CHAPTER 7

METAL STORAGE IN THE RIVER SWALE CATCHMENT

7.1. INTRODUCTION

The previous chapters have demonstrated that tributary, floodplain, and contemporary flood sediments from the River Swale catchment contain high concentrations of mining-related metals such as Pb, Zn and Cd. Historical mining operations are therefore likely to have released large quantities of metal-rich sediment into the tributaries where activities were centred, from which a considerable proportion has been remobilised and subsequently stored in the floodplain of the trunk channel. High metal concentrations observed in contemporary flood sediments suggest that this process is still in operation. Tributary and floodplain sediments are therefore both important sinks and sources of metal-rich sediment in the River Swale system.

The relative importance of tributary and floodplain sediment sinks as stores and sources of mining-related metals is dependent on the amount of material that they contain and the amount of sediment that they supply to the trunk channel. The aim of this chapter is therefore to determine how much metal-rich sediment is stored within the tributaries and floodplain of the River Swale, and to evaluate the importance of contemporary flood sediments as indicators of sediment transfer and storage within the system. A detailed, semi-quantitative sediment budget will be calculated for the Gunnerside Beck study catchment, and patterns that emerge will be used to provide estimates of contaminated sediment storage in other formerly mined tributaries within the Swale catchment. Similar principles will be used to derive estimates of metal storage in the Swale floodplain. Finally, metal deposition rates during contemporary floods will be calculated, and the importance of tributary and floodplain sediments as sources of material will be evaluated.

7.2. METAL STORAGE IN FORMERLY MINED TRIBUTARIES

7.2.1. Introduction

Chapter 4 demonstrates that floodplain soils and channel sediments within the Gunnerside Beck catchment contain extremely high concentrations of metals such as Pb, Zn and Cd. Stream sediment data from other tributaries (British Geological Survey, 1992; 1996) indicate that this is likely to be the case for all the historically mined tributaries in the Swale catchment. The floodplains of Gunnerside Beck and other mined tributaries are therefore likely to represent significant stores of mining-related metals. This section aims to evaluate the importance of historically mined upland tributaries as stores of metals within the Swale catchment. A detailed estimate of metal storage in Gunnerside Beck was produced, and the patterns identified during this process were applied to the derivation of similar estimates of the total metal storage in mined tributaries of the Swale.

7.2.2. Methods: Estimating metal storage in Gunnerside Beck

A wide variety of techniques have been employed in the calculation of sediment-associated metal budgets in fluvial systems. Many methods focus on the quantification of contemporary fluxes through the measurement of suspended and overbank sediment loads (*e.g.* Berndtsson, 1990; Walling *et al.*, 2003a) and geomorphological parameters such as valley floor and channel width (*e.g.* Miller *et al.*, 1999). Others employ depth profiles and cores to calculate the amount of material stored in floodplain sediments (*e.g.* Marron, 1992; Hudson-Edwards *et al.*, 1999b). In this investigation, a variation on the method employed by Hudson-Edwards *et al.* (1999b) to investigate sediment-associated contaminant storage in the Yorkshire Ouse catchment was used. This technique requires detailed data describing the area, depth and metal concentrations of individual floodplain units (Figure 7.1).

An initial field survey identified thirty three discreet floodplain units in the Gunnerside Beck catchment. The spatial extent of each unit was mapped onto 1:10,000 scale OS Landline base maps and subsequently digitised on-screen within ArcMap 8.2. The precise area of each unit was then calculated within the GIS package. The average depth of sediment that is potentially enriched with metals was estimated from the maximum depth of the cores collected during the geochemical survey (Section 4.4), and, where possible,

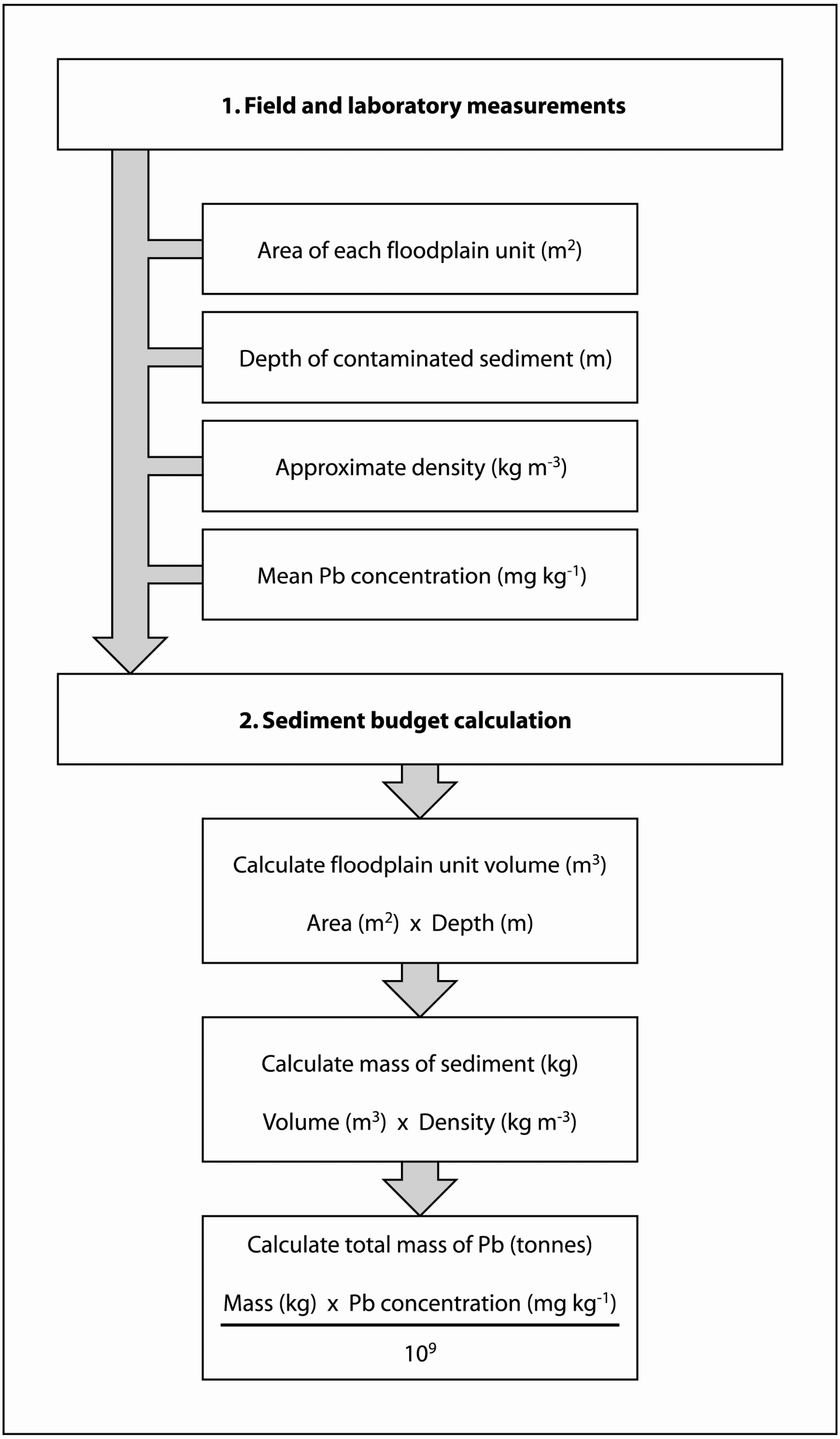


Figure 7.1: Estimating metal storage in tributary and floodplain sediments

exposed bank sections. The volume of each unit was then calculated from these two measurements, and the mass of sediment was estimated. For this investigation, an average density for sandstone of 2399 kg m^{-3} (Daly *et al.*, 1966) was selected as a conversion factor, since rocks of this type are abundant throughout the Gunnerside catchment (*cf.* Hudson-Edwards *et al.*, 1999b). The resulting values were then multiplied by the average Pb concentration of each floodplain unit, thus providing an estimate of total Pb storage within the Gunnerside Beck floodplain.

