# CHAPTER 5

# METAL DISTRIBUTION IN FLOODPLAIN SEDIMENT

## 5.1. INTRODUCTION

A large number of previous investigations have demonstrated that floodplains in historically mined river catchments frequently contain large volumes of metal-rich sediment (*e.g.* Lewin and Macklin, 1987; Marron, 1989; Rang and Schouten, 1989; Bradley and Cox, 1990; Macklin, 1996; Macklin *et al.*, 1997; Miller, 1997). Metals can remain stored in floodplain sediments for hundreds or even thousands of years (Bowen, 1979; Salomons and Förstner, 1984), and frequently has a detrimental impact on environmental quality where they are deposited. However, the floodplain is not necessarily a permanent store of contaminants. Instead, it can be a dynamic environment from which metals can be removed through processes such as bank erosion and returned to storage through lateral and vertical accretion. As a result, metal-rich sediment can continue to cause contemporaneous and future environmental problems in a formerly mined river catchment long after mineral extraction and processing have ceased (*cf.* Stigliani *et al.*, 1991; Miller, 1997).

This chapter aims to evaluate the impact of mining and processing activities on floodplain sediments in the River Swale catchment. Patterns of metal dispersal in the Swale floodplain will be identified, using data from previous studies (Macklin *et al.*, 1994; Taylor and Macklin, 1997; Carter, 1998; Sparks, 1998; Hudson-Edwards *et al.*, 1999b; Sedgwick, 2000) together with fresh data from this investigation. The geomorphological factors that influence both longitudinal and latitudinal dispersal patterns will be identified, and the likely significance of metal storage in floodplain sediments will be evaluated.

## 5.2. METHODS

The floodplain of the River Swale is a highly varied and complex environment, displaying a wide range of geomorphological characteristics that vary considerably between individual reaches. It therefore follows that patterns of metal dispersal in floodplain sediments are likely to be similarly complex and highly variable. It is desirable, therefore, to collect geochemical data from as wide a range of floodplain locations as possible in order to fully characterise metal dispersal patterns along the length of the river. However, it is not feasible to undertake sampling at a large number of sites in sufficient detail to identify metal dispersal patterns due to time constraints and the prohibitive cost of a large number of analyses. Instead, it is more effective to utilise existing geochemical data from the study area (Section 2.3), augmented with further data collected for the purposes of this study.

To provide an indication of metal distribution in floodplain surface sediments, geochemical data were compiled from a number of published (Macklin *et al.*, 1994; Taylor and Macklin, 1997; Hudson-Edwards *et al.*, 1999b) and unpublished sources (Carter, 1998; Sparks, 1998; Sedgwick, 2000). Large gaps in the spatial coverage of geochemical data were identified, and further sampling was targeted at suitable reaches within these areas. Detailed sampling was undertaken across the floodplain at two additional reaches, and single transects were collected from a further four sites. All samples were collected using a stainless steel Edelmann auger, to a depth of 20 cm. The <2 mm size fraction from each sample was digested in $HNO_3$ for one hour at 100°C prior to geochemical analysis using ICP-MS. The <2 mm fraction was selected to ensure comparability within the entire floodplain data set (all secondary sources provided <2 mm data). Full details of sample preparation and analysis can be found in Chapter 3. Full data are presented in Appendix 2. At the end of this procedure, detailed data were available for floodplain surface sediments at 12 study reaches (Table 5.1 and Figure 5.1).

Data on the subsurface distribution of metals in floodplain sediments is also required to give a fuller picture of metal dispersal patterns in the floodplain. Depth profiles were available for each of the sites investigated in detail by other authors, in addition to several single cores from additional floodplain reaches (Macklin *et al.*, 1994; Taylor and Macklin, 1997; Carter, 1998; Sparks, 1998; Hudson-Edwards *et al.*, 1999b; Sedgwick, 2000).

*Table 5.1: Study reach characteristics*

| Study reach | NGR | Distance from source (km) | Length (km) | Area ($km^2$) | Number of samples | Data source |
|---|---|---|---|---|---|---|
| **Hartlakes** | SD 908 003 | 5.6 | 0.25 | 0.02 | 12 | Sedgwick (2000) |
| **Reeth** | SE 034 988 | 22.2 | 1.5 | 0.18 | 155 | This study |
| **Hudswell** | SE 146 007 | 37.1 | 0.5 | 0.06 | 7 | Sedgwick (2000) |
| **Brompton-on-Swale** | SE 213 996 | 47.2 | 2.0 | 0.29 | 168 | This study |
| **Great Langton** | SE 291 961 | 59.0 | 2.2 | 1.14 | 43 | Carter (1998); Sedgwick (2000) |
| **Morton Flatts** | SE 318 921 | 65.9 | 0.75 | 0.46 | 15 | Sedgwick (2000); this study |
| **Fairholme** | SE 322 892 | 70.1 | Single transect | | 12 | This study |
| **Maunby** | SE 341 864 | 75.4 | 2.5 | 0.49 | 28 | Carter (1998) |
| **Holme** | SE 361 825 | 84.3 | Single transect | | 10 | This study |
| **Eldmire** | SE 420 747 | 97.3 | Single transect | | 8 | This study |
| **Thornton Manor** | SE 433 714 | 100.5 | 0.5 | 0.11 | 12 | Sedgwick (2000) |
| **Myton-on-Swale** | SE 432 664 | 115.5 | 2.0 | 0.97 | 16 | Hudson-Edwards *et al*. (1999); this study |

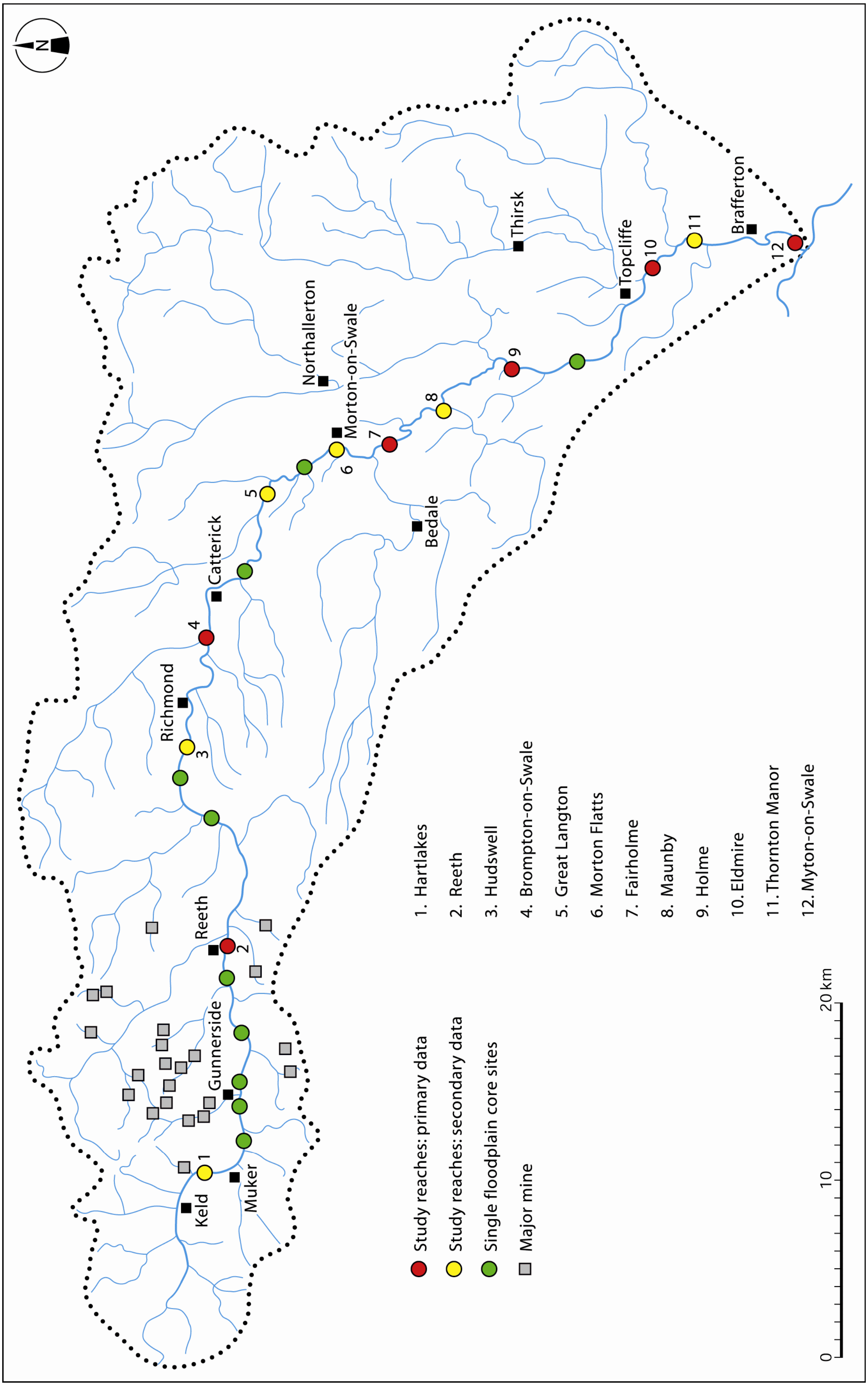

*Figure 5.1: Floodplain sediment study sites in the River Swale catchment*

These were supplemented with short floodplain cores collected using a stainless steel Edelmann auger at a further eight sites.

All geochemical data from primary and secondary sources were used to construct a GIS database of floodplain contamination in the River Swale catchment. These data were plotted against Ordnance Survey 1:10,000 scale Landline base maps to allow the spatial distribution of metal rich sediment in relation to the contemporary River Swale floodplain to be evaluated. Elevation data, in the form of contours and spot heights, was included to allow the influence of the broad geomorphological characteristics of the floodplain to be evaluated.

In order to fully understand patterns of metal dispersal across the floodplain, it is also necessary to consider the position of the channel when mining was at its peak. Sediment cycled through the fluvial system at this time is likely to have contained metals in concentrations that exceed those observed in currently active sediments, since mining waste was discharged directly into the river from dressing floors while they were operational. Areas of floodplain deposited close to the mining-era channel are therefore likely to contain extremely high metal concentrations. Zones of channel change in the Swale catchment were identified by comparing historic map sources with contemporary maps of the channel. 1:10,560 scale first edition Ordnance Survey maps (dated 1854) were digitised using ARC/INFO 3.5.2, and were combined with the Landline data (*c.* 1982). This allowed the position of the channel and bar system at the peak of mining in relation to the contemporary channel and floodplain to be easily identified, along with any areas of floodplain that had been deposited since this time.

## 5.3. METAL DISTRIBUTION PATTERNS

### 5.3.1. Introduction

Previous investigations have demonstrated that metal mining has had a major impact on the River Swale floodplain. Metal-rich material has become incorporated into floodplain sediments through vertical and lateral accretion processes, where it is likely to remain for a considerable period of time. A combination of primary and secondary data will be employed to identify patterns of metal dispersal in floodplain sediment throughout the

River Swale catchment. Broad downstream patterns in metal concentrations will first be evaluated, and reach-scale dispersal patterns will then be described.

### 5.3.2. Downstream metal distribution patterns

Metal concentrations in floodplain sediments are shown in Figure 5.2. Floodplain sediments in the uppermost 10 km of the Swale catchment contain slightly elevated metal concentrations (up to 1000 mg kg$^{-1}$ Pb, 1500 mg kg$^{-1}$ Zn and 10 mg kg$^{-1}$ Cd), with metal-enriched sediment derived from the small mines in the upland headwaters of the river. Metal concentrations increase markedly downstream of more heavily mined tributaries such as Gunnerside Beck and Barney Beck (reaching a maximum of 12,000 mg kg$^{-1}$ Pb, 6000 mg kg$^{-1}$ Zn and 70 mg kg$^{-1}$ Cd), and remain extremely elevated for a considerable distance downstream of the last input of mine waste. Concentrations begin to decline approximately 75 km from the source. This decline is relatively small, however, with mean and maximum concentrations of Pb, and to a lesser extent, Cd, in the lower reaches of the Swale slightly exceeding those observed in the upper 10 km, upstream of the major mine waste inputs (mean Pb 400 mg kg$^{-1}$ *c.* 5 km downstream, compared to 720 mg kg$^{-1}$ *c.* 115 km downstream).

### 5.3.3. Lateral metal distribution patterns

#### *5.3.3.1. Hartlakes*

Metal-rich sediment accumulation at Hartlakes, in the upper reaches of the Swale, is focussed on low and intermediate floodplain surfaces (Figure 5.3). Highest concentrations of Pb, Zn and Cd (1000 mg kg$^{-1}$, 1500 mg kg$^{-1}$ and 10 mg kg$^{-1}$, respectively) occur within or adjacent to the area occupied by the 1854 channel and bars and the floodplain reworked since 1854. Metal concentrations rapidly decline with distance from the current river channel, with samples greater than 50 m from the river containing low concentrations of Pb, Zn and Cd (up to 250 mg kg$^{-1}$, 120 mg kg$^{-1}$ and < 1 mg kg$^{-1}$, respectively). It is likely that floodplain relief is a key factor in controlling this decline in metal concentrations. Terrace surfaces greater than 50 m from the channel are considerably higher than those closer to it, and are therefore unlikely to be inundated frequently.

