Mine Water Rebound: PROCESSES AND PRODUCTS
♦ a UK perspective ♦

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Underground Coal Mine Post-closure Rebound

1. The last shift
Underground Coal Mine
Post-closure Rebound

2. Demolition time ...
Underground Coal Mine
Post-closure Rebound

3. Start surface reclamation ...
Underground Coal Mine
Post-closure Rebound

4. Reclamation advances

Note stratification in water quality during rebound*

Underground Coal Mine
Post-closure Rebound

5. Old site really looking nice now ...

Note stratification in water quality during rebound*

Underground Coal Mine
Post-closure Rebound

6. Whoops! Mine outflow commences

Stratification breaks down: worst water to the fore

Why mine water quality deteriorates during rebound

Acid-storing salts: efflorescent products of *in situ* pyrite oxidation in water-scarce environment

Golden rules:

• The higher the pyritic S content, the worse will be the pollution

• Pyritic S highest in marine-influenced strata

*Golden: as in ‘Fool’s Gold’*
Underground Coal Mine Post-closure Rebound

7. All is not lost: the first flush

Fresh recharge contributes to improving water quality
Underground Coal Mine Post-closure Rebound

8. Gradual water quality improvement
Underground Coal Mine
Post-closure Rebound

9. End of first flush
The 'first flush'

Total acidity vs. Time (scale of decades)

$tf$

Beyond the first flush ... 

- **A long-term handicap race:**
  - Sulfides only oxidise significantly above water table; silicates and carbonates dissolve above and below water table
  - Kinetics of weathering are also unequal:
    - carbonates > sulfides > silicates
  - Relative proportions of sulfides versus carbonates / silicates weathering determines long-term post-flush quality
  - This in turn depends primarily on mineralogy and hydrology of the system in question
Initially, carbonate (e.g. ankerite) weathering is brisk, providing much alkalinity. Later, depletion of carbonates leads to pH drop as water becomes acidic. Eventually, pyrite will be depleted and water becomes alkaline again due to sustained silicate weathering.
After the first flush: Bardon Mill Colliery 40 years after closure
Rising mine waters and reactivation of subsidence

- At least three mechanisms identified:
  - weakening of the floors (and roofs) of mine voids as certain types of strata respond to wetting
  - direct erosion of mine voids etc by rapidly-flowing mine water / pressurised gas
  - reactivation of previously-dormant faults which are intersected by old mine workings subject to recent flooding for the first time
Wetting weakens roof / floor strata and backfill

• Most likely in seat-earths of coal sequences (though also possible in other lithologies)
• Can lead to crown-hole collapses, pseudo-karstification, enhanced groundwater recharge
• More subtle large-scale features (e.g. enhanced settlement of longwall goaf) can form enclosed basins hosting new ponds
Slaking and pillar failure in old workings
Slaking and pillar failure in old workings
Slaking and pillar failure in old workings
Failures ascribed to wetting-induced settlement - I

Near Newcastle Airport, Nov 2000

Photo: BGS
Failures ascribed to wetting-induced settlement - II

Near UK’s main N-S trunk road and Europe’s largest indoor mall (Metro Centre), May 2002
Simplified geological cross-section: Durham Coalfield

Permian: Basal sands and Magnesian Limestone Aquifers

Permian evaporites present offshore

Coal measures

Worked zones

200m
Mine water recovery in E. Durham

Water Level (m bOD)

-450 -400 -350 -300 -250 -200 -150 -100 -50 0

15/06/19 28/10/19 11/03/19 24/07/19 06/12/19 19/04/20 01/09/20 14/01/20

-450 -400 -350 -300 -250 -200 -150 -100 -50 0

<table>
<thead>
<tr>
<th>Date</th>
<th>Water Level</th>
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<td>14/01/20</td>
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</table>

- Graph shows water level recovery over time for different locations.

- Water levels are expressed in meters below Ordnance Datum (m bOD).

- Locations include Hawthorn, Dawdon, and Easington.

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Tidal loading and piezometry

Compression of strata due to tidal loading causes water levels in the mine shafts inland to rise and fall.
Example data - tidal loading

Amplitude of oscillation damped with increasing distance inland
It is important to know what lies at depth before planning for post-rebound period ...

