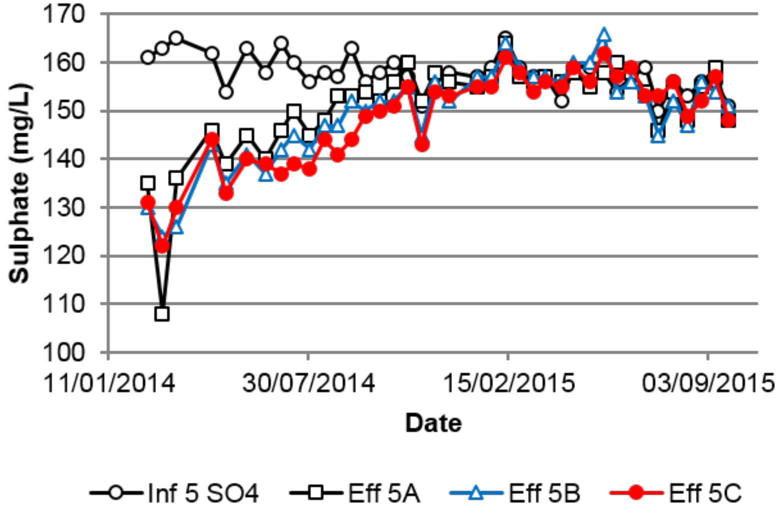
Challenges and limitations

- **System longevity**: How long will it work for? Difficult to estimate with confidence. Major bearing on full life cycle costs
- **System size / optimising performance**: Maximising rates of removal would reduce system size and therefore capital cost, and make treatment of higher flow-rate waters more feasible
- **Cold / extreme climate**: Will systems function in cold weather and / or variable weather?
- **Metal sludge / compost disposal / re-use**: Disposal of metal-rich sludge / compost a significant cost unless metal recovery and / or re-use options developed