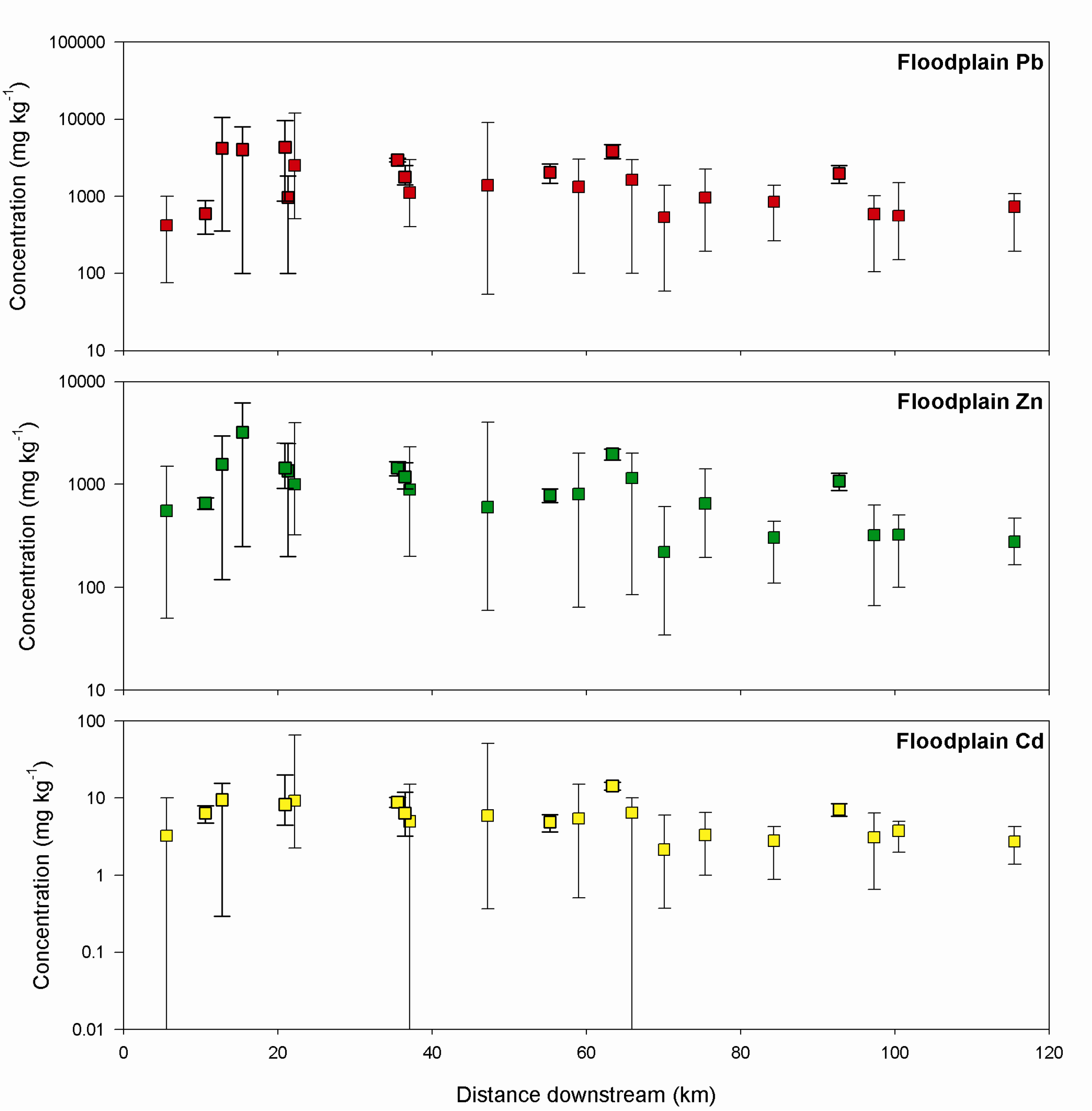

*Figure 5.2: Downstream trends in metal dispersal (mean, minimum and maximum concentrations at each reach are shown)*

Metal concentrations at Hartlakes exhibit a distinct down-profile variation. Concentrations of approximately 400 mg kg$^{-1}$ Pb can be observed in the upper part of the profile (Sedgwick, 2000), with a peak of 1400 mg kg$^{-1}$ at approximately 20 cm depth. Low metal concentrations can be observed below a depth of approximately 25 cm.

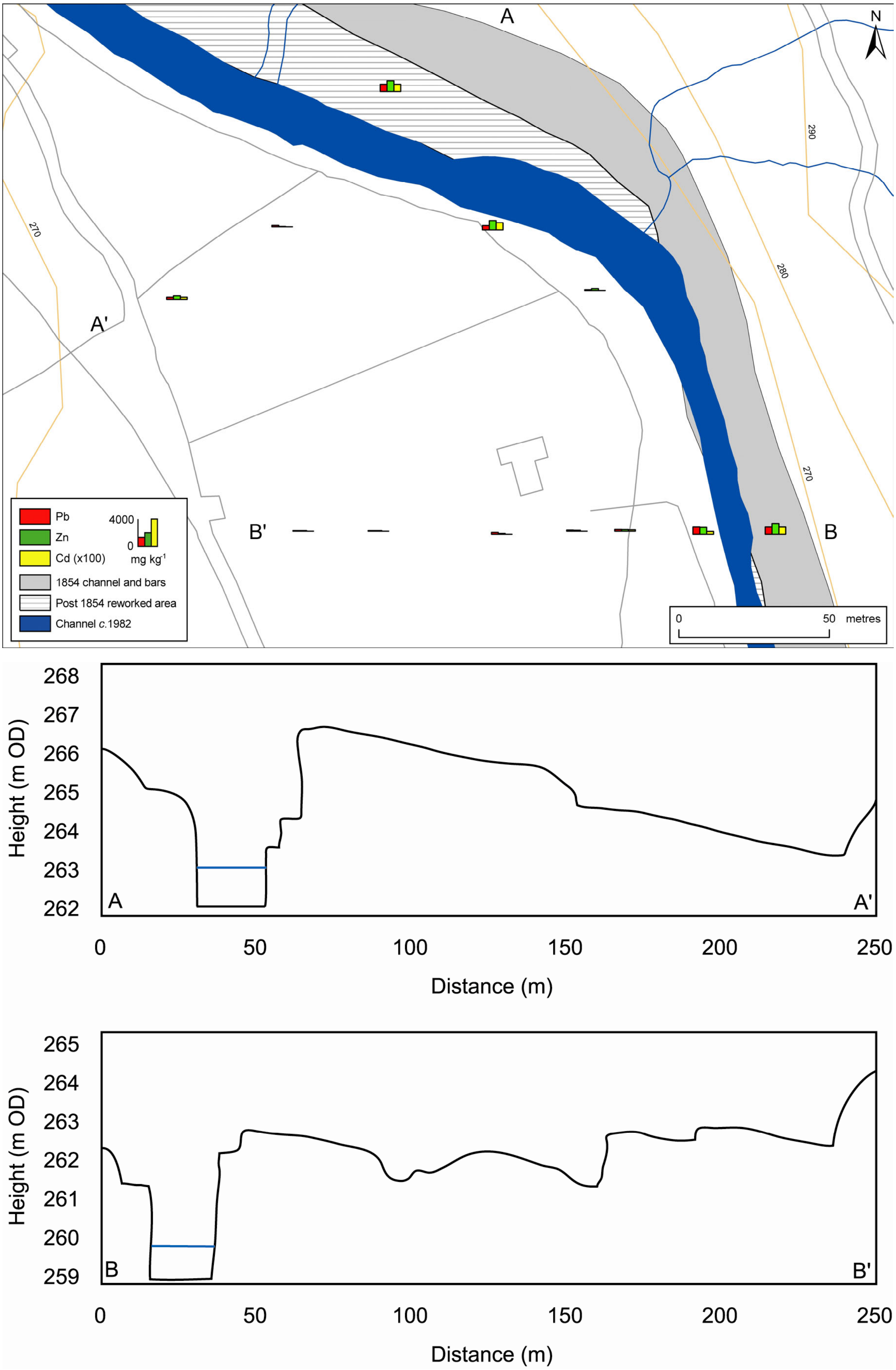

*Figure 5.3: Floodplain metal concentrations and surface topography at Hartlakes*

#### *5.3.3.2. Reeth*

In the highly active reach at Reeth, in the centre of the major mining zone, severe metal contamination can be observed in surface sediments across the entire valley floor (Figure 5.4). The generally low relief of the site means that Pb, Zn and Cd concentrations are elevated on all the floodplain units (> 1000 mg $kg^{-1}$, > 300 mg $kg^{-1}$, and > 2 mg $kg^{-1}$, respectively). Particularly high metal concentrations can be observed in areas in or adjacent to the 1854 channel and bars, and on a low terrace and adjacent drainage ditch in the north west of the site. Maximum concentrations of Pb, Zn and Cd within these zones are 8000 mg $kg^{-1}$, 2400 mg $kg^{-1}$, and 24 mg $kg^{-1}$, respectively. Subsurface metal concentrations display a similar pattern to surface sediments, but metal concentrations are generally higher. Maximum Pb, Zn and Cd concentrations in subsurface sediments are 12,000 mg $kg^{-1}$, 4000 mg $kg^{-1}$, and 47 mg $kg^{-1}$, respectively.

A series of floodplain cores from the Reeth study reach (Macklin *et al.*, 1994; Sparks, 1998; Sedgwick, 2000) indicate that metal concentrations exhibit considerable down-profile variation. Pb concentrations of *c.* 2000 mg $kg^{-1}$ can be observed in floodplain soils to a depth of 60 cm. A series of peaks occur below this depth, reaching up to 30,000 mg $kg^{-1}$ Pb at a depth of approximately 75 cm. Metal concentrations remain elevated to a depth of approximately 110 cm, after which they decline considerably (< 500 mg $kg^{-1}$ Pb).

#### *5.3.3.3. Hudswell*

Metal storage at Hudswell is focussed on lower floodplain surfaces adjacent to the current river channel (Figure 5.5). Concentrations are particularly high on the intermediate terrace unit, approximately 75 m from the current channel (3000 mg $kg^{-1}$ Pb, 2300 mg $kg^{-1}$ Zn, and 15 mg $kg^{-1}$ Cd), and are also elevated in the area occupied by the river channel in 1854 (up to 2000 mg $kg^{-1}$ Pb, 1900 mg $kg^{-1}$ Zn, and 10 mg $kg^{-1}$ Cd). Pb, Zn and Cd concentrations are lower on the highest and lowest floodplain units, but these can still be regarded as elevated (a minimum of 400 mg $kg^{-1}$, 200 mg $kg^{-1}$, and > 1 mg $kg^{-1}$, respectively). A floodplain core indicates that maximum Pb concentrations of 3000 mg $kg^{-1}$ can be observed at 35 cm and between 75 and 90 cm depth. Between these peaks, and in more recent deposits, concentrations of up to 2000 mg $kg^{-1}$ can be observed (Sedgwick, 2000).