Hydrochemical stratification

Iron (mg/l) vs Depth (mbgl)

pH vs Depth (mbgl)
Groundwater source protection zones in East Durham area
Leakage pathway threat to wells in Permian (Magnesian Limestone) aquifer
Water drifts pollution pathway - I

Water well

Old colliery "water drift"

Capped colliery shaft

Old colliery sea drift
Water drifts pollution pathway - II

- Water well
- Old colliery "water drift"
- Capped colliery shaft
- Old colliery sea drift
Water drifts pollution pathway - III

- Water well
- Old colliery "water drift"
- Capped colliery shaft
- Old colliery sea drift
Water drifts pollution pathway - IV

- Water well
- Old colliery “water drift”
- Capped colliery shaft
- Old colliery sea drift
Predicting post-closure changes: rationale and specification

• **Rationale:** *to clarify whether a pollution prevention scheme will be needed post-rebound, and if so to provide site-specific design criteria*

• **Necessary predictions:**
  1. **Hydrological predictions:**
     • Timing of rebound to surface
     • Likely outflow rates after rebound
  2. **Geochemical predictions:**
     • Likely quality of water post-rebound
Hydrological prediction tools*

- Range of modelling tools for a range of scales:
  - **GRAM (Groundwater Rebound in Abandoned Mineworkings):**
    - semi-distributed modelling approach
    - based on concept of mine pools and decants
  - **VSS-NET:**
    - Physically-based, fully 3-D, variably saturated porous medium coupled to pipe network model representing major mine roadways / shafts etc
  - **Conventional distributed groundwater flow models:**
    - Usable at scales at which effects of major mined flow-path features cannot (need not) be resolved

Hydrological prediction tools: choose to suit scale

- CDGWFM
- GRAM
- VSS-NET

Areal extent of system (km²)
VSS-NET

ELEVATION

PLAN

Pipes not to scale

VSS Elements

Lateral Flow (Laminar)

Pipe Flow (Turbulent)

Exchange Flow (Laminar)

~ 100-500 m

~ 1-5 m

Pipe

Vertical Flow (Laminar)

VSS Node

Exchange Flow (Laminar)

VSS cells

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VSS-NET: example application - Whittle Colliery, Northumberland

- Post-audit (in 2004) of 1998 VSS-NET predictions
  - Completion of rebound to 50mAOD:
    - Predicted: May 2002
    - Observed: May 2002
  - Median post-rebound flow rate:
    - Predicted: 1.7 ML/d
GRAM: example application - Blaenant Colliery, S Wales.

I. Pond definition
GRAM: example application – Blaenant Colliery, S Wales.

II. Predicted vs observed rebound
Models of first flush

- Classic analytical approach – feasible but limited real-world applicability
- Full numerical modelling – notionally feasible, but given complex hydraulics would require enormous cpu time
- Empirical models – based on hydrological principles; easy to use
Analytical Model of First Flush - Modified Sauty Solution to ADE

- \( C(t) = 0.5 \ C_o \ \text{erfc}\left(\frac{L - v_a \ t_w}{2(D t_w^{0.5})}\right) + C_a \)

- Where:
  - \( C(t) \) = concentration at outflow from mine at time \( t \) (i.e. the elapsed time since the mine began to overflow)
  - \( C_o = C_p - C_a \)
  - \( C_p \) = peak concentration at start of first flush
  - \( C_a \) = steady concentration at end of first flush
  - \( v_a \) = average groundwater flow velocity within the mine system (L/T)
  - \( t_w \) = “working time”, the difference between the total length of the main flushing period (found on a trial-and-error basis) and time since overflow commenced
  - \( D \) = longitudinal dispersion coefficient (L^2.T^-1)
  - \( \text{erfc} \) is the complementary error function
Example application - Wheal Jane

1992

2006
Application of modified Sauty model to Wheal Jane First Flush

Iron concentration (mg/l)

Time in days since flooding of mine complete
Empirical model for first flush

- **Controls on first flush:**
  
  Hydraulic turnover rate
  
  \[ = F \left( \frac{\text{total pore volume}}{\text{rate of recharge}} \right) \]

- Closely resembles controls on rebound rate (notwithstanding loss of head-dependent mine water sources as water table rises)

- Observations since 1960s suggest exponential first-flush with half-life = duration of preceding rebound period
Empirical model for first flush

$$t_f = (3.95 \pm 1.2) \times t_r$$

$$t_{\frac{1}{2}} = t_r$$

Total acidity

Time (scale of decades)

(Jl. Contam. Hydrol., 44, pp 47 - 69 (2000))
Partial first flush model

- Found to be especially applicable to very large systems in which a large proportion of the workings lie down-gradient from the final surface decant / pumping point
- Where original model states:
  \[ t^{\frac{1}{2}} = t_r \]
- Modified model is:
  \[ t^{\frac{1}{2}} = \nu \cdot t_r \]

where \( \nu \) can range from 0.1 for very large ‘dead-end’ systems to 1 (i.e. original model)
Example: Fendue Lyon Colliery (France)

Model: \( t_{\frac{1}{2}} = t_r \)

Model: \( t_{\frac{1}{2}} = 0.33 \cdot t_r \)
Conclusions

• Proven methodologies exist for predicting:
  - Rebound rates
  - Post-rebound flows
  - Post-rebound water quality evolution
    (established for Fe; POSSUM model under development for all other major contaminants)

• Challenges lie in parameterisation,
  especially *a priori* recognition of ‘dead-end’
  pore space in extensive deep mine systems
Thank you - *Merci - Tapadh leibh*

"The past ... ... we inherit ...

mine water pollution

... the future ...

passive in situ

remediation

... we build"