Interactions Between Channel Change and Historic Mining Sediments

Mining activity and stream activity may interact in the fluvial environment in a number of ways. In the first place mining wastes in the form of solutes and sediments may enter streams where they are dispersed, and are then redeposited in what constitutes a special case of fluvial sedimentation; secondly, the input of materials and the modification of discharge characteristics may lead to repercussions in terms of channel morphology and dynamics. Modern mining practice and environmental legislation both tend to curtail the input of mining wastes into fluvial environments, but this was not the case with historic mining from which much waste has been and continues to be incorporated into fluvial systems active today.

For Britain, the Fifth report of the 1868 Rivers Pollution Commission (1874) pertinently identified the major causes for late nineteenth century concern. The Commission noted especially the problems caused by the discharge of large quantities of fine sediment (from coal washing, tin mining, and china clay working) and the dispersal of toxic metals (notably from lead, zinc, and arsenic mines). This fluvial dispersal of mining wastes is graphically summarized in Figure 23.1. Mobilized wastes may be transported as clastic sediments or as solutes to be deposited or precipitated in a range of
Metal mining in mid-Wales has a long history (Lewis, 1967) but is now inactive. Mining for lead and later zinc was intensively undertaken from the beginning of the nineteenth century when new techniques were adopted: large quantities of wastes were indiscriminately fed into local streams until preventative legislation was enacted (1876). Mining activity also declined as prices fell to a less than economic level in the last decade of the century. Ores were hand-sorted, crushed, and then jigged or 'buddled' to separate metals by water flotation. These processes were inefficient and both the heaps of tailings and the finely divided wastes fed directly into streams from flotation still contained a high proportion of ore particles and metal-rich spoil. In the relatively narrow and steep-sided valleys of mid-Wales, inputs of sediment in the form of country rock and metal particles, and solutes (from mine waters and the subsequent input of soluble salts from the weathering of tailings dumps) were considerable. The Commission reported the rivers near Aberystwyth as being the most polluted:

**Figure 23.1 A Model for the Dispersal of Mining Wastes**

Sedimentary environments. For different types of ore, mining practice and indeed environment, the nature and quantity of dispersal are likely to vary; in this paper we are concerned to examine the dispersion patterns manifest in the depositional phase resulting from historic metal mining in mid-Wales, and to consider what the possible modifications to river channel patterns have been.
"All these streams are turbid, whitened by the waste of the lead mines in their course; and flood waters in the case of all of them bring down poisonous 'slimes' which, spreading over the adjoining flats, either befoul or destroy the grass, and thus injure cattle and horses grazing on the dirtied herbage, or, by killing the plants whose roots have held the land together, render the shores more liable to abrasion and destruction on the next occasion of high water. It is owing to the latter cause as well as to the immense quantity of broken rock which every mine sends forth that the small rivers Rheidol and Ystwyth present such surprising widths of bare and stony bed." (Rivers Pollution Commission, 1874, p. 15)

As we shall see later, the quantity of 'broken rock' is here perhaps a little overdrawn in view of the normal state of local gravel rivers, but the waste heaps have certainly continued to provide sediment in the century that has followed. The spoil is commonly permeable, lacking in nutrients and rich in toxic metals to an extent which prevents a vegetation cover; both weathering and the physical entrainment of metals and crushed country rock makes the extensively gullied heaps a continuing source of solutes and sediments.

It has long been appreciated that this situation leads to serious agricultural and biological problems (Griffith, 1918; Newton, 1944; Alloway and Davies, 1971); most research has understandably been biological in focus, and only recently have attempts been made to identify patterns of fluvial dispersal and channel activity (Davies and Lewin, 1974; Grimshaw, Lewin and Fuge, 1976). This paper adopts such an approach, taking the River Ystwyth as a case study.

River Ystwyth Study Sites

The River Ystwyth drains a catchment area of 193 km²; along the lowest 20 km of the river, sections of alluvial valley floor are separated by short steeper-gradient rock-cut channels (Brown, 1952). The river can be classified as a coarse bed load stream, deriving much of its present sediment load from channel sources (Grimshaw and Lewin, 1976). The river channel actively migrates across the alluvial sections except where confined by road, railway or valley side. Into this active fluvial system, mining wastes have been injected from a number of sources, notably the crushing mills, dressing floors, flotation plant, and spoil tips at Cwm Ystwyth, Pontrhydygroes, Frongoch, and Grogwynion (Fig. 23.2). Details of mine histories appear in Jones (1922), Lewis (1967) and Bick (1974).