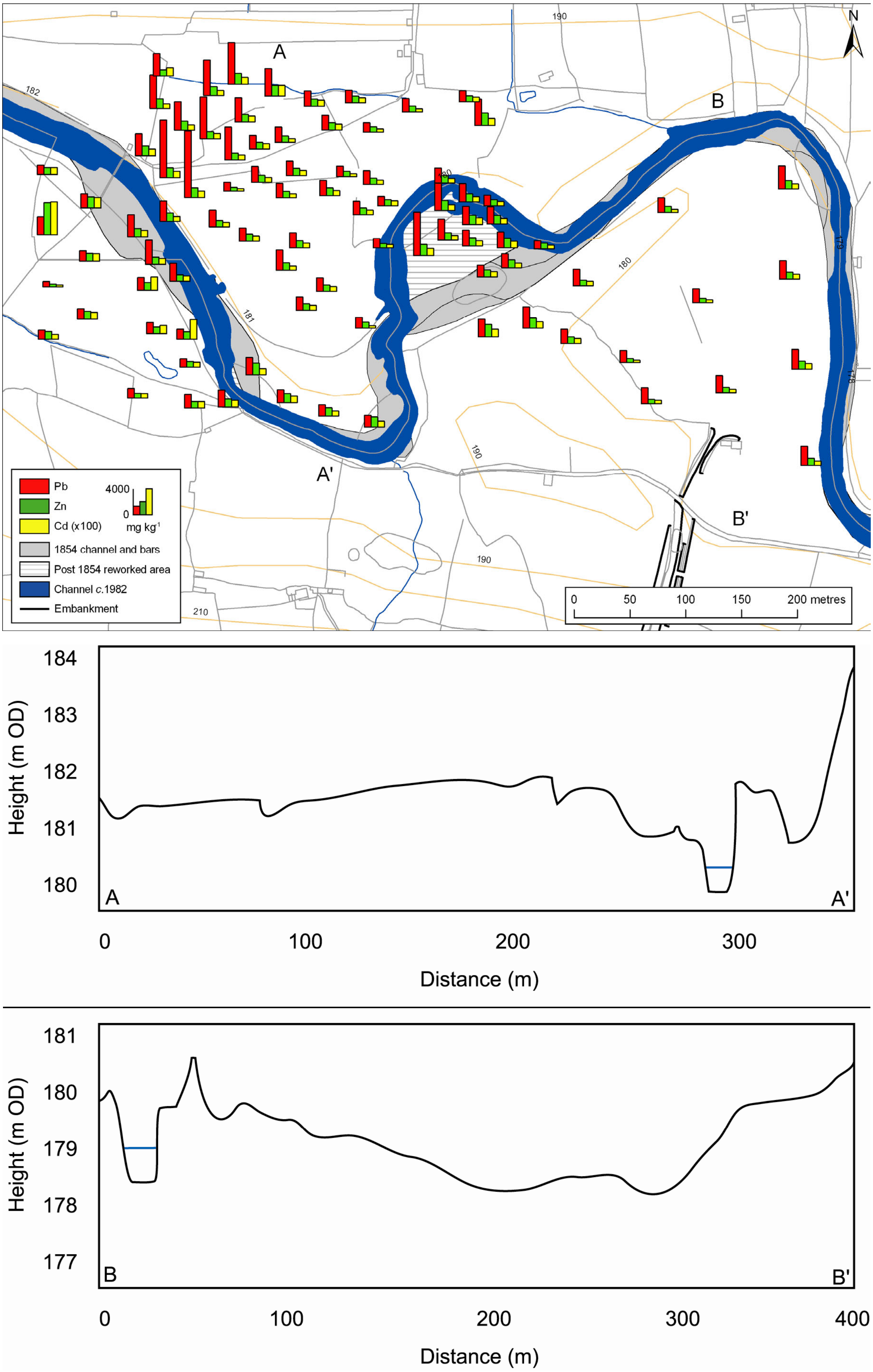

*Figure 5.4: Floodplain metal concentrations and surface topography at Reeth*

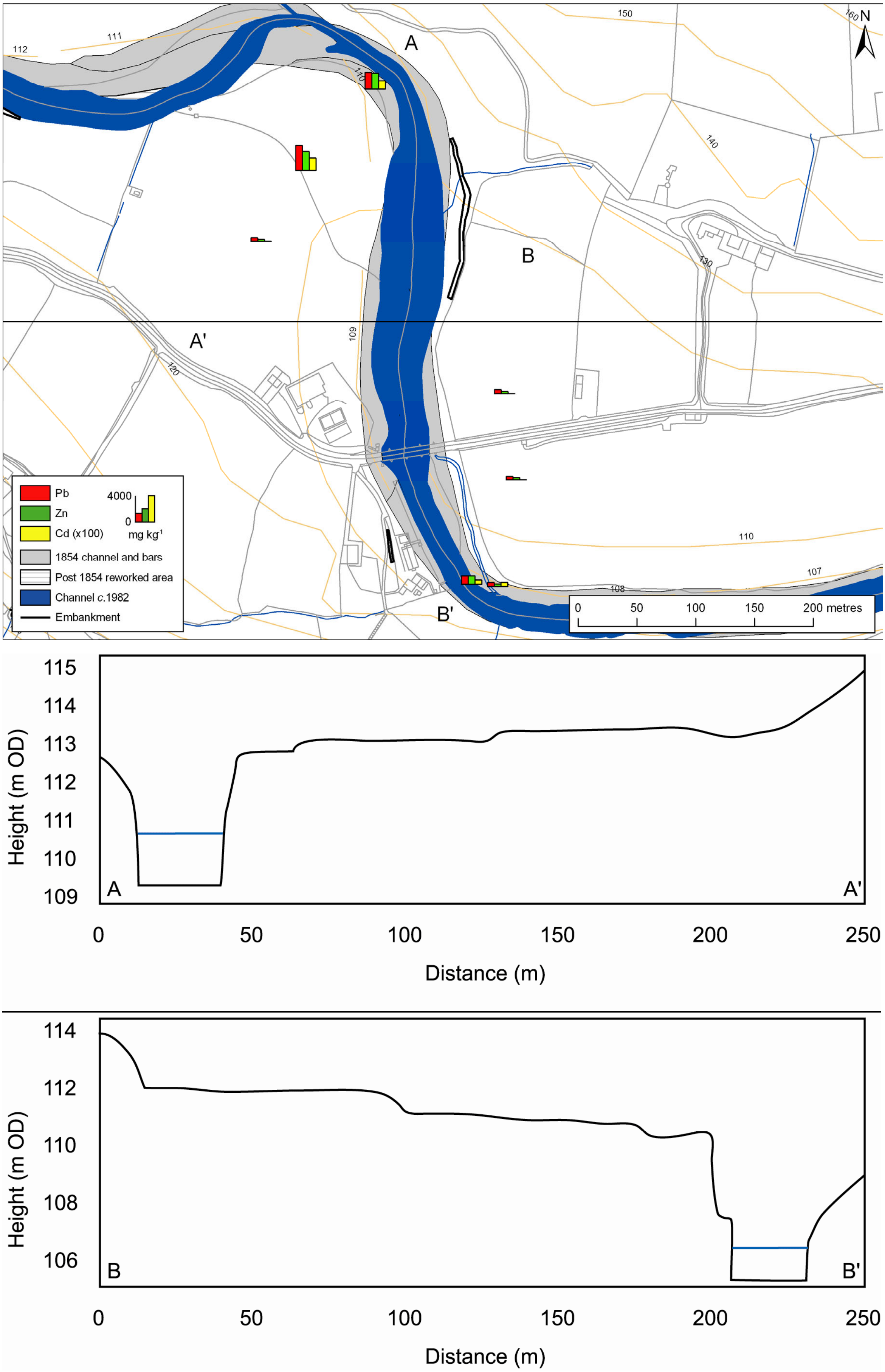

*Figure 5.5: Floodplain metal concentrations and surface topography at Hudswell*

### *5.3.3.4. Brompton-on-Swale*

At Brompton-on-Swale, metal accumulation is greatest on the lower floodplain units (Figure 5.6). Highest concentrations can be observed in, or adjacent to, the 1854 channel and bars, and are especially high in a bar that was partially vegetated during the mining era. Surface Pb, Zn and Cd concentrations peak at 3500 mg kg$^{-1}$, 2500 mg kg$^{-1}$, and 18 mg kg$^{-1}$, respectively. Subsurface concentrations are considerably higher, reaching 9000 mg kg$^{-1}$ Pb, 4100 mg kg$^{-1}$ Zn, and 51 mg kg$^{-1}$ Cd. Both surface and subsurface sediments on higher floodplain surfaces at the site have considerably reduced metal concentrations (< 300 mg kg$^{-1}$ Pb, 200 mg kg$^{-1}$ Zn, and 1 mg kg$^{-1}$ Cd). This demonstrates that elevation is an important factor in controlling metal concentrations at Brompton-on-Swale.

A series of floodplain cores (Taylor and Macklin, 1997) and bank sections from the Brompton-on-Swale study reach demonstrate that metal concentrations reach a peak between 20 and 50 cm depth, below which they steadily decline. Floodplain sediments below 100 cm depth generally contain low metal concentrations.

### *5.3.3.5. Great Langton*

Metal storage at Great Langton is generally focussed on intermediate floodplain surfaces and in the area occupied by the channel and bar systems in 1854 (Figure 5.7). The highest Pb, Zn and Cd concentrations (3000 mg kg$^{-1}$, 2000 mg kg$^{-1}$, and 15 mg kg$^{-1}$, respectively) can be observed on the terrace unit either side of a large flood embankment, constructed between 1808 and 1814 (with subsequent reconstruction as the river channel has migrated; Langton Estate records, A. Fife *pers. comm.*). Metal concentrations on the higher units generally decrease with distance from the current channel, and are generally low beyond 300 m (up to 230 mg kg$^{-1}$ Pb, 120 mg kg$^{-1}$ Zn and 0.5 mg kg$^{-1}$ Cd). Lower floodplain surfaces adjacent to the channel have generally lower metal concentrations (< 1000 mg kg$^{-1}$ Pb and Zn, < 8 mg kg$^{-1}$ Cd).

A floodplain core from the site shows that Pb concentrations increase from 3000 mg kg$^{-1}$ in surface sediments to 4700 mg kg$^{-1}$ at a depth of 50 cm. Concentrations decline below this, falling to 1300 mg kg$^{-1}$ Pb at a depth of 110 cm. A further zone of enrichment can be observed at a depth of 160 cm, where Pb concentrations reach 4200 mg kg$^{-1}$. Below this, Pb concentrations remain relatively constant at *c.* 4000 mg kg$^{-1}$ until a depth of 260 cm, after which they decline gradually.

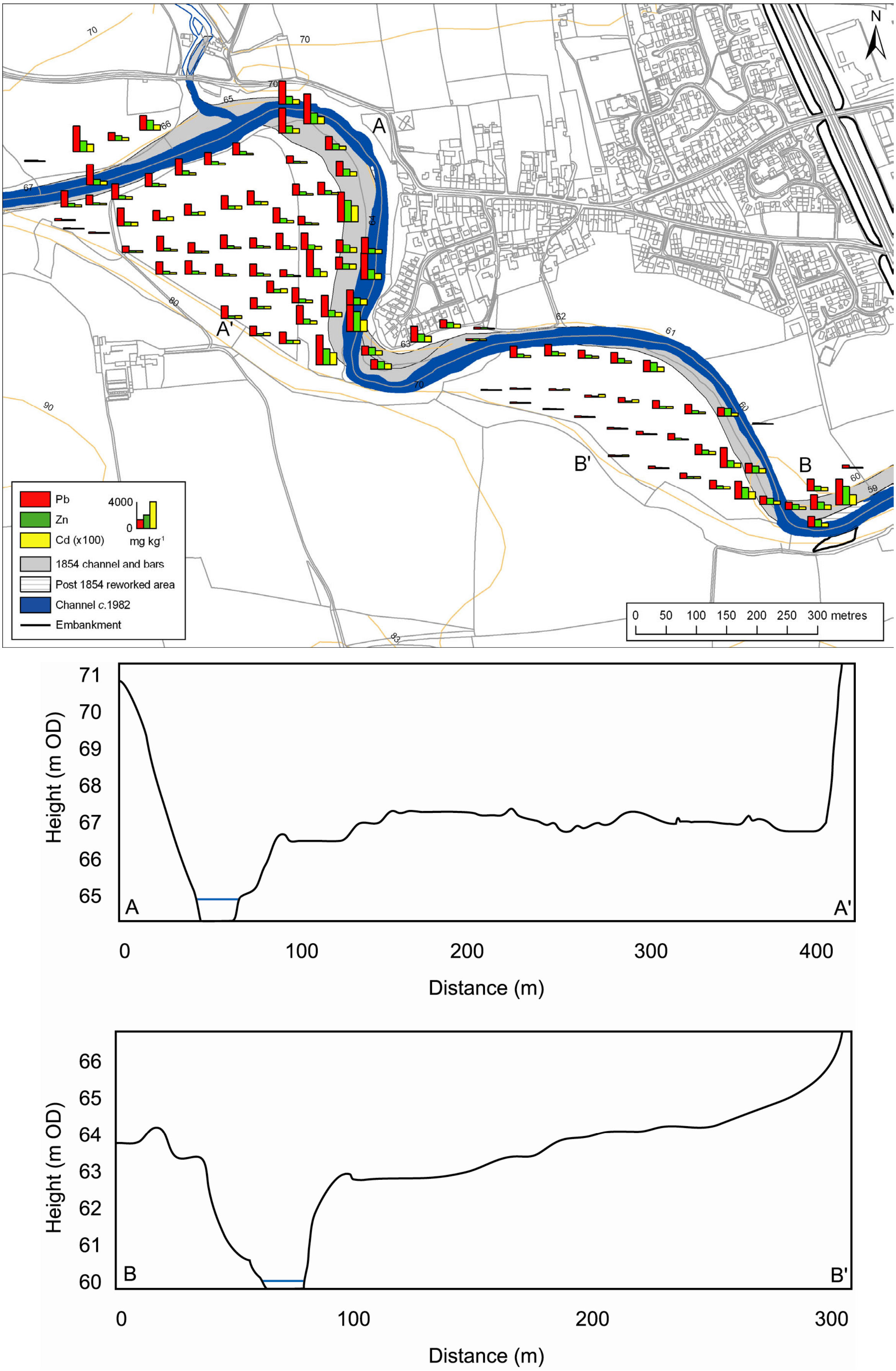

*Figure 5.6: Floodplain metal concentrations and surface topography at Brompton-on-Swale*

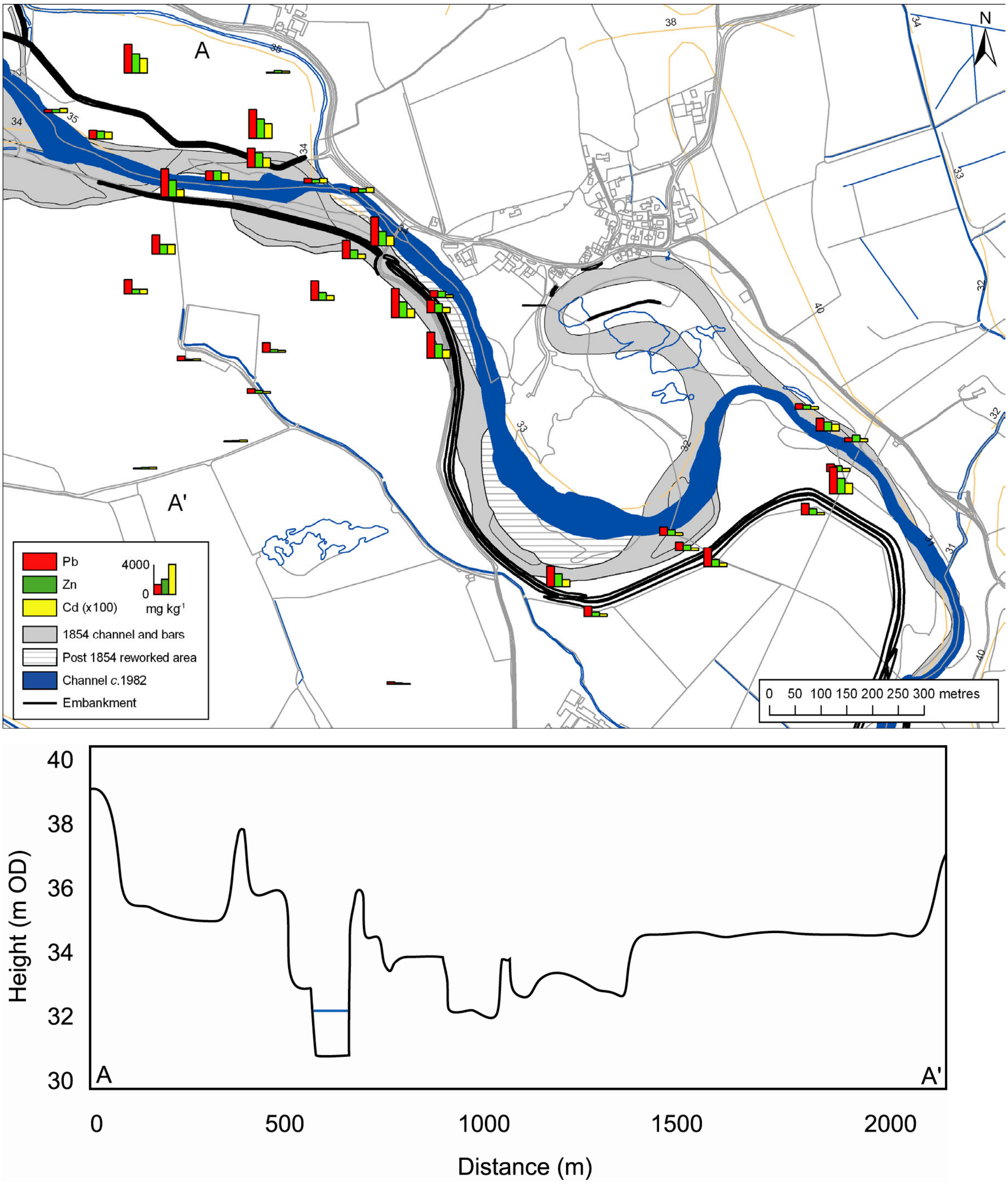

*Figure 5.7: Floodplain metal concentrations and surface topography at Great Langton*

### *5.3.3.6. Morton Flatts*

At Morton Flatts, metal accumulation is greatest in, or adjacent to, the 1854 channel and bar system (Figure 5.8). Pb, Zn and Cd concentrations are especially high in a meander that was cut off by the construction of a railway embankment prior to 1854 (3000 mg kg$^{-1}$, 2000 mg kg$^{-1}$, and 10 mg kg$^{-1}$, respectively). Metal concentrations remain high outside the flood embankment, but are considerably lower beyond 400 m from the channel (100 mg kg$^{-1}$ Pb and Zn, < 1 mg kg$^{-1}$ Cd).