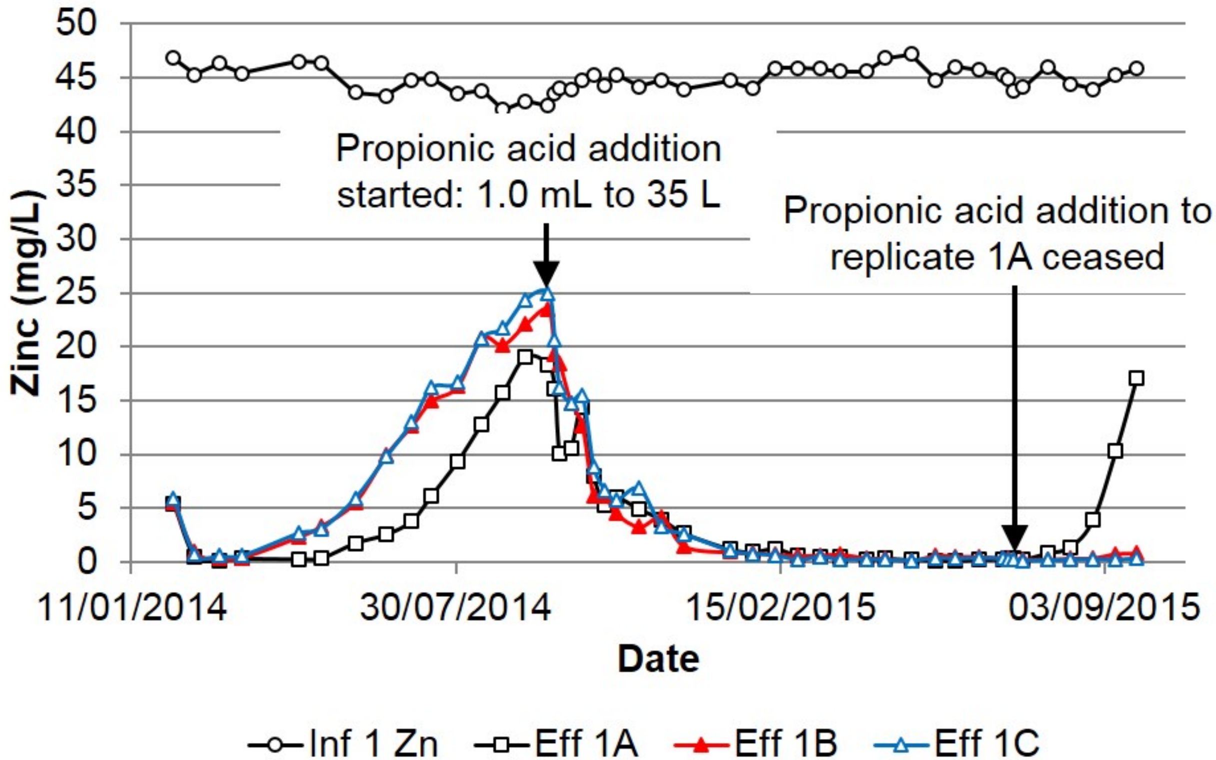
Optimising VFP performance



- Column experiments: After ~ 5 months deterioration in performance with respect to Zn
- Rate of sulfate reduction decreases over similar period

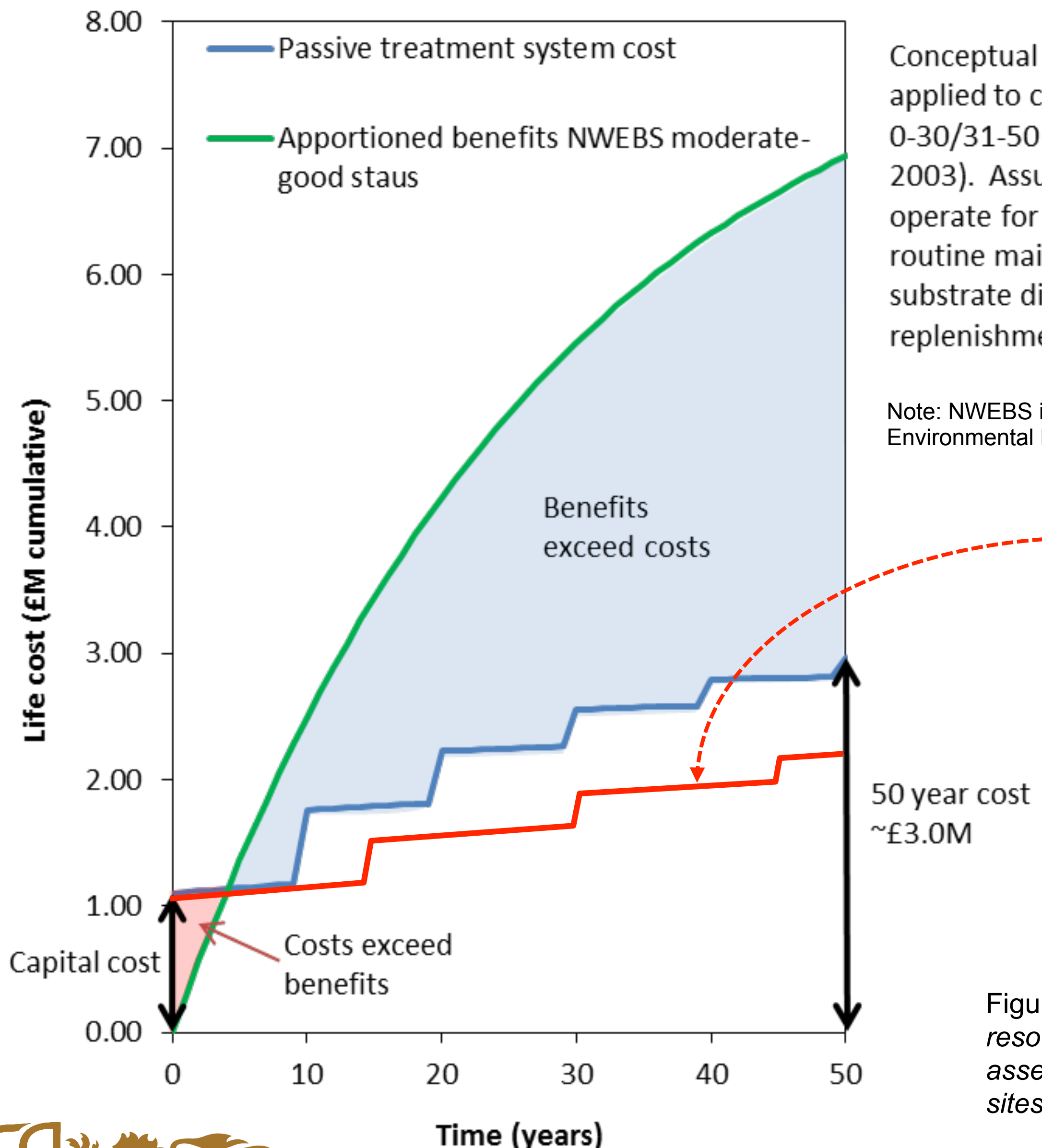


Optimising VFP performance



- Propionate oxidising sulfate reducing bacteria identified in compost
- Therefore propionic acid added to enhance performance
- Effective treatment of very polluted water and / or reduced system size