7.2.3. Metal storage in Gunnerside Beck

The results of the sediment budgeting calculations described in section 7.2.2 suggest that approximately 55,000 m^3 of metal-rich sediment is stored within the Gunnerside Beck catchment. These floodplain deposits contain approximately 1600 tonnes of Pb; 911 tonnes in the <63 μm fraction, and a further 702 tonnes in the 2000 – 63 μm fraction (Figure 7.2). The floodplain units in the upper reaches of Gunnerside Beck are generally relatively small stores of metal-rich sediment, reflecting the small-scale nature of mining in this part of the catchment. An exception is the unit beneath the Blakethwaite dressing floor, which contains approximately 21 tonnes Pb within 775 m^3 sediment. The amount of Pb storage generally increases further downstream, particularly in floodplain units downstream of the extensive dressing floors of the Old Gang and Lownathwaite mines. The most significant stores of contaminated sediment in the Gunnerside catchment are the floodplain units on which the Sir Francis Level dressing floors stand. These large, deep units contain 1160 tonnes of Pb; approximately 72 % of the total Pb stored in the catchment. It is likely that a proportion of the Pb stored in these units is derived directly from the dressing floors, although the volume and alluvial setting of these units suggests that the majority is probably sourced from the extensive mining operations located further upstream. The final floodplain zone, formed in a low gradient reach downstream of the lower bedrock gorge (Section 4.2.3), contains a further 200 tonnes of Pb in 6000 m^3 of sediment, all of which is derived from mines further upstream. This procedure clearly demonstrates that large amounts of metal-rich sediment are stored in the Gunnerside Beck floodplain. The distribution of contaminated sediment storage zones is likely to be primarily controlled by alluvial processes, as demonstrated by the large volume of material stored in the wide floodplain reach at Sir Francis Level. The location of mine waste inputs is also likely to play an important, albeit secondary, role in floodplain storage patterns.

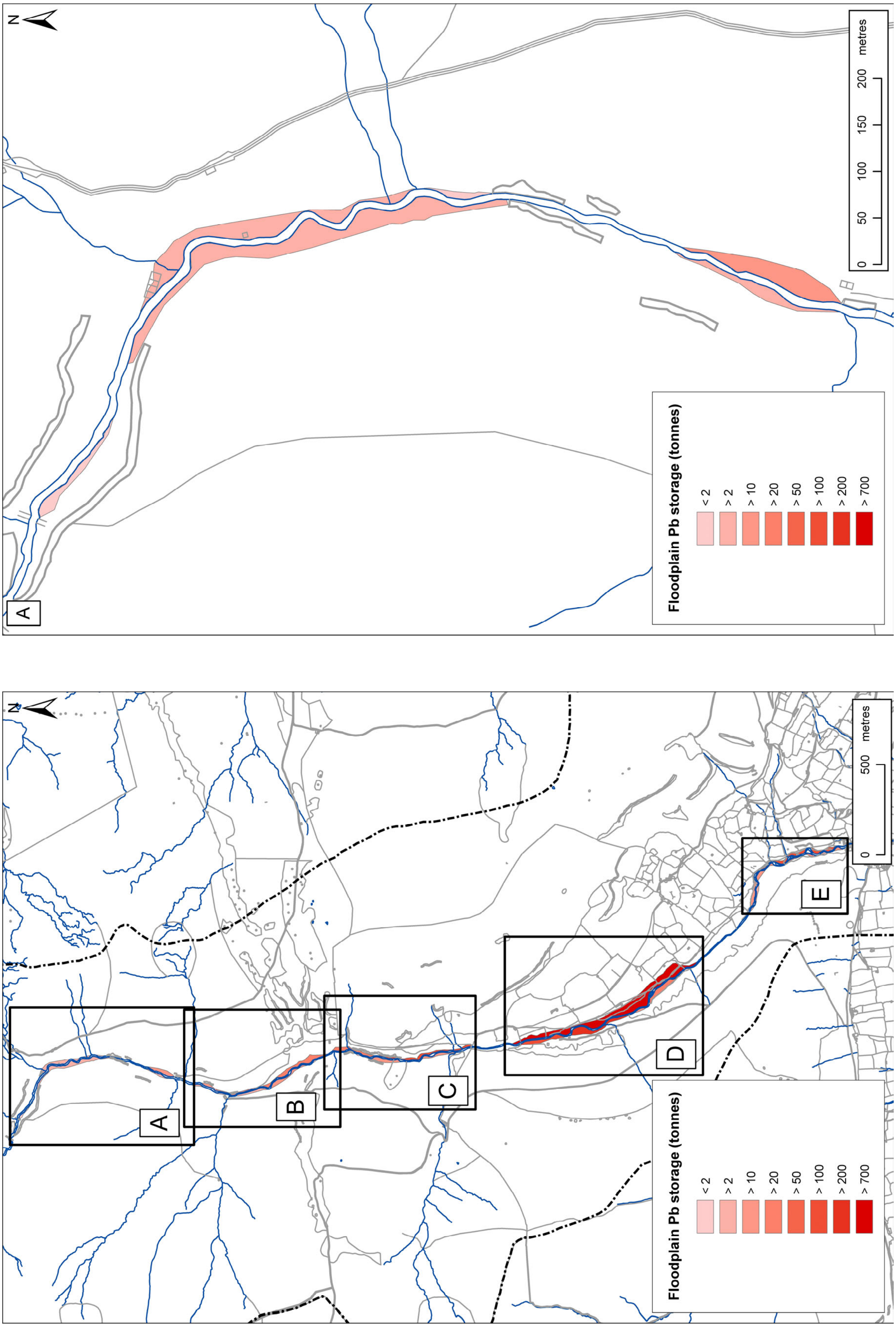


Figure 7.2: Floodplain Pb storage in Gunnerside Beck (tonnes of Pb in each floodplain unit)