We have analysed sediment samples for Pb, Zn, Cu, and Cd using atomic absorption spectrophotometry (air/acetylene flame) at three floodplain sites down-river from the former mine locations, together with some reconsideration of a site previously discussed in Alloway and Davies (1971). Analytical
THE YSTWYTH CATCHMENT, MID-WALES

The main floodplain sites are shown in relation to the larger mines.
Interactions Between Channel Change and Historic Mining Sediments

methods were as described in Davies and Lewin (1974), except that in some cases particular size fractions of sediment have also been analysed (see Figure 23.6).

Study sites were selected in the light of information on the dynamics of channel change derived both from recent field observations (Lewin, 1976) and from analysis of available manuscript and printed maps and air photography (Lewin and Hughes, 1976). Each site will be discussed in turn, the metal data being listed in Table 23.1.

Llanilar (SN 6275)

The floodplain morphology and contemporary channel activity at this site have been examined previously in some detail (Lewin and Manton, 1975; Lewin, 1976): metal values taken on a floodplain cross-profile are shown diagrammatically in Figure 23.3 whilst further data for these and other samples are given in Table 23.1.

Three points are of immediate interest. Firstly, metal values are hardly anomalous (as defined in Alloway and Davies, 1971, Table II) unless on the floodplain within reach of river activity. Secondly, the highest values occur to the south of the railway embankment in an area now protected from channel activity, but on the site of the active channel prior to railway construction in the 1860s. Thirdly, contemporary river sediment has comparatively low metal values, though this situation is liable to vary locally where the river impinges on nineteenth-century channelway sediments.

In Table 23.1 (column 3), an attempt is made to classify sample sites according to the sedimentary environment prevailing and relevant to the deposition of mining waste. On this basis three categories of metal levels are clear: valley slopes, areas which have been or are flood liable, and areas of channel activity dating to the nineteenth century. The present active channel (sample number 367), an old cutoff formed prior to the nineteenth century (366), and the other floodplain soils (370, 371, 377), all group together as having anomalous metal contents, though with Pb concentrations an order of magnitude less than those with channels active in the mining heyday. Hence only parts of the floodplain have very high metal values: these parts cannot be distinguished by morphology or location, but only by the dating of active sedimentation at channel margins.

Dol Fawr (6574)

The same pattern emerges at Dol Fawr in data previously reported by Alloway and Davies (1971): the 1845 tithe map shows that samples 2001 and 2002 are from areas that were part of the active channel at that time; samples 2003 and 2004 have Pb concentrations an order of magnitude less (and not so high as in equivalent locations further downvalley); slope soils are only marginally anomalous.
Here a meander loop, with a radius of approximately 250 m and arc length 130°, has oscillated within a band of about 100 m width without major development for at least 150 years; to the north the valley side rises steeply, but a terrace exists to the south (Figure 23.4). High values occur in areas marginal to channel activity during mining (382, 383); lower values occur in contemporary sediments (381) but with the highest values of all in a disused mill race (384). This is mapped as having a functioning race and dam across the river in 1886, but the dam had gone by 1904. There can be little

<table>
<thead>
<tr>
<th>Table 23.1 Sample Analytical Data</th>
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<tbody>
<tr>
<td><strong>Sample</strong></td>
</tr>
<tr>
<td>Llanilar</td>
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Interactions Between Channel Change and Historic Mining Sediments

