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The impact of the October–November 2000 floods on contaminant metal dispersal in the River Swale catchment, North Yorkshire, UK

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Abstract:

During the autumn of 2000, large areas of England and Wales were affected by severe flooding, which caused widespread disruption and significant damage to property. This study attempts to determine the impact of these flood events on contaminated sediment dispersal and deposition in the River Swale catchment, Yorkshire, UK, where lead and zinc were extracted and processed in large quantities during the nineteenth century.

Seventy samples of overbank and channel-edge sediments were collected at 35 sites along the River Swale. Inductively coupled plasma-mass spectrometry was used to measure contaminant metal concentrations in the 2000–63 μm (sand) and <63 μm (silt and clay) size fractions. In both the channel-edge and overbank sediments collected from the upper and middle reaches of the River Swale, concentrations of lead, zinc and cadmium were found to exceed MAFF guidelines. Highest concentrations correspond to the input of contaminated material from intensively mined tributaries, and elevated levels can be observed 5–10 km downstream of these inputs. This indicates that the remobilization of contaminated material during major flood events is potentially a serious problem for activities such as agriculture that utilize the Swale floodplain. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS autumn 2000 floods; River Swale; contaminant metals; historical metal mining; sediment remobilization

INTRODUCTION

During October and November 2000 large areas of the UK were affected by unusually severe flooding, causing widespread disruption and damage to property estimated to be approximately £1 billion. The counties of North and West Yorkshire in northern England were particularly badly affected. These were the largest floods in the Yorkshire Dales since Hurricane Charley in 1986 (Newson and Macklin, 1990), and at York water levels were the highest recorded for 375 years (Rennard, 2000).

This investigation examines the importance of flooding on the dispersal and deposition of metal-contaminated sediment in the River Swale, a major tributary of the River Ouse. The Swale catchment was severely polluted by base-metal mining activities (predominantly Pb) in the nineteenth century and this has left a legacy of high contaminant metal levels in floodplain and river-channel sediments (Macklin *et al*., 1994; Taylor and Macklin, 1997; Sedgwick, 1998; Hudson-Edwards *et al*., 1999). The autumn 2000 floods resulted in widespread channel and slope erosion in the mined headwaters of the Swale and extensive bank erosion in the middle and lower reaches of the catchment. In light of the significant remobilization of mine waste that occurred during the 1986 Hurricane Charley flood event (Macklin, 1997), river sediments deposited both within the channel and on the floodplain during the autumn 2000 floods were sampled and analysed for contaminant metals. One of the key questions we sought to answer was to evaluate the environmental significance of metal contaminated sediment deposited along the riparian corridor.

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STUDY AREA

The River Swale is the northernmost tributary of the Yorkshire Ouse and its headwaters are located in the eastern Yorkshire Dales, from where it flows through Swaledale in a south-easterly direction from the Pennines (Figure 1). After passing through the major settlements of Richmond and Catterick, the river turns southwards and joins the River Ure in the Vale of York. The Swale has a catchment area of 1446 km^2 and a length of 117·8 km. The land use is predominantly agricultural. Sheep grazing is predominant in upland areas, whereas arable farming is more important in the lower reaches of the river, particularly in the Vale of York.

The Swale catchment contains three distinct geological areas. Its upland headwater reaches are underlain by Namurian and Dinantian limestones and sandstones, which make up the Askrigg Block and form the southern part of the Northern Pennine Orefield (Dunham and Wilson, 1985). Downstream of Richmond, a band of Permian limestone crops out. The lower reaches of the Swale, in the Vale of York, are underlain by Triassic sandstones, mudstones and limestones. The pH of soils and sediments in the catchment is predominantly neutral to alkaline.

