CHAPTER 9

CONCLUSIONS

9.1. SUMMARY OF FINDINGS

9.1.1. Metals in tributary sediments

- Channel and floodplain sediments within Gunnerside Beck, a formerly mined tributary of the Swale, exhibit extremely high concentrations of Pb, Zn and Cd (exceeding 48,000 mg kg^{-1}, 5000 mg kg^{-1} and 50 mg kg^{-1}, respectively).
- Metal concentrations are at their greatest in floodplain sediments that were formed during the peak of mining operations, and in channel sediments downstream of the major dressing floors.
- Downstream patterns in metal dispersal are controlled by the location of mine waste inputs, and geomorphological characteristics that influence stream power and sediment storage, such as channel gradient, channel width and valley floor width.
- The release of sediment from historical mining activities, primarily hushing and ore processing, caused enhanced floodplain development and lead to the initiation of braiding. The decline in sediment supply since the cessation of mining has caused a partial reversion to a single thread channel and incision into floodplain sediments.
- Metal mining has had a major impact on the Gunnerside Beck catchment, causing severe contamination and long-term geomorphological alterations. It is probable that similar impacts can be observed in other formerly mined tributaries, with potentially serious implications for the Swale catchment as a whole.

9.1.2. Metals in floodplain sediments

- Floodplain sediments from throughout the River Swale catchment contain high concentrations of Pb, Zn and Cd (exceeding 12,000 mg kg^{-1}, 6000 mg kg^{-1} and 70 mg kg^{-1}, respectively).
- Metal concentrations are particularly high in reaches close to formerly mined tributaries such as Gunnerside Beck and Barney Beck, but remain elevated along the entire length of the river.
- Downstream patterns of metal accumulation are strongly influenced by the location of formerly mined tributaries, valley morphology and gradient.
- As observed in Gunnerside Beck, metal concentrations are most elevated in floodplain sediments that were formed during the peak of mining activities. Post-mining incision means that these units generally occur as low and intermediate terrace surfaces, adjacent to the current channel.
- Floodplain sediments from throughout the Swale catchment indicate that historical metal mining has had a major and long-lasting impact on much of the river corridor that has been active since the mines were operational.

9.1.3. Metals in flood sediments

- Channel-edge and overbank sediments deposited during floods in 2000, 2001 and 2002 contain high concentrations of Pb, Zn and Cd (exceeding 95,000 mg kg^{-1}, 29,000 mg kg^{-1} and 97 mg kg^{-1}, respectively).
- Metal concentrations are highest downstream of formerly mined tributaries such as Gunnerside Beck and Barney Beck, and decline with increasing distance from the mines. However, concentrations remain elevated along the entire length of the river.
- Downstream patterns of metal enrichment are primarily controlled by the location of sediment inputs from tributary and floodplain sediments. The geomorphological characteristics of the river channel and valley are also likely to have an influence, although precise relationships are unclear.
- Metal concentrations are greater in low to intermediate floods than in larger events. This is attributable to variations in the degree of dilution and the activation of sources of metal-rich sediment, and suggests that smaller, more frequent events have a greater impact on floodplain geochemistry than larger, less frequent floods.

- Some of the highest metal concentrations observed in the Swale catchment were identified in fresh flood sediments, and large quantities of metals are deposited on the floodplain surface during flood events (exceeding 250 g m^{-2} Pb, 55 g m^{-2} Zn and 0.2 g m^{-2} Cd). This means that historical metal mining continues to have a serious impact on the River Swale catchment more than 100 years after the cessation of mining activities.

9.1.4. Metal storage in the Swale catchment

- The River Swale catchment may contain as much as 155,000 tonnes of Pb; 32,000 tonnes in formerly mined tributaries and 123,000 tonnes in floodplain sediments covering an area of 29.1 km^2.
- Total storage represents 28 % of the estimated total Pb output of mines in the catchment.
- Considerable quantities of metals are removed from tributary and floodplain storage during flood events. These are redeposited on the floodplain surface further downstream, or transported out of the catchment.
- Less than half of the metal-rich sediment that is likely to have been released into the river has been removed from the catchment in the 100 years since mining operations were abandoned. The impacts of mining on the River Swale catchment, and possibly the wider Ouse system, are therefore extremely long-lasting.

9.1.5. The environmental impact of mining

- Metal concentrations in tributary, floodplain and flood sediments from the River Swale catchment are well in excess of current U.K. environmental quality guidelines.
- Background metal concentrations are also greatly exceeded.
- Environmental quality guidelines were not specifically designed for application to fluvial sediments affected by historic mining activities, making the assessment of the severity of contamination problematic.
- Background metal concentrations should therefore be employed in combination with the most applicable environmental quality guidelines when assessing the impact of historic mining activities on the fluvial system.

- This demonstrates that historical mining activities have greatly enhanced the metal content of fluvial sediments from throughout the Swale catchment. A high proportion of fluvial sediments in the catchment, most notably the floodplain of the trunk channel, are used for pastoral and arable agriculture. Metal contamination is therefore likely to pose a considerable threat to agriculture and ecosystem health throughout the River Swale catchment.

9.2. OVERALL CONCLUSIONS

- Historical mining activities have released large volumes of metal-rich sediment into the River Swale catchment.
- As a result, tributary, floodplain and flood sediments contain extremely elevated concentrations of Pb, Zn and Cd. Metal enrichment is so severe that these sediments may pose a serious risk to plant and animal health.
- Extensive storage and the continued cycling of mining-related metals, particularly in small and intermediate floods, suggest that the impacts of mining on the Swale catchment will be apparent for a considerable period of time.
- Historical metal mining has therefore had a serious detrimental impact on the River Swale catchment. A high proportion of the active river corridor, both within tributaries and in the trunk channel, has been severely contaminated, and is likely to remain so for a considerable period of time.