### Table 23.1 (cont'd)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Grid Reference (SN)</th>
<th>Site type</th>
<th>Ignition loss (%)</th>
<th>Metal (p.p.m.)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pb</td>
</tr>
<tr>
<td>Grogwynion 2</td>
<td>697718</td>
<td>S</td>
<td>12.3</td>
<td>240</td>
</tr>
<tr>
<td>151</td>
<td>F</td>
<td>2.8</td>
<td>1507</td>
<td>461</td>
</tr>
<tr>
<td>152</td>
<td>Ca</td>
<td>4.6</td>
<td>1593</td>
<td>587</td>
</tr>
<tr>
<td>153</td>
<td>F</td>
<td>1.7</td>
<td>821</td>
<td>377</td>
</tr>
<tr>
<td>154</td>
<td>F</td>
<td>3.0</td>
<td>1422</td>
<td>753</td>
</tr>
<tr>
<td>155</td>
<td>S</td>
<td>7.9</td>
<td>104</td>
<td>140</td>
</tr>
<tr>
<td>156</td>
<td>F</td>
<td>0.6</td>
<td>1024</td>
<td>501</td>
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<td>157</td>
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<tr>
<td>Grogwynion 1</td>
<td>713721</td>
<td>S</td>
<td>14.4</td>
<td>435</td>
</tr>
<tr>
<td>158</td>
<td>Cm</td>
<td>6.9</td>
<td>2105</td>
<td>379</td>
</tr>
<tr>
<td>159</td>
<td>Ca</td>
<td>1.8</td>
<td>1047</td>
<td>607</td>
</tr>
<tr>
<td>160</td>
<td>Cm</td>
<td>6.5</td>
<td>3423</td>
<td>793</td>
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<tr>
<td>161</td>
<td>F</td>
<td>6.0</td>
<td>1550</td>
<td>566</td>
</tr>
<tr>
<td>162</td>
<td>S</td>
<td>10.0</td>
<td>573</td>
<td>1905</td>
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<tr>
<td>163</td>
<td></td>
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S, valley slope; T, terrace; F, area currently or historically flood liable; Ca, active channel; Cm, channel active since 1800; Ch, old channel active before 1800.

There is some doubt that finer metal sediments were especially liable to sedimentation here.

Sample 379 is particularly interesting since it comes from a terrace above contemporary flood limits (cf. Alloway and Davies, 1971, Table IV): values are, however, comparable with those previously quoted for floodplain areas not within the bounds of active channel migration in the mining era. This raises the whole question of the role of floods, for previous writers have often implied that flood discharges deposit a flood drape of polluted sediments right across areas liable to flood. In practice, however, most flood sediments, together with those transported near bankfull stage, are deposited at the channel margins, and suspended sediments from mining processes may be unlike ‘natural’ sediments in that inputs and transport can be

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**Figure 23.3 A Profile of the Ystwyth Floodplain at Llanilar (SN 628754)**
high on quite moderate discharges. Such sediment may be inserted directly into streams, not entrained on slopes following precipitation; at less than overbank flows they can only be redeposited within the channel margins. Hence fairly high metal values elsewhere on the occasionally-inundated floodplains could also result from predocumentary channel deposition during many centuries of less-intensive mining activity prior to the nineteenth century. Alternatively (and this must apply to river terrace deposits) erosion of exposed lodes may have contributed metals to alluvial sediments for millenia. Thus whilst the role of floods during and after mining activity has certainly been to entrain and transport mining sediments, these sediments have been redeposited especially in and near active channels. Some metals may have been transported as far as the limits of flood inundation (and the waters may have been toxic with dissolved metal salts subsequently precipitated), but there are other explanations for the moderately high metal values on the floodplain and terraces.

Grogwynion (7071)

For nearly 2 km above Llanafan Bridge (D in Figure 23.2), the Ystwyth passes through a steep-sided valley, 200 m deep with a relatively narrow
Interactions Between Channel Change and Historic Mining Sediments

floor, which has been swept across by the river in the last 130 years (Figure 23.5). Much of this floor consists of bare gravel cut into by active and abandoned channels.

Several lodes parallel the valley on the north, and adit mining has been operated intermittently for centuries at Gwaithgoch (710723) and more importantly at Grogwynion (714723): mining here was particularly active from the 1860s to the early 1880s. In addition, the Gwaithgoch crushing mill was installed in the First World War to rework the Frongoch waste tips for lead and zinc; an aerial ropeway was completed after the Great War to the tips 3 km away and these were worked for their ore content, particularly in the late 1920s when prices improved, but operations ceased at the end of that decade (Bick, 1974).

It is tempting to regard the locally exceptional braided channel as a response to the input of mining sediment: the 1845 tithe map (Figure 23.5), and the series of sketched maps of the mine dated 1741, 1792, and c. 1800 held in the Gogerddan Collection in the National Library of Wales, all show a single channel. However, the quality of these pre-nineteenth century maps is not such that great reliance can be placed on them.

Furthermore, there is little real evidence that large quantities of coarse sediment (of which the valley floor is composed) were fed locally into the river during mining: the spoil dumps at Grogwynion do not appear to have been undercut, whilst the size and roundness characteristics of the floodplain sediments in the supposedly affected reach are not anomalous compared with trends in the river system as a whole.

The input of toxic metals has probably been more important: sampling undertaken on two traverses across the valley (Profiles 1 and 5; Table 23.1) show high metal values across the valley floor, and it seems likely that the lack of vegetation contributes to greater bank and floodplain erodibility.