The upland tributaries of the Swale catchment have been subject to widespread and intensive historical mining. The rocks of the Askrigg Block contain a large number of baryte, witherite and calcite fissure veins, which contain significant amounts of metalliferous ores. The most abundant of these is the lead ore galena (PbS), although zinc and copper ores have also been found in workable quantities. Upland tributaries of the River Swale, most notably Gunnerside Beck, Barney Beck, Arkle Beck and Marske Beck, cross the most heavily mineralized zone in the southern part of the Northern Pennine Orefield (Dunham and Wilson, 1985). Lead ores have been extracted since the Roman period, with large-scale production occurring in the eighteenth and, particularly, in the nineteenth centuries when more than 350 000 t of lead concentrates were produced

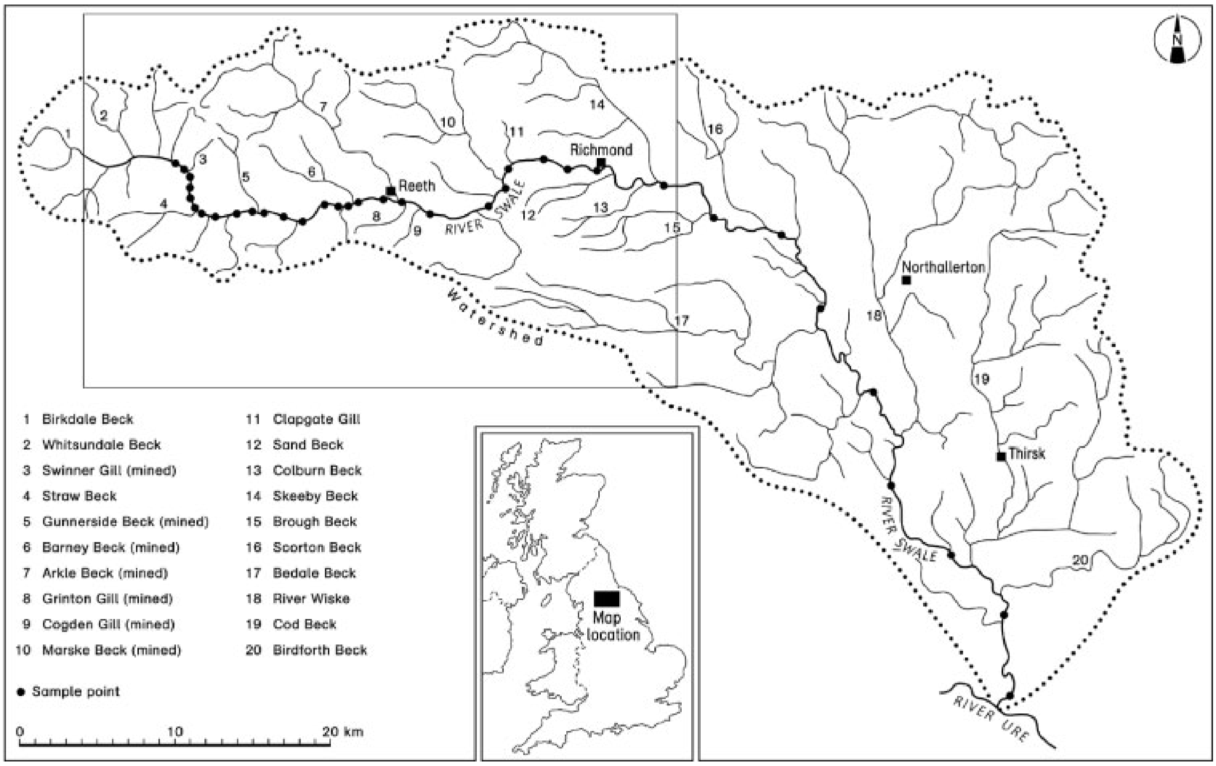

Figure 1. The River Swale catchment, showing drainage network, location of sample sites and major tributaries. Box shows the location of Figures 2 and 3

from mines in the Swale catchment (Figure 2) (Dunham and Wilson, 1985). Once extracted, ores were sorted, crushed and smelted within the upper Swale catchment (Figure 3) (Raistrick and Jennings, 1965; White, 1998; Gill, 2001). These activities introduced large amounts of metalliferous waste into the fluvial system, resulting in the severe contamination of river channels and floodplains in the Swale catchment (Macklin *et al*., 1994, Taylor and Macklin, 1997, Sedgwick, 1998, Hudson-Edwards *et al*., 1999).

