Management of metal mining-contaminated river systems in the UK and the Lower Danube Basin

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Outline of Presentation

- History & environmental legacy of metal mining in the UK
- Dispersal & storage of mine waste in river systems
- Changing climate & WFD: remediation versus management
- Approaches to managing historically metal contaminated rivers
- The next steps
- The Lower Danube Basin
Mining History

Mining Output:
- 8.5 m tonnes lead
- 1.3 m tonnes zinc
- 0.13 m tonnes copper

Peak mining mid-late 19th century

Dating back over 4000 years to the Bronze Age

After Dunham et al., 1978, and Lewin and Macklin, 1987
The Environmental Legacy of Metal Mining

- No environmental protection legislation during 18th and 19th centuries
- Inefficient processing during this period: 60-70% metal recovery
- Fine-grained (< 2 mm) solid and liquid waste discharged directly into river systems
Dispersal and Storage of Mining Waste in River Systems

- Majority of metal contaminant dispersal (90%) occurred in sediment-associated form.
- Metal-rich sediment transported, generally as suspended load, 10s to 100s of km from source.
- Deposited and stored in channel and floodplain environments through vertical and lateral accretion processes.
Dispersal and Storage of Mining Waste in River Systems

- Long residence times (100s – 1000s years)
- Remobilised from channel and floodplain storage through physical and chemical processes
- Mining-related contamination started as a point source but has evolved to a large-scale diffuse source
UK river catchments contaminated by historical metal mining

- 12,000 km² of rivers in northern England alone are contaminated

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Ore field</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Tyne</td>
<td>Northern Pennines</td>
</tr>
<tr>
<td>Wear</td>
<td>Northern Pennines</td>
</tr>
<tr>
<td>Tees</td>
<td>Northern Pennines</td>
</tr>
<tr>
<td>Swale, Wharfe, Nidd, Ure</td>
<td>Yorkshire Dales</td>
</tr>
<tr>
<td>Glenridding Beck</td>
<td>Lake District</td>
</tr>
<tr>
<td>Ecclesbourne, Hamps, Manifold, Derwent</td>
<td>Southern Pennines (Derbyshire)</td>
</tr>
<tr>
<td>Rea Brook</td>
<td>West Shropshire</td>
</tr>
<tr>
<td>Afon Goch</td>
<td>Mynydd Parys</td>
</tr>
<tr>
<td>Twymyn</td>
<td>Central Wales</td>
</tr>
<tr>
<td>Rheidol</td>
<td>Central Wales</td>
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<tr>
<td>Ystwyth</td>
<td>Central Wales</td>
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<tr>
<td>upper Severn</td>
<td>Central Wales</td>
</tr>
<tr>
<td>Yeo</td>
<td>Mendip</td>
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<tr>
<td>Axe</td>
<td>Mendip</td>
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<tr>
<td>Camel</td>
<td>Devon-Cornwall</td>
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<tr>
<td>Erme</td>
<td>Devon-Cornwall</td>
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<td>Fal</td>
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<tr>
<td>Fowey</td>
<td>Devon-Cornwall</td>
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<tr>
<td>Gannel</td>
<td>Devon-Cornwall</td>
</tr>
<tr>
<td>Tamar</td>
<td>Devon-Cornwall</td>
</tr>
</tbody>
</table>
Mean contaminant metal concentrations in floodplain sediments (mg/kg)

River systems affected by historical metal mining

<table>
<thead>
<tr>
<th>River</th>
<th>Pb</th>
<th>Zn</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swale, northern England</td>
<td>1360</td>
<td>970</td>
<td>314</td>
</tr>
<tr>
<td>Tyne, northern England</td>
<td>2830</td>
<td>5500</td>
<td>93</td>
</tr>
<tr>
<td>Ystwyth, Wales</td>
<td>1800</td>
<td>530</td>
<td>24</td>
</tr>
</tbody>
</table>