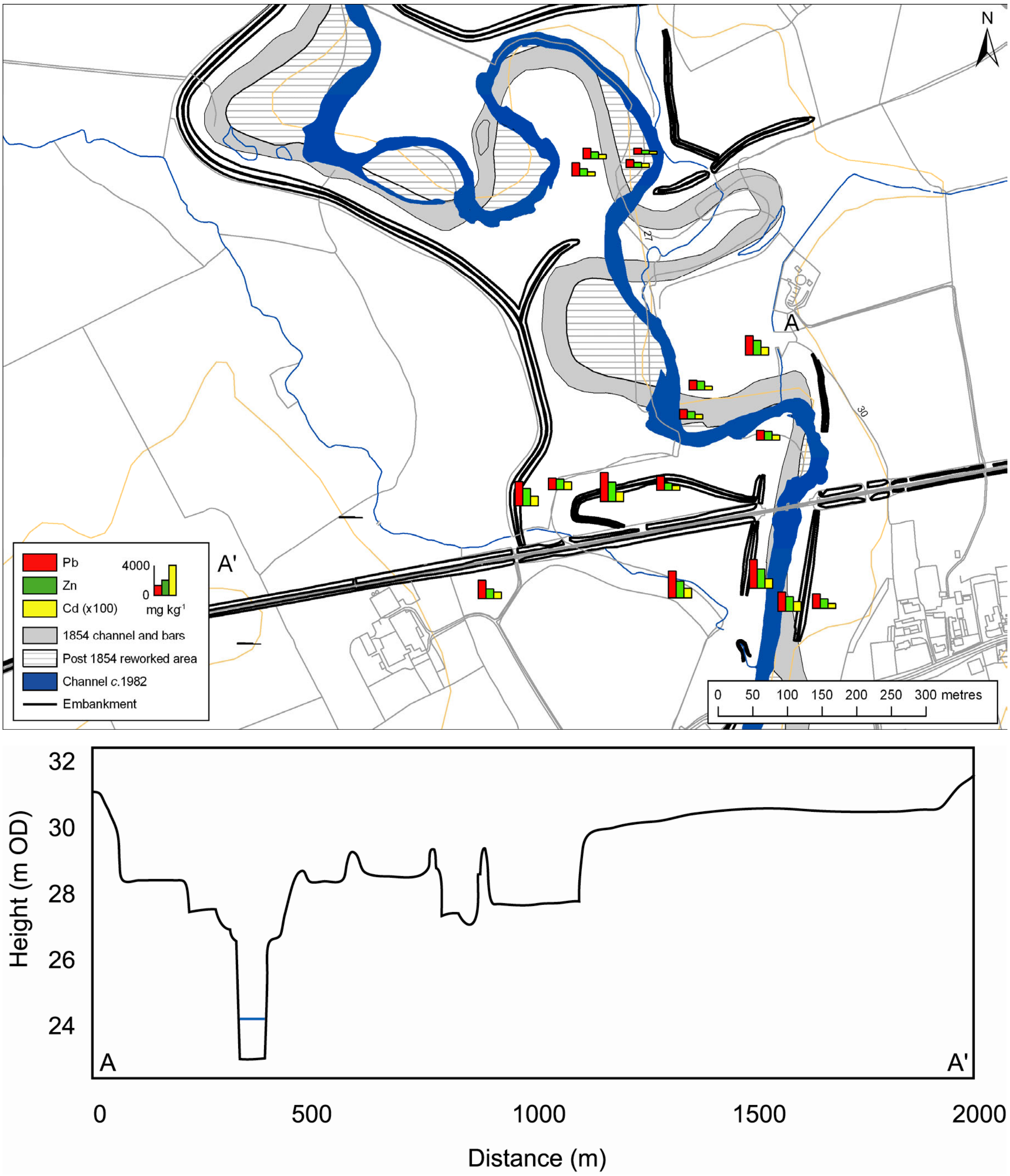

*Figure 5.8: Floodplain metal concentrations and surface topography at Morton Flatts*

A floodplain core from the north of the site suggests that metal concentrations increase steadily with depth. Surface sediments contain 1000 mg kg$^{-1}$ Pb, rising to 2000 mg kg$^{-1}$ below a depth of 10 cm. A peak of 3000 mg kg$^{-1}$ Pb can be observed between 50 and 70 cm, below which concentrations return to *c.* 2000 mg kg$^{-1}$. A deeper core collected by Sedgwick (2000) suggests that Pb concentrations continue to increase, reaching 5800 mg kg$^{-1}$ at a depth of 120 cm.

### *5.3.3.7. Fairholme*

At Fairholme, metal concentrations are greatest on the lower floodplain units, and decrease with height and distance from the channel (Figure 5.9). Highest concentrations are observed on the low unit inside the flood embankment (1400 mg kg$^{-1}$ Pb, 560 mg kg$^{-1}$ Zn and 6 mg kg$^{-1}$ Cd). Metal concentrations decrease markedly outside the embankment (990 mg kg$^{-1}$ Pb, 330 mg kg$^{-1}$ Zn and 3 mg kg$^{-1}$ Cd), and continue to decline on the upper terrace units (< 200 mg kg$^{-1}$ Pb, < 100 mg kg$^{-1}$ Zn and < 1 mg kg$^{-1}$ Cd).

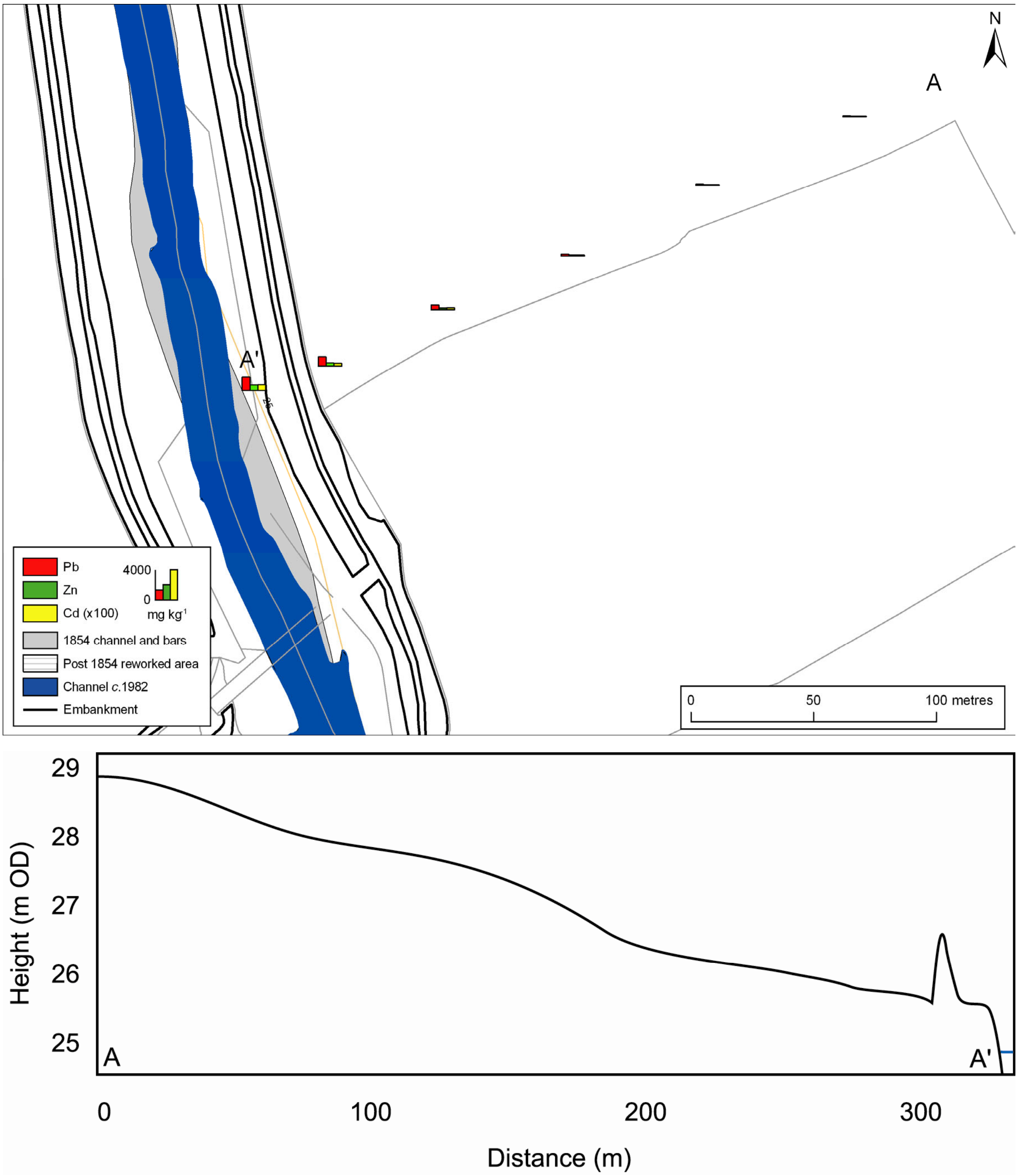

*Figure 5.9: Floodplain metal concentrations and surface topography at Fairholme*

### *5.3.3.8. Maunby*

Metal accumulation at Maunby is focussed on intermediate floodplain surfaces on either side of a large flood embankment (Figure 5.10). Highest concentrations are observed outside the embankment (2300 mg kg$^{-1}$ Pb, 700 mg kg$^{-1}$ Zn, and 7 mg kg$^{-1}$ Cd), although similar concentrations are observed on equivalent surfaces inside the embankment. A floodplain core shows that Pb concentrations increase from approximately 2000 mg kg$^{-1}$ at the surface to 3000 mg kg$^{-1}$ at a depth of 50 cm. Sediments below 70 cm contain ‘background’ metal concentrations (Carter, 1998).

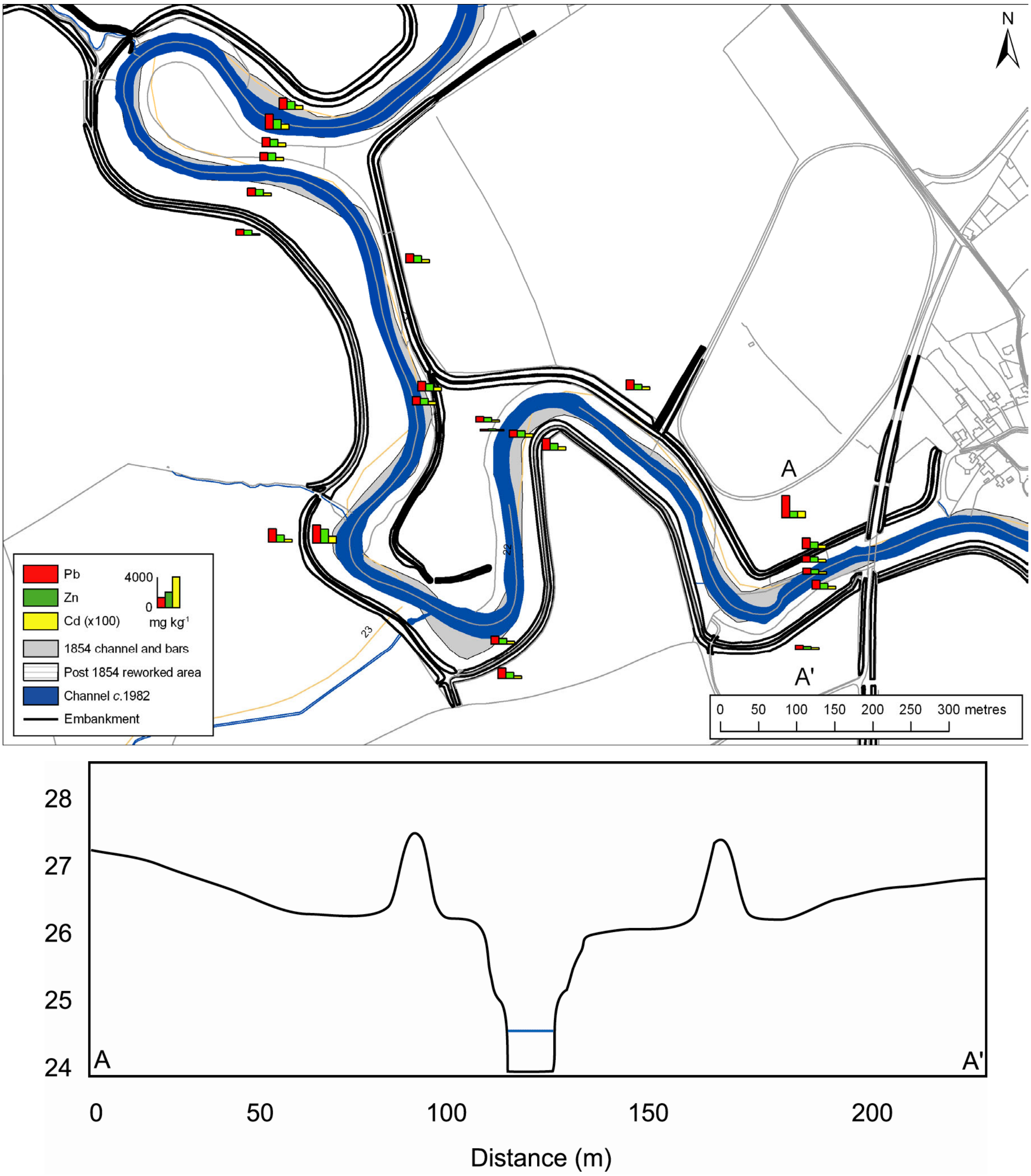

*Figure 5.10: Floodplain metal concentrations and surface topography at Maunby*

### *5.3.3.9. Holme*

At Holme, metal concentrations are greatest in floodplain sediments outside the large flood embankment (Figure 5.11). Concentrations observed on the lowest unit, inside the embankment, are low (260 mg kg$^{-1}$ Pb, 150 mg kg$^{-1}$ Zn and 1.5 mg kg$^{-1}$ Cd). Concentrations increase markedly outside the embankment, rising to 1400 mg kg$^{-1}$ Pb, 450 mg kg$^{-1}$ Zn and 4 mg kg$^{-1}$ Cd on the lowest surface. Metal concentrations decline across the floodplain surface, decreasing with increasing elevation and distance from the river channel.