METHODS

Seventy samples of fine grained (<2000 μm) overbank and channel-edge flood sediment were collected at 35 sites along the River Swale (Figure 1). Upstream of Richmond, within the former mining field, samples were taken downstream of each major tributary in order to pinpoint sources of contaminated material. Downstream of Richmond, where no tributary streams have been affected by large-scale mining, the samples were taken every 5 km. Sediment deposited on floodplains during the autumn 2000 floods was easily identifiable by the fact that it had buried riparian vegetation. Overbank flood sediment was sampled within 10 m of the bank line, and at each sampling point 10 spot samples were collected within a circle of 5 m radius, and combined to minimize the effects of small-scale heterogeneity. Samples of channel-edge material were collected in the same way, from the surface of gravel bars.

Prior to analysis, all samples were oven dried and disaggregated. They were then dry-sieved through stainless steel mesh, and separated into 2000–63 μm (sand) and <63 μm (silt and clay) size fractions. Both size fractions were digested in concentrated nitric acid for 1 h at a temperature of 100 °C.

Inductively coupled plasma-mass spectrometry (ICP-MS) was used to measure Pb, Zn and Cd concentrations, which are the principal contaminant metals found within the Swale catchment (Macklin *et al*., 1994). This technique allows a range of elements to be measured simultaneously in a very short period, with sample