VFP system longevity



Conceptual model. 3.5/3.0% DCF applied to costs and benefits over 0-30/31-50 years (HM Tresury 2003). Assumed that system will operate for 50 years with only routine maintenance and substrate disposal and replenishment

Note: NWEBS is the National Water Environmental Benefits Survey

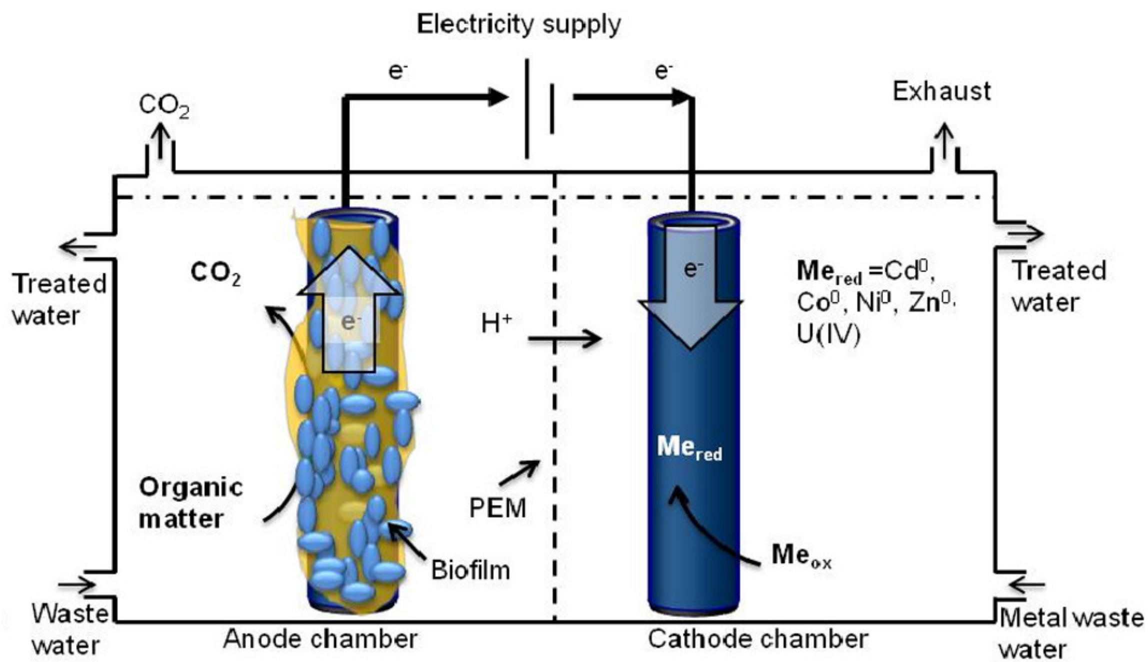
If system made to operate longer without compost replacement, and replacement costs reduced by recovering metals, costs decrease and benefits increase

Figure adapted from: Bailey. M.T. (2016) *Recovering resources from abandoned metal mine waters: An assessment of the potential options at passive treatment sites*. Unpublished PhD thesis, Newcastle University, UK

Possible future developments

- ‘Enhanced’ passive treatment, using carbon sources to increase rates of sulfate and metal removal
- Resource recovery from waste
- New technologies: Bioelectrochemical Systems (BES)?

Microbial Electrolysis Cells (MECs)



From: Nancharaiah *et al.*, (2015) Metals removal and recovery in bioelectrochemical systems: A review, *Bioresource Technology*, **195**, 102-114

- Metal *recovery* with limited energy requirement
- Scale-up a big issue:

Microbial Fuel Cell research (data from Web of Science, pers. comm. Prof. Tom Curtis, Newcastle University):

6 250 lab-scale studies	**20** pilot-scale studies	**3** pilot-scale studies using real wastewater in ambient environmental conditions


THANK
YOU!