This particular type of multiple channel is also not generally characteristic of a high sediment input (Smith, 1974; Fahnestock and Bradley, 1974). The relatively low gradient (0.015), the pattern of long diagonal channels connected by shorter crossovers, and the rate of channel change, closely resemble the Knick River in Alaska, in kind if not in size (Fahnestock and Bradley, 1974). Whilst channel change rates are certainly more rapid than on most local meandering streams, short-term bedform changes do not compare with other braided rivers where a multiplicity of lowstage channels reflects the intricacy of the numerous mobile unit bedforms active at higher stages. Instead, changes observed over a 6-year period (1969–75) have been in response to relatively few high flows, involving point-bar and confluence bar sedimentation and the reactivation of an abandoned channel by crevassing to reform a multiple system during a flood in August 1973. Otherwise much of the braided appearance of the valley results from the flooding of inactive channels, and a lack of vegetation. It may also be noted in passing that the channel here is not noticeably aggrading nor are the sediments
Ac11ve floodplain gravels
A Tailing from Growynion mine
B SwiUingoch crushing and dressing mill

1845 1886 1904 1946 1960 1969

Figure 23.5 The Ystwyth Floodplain at Growynion (SN 7971)

Top: The Channel at various dates; Bottom: Floodplain profiles in 1969

Discussion

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Interactions Between Channel Change and Historic Mining Sediments

fine: both criteria have been previously identified with the development of channel patterns of this type (Smith, 1974; Chitale, 1970).

Discussion

We can conclude on the basis of this and our other studies, that historic mining in mid-Wales led to the rapid dispersal of toxic waste, and that sedimentation at channel margins, which probably covered approximately 1.7 km² of the Ystwyth catchment during the mining heyday 1820–1880, was a preferred environment for the redeposition of metal sediments. The remainder of the floodplain (2.5 km²) and some gravel terraces also have high metal concentrations as a result of flood dispersal or previous channel margin activity.

Since the mining phase, there has been a fall-off in metal levels in floodplain sediments (Davies and Lewin, 1974) until contemporary channel sediments are relatively but by no means absolutely 'clean.' Nineteenth-century floodplain sediments now themselves form sources of metal (possibly the most active source at present), in addition to the still-remaining waste tips, so that a continued input of metals is assured. With further data we feel it will be possible to establish temporal decay models giving fall-off rates for metal values applicable to varying types of floodplain environment.

This can be balanced by a model for downstream changes in the metal contents of materials of different particle size, as illustrated by active sediments on a tributary of the Ystwyth draining from Wemyss mine and spoil heaps (Figure 23.6). Both lead and zinc contents decrease downstream until about 4000–5000 m, when the lead curve shows a small peak, whereas zinc appears to be increasing more uniformly. Furthermore, the fall off in zinc concentration is less than lead, particularly in the 63 μm fraction. The increase in metal concentration at 4000–5000 m can be attributed to sediment lying upstream of the sampling point in an old mill race. A small pulse of material injected into the river channel at the latter would increase the proportion of 'polluted' to 'clean' sediment, thus giving rise to an overall higher metal level downstream. There may, however, be other possible processes and chemical changes involved.

If the downstream dispersal is a simple clastic process then several possibilities can be considered. The metal-rich material entering the stream is broadly of two kinds, namely crushed gangue minerals and wall rock. In addition there are small particles of galena (PbS) which were not separated during the dressing process, and sphalerite (ZnS) particles of varying size which either also escaped separation or were deliberately discarded for lack of economic value. Galena is much heavier than sphalerite (densities 7.5 and 4.1 g/cm³, respectively) and both are denser than the rest of the detritus. Consequently, running water might be expected to cause differential downstream movement with, the lightest material travelling furthest from the...
source, and the rate of transport might have been such that an increase in concentration since insertion had proceeded only a restricted distance downstream by the time of observation. Insertion is, however, a continuing slow process not a massive singularity, and the rate of transport of finer sediments is much too great for this model to be appropriate, in general, for the fall-off in metal values. More generally, the input of 'clean' sediment from downstream slopes and channel banks must imply that metal sediments form a decreasing proportion of the total sediment load in any size range, and this will lead to a fall off in concentrations down-valley.