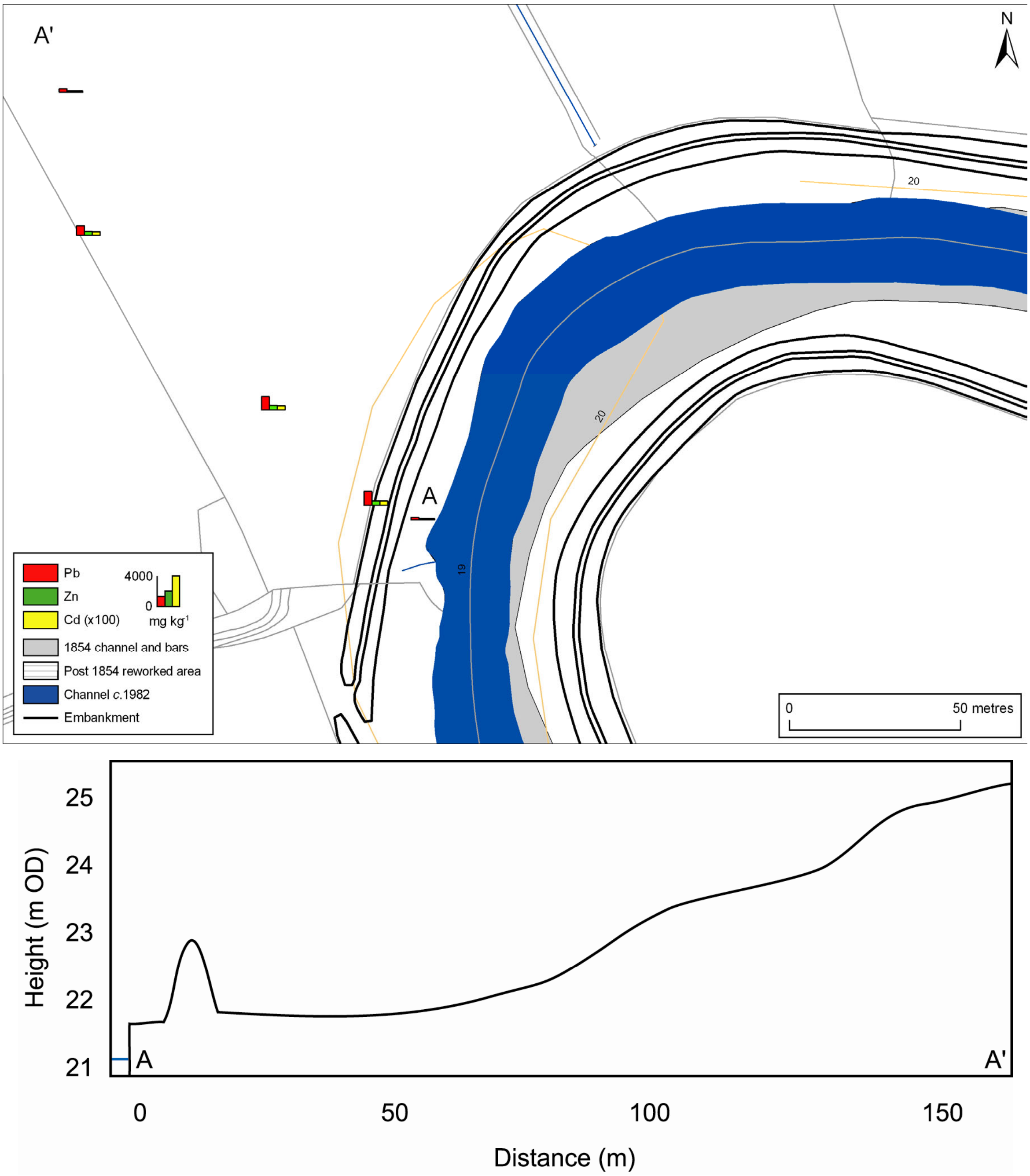

*Figure 5.11: Floodplain metal concentrations and surface topography at Holme*

### *5.3.3.10. Eldmire*

Metal concentrations at Eldmire decline with increasing elevation and distance from the channel (Figure 5.12). Highest concentrations are observed on a low unit approximately 50 m from the river channel (1000 mg $kg^{-1}$ Pb, 630 mg $kg^{-1}$ Zn and 6 mg $kg^{-1}$ Cd), and lowest concentrations are observed on the highest floodplain surface (100 mg $kg^{-1}$ Pb, < 70 mg $kg^{-1}$ Zn and < 1 mg $kg^{-1}$ Cd). The lowest floodplain unit, adjacent to the channel, does not fully conform to this pattern, however (850 mg $kg^{-1}$ Pb, 430 mg $kg^{-1}$ Zn and 4 mg $kg^{-1}$ Cd).

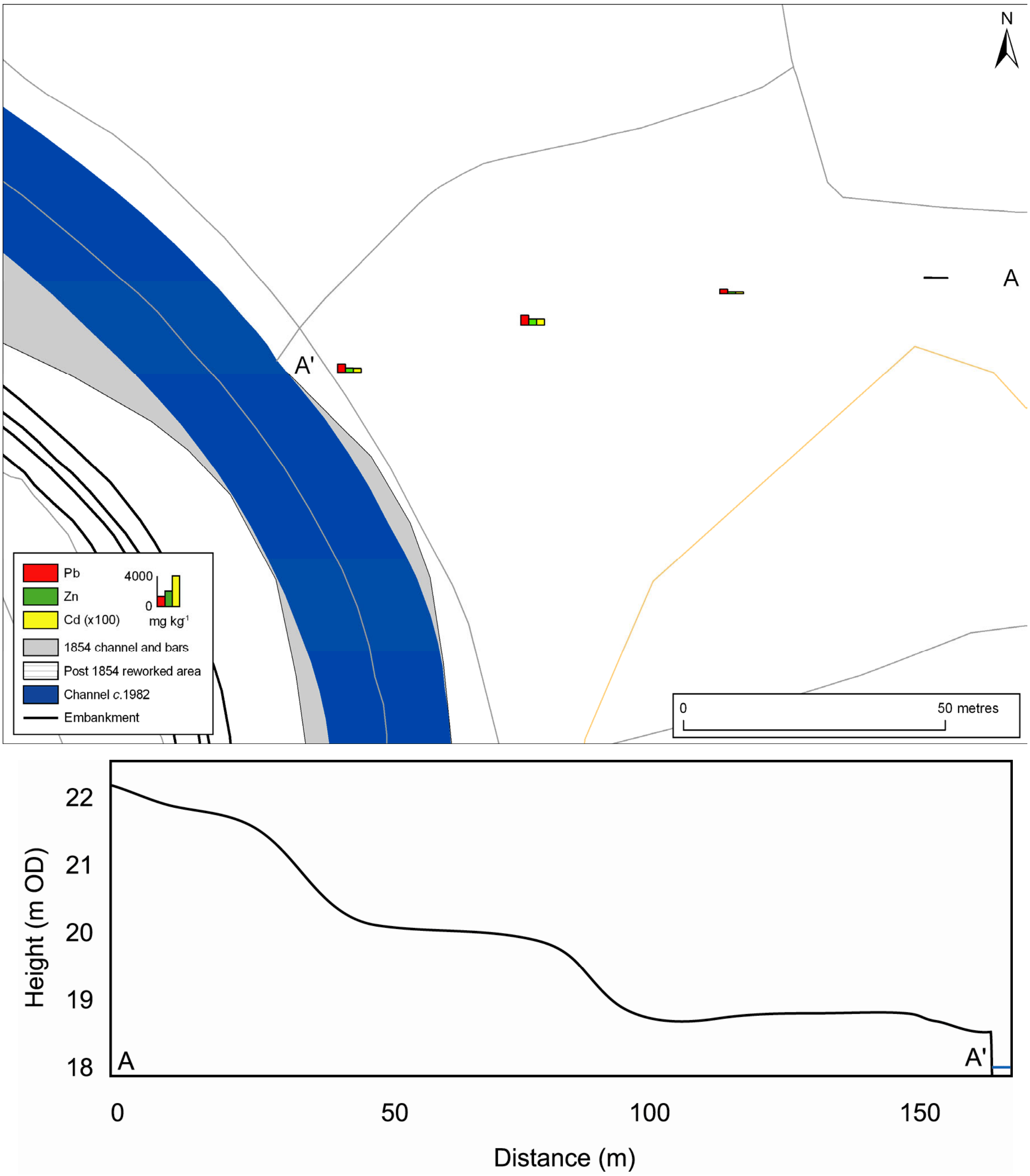

*Figure 5.12: Floodplain metal concentrations and surface topography at Eldmire*

### *5.3.3.11. Thornton Manor*

At Thornton Manor, in the lower reaches of the Swale, metal concentrations are slightly elevated across much of the floodplain (minimum concentrations of 500 mg kg$^{-1}$ Pb, 250 mg kg$^{-1}$ Zn, and 2 mg kg$^{-1}$ Cd) (Figure 5.13). Pb, Zn and Cd concentrations are generally greatest inside the flood embankment and outside the embankment on the western side of the river (up to 1500 mg kg$^{-1}$, 500 mg kg$^{-1}$, and 5 mg kg$^{-1}$, respectively). Concentrations are Zn and Cd are lower outside the embankment on the eastern side of the channel, but Pb levels remain similar to those observed elsewhere at the site.

Pb concentrations in subsurface sediments are generally uniform at *c.* 300 mg kg$^{-1}$ with depth, although the top of the section displays some enrichment. This may be attributable to traffic pollution from a road close to the core site (Sedgwick, 2000).

### *5.3.3.12. Myton-on-Swale*

Metal-rich sediment at Myton-on-Swale, close to the Swale-Ure confluence, is spread across a wide area of floodplain (Figure 5.14). Highest metal concentrations are observed on a low unit immediately behind a large flood embankment (1100 mg kg$^{-1}$ Pb, 400 mg kg$^{-1}$ Zn and 4 mg kg$^{-1}$ Cd), and remain elevated at least as far as 400 m from the channel ($>$ 600 mg kg$^{-1}$ Pb, $>$ 200 mg kg$^{-1}$ Zn and $\leq$ 3 mg kg$^{-1}$ Cd). Samples collected beyond 800 m from the channel contain low concentrations of Pb and Zn.

A floodplain core from the site demonstrates that peak Pb concentrations of 930 mg kg$^{-1}$ can be observed at depth, with concentrations decreasing towards the surface. Sediments are generally uncontaminated below 145 cm (Hudson-Edwards *et al.*, 1999b).

### *5.3.3.13. Additional floodplain cores*

A number of floodplain cores have been collected in the upper reaches of the River Swale (Figure 5.1). The first, upstream of Gunnerside Beck, shows maximum Pb concentrations of approximately 1500 mg kg$^{-1}$ at a depth of 70 cm (Macklin *et al.*, 1994). Cores collected downstream of Gunnerside Beck and Barney Beck show much higher Pb concentrations (8000 mg kg$^{-1}$ at 65 cm depth and 30,000 mg kg$^{-1}$ at 70 cm depth, respectively), reflecting the input of metal-rich sediment from these tributaries.

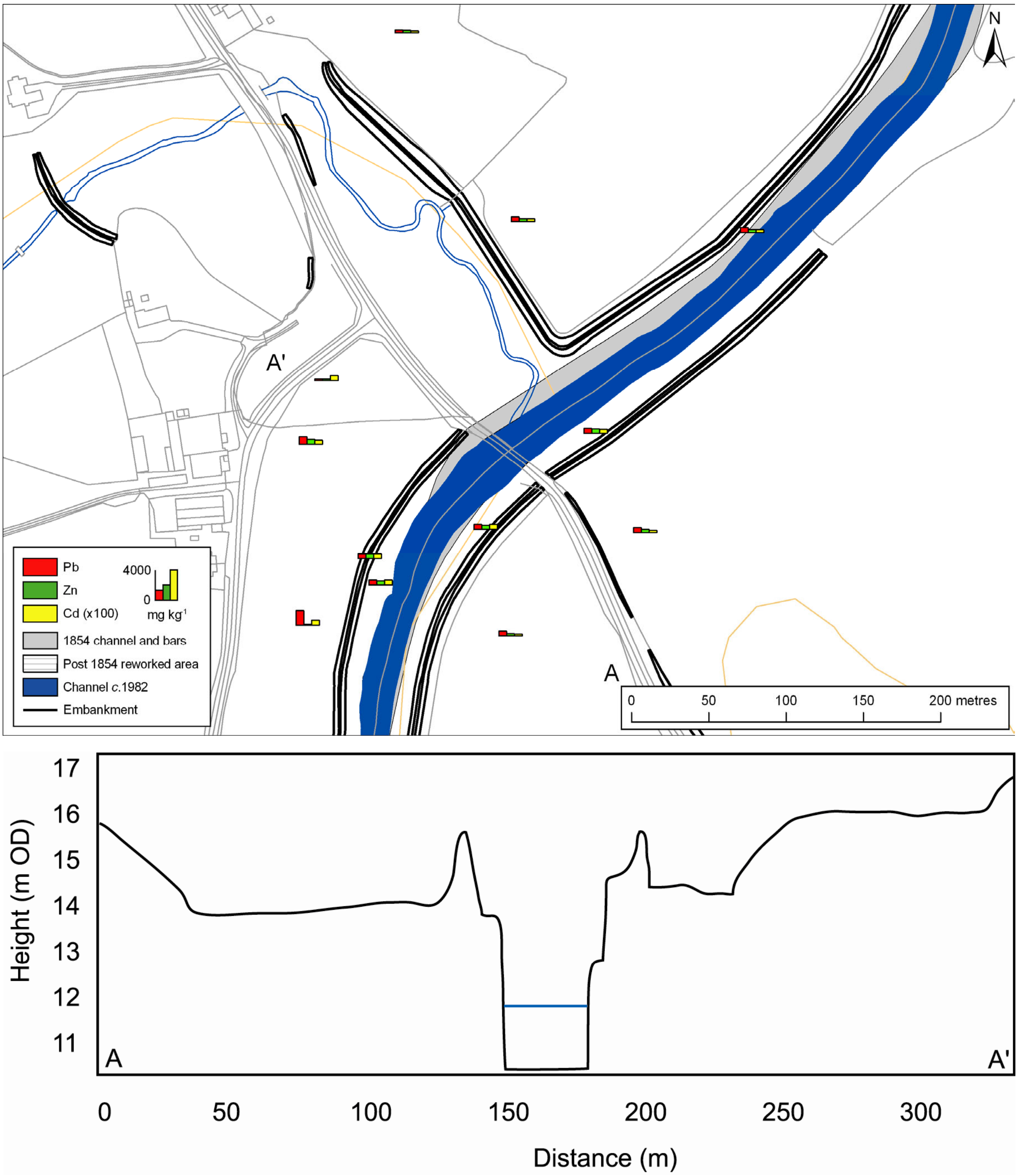

*Figure 5.13: Floodplain metal concentrations and surface topography at Thornton Manor*