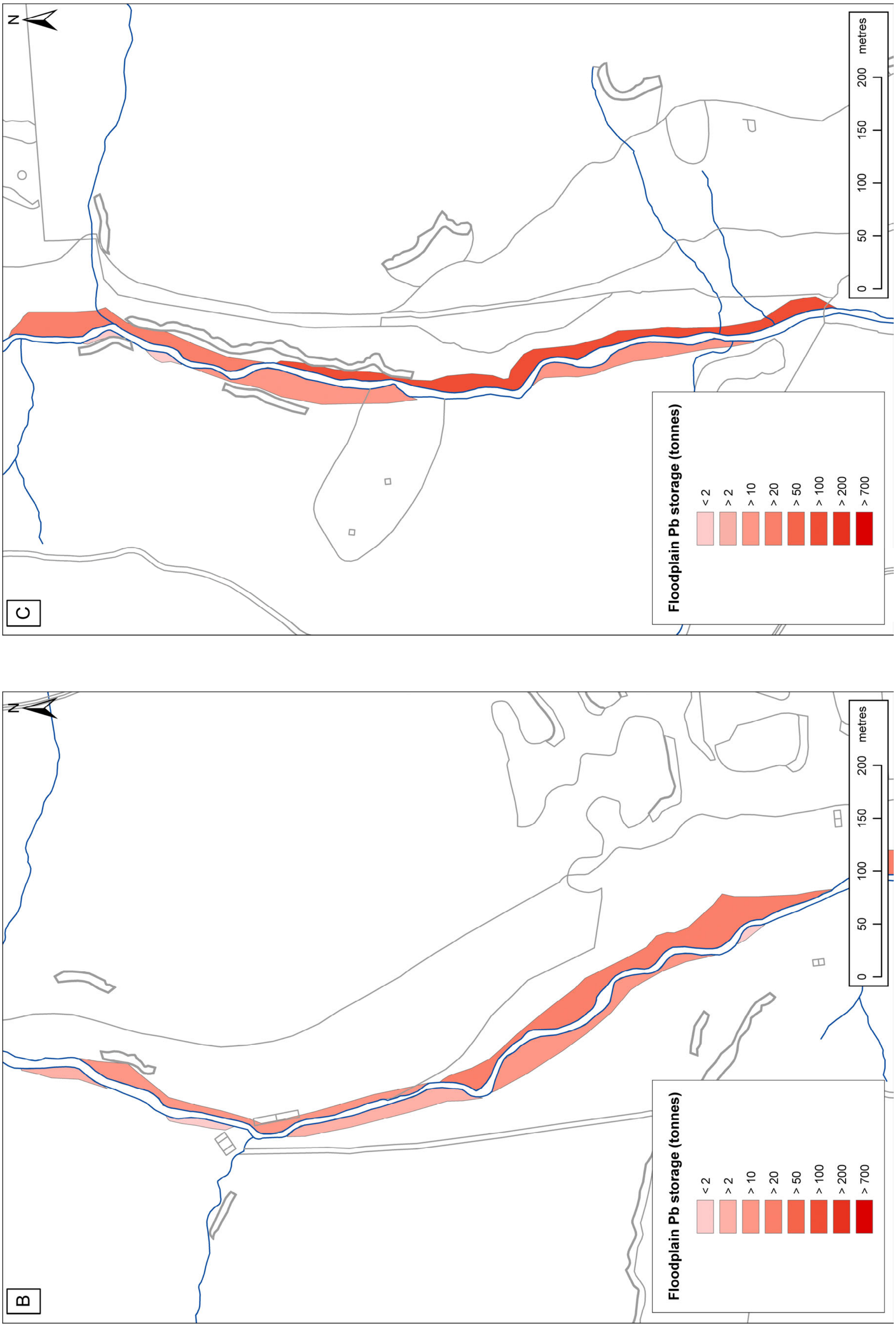
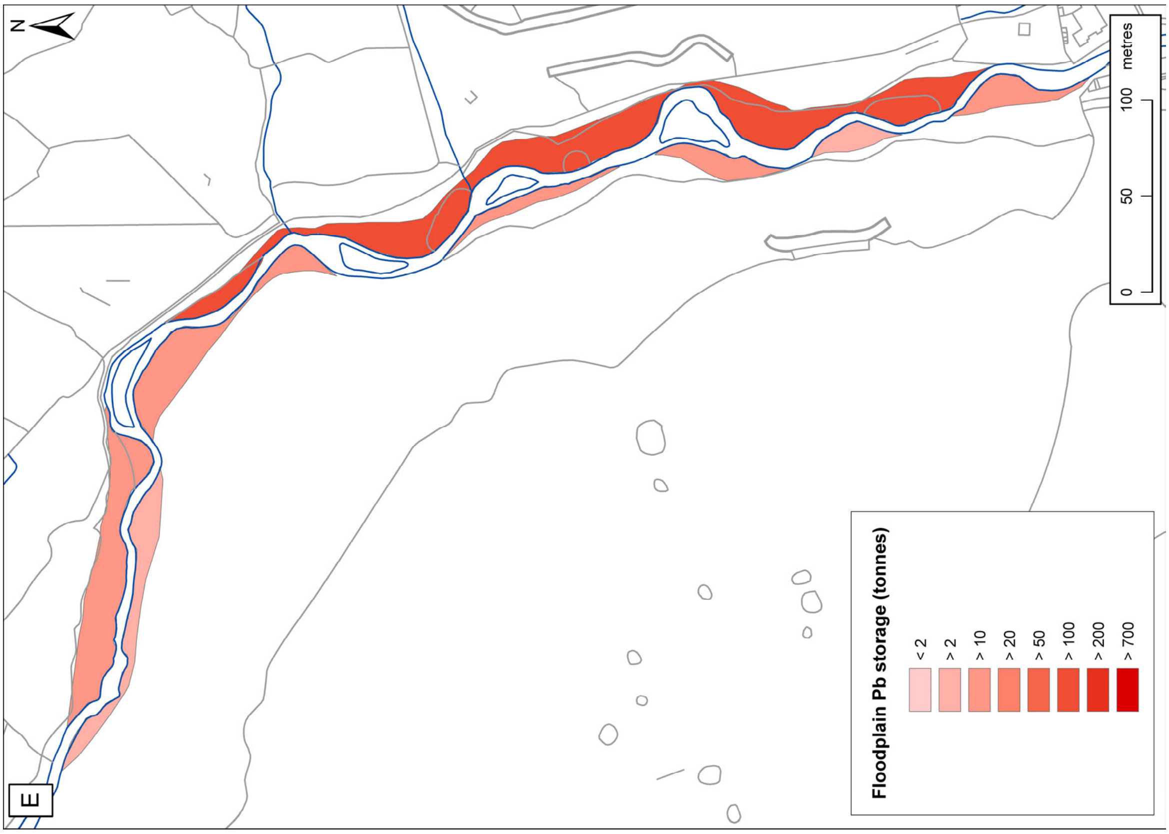


Figure 7.2 (continued): Floodplain Pb storage in Gunnerside Beck (tonnes of Pb in each floodplain unit)



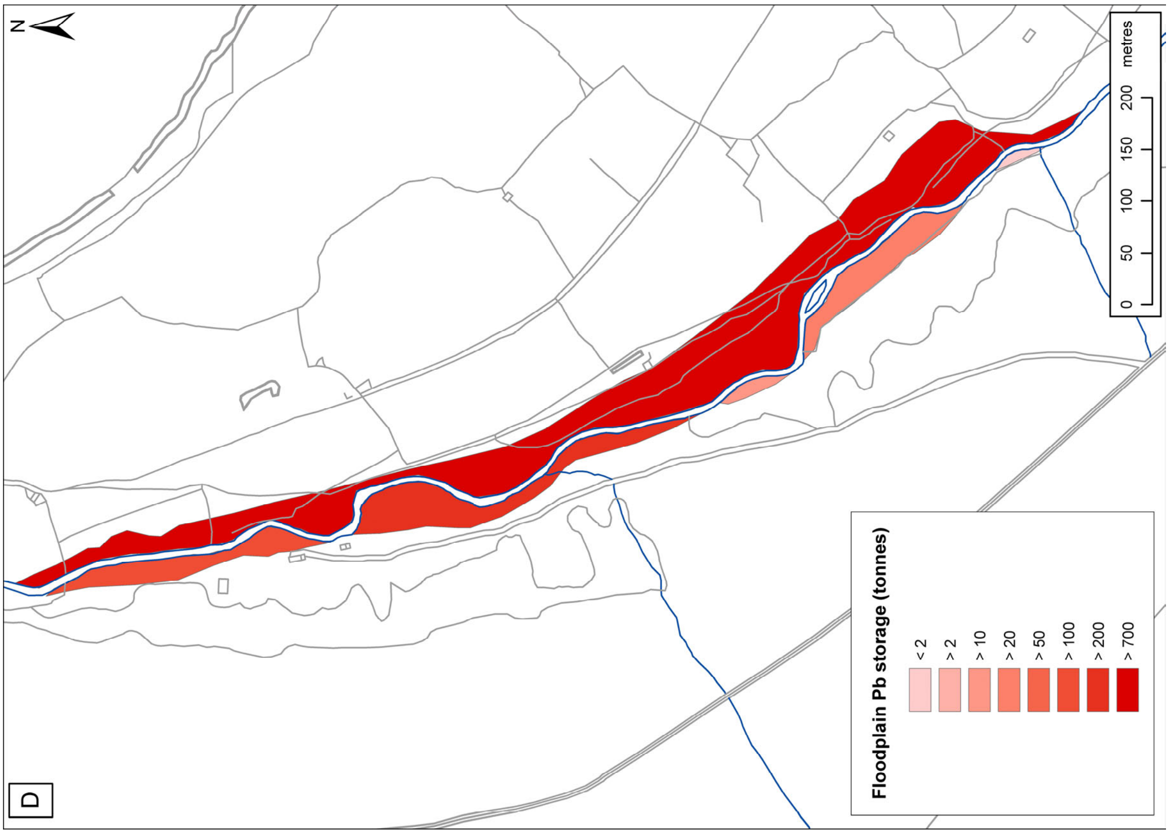


Figure 7.2 (continued): Floodplain Pb storage in Gunnerside Beck (tonnes of Pb in each floodplain unit)