A further complication arises from the fact that the ore particles are not inert: they dissolve and react in water and the resulting weathering products migrate in different ways. Under acid conditions such as moorland waters of low redox potential ($E_h$) or within spoil heaps containing pyrite (FeS) the sulphide ores oxidize to sulphates. If carbonic acid is present as in some heaps (calcite rather than quartz is the chief gangue mineral in some mines), or in soils, metal carbonates are likely to form. These different metal salts have very different solubilities (Table 23.2) and those of zinc are all more soluble, i.e. more mobile, than the corresponding lead compounds. Garrels and Christ (1965) give a detailed review of the controls of $E_h$ and pH on metal compound solubilities.

However, it is unlikely that metals migrate to any appreciable extent as
Interactions Between Channel Change and Historic Mining Sediments

Table 23.2 Solubility of Salts of Lead and Zinc

<table>
<thead>
<tr>
<th>Solubility of salt (mol/l)</th>
<th>M = Pb</th>
<th>M = Zn</th>
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</thead>
<tbody>
<tr>
<td>MS</td>
<td>1.78 x 10^{-14}</td>
<td>1.26 x 10^{-12}</td>
</tr>
<tr>
<td>MSO_{4}</td>
<td>1.26 x 10^{-12}</td>
<td>5.37</td>
</tr>
<tr>
<td>MCO_{3}</td>
<td>2.18 x 10^{-7}</td>
<td>3.97 x 10^{-6}</td>
</tr>
<tr>
<td>MCl_{2}</td>
<td>1.58 x 10^{-2}</td>
<td>18.01</td>
</tr>
</tbody>
</table>

Simple ions. They are adsorbed by fine particles, especially those <2 μm, and it is noteworthy that, as illustrated in Figure 23.6, metal contents increase with decreasing particle size. Lead is more strongly adsorbed than zinc. The metals are also readily complexed (chelated) by organic substances which can considerably modify their geochemical dispersal (see Davies, 1976) and most chelating agents complex lead more strongly than zinc.

Thus it can be seen that downstream dispersal is a complex process and detailed investigations are needed. Spatial and temporal decay functions of metal concentrations are composite and result from several possible physical and chemical processes as well as from varying levels of mining activity. Quite apart from the relevance to the practical problem of the dispersal of toxic mine waste, clarification of the processes may allow metal sediments to be used as tracers in long-term sedimentological experiments (cf. Gross, 1972). The input of dated volumes of 'labelled' sediment could allow volumes and sources for other sediment to be derived. This possibility will be developed elsewhere.

Although downstream fall-off in lead values occurs on smaller streams, the same is not the case for active sediments on streams with floodplains, nor for floodplain sediments of the same date for comparable environments. Here again a number of explanations may be advanced. Previous work suggests that comparatively little fine sediment is provided by the lowland parts of west Wales catchments, so that 'clean' fine sediment is not so available to diminish the proportional significance of metal sediments downstream. Alternatively, erosion of 'old' metal-rich floodplain sediments can lead to local metal enrichment. Finally, and concerning floodplain sediments in particular, metals are liable to pedogenic translocation so that the values now observed may no longer be those that obtained when sediments were emplaced.

A final point for discussion concerns channel dynamics: here again the input of toxic fine sediments seems to have been of more significance than the input of voluminous but inert waste. This conclusion contrasts with that of some earlier writers such as Jones (1940) who suggested that at Llanilar (8 km downstream from the nearest mine) the channel was 'silted up with
J. Lewin, B. E. Davies, and P. J. Wolfenden

vast quantities of stone, rubble and gravel that have come down from the mine workings. 'The nature of this gravel, and the alternative sources available for it, is not in fact that unusual for local rivers, and these are likely to have been affected locally rather than regionally by the input of inert coarse mining spoil.

Conclusions

It is clear from the above discussion that within the framework of a general model (Figure 23.1) which has both spatial and temporal dimensions, very specific and individual patterns of metal dispersal and channel modification may take place in particular locations. In this case, a syngenetic secondary dispersal pattern (Hawkes and Webb, 1962) dominates, involving dispersal of metal fines rather than large volumes of country rock. Partly this is a reflection of the nature of the mining operation and ores involved, but the nature of the local fluvial process system is also crucial. It is highly unlikely that even identical mining operations in contrasting fluvial environments would produce similar patterns of environmental interaction, and a specific input of solutes or sediments could prove quite acceptable in one environment but not in another. An understanding of channel processes and dynamics in a variety of environments therefore appears highly desirable from an environmental management point of view.

Acknowledgements

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References

Interactions Between Channel Change and Historic Mining Sediments 367


w POLLUTION Commission (1868). 1874. Fifth report of the commissioners appointed in 1868 to inquire into the best means of presenting the pollution of rivers.

River Channel Changes

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