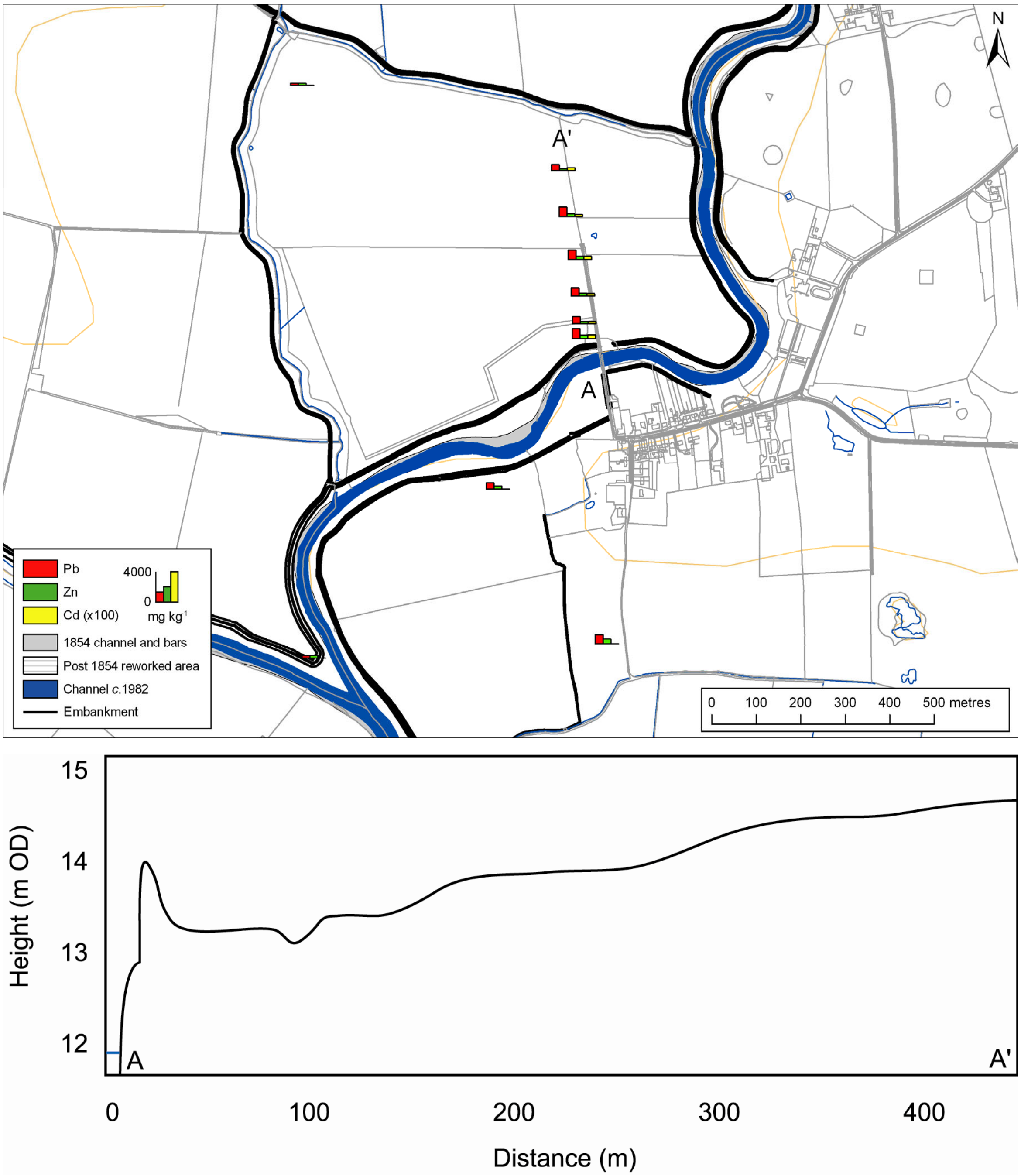

*Figure 5.14: Floodplain metal concentrations and surface topography at Myton-on-Swale*

Cores collected further downstream demonstrate that floodplain soils outside the mining area are also highly metal-enriched at depth. A core collected upstream of Richmond shows peak Pb concentrations of 2500 mg kg$^{-1}$ at a depth of 80 cm. At Ellerton, downstream of Catterick, peak concentrations of 2700 mg kg$^{-1}$ Pb are observed between 60 and 75 cm depth, while at Catton, upstream of Topcliffe, elevated metal concentrations are observed in the upper 40 cm of the profile.

### 5.3.4. Summary: Metal distribution patterns in floodplain sediments

This section demonstrates that floodplain sediments in the River Swale catchment contain high concentrations of metals such as Pb, Zn and Cd. In general, metal concentrations increase downstream of major inputs of mine waste such as Gunnerside Beck and Barney Beck, before gradually declining with increasing distance downstream. Appreciable metal enrichment can be observed even at the most downstream sites, however, indicating that historic metal mining has had a major impact on floodplain sediments throughout the River Swale catchment.

Reach-scale patterns of metal dispersal are more complex. Within each reach, metal concentrations are generally greatest at depth, in sediments that are likely to have been deposited during the peak of mining activities. In surface sediments, particularly high metal concentrations are observed on lower floodplain surfaces, at sites in or adjacent to the nineteenth century channel and bar system, and in parts of the floodplain that have been reworked since the mining era. Conversely, the lowest metal concentrations are generally observed on higher floodplain surfaces, often situated a considerable distance from the present day river channel. In addition, metal concentrations in the lowest floodplain unit are frequently lower than those observed in adjacent higher units.

This section indicates that, on a broad catchment scale, metal dispersal patterns are relatively simple. On a more detailed reach scale, however, patterns are extremely varied, strongly reflecting conditions within each study reach. The factors that are potentially important in determining the patterns of metal dispersal in floodplain surface sediments will be discussed in the subsequent section.

## 5.4. CONTROLS ON METAL DISTRIBUTION

### 5.4.1. Introduction

The complex reach-based patterns and more general catchment-scale trends described in Section 5.3 are probably a result of the interaction of flood frequency, flood magnitude, and floodplain morphology, across a range of scales. These interactions will be discussed in the following section.

### 5.4.2. Longitudinal distribution patterns

Section 5.3.2 demonstrates that metal concentrations in floodplain sediment decline with distance from the major mined tributaries in the upper reaches of the Swale. The downstream decline in metal concentrations with distance from the source of metal-rich material has been well documented in channel (*e.g.* Lewin *et al.*, 1977; Wolfenden and Lewin, 1978; Axtmann and Luoma, 1991) and overbank sediments (*e.g.* Bradley and Cox, 1986; Leenaers, 1989; Macklin and Dowsett, 1989; Macklin and Klimek, 1992; Macklin *et al.*, 1997). This trend has been attributed to a variety of factors, including loss to floodplain storage (Lewin and Macklin, 1987). It is therefore logical that a similar downstream decline can be observed in floodplain sediments themselves, since the amount of metal-rich sediment available for incorporation into the floodplain decreases with increasing distance from the source of contamination. This trend is likely to be influenced by two principle factors, namely the location of the inputs of metal-enriched sediment, and the morphology of the valley in which floodplain sediments are deposited.

The location of contaminated sediment inputs is an important factor in determining downstream patterns of metal dispersal in floodplain sediments in the Swale catchment (Figure 5.15). This is evident in the upper 40 km of the river, where floodplain metal concentrations increase markedly downstream of historically mined tributaries such as Gunnerside Beck, Barney Beck and Arkle Beck. Indeed, mean metal concentrations in floodplain sediments are similar to those observed in the tributaries that supply the metal-rich sediment. Further downstream, however, the tributaries that enter the river are unmineralised and have no history of mining or processing activities. Floodplain metal concentrations are considerably higher than those observed in the tributaries, reflecting the extensive storage of metal-rich sediment derived from further upstream. A possible exception can be observed *c.* 90 km downstream, where locally enhanced floodplain metal concentrations may reflect enrichment from two tributaries with slightly elevated metal levels. The supply of uncontaminated sediment from the unmineralised lowland tributaries is likely to be partly responsible for the gradual decline in floodplain metal concentrations, alongside other factors which influence the transport of metal-rich sediment from its original source (*cf.* Lewin and Macklin, 1987).

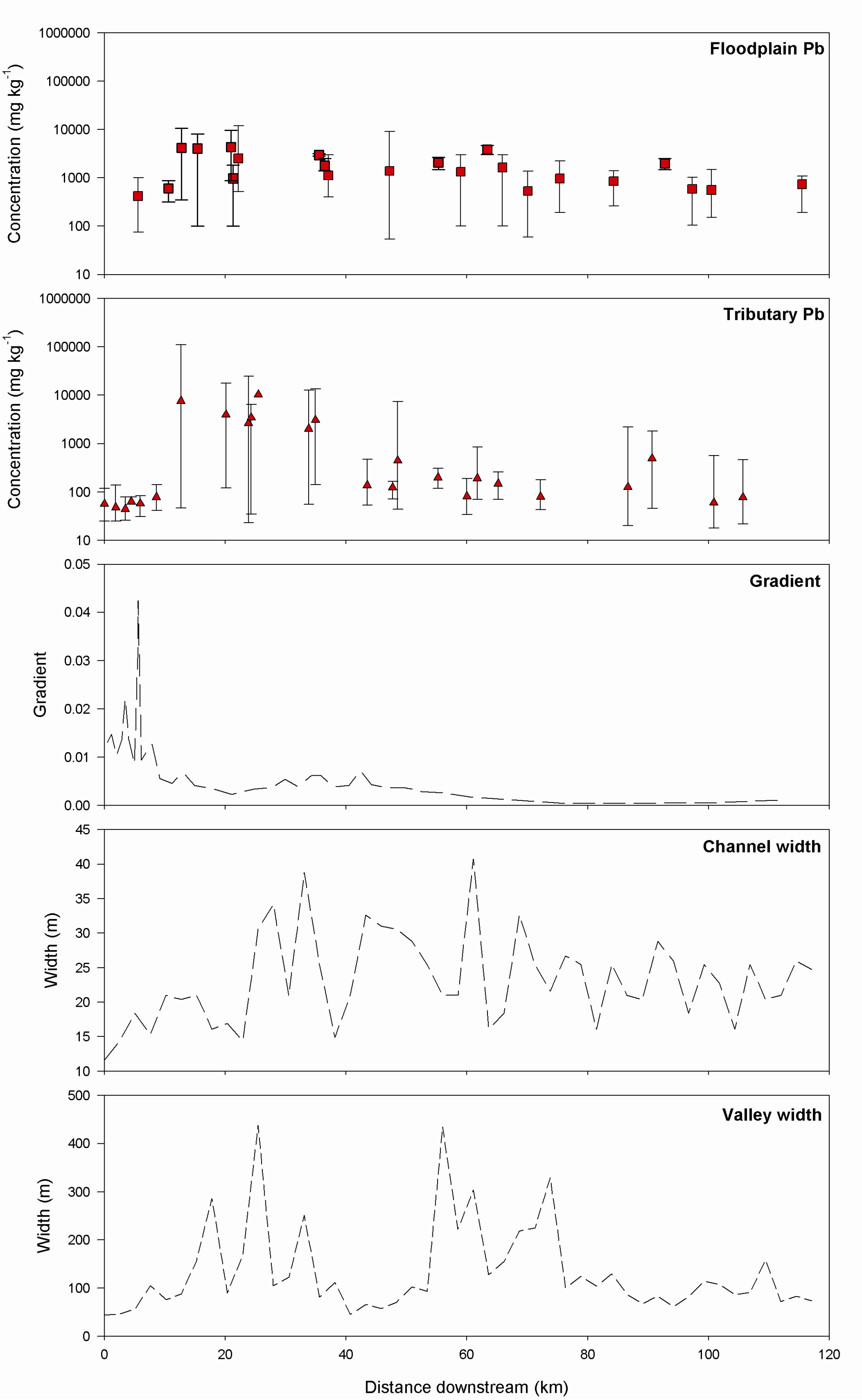

*Figure 5.15: Pb concentration in floodplain and tributary sediments (mean, minimum and maximum concentrations are shown), and geomorphological characteristics of the Swale*

Evidence from Gunnerside Beck (Chapter 4) demonstrates that simple geomorphological factors such as gradient, channel width and valley width are likely to play a role in controlling metal concentrations in fluvial sediments. However, these relationships are most pronounced for channel sediments; floodplain sediments from the tributary appear to be poorly constrained by these simple controls. Nevertheless, it is possible that these factors will exhibit a greater degree of control in the depositional environment of the trunk system than in Gunnerside Beck, which is generally not a depositional system. Multiple regression analysis indicates that a large proportion of the variation in floodplain metal concentrations can indeed be explained by variations in channel width, valley width, and channel gradient (44.5 %; Table 5.2). Valley width appears to be the most important factor, with a reasonably strong positive relationship with metal concentrations. This may simply reflect the increased storage capacity of wider reaches (*e.g*. Macklin, 1996). Indeed, extremely high metal concentrations can be observed in wide floodplain reaches *c.* 7, 20, 25 and 38 km downstream (Figure 5.15; note that the narrow valley observed from *c.* 80 km downstream is a result of the large flood embankments which border the river). Metal concentrations in narrower reaches are generally lower; however, narrow reaches *c.* 65, 75, 95 km downstream exhibit metal concentrations in excess of those observed in wider reaches nearby. This may be attributable to the focussing of metal-rich sediment deposition on a small area, and suggests that narrow floodplain reaches can act both as conduits through which metals are rapidly moved prior to deposition in wider reaches, and as concentrated stores of metal-rich sediment.

*Table 5.2: Multiple regression results: The relationship between floodplain metal concentrations and geomorphological parameters*

| **Sediment** | **$r^2$** | **Significance level (p)** | **Individual parameters** | |
|---|---|---|---|---|
| <2 mm floodplain | 0.445 | 0.173 | Gradient | 0.232 (-) |
| | | | Channel width | 0.091 (+) |
| | | | Valley width | 0.242 (+) |

Channel gradient also has a relatively strong negative relationship with metal concentrations. As discussed in Section 4.4, gradient is likely to strongly influence stream power and rates of sediment deposition within a reach (*cf*. Richards, 1982). Low gradient reaches with low stream power are therefore likely to become foci of sediment and metal accumulation. In contrast to patterns observed in Gunnerside Beck, channel width has a positive relationship with metal concentrations, although its influence is less marked than the previous variables. This is not unexpected, since floodplain sediments are generally formed outside the confines of the river channel, where they are subject to the influence of existing floodplain morphology (*cf.* Section 4.4).

Multiple regression analysis therefore suggests that a large proportion of the variation observed in floodplain metal concentrations is explained by variations in valley width, channel gradient, and, to a lesser extent, channel width. It should be noted, however, that the regression relationships would not normally be considered to be statistically significant, since $p$ = >0.05 (*e.g.* Shaw and Wheeler, 1994). In this case, the low significance level is likely to be attributable to the small number of data points employed in the analysis (12 study reaches). It is therefore likely that the results yielded by the analysis can be employed as an indicator of the importance of geomorphological factors in controlling metal concentrations in floodplain sediments. This therefore suggests that metal concentrations are greatest in wide, low gradient reaches with a wide, low-energy channel (*cf.* Macklin and Lewin, 1989; Marron, 1989; Macklin, 1996).