The total weight of Pb stored in floodplain sediments within Gunnerside Beck represents approximately 9 % of the estimated total tonnage of Pb produced in the catchment between AD 1700 and AD 1900 (18,000 tonnes; based on figures from Gill, *pers. comm.*). This serves to highlight the inefficiency of the procedures employed in the processing of Pb ore (Chapter 2), during which large amounts of metal-rich sediment were produced. An indication of the amount of Pb released into the river system can be made by comparing recorded production figures with published recovery statistics for Pb metal from galena. Hunt (1848a; 1848b) suggests that 60 to 70 % of the processed ore mined in the catchment was recovered as Pb, while galena contains a total of 86.6 % Pb (Dunham and Wilson, 1985). This means that between 16.6 and 26.6 % of the Pb mined in the catchment was lost during the processing of the ore. It is therefore likely that between 3000 and 4700 tonnes of Pb were discharged directly into the river, discarded on waste and slag tips, or volatilised during the smelting process and released into the atmosphere. Of these options, storage on spoil tips and direct and subsequent release into the river are likely to be the most significant. The fact that 1600 tonnes of Pb remains suggests that between 34 and 55 % of the total Pb available for release into the catchment is currently stored in floodplain sediments. The remaining Pb is likely to be stored in spoil tips and channel-bed sediments, or has already been transported out of the catchment (*cf.* Hudson-Edwards *et al.*, 1999b).

It should be noted that the contaminant budget estimates do not attempt to include the large volumes of metal-rich sediment that are stored in spoil tips throughout the catchment. These waste tips contain a considerable amount of Pb and other heavy metals, and are likely to be a long-term source of metal-rich sediment to the river system. Furthermore, the contaminant budget estimates represent the amount of Pb stored in floodplain sediments 100 years after the cessation of mining. It is probable that a high proportion of the Pb available for release into the catchment has already been removed from the floodplain store and spoil tips and transported out of the catchment. Indeed, the high metal concentrations observed in contemporary channel sediments within the beck, and in the River Swale downstream of the village of Gunnerside (Chapter 6), support this argument. The fact that large volumes of Pb remain stored a century after the cessation of mining strongly suggests that the Gunnerside Beck system will continue to act as a source of contaminated sediment to the trunk system for a significant period of time.

7.2.4. Potential metal storage in tributary sediments

It is clear from the sediment-associated metal budget that large quantities of metal-rich sediment are stored in the Gunnerside Beck catchment. This is also likely to be true of the other historically mined tributaries in the Swale catchment, many of which share the same basic geomorphological characteristics of Gunnerside Beck, and all of which are likely to contribute mining-related metals to the trunk channel. Although it is not practical to conduct highly detailed geochemical investigations in each tributary of the Swale, the results of this study can be extrapolated to provide estimates of the amount of metal-rich sediment they contain. It can be assumed that mining and processing techniques were similar, if not almost identical, throughout the wider Swale catchment. It may be possible, therefore, to estimate the amount of Pb stored within each tributary as a percentage of the recorded metal production, assuming that 9 % of the total is currently retained in the floodplain.

The results of this process indicate that approximately 32,000 tonnes of Pb potentially remain stored within formerly mined tributaries in the upper Swale catchment (Table 7.1). As would be expected, storage is focussed in the most intensively mined tributaries. The largest amount of Pb (21,000 tonnes) is likely to be stored within Barney Beck, a relatively small tributary which housed the extremely productive Surrender Mine and large parts of the intensive Old Gang mining operations (*cf.* Section 4.3). This tributary accounts for almost half of the total storage of Pb in the tributaries of the upper Swale. The much larger Arkle Beck sub-catchment is likely to contain 3410 tonnes of Pb. This reflects the nature of mining in the tributary; operations in Arkle Beck were generally small, and not on the intensive industrial scale of those in Barney Beck. Other relatively small, intensively mined tributaries such as Swinner Gill, Gunnerside Beck, Birks Gill and Cogden Beck contain the bulk of the remaining Pb that is likely to be stored within the formerly mined tributaries of Swaledale.

7.2.5. Summary: Metal storage in tributary sediments

This section demonstrates that large amounts of metal-rich sediment are stored within formerly mined tributaries in the upper Swale catchment. Detailed investigations in Gunnerside Beck indicate that 55,000 m^3 of metal-rich sediment, containing 1600 tonnes of Pb, remain stored within the tributary. This represents between 34 and 55 % of the total

Table 7.1: Estimated storage of Pb in formerly mined tributaries

Tributary	Catchment area (km^2)	Total Pb production (tonnes)	Estimated Pb retention (tonnes)
Great Sleddale Beck	9.92	461.32	41.52
Whitsundale Beck	18.96	172.53	15.53
Stonesdale Beck	12.17	723.93	65.15
Swinner Gill	2.67	11187.20	1006.85
Straw Beck	19.94	774.45	69.70
Oxnop Beck	5.83	299.14	26.92
Gunnerside Beck	13.78	17795.85	1601.63
Summer Lodge Beck	5.38	3102.60	279.23
Birks Gill	1.06	13373.70	1203.63
Barney Beck	17.19	236844.22	21315.08
Arkle Beck	66.98	37886.70	3409.80
Grinton Gill	3.44	1606.68	144.60
Cogden Beck	4.18	19460.39	1751.44
Hags Gill	1.42	163.80	14.74
Marske Beck	39.09	13166.58	1184.99
Total	**222.02**	**357009.09**	**32103.82**

amount of Pb that is likely to have been released during ore processing, or 9 % of the total recorded Pb production in the catchment. If it is assumed that similar retention rates occur in other historically mined tributaries, a total of 32,000 tonnes of Pb may remain stored within the upland tributaries of the Swale.

There are several limitations with the sediment budgeting method that need to be considered, however. Although the estimated weight of Pb stored in the floodplain of Gunnerside Beck is relatively reliable, there is a caveat when this figure is quoted as a percentage. The Pb production figures on which the percentage is based are incomplete, and are likely to significantly underestimate the total amount of Pb produced in the catchment. This means that the percentage of material stored in the floodplain is likely to be an overestimate of the true amount of Pb extracted within the catchment. The extent to which this is the case is difficult to quantify, given that production records are not available prior to *c.* AD 1700, and those that exist after this date are far from complete. In addition to this, the use of Pb production figures in estimates of the proportion of total Pb stored in the floodplain of mined tributaries gives no indication of the total amount of contaminated sediment released into the river system. However, no records of the volume of sediment released into the tributaries exist, and it is difficult to estimate with any accuracy the proportion of metal that these sediments would contain. Recorded Pb recovery can give an indication of how much metal is likely to have been lost during the processing and smelting of the ore, although it does not quantify the amount of metal-rich sediment that was released into the river itself. However, this may provide the only available estimate of the amount of Pb supplied to the tributaries. The resulting proportions of Pb retained in the tributaries compare favourably with that recorded in similar studies (*e.g.* Gilbert, 1917; James, 1989; Marron, 1992), which report retention rates of between 18 and 87 % of the sediment supplied.

Additional potential problems may be introduced with the extrapolation of the patterns observed within Gunnerside Beck across all the formerly mined tributaries in the Swale catchment. Geomorphological parameters within individual tributaries strongly influence metal storage capacity, as do patterns of metal production. For example, a large, low relief tributary with extensive area for metal storage but low production may contain the same volume of stored contaminants as a small, high relief tributary with little area for storage but high metal production. However, when compared to other mined tributaries in Swaledale, Gunnerside Beck is likely to represent a good average of metal production and potential area for storage. Other tributaries are larger (*e.g.* Arkle Beck), smaller (*e.g.* Swinner Gill), more intensively mined (*e.g.* Barney Beck) or have a less extensive history of metal extraction (*e.g.* Straw Beck). The patterns observed in Gunnerside Beck are therefore likely to be suitable for extrapolation in other tributaries, in order to provide a good initial estimate of total metal storage.