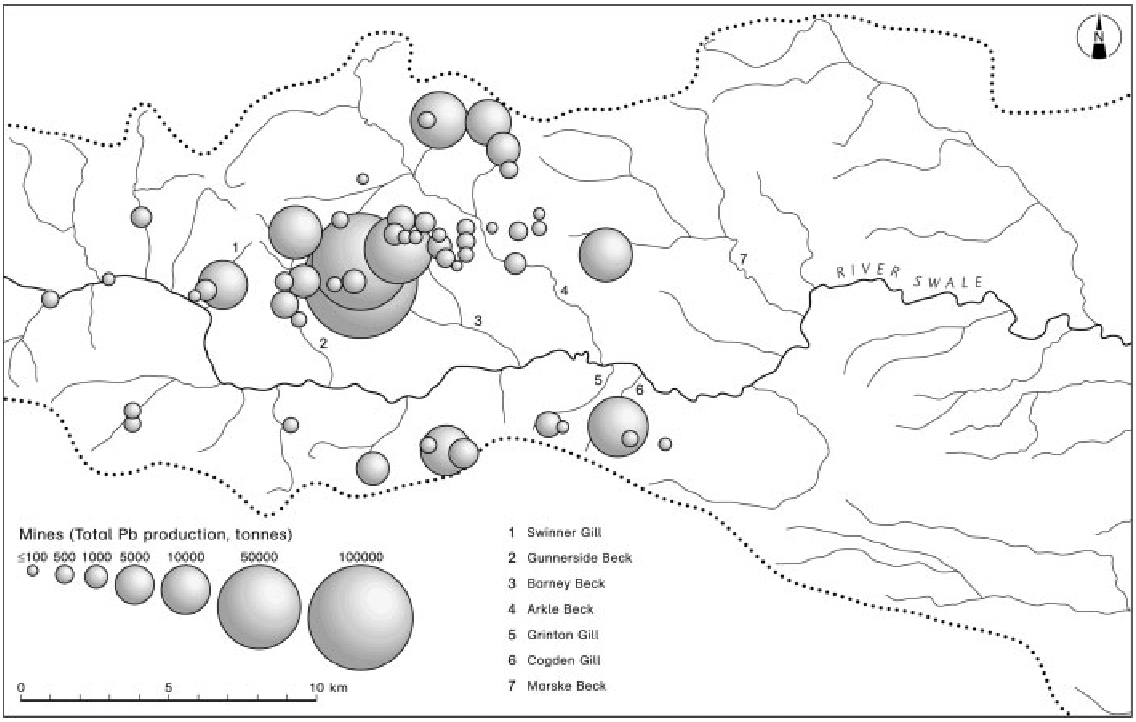

Figure 2. Location and output (*c*. 1700–1900) of Pb mines in Swaledale

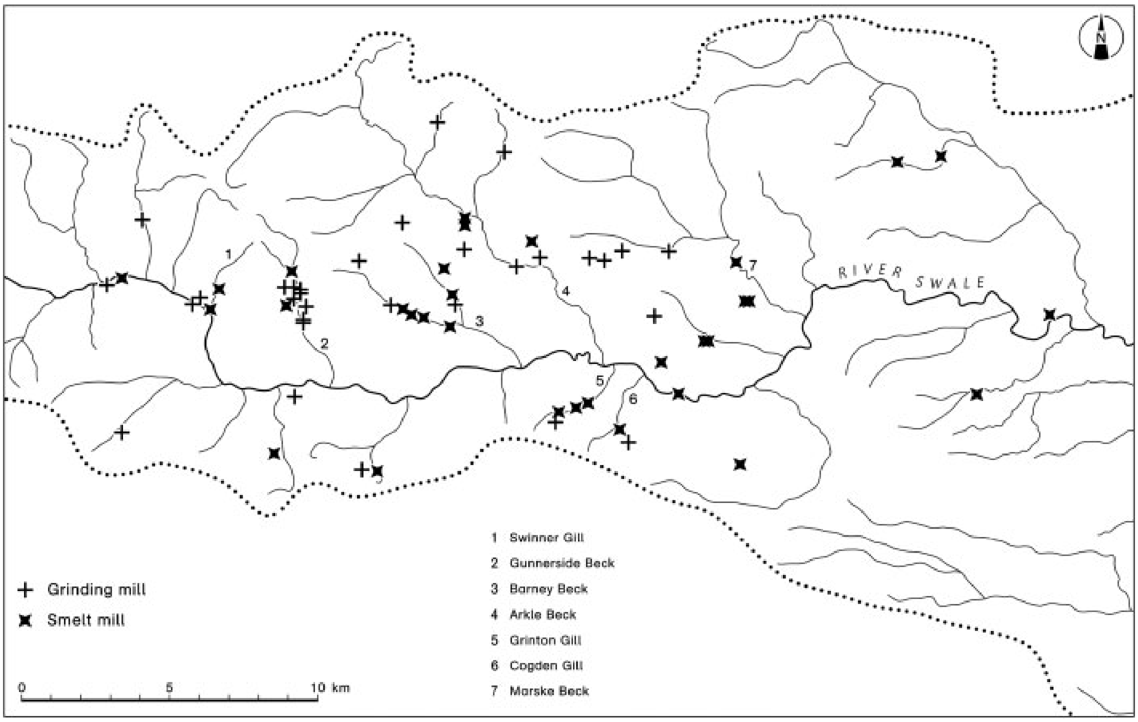

Figure 3. Location of grinding mills and smelters

analysis typically lasting under 60 s (Jarvis, 1997). The ICP-MS technique is extremely precise, with a relative standard deviation of between 2 and 5%. Measurements are also highly accurate, lying within 5% of the absolute value.

In order to determine the impact of the autumn 2000 floods on contaminant metal loading on floodplain and river channel environments, and to determine probable sources of contaminated sediment, metal data from the flood deposits were compared with metal levels in sediment collected and analysed before 2000. These were: channel-edge sediment from the River Swale (Gamesby, 1997), tributary stream sediment data collected by the British Geological Survey (1992, 1996) and floodplain material (Macklin *et al*., 1994; Taylor and Macklin, 1997; Carter, 1998; Sparks, 1998; Hudson-Edwards *et al*., 1999; Sedgwick, 2000).

PHYSICAL SPECIATION AND CONCENTRATIONS OF CONTAMINANT METALS IN FLOOD SEDIMENTS

Contaminant metal concentrations in channel-edge flood sediment

Sand-size fraction. Concentrations of Cd, Pb and Zn observed in the channel-edge sediment vary considerably between the two size fractions analysed, with the highest levels occurring in the silt and clay fraction (Figures 4–6). Approximately 6 km from the source of the Swale, metal concentrations increase sharply immediately downstream of Swinner Gill. Two further peaks occur at 12 km and 20 km downstream, and these can be attributed to the input of metal-rich sediment from Gunnerside and Barney Beck, both of which were the focus of metal extraction and processing in the nineteenth century. Metal concentrations do, however, fall rapidly downstream of each input, suggesting that most of the contaminated sand-sized material from historically mined tributary streams is deposited soon after it is introduced into the main channel. Approximately 25 km downstream, metal concentrations again rise. This is attributable to the input of material from Arkle