This section demonstrates that the longitudinal dispersal of metals in floodplain sediments is influenced by both the location of tributary inputs of metal-rich sediment, and geomorphological factors which influence the storage capacity and depositional environment of individual reaches. Morphological parameters may account for as much as 44.5 % of the variation in metal concentrations; it is likely that the location of metal-rich sediment inputs, as described earlier, accounts for a large proportion of the remaining variation in longitudinal metal dispersal.

### 5.4.3. Lateral distribution patterns

Section 5.3.3 demonstrates that metal-rich sediment accumulation is focussed on lower and intermediate floodplain units, with the lowest and highest surfaces displaying considerably lower metal concentrations. A range of factors such as floodplain relief, inundation frequency, stability and time of formation are likely to have interacted to produce the patterns observed in the Swale floodplain.

Floodplain reworking associated with channel migration is likely to be an important factor in controlling metal-rich sediment dispersal. Changes in riverine metal loading during floodplain formation can lead to significant variations in metal concentrations, with sediments deposited during the peak of mining activities, and therefore metal-rich sediment supply, frequently containing the greatest metal concentrations (Davies and Lewin, 1974; Lewin *et al.*, 1983). The location of the mining-era channel, and of any areas of the floodplain that have been reworked as that channel migrated, are therefore likely to be important factors in controlling metal dispersal in floodplain sediments. At sites that have displayed a degree of historic instability, such as Hartlakes, Reeth, Brompton-on-Swale and Morton Flatts, metal concentrations are greatest in or adjacent to mining-era channel and bar systems, and in parts of the floodplain that have been reworked since that time. This demonstrates that metal-rich sediment deposition is focussed in laterally accreting floodplain deposits that were formed during the height of mining activities.

Metal concentrations in vertically accreting floodplain units are likely to be influenced by the same variations in metal fluxes as laterally accreting units. The deposition of the sand-sized metal-rich sediment discussed in this chapter is frequently focussed on areas of the floodplain that are adjacent to the river channel, due to factors such as grain size, particle density and inundation frequency (Alloway and Davies, 1971; Marron, 1989; Graf *et al.*, 1991; Marron, 1992; Macklin, 1996; Zhao *et al.*, 1999; Middelkoop, 2002; Martin, 2004). Areas adjacent to the mining-era channel are therefore likely to contain particularly high metal concentrations. At the majority of study reaches along the River Swale (*e.g.* Hartlakes, Hudswell, Brompton-on-Swale, Great Langton, Fairholme, Maunby, Holme, Eldmire and Myton-on-Swale), metal concentrations are generally greatest on low and intermediate floodplain surfaces. These surfaces are likely to represent the mining-era floodplain and adjacent low terraces, and as such are likely to have been regularly inundated during the mining period. The higher floodplain surfaces observed at many of the study reaches display considerably lower metal concentrations than those below them (*e.g.* at Hudswell, Brompton-on-Swale, Great Langton, Fairholme, Holme, Eldmire, and Myton-on-Swale). This suggests that these units were formed prior to the onset of industrial-scale metal mining and processing activities in the catchment, and were not regularly inundated by mining-era flood waters. Furthermore, incision since the cessation of mining operations has lead to the creation of a low floodplain surface adjacent to the river channel, which can be observed at many of the study sites (*e.g.* at Hudswell, Brompton-on-Swale, Great Langton, Maunby, Holme and Eldmire). Although this unit has received some metal-rich sediment during post-mining floods, it has not been the focus of metal accumulation in the same way as the mining-age floodplain has been.

These patterns suggest that floodplain topography is an important factor in controlling the distribution of metal-rich sediment in floodplain surface sediments, since low surfaces can generally act as the focus for metal deposition (Alloway and Davies, 1971; James, 1989; Brewer and Taylor, 1997; Lecce and Pavlowsky, 2001; Middelkoop, 2002). Within the Swale catchment, metal-rich sediment is fairly evenly distributed across the floodplain surface at reaches with little variation in floodplain elevation (*e.*g. Reeth, Morton Flatts, Thornton Manor and Myton-on-Swale) (*cf.* Bradley and Cox, 1990; Foster and Charlesworth, 1996). At sites with more variation in relief, metal-rich sediment accumulation is more focussed on the lower terrace surfaces (*e.g.* at Hartlakes, Hudswell, Brompton-on-Swale, Great Langton, Fairholme, Maunby, Holme and Eldmire). When metal data are plotted against surface height, however, few of the study reaches exhibit a strong relationship between elevation and floodplain metal concentrations (Figure 5.16). Exceptions to this general pattern can be observed at Fairholme and Eldmire, which both show a strong negative relationship between elevation and metal concentrations ($r^2$ = 0.82 and 0.90, respectively). The topography of these sites is relatively simple, with floodplain surface height increasing steadily with distance from the river channel. This suggests that floodplain topography is a dominant control on metal concentrations at Fairholme and Eldmire. At other sites, however, simple height relationships may be insufficient to explain these patterns (Martin, 2004). It is likely that floodplain topography influences floodplain metal concentrations primarily through controlling inundation frequency, and, as a result, metal-rich sediment delivery (Brewer and Taylor, 1997). Previous investigations have shown that lower, frequently inundated floodplain units receive large volumes of metal-rich sediment (Rang *et al.*, 1987; Leenaers, 1989; Graf *et al.*, 1991), while higher units are only inundated during large floods when suspended metals are more diluted (Alloway and Davies, 1971; Rowan *et al.*, 1995). Work undertaken at Reeth and Brompton-on-Swale by Brewer *et al*. (2005) demonstrates that, while floodplain metal concentrations are strongly influenced by inundation frequency, the relationship between the two is complex. Floodplain metal concentrations at the two sites were compared to simulated inundation frequency, derived using HEC-RAS version 3.11 (United States Army Corps of Engineers, 2002).

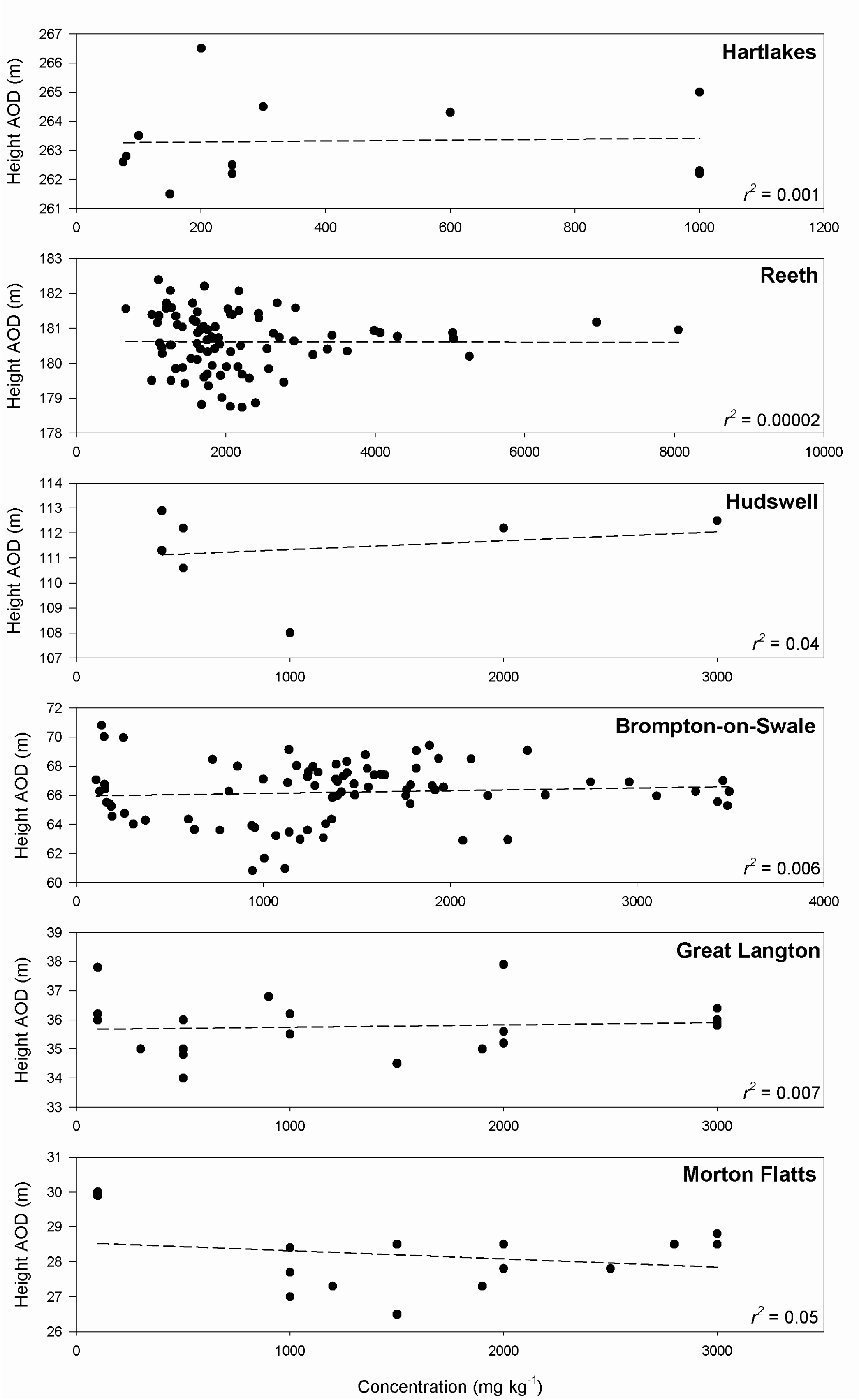

*Figure 5.16 (a): Floodplain Pb concentrations and elevation, Hartlakes – Morton Flatts*

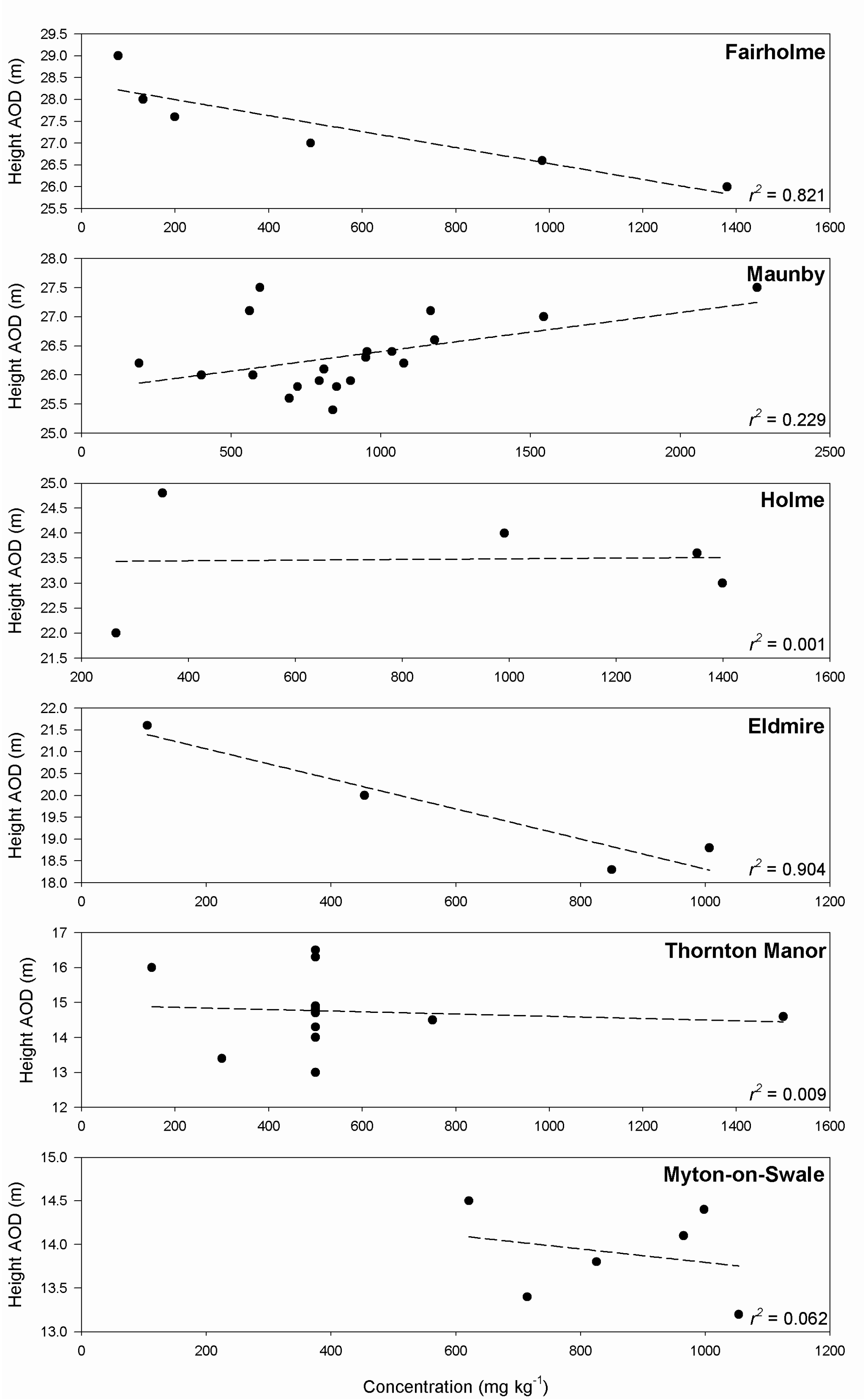

*Figure 5.16 (b): Floodplain Pb concentrations and elevation, Fairholme – Myton-on-Swale*

Metal concentrations at Reeth are greatest in areas of the floodplain inundated by floods with a 1 year return period, and appear to decrease slightly with decreasing inundation frequency (1.5 – 1000 years; Figure 5.17) (*cf.* Rang *et al.*, 1987). However, much of the reach is inundated by a 1.5 year flood, and the additional area covered by the 2 – 1000 year floods is small. Furthermore, areas above the simulated level of the 1000 year flood exhibit similar metal concentrations to those flooded on an annual basis. This pattern suggests that the entire floodplain at Reeth received metal-rich sediment during large floods during the mining-era. Metals stored at this time have been subsequently diluted by 'cleaner' sediment during large post-mining floods, although these are unlikely to have been of sufficient magnitude to considerably dilute the highest floodplain surfaces (*cf.* Alloway and Davies, 1971; Rowan *et al.*, 1995). In addition, the most frequently inundated floodplain sediments have continued to be enriched with metal-rich material, since contaminant loadings are often at their greatest during lower overbank flows (*cf.* Leenaers, 1989; Graf *et al.*, 1991). At Brompton-on-Swale, sites above the level of the simulated 1000 year flood have low metal concentrations, while those below exhibit considerably higher metal concentrations (Figure 5.18). The most frequently inundated areas of the floodplain (up to 1 year flood return period) have relatively low metal concentrations, while the highest metal levels are observed in parts of the floodplain that are inundated by floods with a return period of between 10 and 50 years. This pattern suggests that metals within the most frequently inundated parts of the floodplain have been diluted with 'clean' sediments, while those above the level of the 1000 year flood have not received large volumes of metal-rich material. Areas that are inundated by floods in between these limits are likely to have been inundated during high-magnitude mining-era floods (*cf.* Longfield and Macklin, 1999), and continue to receive metal-rich sediment during relatively large contemporary floods with high metal loadings.