Although the sediment budgeting technique has limitations that need to be considered, it is likely to provide reliable, semi-quantitative estimates of the amount of Pb currently stored in floodplain sediments within formerly mined tributaries. The extremely large quantities of Pb and metal-rich sediment that are predicted to remain stored in the tributaries of the upper River Swale are likely to represent between one third and one half of the total amount of material that was originally released through mining activities. A large proportion of the remainder is likely to have been transferred to floodplain sediments in the trunk channel of the Swale. This likely floodplain storage of metals will be discussed in the subsequent section.

7.3. METAL STORAGE IN FLOODPLAIN SEDIMENTS

7.3.1. Introduction

The previous section has demonstrated that large amounts of metal-rich sediment are likely to be stored within the formerly mined tributaries of the upper Swale catchment. The volume of material retained in the tributaries represents only a portion of that that is likely to have been generated as a result of historic mining activities. Much of the remainder is likely to have been transported out of the tributaries and transferred into the trunk channel, from where it may have become incorporated into floodplain sediments. Indeed, extremely high metal concentrations have been observed in floodplain sediments collected from throughout the catchment (Chapter 5). This section aims to evaluate the importance of floodplain sediments as stores of metals in the Swale catchment. The amount of metal-rich sediment likely to be stored in the detailed floodplain study reaches discussed in Chapter 5 will be estimated, and the likely maximum extent of floodplain metal enrichment will be delimited.

7.3.2. Methods: Estimating floodplain metal storage

Chapter 5 has demonstrated that sediments from floodplain reaches throughout the Swale catchment contain highly elevated concentrations of mining-related metals. Like the floodplains of formerly mined tributaries such as Gunnerside Beck, the Swale floodplain is therefore likely to store considerable quantities of metal rich-sediment. The budgeting technique applied to assessing metal storage in Gunnerside Beck (Section 7.2.2) was initially employed to provide estimates of the total amount of mining-related sediment stored in nine of the detailed floodplain study reaches described in Chapter 5 (Hartlakes, Reeth, Hudswell, Brompton-on-Swale, Great Langton, Morton-on-Swale, Maunby, Thornton Manor and Myton-on-Swale; the Fairholme, Holme and Eldmire reaches were omitted due to a lack of suitable depth profile data).

These catchment scale patterns were then used in a two-stage process to derive estimates of total metal storage in the Swale floodplain. First, the total floodplain area that is likely to have high concentrations of metal-rich sediment was delimited. As reach-scale investigations have demonstrated, some of the highest metal concentrations occur in areas that were formed during, or soon after, the peak of the mining period. This area of this reworked zone was obtained by comparing digitised 1:10,560 scale First Edition Ordnance Survey maps of the Swale catchment with 1:10,000 scale OS Landline data (*cf.* Section 5.2). The identification of the likely maximum extent of floodplain metal enrichment was more problematic, however. Although this is clearly influenced by floodplain topography, the precise nature of the relationship at individual sites was difficult to determine. Nevertheless, it is unlikely that parts of the floodplain that are considerably higher than the current and mining-era floodplain have received significant volumes of metal-rich sediment. Analysis of data from the detailed study reaches suggested that, although this division varied in distance from the current channel, it was generally marked by the boundary between the lower, frequently inundated floodplain and terrace surfaces, and the upper terraces and valley sides. The position of this boundary was identified using a combination of 1:10,000 scale OS Landline data (*e.g.* contours, spot heights, field boundaries and the location of buildings) and 1:5000 scale aerial photography. The maximum likely extent of floodplain metal enrichment was estimated for a 113 km-long reach of the River Swale, between Hoggarths in the upper reaches and 3 km downstream of Brafferton in the lower reaches of the Swale. The short reaches upstream of Hoggarths and downstream of Brafferton were excluded due to the absence of mining activity and difficulties in delineating floodplain extent close to the Swale-Ure confluence, respectively. Finally, the average metal storage within all nine study reaches, expressed in terms of tonnes per square metre of floodplain, was applied across the entire area of floodplain that is likely to have received metals, in order to provide an estimate of total floodplain Pb storage.

7.3.3. Metal storage in the River Swale floodplain

The results of the sediment budget calculations suggest that large volumes of metal-rich sediment are stored in the nine floodplain reaches included in this investigation (Table 7.2). Approximately 19,000 tonnes of Pb, equivalent to 5 % of the total recorded production in the catchment, is likely to be stored in the study reaches, within approximately 5,450,000 m^3 of sediment. In absolute terms, metal storage is greatest in the Great Langton reach, reflecting the large size and deep alluvium at the site. When storage is expressed in terms of tonnes per cubic metre of sediment, however, metal storage is greatest at Reeth, reflecting its position at the heart of the mining zone. Large volumes of mining-related metals are also stored in the floodplain reaches downstream of the mined zone; this storage is most concentrated at Hudswell and Morton-on-Swale. Metal storage decreases further downstream, in the lower reaches of the river, both in absolute terms and in intensity of storage (*cf.* Section 5.3). A considerable quantity of Pb is stored in the floodplain as far downstream as the Swale-Ure confluence, however.

Table 7.2: Estimated storage of Pb in floodplain sediments (see Chapter 5 for full details of each floodplain reach)

Floodplain reach	**Floodplain area (km^2)**	**Total Pb storage (tonnes)**	**Relative concentration ($t\ m^{-3}$)**
Hartlakes	0.002	15.51	0.0008
Reeth	0.18	1644.99	0.0077
Hudswell	0.06	214.17	0.0043
Brompton-on-Swale	0.29	1654.19	0.0029
Great Langton	1.14	10623.32	0.0036
Morton-on-Swale	0.46	2750.04	0.0046
Maunby	0.49	1052.94	0.0027
Thornton Manor	0.11	55.98	0.0010
Myton-on-Swale	0.97	1025.36	0.0018
Total	**3.72**	**19036.49**	

The results of the second part of the procedure suggest that large areas of the Swale floodplain are likely to contain metal-rich sediment from historic mining operations (Figure 7.3). Approximately 3.7 km^2 floodplain are likely to contain the highest concentrations of mining-related metals (the 1854 channel and bar system), while a further 25.4 km^2 are likely to contain metal-enriched sediment. When combined, these figures suggest that over 55 % of the total Swale floodplain (or 2 % of the catchment as a whole)