River systems affected by tailings dam failures

<table>
<thead>
<tr>
<th>River</th>
<th>Pb</th>
<th>Zn</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guadiamar, SW Spain</td>
<td>1000</td>
<td>1200</td>
<td>29</td>
</tr>
<tr>
<td>Someș, NW Romania</td>
<td>200</td>
<td>850</td>
<td>18</td>
</tr>
</tbody>
</table>
The sediment-water contamination link

- Water in mining-affected river systems is contaminated with heavy metals (Pb, Cu, Cd, Zn) and arsenic through:
  - Direct discharge of adit or spoil heap waters
  - Acid mine drainage
  - *In situ* weathering of contaminated alluvium through changes in pH and redox potential
  - High-flow events that result in desorption of metals from sediments
If this problem has been around for more than 100 years, why has it now become a major issue?

- Recent increase in flooding (e.g., Millennium Floods)
- Greater seasonality of water tables in floodplains (wetting and drying)
- Need to comply with Water Framework Directive
Autumn 2000 floods – a ‘wake-up call’ for catchments affected by past metal mining
Swale catchment, northern England

Key
- Mine
- Settlement

0 10 km
Pb in Swale catchment

- ICRCL 70/90
- Swale floodplain Pb
- Tributary channel Pb
- Swale overbank Pb

Concentration (mg kg\(^{-1}\))

Distance downstream (km)
Implications of climate change for catchments affected by past metal mining

- Most of the severely affected river systems are in the north and west of Britain where the greatest increase in flooding is expected to occur in the next 10-50 years.

- Floodplain sediments contaminated by mine waste represent a major diffuse source and (because of increased flooding) they are likely to become the predominant supplier of sediment-associated metals in many catchments.
If this problem has been around for more than 100 years, why has it now become a major issue?

- Recent increase in flooding (e.g., Millennium Floods)
- Greater seasonality of water tables in floodplains (wetting and drying)
- Need to comply with Water Framework Directive
Remediation versus Management

- River are dynamic, and contaminated sediment is frequently added to channels and floodplain surfaces after flooding.
- Physical and chemical remobilisation of contaminated sediment are long-term and ongoing processes.
- Large scale nature of historical metal mining contamination makes remediation generally unfeasible (e.g., 29.1 km² of valley floor of River Swale contaminated with Pb, Zn, Cd; Brewer et al., 2005)
Approaches to managing historically metal-contaminated rivers

1. Establish mining chronology, identify production records and locate major mines and processing sites
2. Undertake literature review and collate available geomorphological, topographical and geochemical data
3. Create 1:10,000 river corridor GIS base map using OS digital map data
4. Digitise channel margins and bars present on all available georeferenced maps and aerial photos. Create separate GIS layer for each archive data set
5. Are river channel change data available?
   - Yes
     - Identify location of mining-era river channels (likely to be contamination 'hot spots')
   - No
     - Carry out valley floor sediment sampling programme. Collect < 2 mm samples from channel bars and floodplain and terrace surfaces (0-20 cm and 20-50 cm)
6. Are valley floor metal concentration data available?
   - Yes
     - Create GIS database with geographical coordinates, elevation and metal concentration data for each sample point
   - No
Lead Production in the upper Severn Valley

Total recorded Pb production (1845-1913)
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5. Are river channel change data available?
   - No: Continue with next steps.
   - Yes: Identify location of mining-era river channels (likely to be contamination 'hot spots').
6. Are valley floor metal concentration data available?
   - No: Carry out valley floor sediment sampling programme. Collect < 2 mm samples from channel bars and floodplain and terrace surfaces (0-20 cm and 20-50 cm).
   - Yes: Create GIS database with geographical coordinates, elevation and metal concentration data for each sample point.
River Nent, South Tyne Basin
Approaches to managing historically metal-contaminated rivers

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4. Digitise channel margins and bars present on all available georeferenced maps and aerial photos. Create separate GIS layers for each archive data set.

5. Are river channel change data available?
   - Yes: Identify location of mining-era river channels (likely to be contamination 'hot spots').
   - No: No further action.