9.3. IMPLICATIONS

- This investigation has clearly demonstrated that the River Swale catchment has been severely affected by historical metal mining, with tributary and floodplain sediments displaying evidence of extreme contamination. Contemporary flood sediments are also highly contaminated, suggesting that metal mining continues to have a serious impact on the catchment more than a century after the cessation of mining activities. The severity and extent of fluvial contamination may have serious implications for agriculture and environmental health within the catchment.

- It is unlikely that the negative impacts of metal mining are confined to the River Swale catchment, since a proportion of the metals derived from Swaledale are likely to have been transferred into the wider Yorkshire Ouse system. Furthermore, several of the other tributaries of the Ouse have a history of metal mining, most notably the Rivers Ure and Wharfe. The scale and spatial extent of the mining industry in these two catchments was smaller than that of the Swale (Raistrick and Jennings, 1965), but the nature, if not severity, of the impacts is likely to be similar.
- The methods used in the identification of tributary, floodplain and flood contamination in the Swale catchment, as well as those used in the assessment of metal storage and contamination severity are generic and therefore suitable for application in any temperate river system that has been influenced by mining activities.
- Investigations in the Swale catchment have demonstrated that the impacts of metal mining are not confined to those sub-catchments where mining takes place. Instead, major impacts can be observed for a considerable distance downstream of the focus of mining activities. This is likely to be the case in the majority of mined river catchments.
- Investigations in the Swale catchment have demonstrated that the downstream distribution of metal-rich sediment in tributary, floodplain and flood sediments is strongly influenced by geomorphological factors such as the location of mine waste inputs and simple geomorphological parameters such as valley floor width and channel gradient. These patterns are likely to be observed in other formerly mined river systems in Britain and other temperate areas.
- The patterns of mining impact and metal dispersal observed in the Swale catchment are therefore likely to be similar to those found in a wide range of formerly mined river catchments in temperate environments throughout the world. They are therefore suitable to aid the development of conceptual and mathematical models of river behaviour in mined river catchments (Section 9.4).
- Although the patterns of contamination observed in the River Swale catchment are similar to those observed in other formerly mined river catchments (*e.g.* as described in Lewin and Macklin, 1987; Macklin, 1996; Miller, 1997), the severity and spatial extent of contamination appears to be considerably greater. This difference appears to be most pronounced when the Swale is compared to

catchments where industrial-scale mining has a relatively short history, even in cases where tailings dam failures have recently occurred (*e.g*. Bird *et al.*, 2003; Macklin *et al.*, 2003). This suggests that historically-mined river catchments are more likely to be severely contaminated than catchments that are currently being mined.

9.4. RECOMMENDATIONS FOR FURTHER RESEARCH

- This investigation has focussed on the physical behaviour of metals in the Swale system. However, chemical processes may also an important role in controlling this behaviour. Metal partitioning data are therefore required to assess the importance of chemical factors in the cycling of metals in the catchment.
- Further investigation is required to fully establish the importance of floods in the cycling of metals through the Swale catchment. Measurements of metal concentrations in suspended sediment during floods of different magnitudes may clarify the relationship between flood discharge and resulting metal concentrations in overbank and channel-edge deposits. Temporal variations in suspended metal concentration within individual floods may add further insights into the dynamics of metal transport during periods of high flow.
- The extremely high concentrations of mining-related metals observed in the catchment are likely to pose a threat to plant and animal (including humans) health. Investigations by Macklin (*pers. comm.*) and Druery *et al*. (*pers. comm.*) indicate that herbage and grasses contain elevated concentrations of Pb, Zn and Cd. Furthermore, work by Stewart and Allcroft (1956) suggests that the health of sheep in parts of the Swale catchment is negatively affected by the ingestion of toxic metals from mine spoil. Further data are required to assess the extent of plant metal uptake throughout the catchment, and to establish possible linkages between fluvial contamination and poor animal health.
- This investigation has shown that large volumes of metal-rich sediment have been transported out of the River Swale catchment. Further research is required to assess the wider impacts of metals transported from the Swale into the Ure-Ouse system. Although previous investigations have identified the importance of the Northern Pennine Orefield in the supply of metals to the Humber and North Sea

(*e.g.* Macklin *et al.*, 1997; Neal *et al.*, 1999; Neal and Robson, 2000), the relative importance of rivers such as the Swale and Ure has not yet been established. Sediment sourcing techniques such as composite fingerprinting (*e.g*. Walling *et al.*, 1999a), mineralogical and lead isotope analysis (*e.g*. Hudson-Edwards *et al.*, 1999a; 2001), and cellular modelling (*e.g*. Coulthard and Macklin, 2003; Shennan *et al.*, 2003) may prove useful in discriminating between metals derived from different sources.

- This investigation has demonstrated that the behaviour of metals in fluvial sediments is strongly influenced by the geomorphology of the catchment. Further research is required to examine this further, using the TRACER model developed by Coulthard and Macklin (2003). The sensitivity of the River Swale to mining should be explored in detail, both in formerly mined tributaries (*e.g.* the Gunnerside Beck sub-catchment) and across the catchment as a whole. The relative importance of formerly mined tributaries and floodplain sediments should also be evaluated, as can variations in sediment supply through time. Finally, the response of the catchment to climatic fluctuations, and the longevity of the impacts of mining should be investigated at a high resolution using TRACER (*cf.* Coulthard and Macklin, 2003).