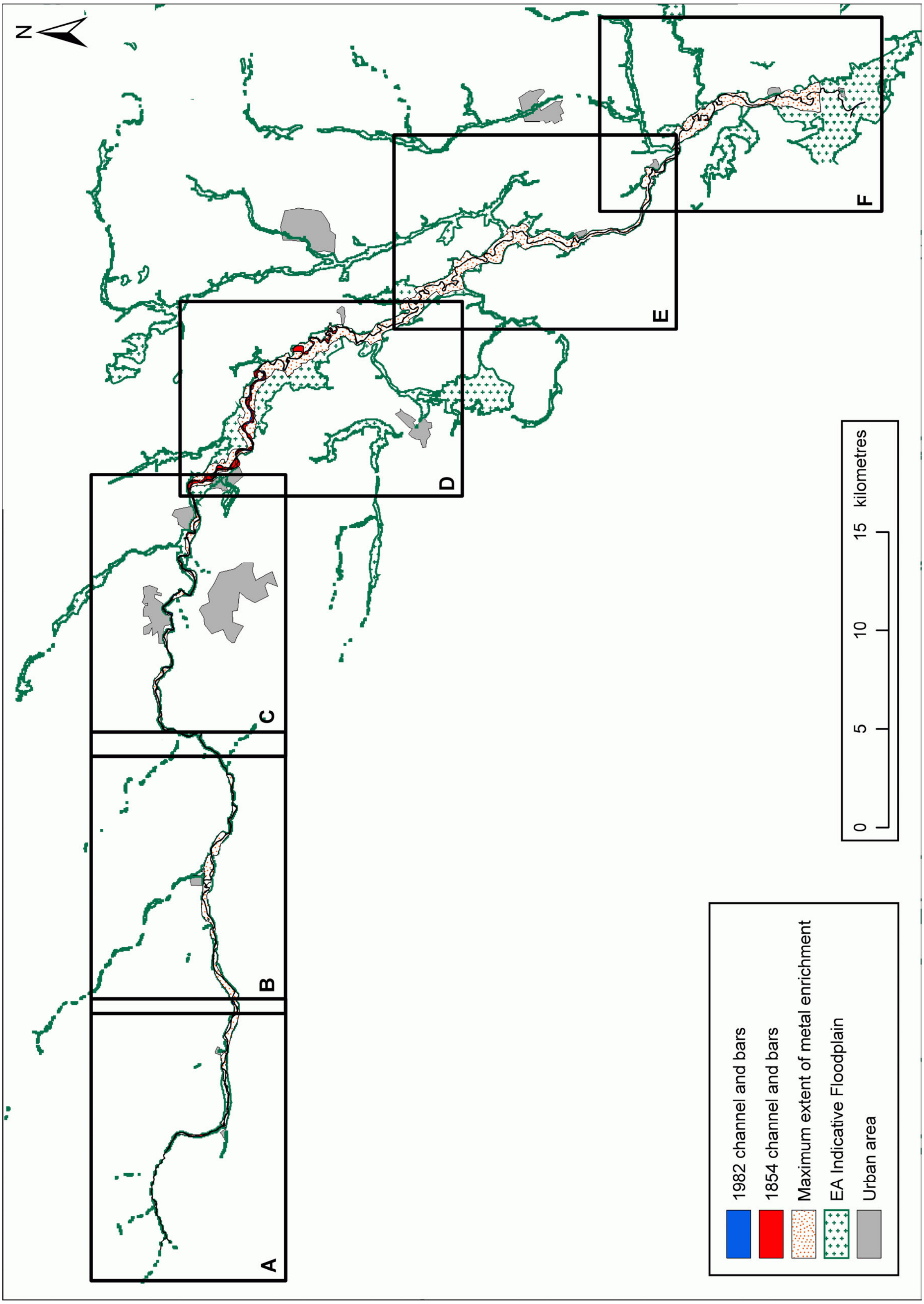


Figure 7.3: Likely maximum extent of floodplain metal storage in the Swale catchment

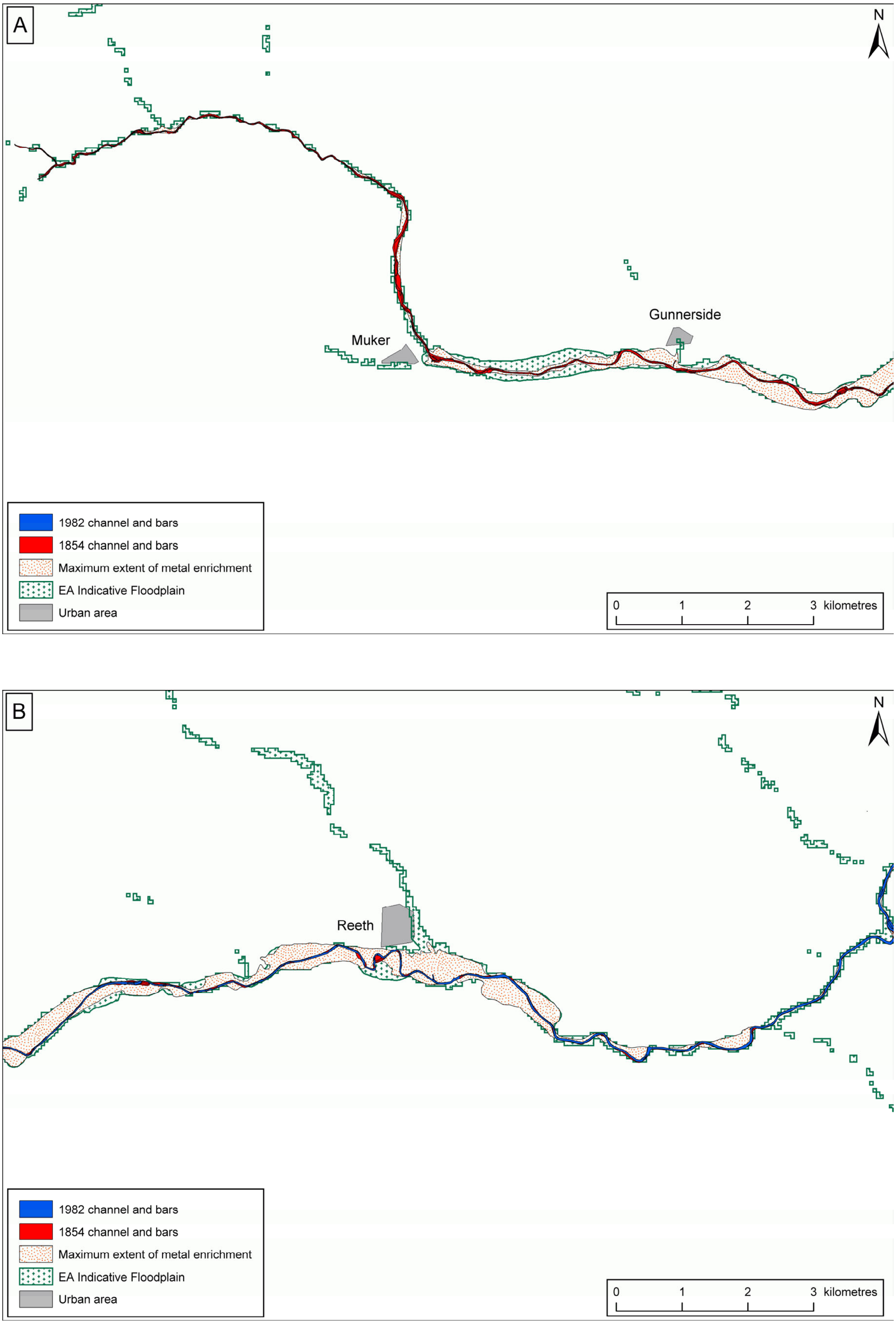


Figure 7.3 (continued): Likely maximum extent of floodplain metal storage in the Swale catchment