6. Are valley floor metal concentration data available?
   - Yes: Create GIS database with geographical coordinates, elevation and metal concentration data for each sample point.
   - No: Carry out valley floor sediment sampling programme. Collect < 2 mm samples from channel bars and floodplain and terrace surfaces (0-20 cm and 20-50 cm).
Historical channel patterns
Approaches to managing historically metal-contaminated rivers

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4. Digitise channel margins and bars present on all available georeferenced maps and aerial photos. Create separate GIS layer for each archive data set.
5. Are river channel change data available?
   - No: Proceed to next step.
   - Yes: Identify location of mining-era river channels (likely to be contamination 'hot spots').
6. Are valley floor metal concentration data available?
   - No: Carry out valley floor sediment sampling programme. Collect < 2 mm samples from channel bars and floodplain and terrace surfaces (0-20 cm and 20-50 cm).
   - Yes: Proceed to next step.
7. Create GIS database with geographical coordinates, elevation and metal concentration data for each sample point.
Calculate background concentration thresholds for contaminant metals using BGS G-BASE stream sediment data and valley floor sediment metal concentration data

Are background metal concentration data available?

Yes

Establish quantitative relationships between metal concentrations and geomorphological variables

Conc. v. height above river channel

Conc. v. distance from present river channel

Conc. v. inundation frequency

Conc. v. age of sediment unit

Conc. v. distance downstream

Conc. v. sedimentary environment

Use the most significant quantitative relationships to identify key criteria for mapping floodplain and river terrace metal contamination

Using key criteria, construct GIS-based valley floor maps showing likelihood of metal contamination with respect to background threshold values

Refine contamination limits using LiDAR data, aerial photographs and additional geochemical samples (ground-truthing)

Produce final contamination maps to identify areas where contaminant metals may pose a hazard to ecosystem and human health
Background Threshold Determinations

- Derived using cumulative frequency curves
- Include all available data
  - Floodplain samples
  - BGS G-BASE stream sediment data
Background Pb threshold

Threshold = 99.96 mg kg\(^{-1}\)
Calculate background concentration thresholds for contaminant metals using BGS G-BASE stream sediment data and valley floor sediment metal concentration data

Are background metal concentration data available?

- Yes
  - Establish quantitative relationships between metal concentrations and geomorphological variables

  - Conc. v. height above river channel
  - Conc. v. distance from present river channel
  - Conc. v. inundation frequency
  - Conc. v. age of sediment unit
  - Conc. v. distance downstream
  - Conc. v. sedimentary environment

- No

Use the most significant quantitative relationships to identify key criteria for mapping floodplain and river terrace metal contamination

Using key criteria, construct GIS-based valley floor maps showing likelihood of metal contamination with respect to background threshold values

Refine contamination limits using LiDAR data, aerial photographs and additional geochemical samples (ground-truthing)

Produce final contamination maps to identify areas where contaminant metals may pose a hazard to ecosystem and human health
Height above low-flow channel, River Swale
Calculate background concentration thresholds for contaminant metals using BGS G-BASE stream sediment data and valley floor sediment metal concentration data.

Are background metal concentration data available?

- No

Establish quantitative relationships between metal concentrations and geomorphological variables.

- Conc. v. height above river channel
- Conc. v. distance from present river channel
- Conc. v. distance downstream
- Conc. v. age of sediment unit
- Conc. v. inundation frequency
- Conc. v. sedimentary environment

Use the most significant quantitative relationships to identify key criteria for mapping floodplain and river terrace metal contamination.

- Using key criteria, construct GIS-based valley floor maps showing likelihood of metal contamination with respect to background threshold values

Refine contamination limits using LiDAR data, aerial photographs and additional geochemical samples (ground-truthing).