This investigation demonstrates that, while a relationship exists between inundation frequency and floodplain metal concentrations, it is relatively complex. Both sites demonstrate that high metal concentrations are observed across a range of flood return periods. The patterns observed at each site are quite different, however. At Reeth, the most frequently inundated areas contain high metal concentrations, while corresponding areas at Brompton-on-Swale contain relatively low concentrations. This may reflect differing metal loads in flood sediments deposited at each site; overbank sediments from the upstream reach contain higher metal concentrations than those from the downstream

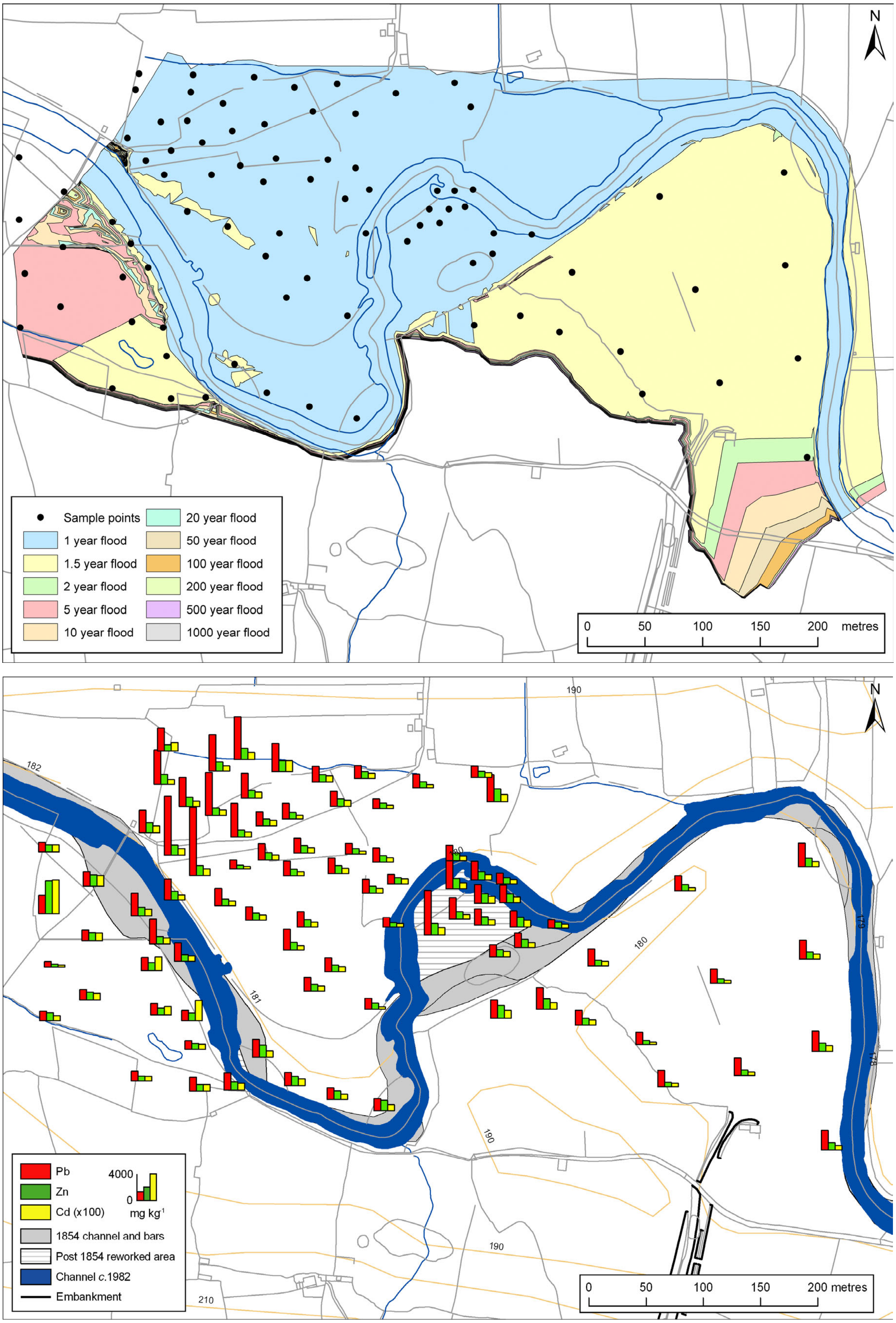

*Figure 5.17: Simulated inundation frequency and floodplain metal concentrations at Reeth*

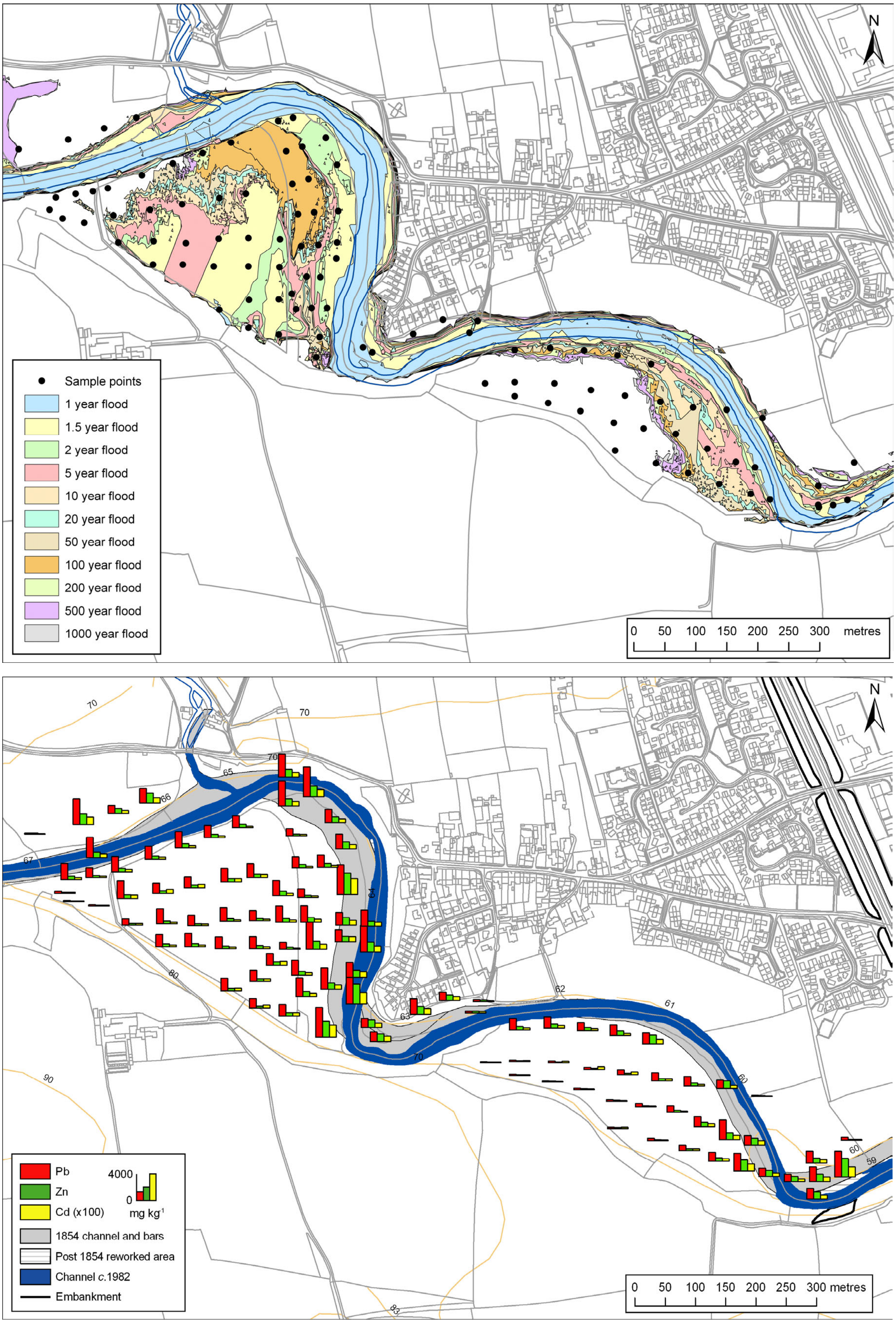

*Figure 5.18: Simulated inundation frequency and floodplain metal concentrations at Brompton-on-Swale*

site, due to factors such as hydraulic sorting, dilution and loss to floodplain storage further upstream (*cf.* Lewin and Macklin, 1987). Similarly, metal concentrations outside the limit of the 1000 year flood are extremely high at Reeth, but are low at Brompton-on-Swale. This may be also be indicative of differing metal loadings at the two sites, but is also likely to reflect differing flood histories and post-mining geomorphic development at each site. This demonstrates that, although there is a relationship between inundation frequency and floodplain metal concentrations, this relationship is complex and strongly influenced by site-specific geomorphological characteristics and metal loadings.

This section demonstrates that the dispersal of metals in floodplain sediments is likely to be influenced by a number of factors, including proximity to the channel, floodplain relief, inundation frequency and channel stability. The primary control is likely to be metal fluxes and delivery rates during floodplain formation; areas formed while mining was operational, and those that were regularly inundated during this time, have the highest metal concentrations (*cf.* Section 5.4.4). Conversely, parts of the floodplain that were formed prior to the onset of mining, and were not regularly inundated by mining-era floods, or were formed after mining operations had ended, contain considerably lower metal concentrations. Proximity to the mining-era channel is also important, since lateral and vertical accretion processes, and thus metal deposition, have been most focussed close to the river. Floodplain topography and inundation frequency also appear to influence metal concentrations, although the precise strength of the relationship between these factors and metal concentrations is difficult to determine, since the lower, more frequently inundated parts of the floodplain were generally formed during the mining era. However, it is likely that these factors helped to determine metal distribution patterns in the mining era floodplain, ultimately giving rise to the patterns that are observed today.

This section has also highlighted the fact that the large flood embankments observed along the Swale downstream of Great Langton do not appear to have had a significant impact on floodplain metal concentrations. Indeed, concentrations at Great Langton and Maunby may be slightly higher outside the embankment than on the corresponding surface inside the structure. This may be indicative of metal contamination prior to the construction of the embankments, and of the ponding of metal-enriched floodwater behind these structures during large mining-era floods. Alternatively, it is possible that subsurface metal concentrations inside the levees may be equal or greater to those outside. If this is the case, the comparatively low metal concentrations inside the structures are likely to reflect dilution through the frequent receipt of relatively uncontaminated post-mining sediment during contained overbank floods.

### 5.4.4. Metal distribution patterns with depth

Section 5.3.3 demonstrates that metal concentrations along the River Swale floodplain display a distinct variation with depth. Metal concentrations are generally elevated in the upper part of the floodplain, increase markedly with depth, before decreasing considerably towards the base of the core. Down-profile metal concentrations are likely to be a product of variations in the supply of metal-rich and uncontaminated sediment, and as such reflect historic variations in mining activity, and the longitudinal and lateral dispersal of metals across the floodplain surface (Macklin *et al.*, 1994; Swennen *et al.*, 1994; Martin, 2004). The depth and intensity of metal enrichment in a floodplain profile is dependent on site specific factors that influence the delivery of metal-rich sediment, such as suspended metal load, inundation frequency and the down-profile mobility of metals (Bradley and Cox, 1986; Swennen *et al.*, 1994; Taylor, 1996). Thus, while it is clear that metal concentrations are low in pre-mining sediments, at their greatest in mining-age sediments, and elevated in post-mining sediments, it is difficult to predict the depth of transition between these phases in individual floodplain cores.

### 5.4.5. Summary: Controls on metal distribution in floodplain sediments

This section demonstrates that the dispersal of metal-rich sediment in the Swale floodplain is controlled by the complex interaction of a host of factors, including the location of metal inputs, historical variations in metal fluxes, valley morphology, floodplain reworking, and inundation frequency. Of these, historic metal delivery is likely to be one of the most important factors. Metal concentrations are greatest in parts of the floodplain that were formed during the mining-era, or received large quantities of sediment during that time. Areas formed prior to the onset of mining, and after mining operations ceased, generally exhibit lower metal concentrations. This pattern can be seen to operate both laterally across the floodplain surface, and down through the floodplain profile.

## 5.5. CONCLUSION

This investigation has demonstrated that floodplain sediments in the River Swale catchment are severely contaminated with sediment-associated Pb, Zn and Cd. Metal concentrations are particularly high in reaches close to the formerly mined area in Swaledale, but remain elevated along the entire length of the floodplain downstream of this zone. This suggests that large amounts of metal-enriched sediment released through historic mining activities have been stored in floodplain sediments throughout the Swale catchment, often at a considerable distance from their likely original source. Within individual reaches, metal concentrations are at their greatest in floodplain sediments that were deposited during the mining era, when metal fluxes from mining and processing were at their maximum. These mining age deposits generally occur on low to intermediate floodplain surfaces, close to the mining-era channel, and at depth.

This chapter demonstrates that a large amount of metal-enriched sediment is stored in the Swale floodplain, over a wide area and often at considerable depth. Floodplain sediments are therefore likely to act as a major source of sediment-associated metals to the River Swale system, since stored metals are likely to be remobilised through bank erosion and subsequently redeposited further downstream. This raises several important questions:

- How much metal-rich sediment is stored within the Swale floodplain?
- How important is the floodplain as a source of metal-rich sediment?
- How much metal-rich sediment is added to the floodplain?
- What is the likely environmental significance of floodplain metal enrichment?

These issues will be explored in subsequent chapters. Sediment budgeting techniques will be applied to provide an estimate of total metal storage within the floodplain, and measurements of overbank sediment accumulation will be used to provide estimates of present-day metal erosion and deposition patterns. Finally, the likely impact of floodplain metal enrichment will be assessed by comparison with U.K. environmental quality guidelines and estimates of 'natural' background metal concentrations.