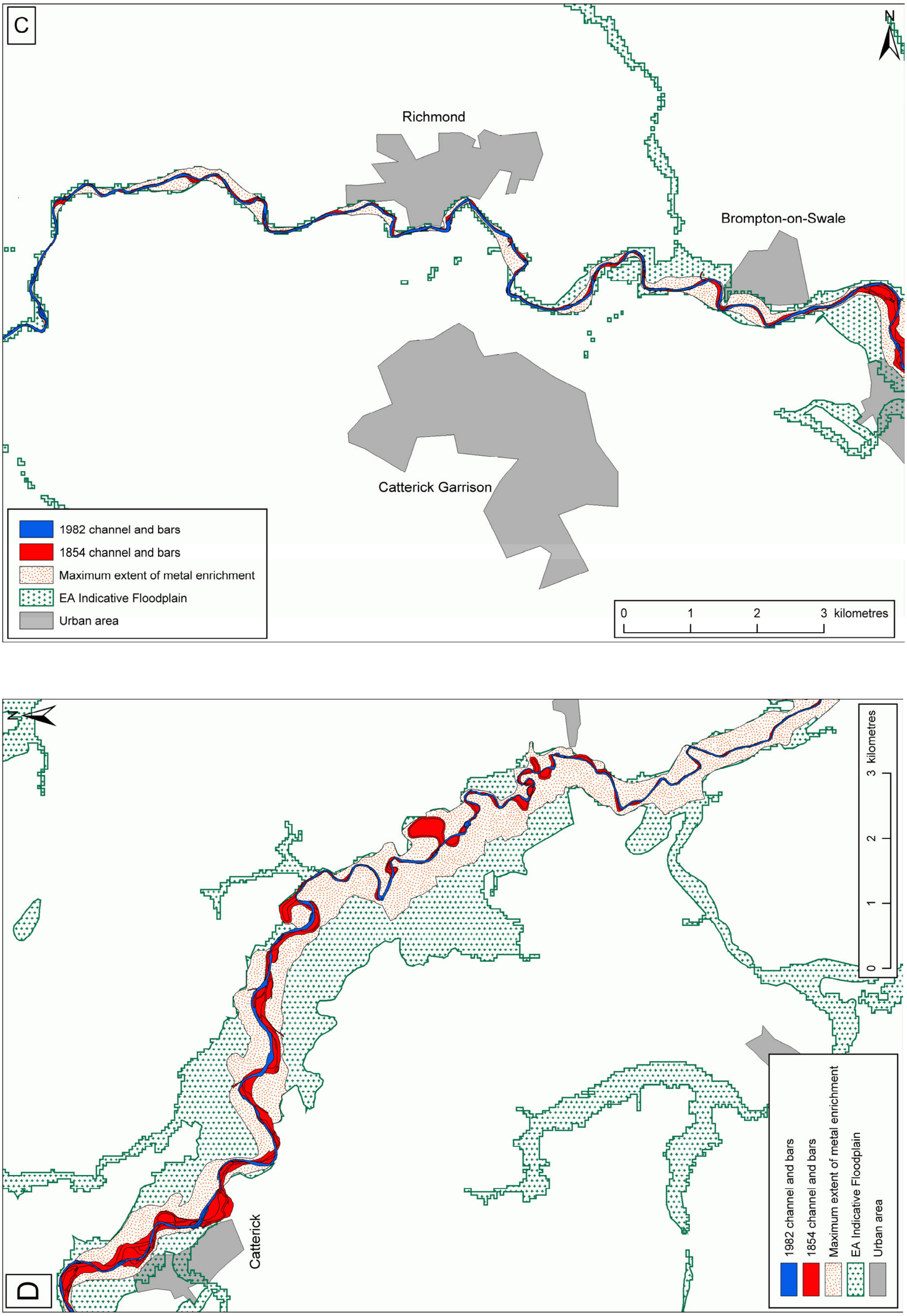
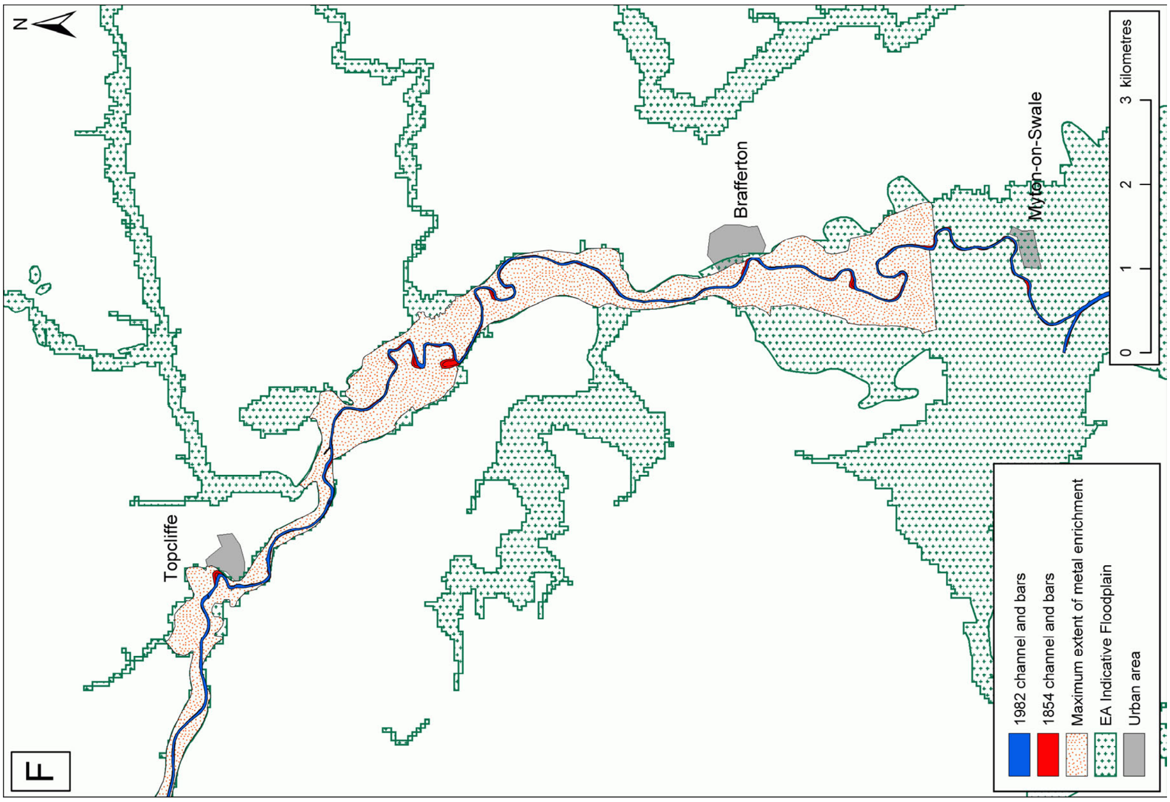


Figure 7.3 (continued): Likely maximum extent of floodplain metal storage in the Swale catchment



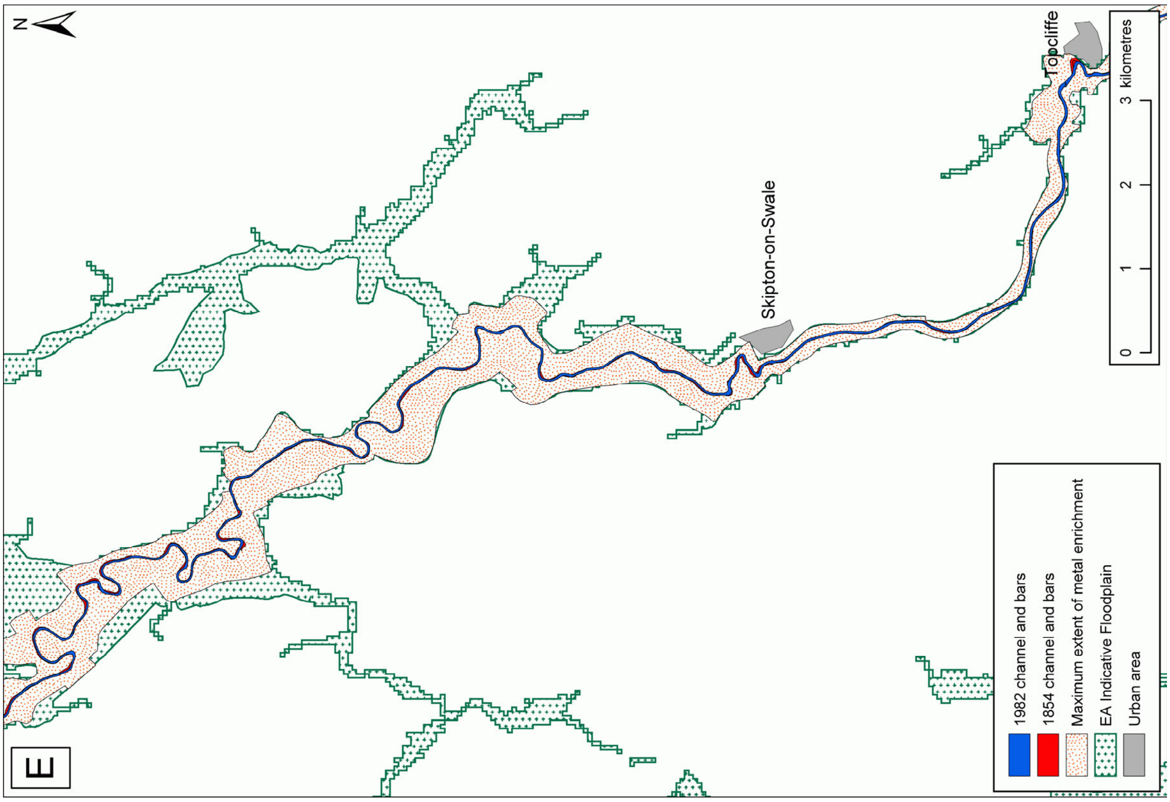


Figure 7.3 (continued): Likely maximum extent of floodplain metal storage in the Swale catchment

has received metal-rich sediment from historic mining operations. Along much of the course of the river, particularly in the upper reaches and in the lower reaches downstream of Morton-on-Swale, land that is likely to contain metals takes the form of narrow strips of land formed by small-scale channel migration and/ or channel narrowing since the cessation of mining activities (Figure 7.3). Larger areas of land that is likely to be enriched in mining-related metals can be observed in the middle reaches, between Catterick and Morton-on-Swale. The channel has migrated extensively in this reach, and a number of large meander loops have been cut off since the cessation of mining. As would be expected, the spatial extent of land that is likely to contain metals strongly reflects the width of the floodplain. The area is generally narrow as far downstream as Catterick, after which it opens out on the wider floodplain within the Vale of York.