Produce final contamination maps to identify areas where contaminant metals may pose a hazard to ecosystem and human health.
River Swale Metal Contaminant Hazard Map
ACTION

- Investigate source-pathway-receptor relationships (e.g. suspended and dissolved metal concentrations, plant uptake, animal exposure, metal speciation)
- Develop and implement contaminant monitoring programmes
- Develop policy guidelines for management and remediation of contaminated river and floodplain land
The Next Steps

- Test and upscale our management approach in larger river systems currently affected by metal mining (e.g. Lower Danube Basin)
The Danube Basin

- The Danube River Basin is Europe's second largest river basin: total area 801,463 km², 2,870 km long

- It is the world's most international river basin: it includes the territories of 18 countries

- The ecosystems of the Danube River Basin are highly valuable in environmental, economic, historical and social terms, but they are subject to increasing pressure and serious pollution from agriculture, industry, urban areas and mining

- High potential for trans-border transfer of contaminants, this issue was highlighted following the Romanian tailings dam failures in 2000

(ICPDR, 2006)
Map 8: Hot Spots in the Danube Basin Countries
Based on National Planning Workshop Reports 1998, Updates March 1999

LEGEND
- Red: Hot Spots
  - Metropolises (>1 Million inhabitants)
  - Cities (250,000 - 1 Million inhabitants)
  - Towns (100,000 - 250,000 inhabitants)
- Blue: Danube River Basin
- Orange: Municipal (Mun)
- Yellow: Industrial (Ind)
- Green: Agricultural (Agr)
- Purple: Hot Spot Ranking:
  - High Priority (HP)
  - Medium Priority (MP)
  - Low Priority (LP)

Hot Spots in the Countries
- Municipal (Mun)
- Industrial (Ind)
- Agricultural (Agr)
- Count

Scale: 1:5 000 000
Contamination sources - AMD
Contamination sources - floodplains
Contamination sources – tailings dam failures

The 64 m high Mialu tailings dam in the Certej River catchment

But what is the extent and magnitude of heavy metal contamination in the lower Danube Basin?

To address this question, an extensive 5 year survey of metal and As contamination in surface water, groundwater, river channel and floodplain sediment undertaken.

Over 2,000 water and sediment samples, collected from over 750 sites in the Tisa and North Bulgaria sub-basins.
North Bulgaria - As in surface water
North Bulgaria - As in river channel sediment

[Map showing distribution of As in river channel sediment across North Bulgaria, with color coding for different concentration levels.]

Channel sediment: As-75

Legend:
- ≤ 29 mg kg⁻¹
- > 29
- > 55
- > 100
- > 1000

Main rivers
National boundary
Settlements

Scale:
0 50 100 Kilometres
0 10 20 Kilometres

Locations:
VIDIN
RUSE
VARNA
SOFIA
OGosta
ISKUR
MONTANA
North Bulgaria - As in floodplain sediment
The Lower Danube Basin

- Water and sediment quality in the lower Danube Basin is highly variable; in general, highest metal & As levels found in tributary catchments where water and sediments can be grossly polluted.

- Little evidence of extensive downstream or trans-border dispersal, this is because of dilution by ‘clean’ sediment.

- But, for effective management and ultimate remediation of metal mining affected rivers systems, we need to know the sources of contamination ........
Pb isotopic fingerprinting

Pb isotope ratios - Bulgaria Ores (base data)
Pb isotopic fingerprinting

Pb isotope ratios 207/206 v 208/206 for spoil/tailings in N Bulgaria and Romania, with Channel and floodplain sediment isotope ratios for the R Danube in Bulgaria
Sediment mixing models

e.g. River Aries, Romania
Implications and conclusions

- Evidence of a recent increase in flood frequency in the Danube River Basin

- It is highly likely that increased flooding will remobilise contaminated floodplain material which will then become a major secondary source of contaminant metals in the Ogosta and Iskăr Rivers, in particular
Implications and conclusions

- From a management perspective it is therefore essential to protect floodplain environments from contamination by sediment associated pollutants.

- We need to learn the lessons from the environmental impacts of historical metal mining in the UK in order to effectively manage and protect river system affected by present and future mining activity.