This section demonstrates that 5,450,000 m^3 of metal-rich sediment, containing 19,000 tonnes of Pb, are stored within the 3.7 km^2 floodplain examined in detail in this investigation. This area represents approximately 7 % of the total Swale floodplain, and 13 % of the floodplain that is likely to have received mining-related metals. It should be noted, however, that considerable uncertainty may be attached to these estimates, principally as a result of the limited down-profile data that are available for use in the contaminant budget. Nevertheless, these estimates are likely to provide a valuable indication of the level of floodplain metal storage, and the maximum extent of floodplain storage, in the Swale catchment. When the average quantity of metal storage is applied to the maximum extent of floodplain metal enrichment, a total of 123,000 tonnes Pb may be stored in the Swale floodplain as a whole. This represents 35 % of the total recorded metal production in the catchment. The Swale floodplain is therefore likely to represent the single largest store of metal-rich sediment in the catchment, containing six times as much Pb as the formerly mined tributaries in the upper reaches of the catchment.

7.3.4. Summary: Metal storage in floodplain sediments

This section demonstrates that extremely large quantities of metal-rich sediment are likely to be stored in the Swale floodplain, affecting a large area of the catchment. Approximately 19,000 tonnes of Pb are stored within nine of the detailed study reaches discussed in Chapter 5, covering a combined area of 3.7 km^2. Catchment-wide estimates suggest that approximately 29.1 km^2 of the Swale floodplain is likely to store metal-rich sediment; as much as 123,000 tonnes Pb may be stored within this area. This suggests that considerable volumes of metal-rich sediment, initially produced in the formerly mined tributaries of the upper Swale, have been transferred to the floodplain of the trunk channel (*e.g.* Chapter 6).

7.4. METAL STORAGE AND FLUXES IN THE RIVER SWALE CATCHMENT

The previous sections have demonstrated that large volumes of metal-rich sediment remain stored within historically mined upland tributaries and the floodplain of the River Swale. As much as 32,000 tonnes of Pb remain stored in the floodplain of the formerly mined tributaries, and a further 123,000 tonnes may be stored in floodplain sediments from the main river. This suggests that as much as 155,000 tonnes of sediment-associated Pb may remain in storage in the River Swale catchment. This represents approximately 43 % of the total recorded Pb production from mines in the catchment, or 28 % of estimated total Pb production (Dunham and Wilson, 1985). It should be noted that these estimates of total metal storage do not include any material that is stored within the river channel. Walling *et al*. (2003a) have demonstrated that between 0.094 and 0.395 g m^{-2} Pb were stored in channel sediments between February 1998 and December 1999. Channel sediments are therefore a relatively small-scale store of metals when compared to floodplain and tributary sediments, and are important only in the transfer of material between stores. Indeed, channel sediments represent only a temporary store of fine-grained sediment and associated metals (*cf.* Walling *et al.*, 1998b).

Davies (1980a) suggests that 50 % of metal output was released into the fluvial system during inefficient processing operations associated with historic mining. Assuming that the estimated Pb production figure is more representative than the total recorded production, this suggests that 275,000 tonnes of Pb were released into the River Swale catchment while the mines were operational. This suggests that as much as 44 % of the Pb released from mining operations, or 121,000 tonnes of Pb, has been removed from storage in the catchment since the cessation of mining. If sediment removal continues at the present rate, it is likely to take several centuries for the remaining Pb to be removed from storage in the catchment. Indeed, a series of simulations by Coulthard and Macklin (2003) suggest that metal mining is indeed a long term problem, with considerable amounts of metal-rich sediment remaining within the catchment more than 200 years after the cessation of mining.

Previous reconstructions of sediment fluxes in the Swale catchment suggest that of the 61,566 tonnes of sediment that are delivered to the channel every year, 31 % is stored on the floodplain surface, and 6 % remains stored within the channel (Walling *et al.*, 1998b; 1999b). The remaining 63 % is likely to be transported out of the catchment. Retention rates of mining-related metals may be proportionally higher, however. Walling and Owens (2003) and Walling *et al*. (2003a) suggest that, on average, 45 % of the total load of Pb, or 24.49 tonnes, is retained within the catchment each year (Section 6.3.6). The remainder of the total load, or 29.40 tonnes of Pb, is exported into the wider Ouse system (Walling and Owens, 2003; Walling *et al.*, 2003a). If the removal of metal-rich sediment continues at this rate, it may take more than 5000 years for all the Pb to be removed from the catchment. This estimate may appear overlong when compared with the estimated 121,000 tonnes of Pb that have already been removed from the catchment in the *c.* 100 years since the cessation of mining activities. However, it should be noted that this figure is likely to include considerable volumes of metals that were discharged directly into the river channel. It is probable that a large proportion of these metals was rapidly transported out of the catchment (*cf.* Walling *et al.*, 1998b; Walling *et al.*, 1999b), and as such never became incorporated into floodplain sediments. In addition, increased flood magnitude and discharge during the peak of mining activities (*cf.* Longfield and Macklin, 1999; Merrett and Macklin, 1999) suggests that sediment removal fluxes were greater at this time than in the present day. This suggests that the Swale catchment will continue to act as a source of metal-rich sediment for a considerable period of time.

The Swale is likely to be one of the most important sources of fine grained sediment to the River Ouse at York, accounting for 82 % of the total (Walling *et al.*, 1999a). The removal of metal-rich sediment from storage in the Swale catchment may therefore represent a serious threat to environmental quality in an extremely large area, although metals are likely to be considerably diluted further downstream. Nevertheless, Hudson-Edwards *et al*. (1999a) identified the Northern Pennine Orefield, an intensively mineralised part of which is drained by the River Swale, as an important source of Pb in Mediaeval sediments from the River Ouse at York. The likely longevity of the Swale catchment as a source of metals suggests that this may be a potentially serious environmental problem.

7.5. CONCLUSION

This chapter demonstrates that large amounts of metal-rich sediment remain stored in floodplain sediments within formerly mined tributaries and the trunk channel of the River Swale. As much as 32,000 tonnes of Pb may be stored in historically mined tributaries such as Gunnerside Beck and Barney Beck, and a further 123,000 tonnes of Pb may be stored within the floodplain of the River Swale itself. This suggests that 155,000 tonnes of Pb, or 28 % of estimated total production, is stored within fluvial sediments in the Swale catchment. Considerable quantities of metal-rich sediment are remobilised from storage in both the tributaries of Swaledale and the floodplain of the main river, and redeposited on the floodplain surface during overbank floods. It is likely that approximately half of the metal-rich sediment transported in the river is removed from the catchment, leading to a gradual reduction in the amount of metal that is stored in tributary and floodplain sediments. Indeed, it is possible that approximately 44 % of the total amount of Pb released into the river system has been removed from the catchment in the *c*. 100 years since the cessation of mining operations. However, assuming that current Pb fluxes at the base of the catchment are representative of long-term (and future) averages, it may take more than 5000 years for all the metal-rich sediment to be completely removed from the catchment.

Metal mining has therefore had a severe and lasting impact on the River Swale catchment, and may also impact on the wider Ouse catchment of which the Swale is a tributary. This and previous chapters have demonstrated that tributary, floodplain and flood sediments contain large quantities of metal-rich sediment. However, the environmental consequences of this metal cycling and storage have not been evaluated thus far. The environmental impact of metal-rich sediment from historic mining operations will therefore be discussed in the subsequent chapter.