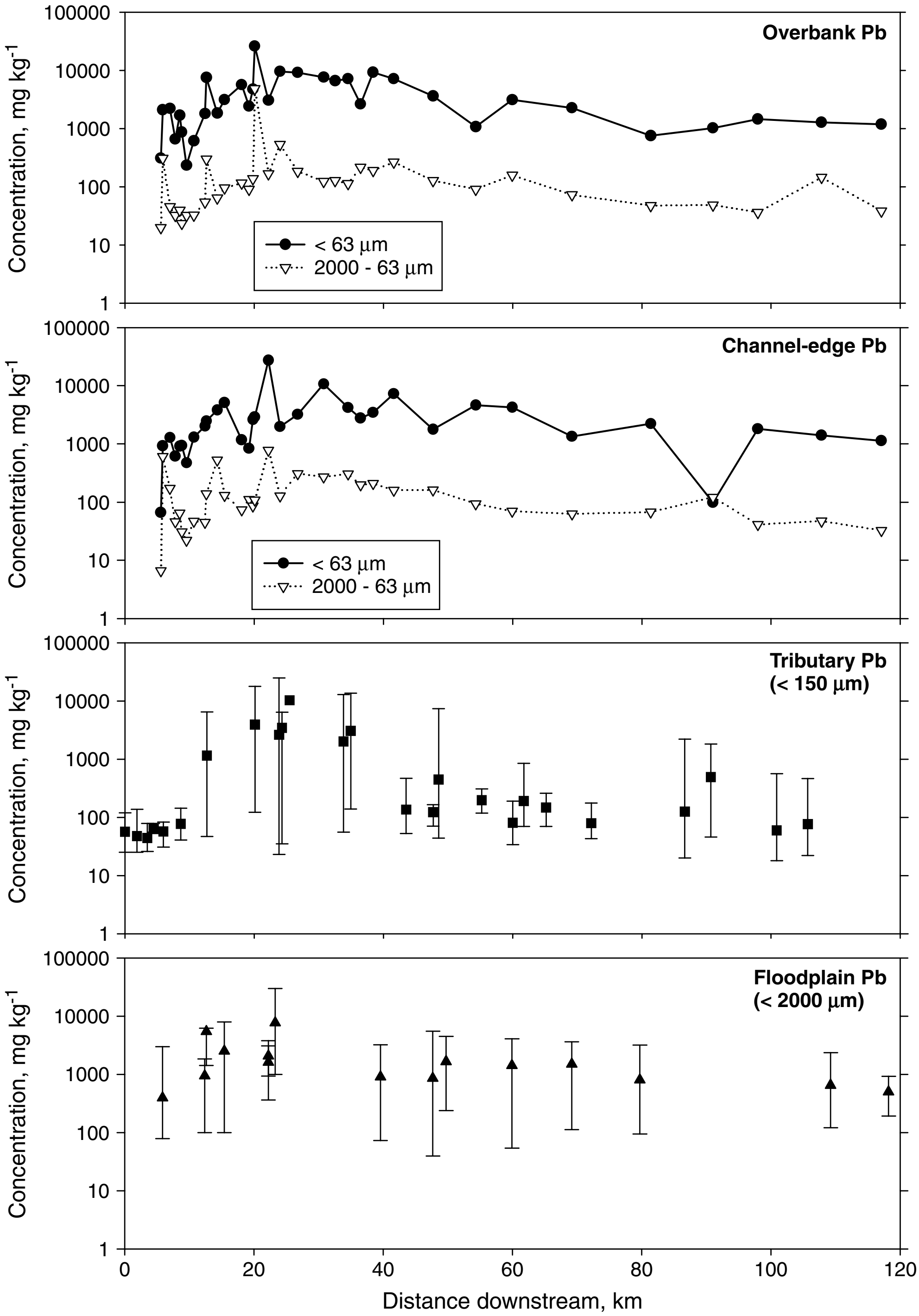

Figure 4. Pb concentrations in autumn 2000 flood sediments compared with tributary stream and floodplain Pb values (mean, maximum and minimum concentrations are shown)

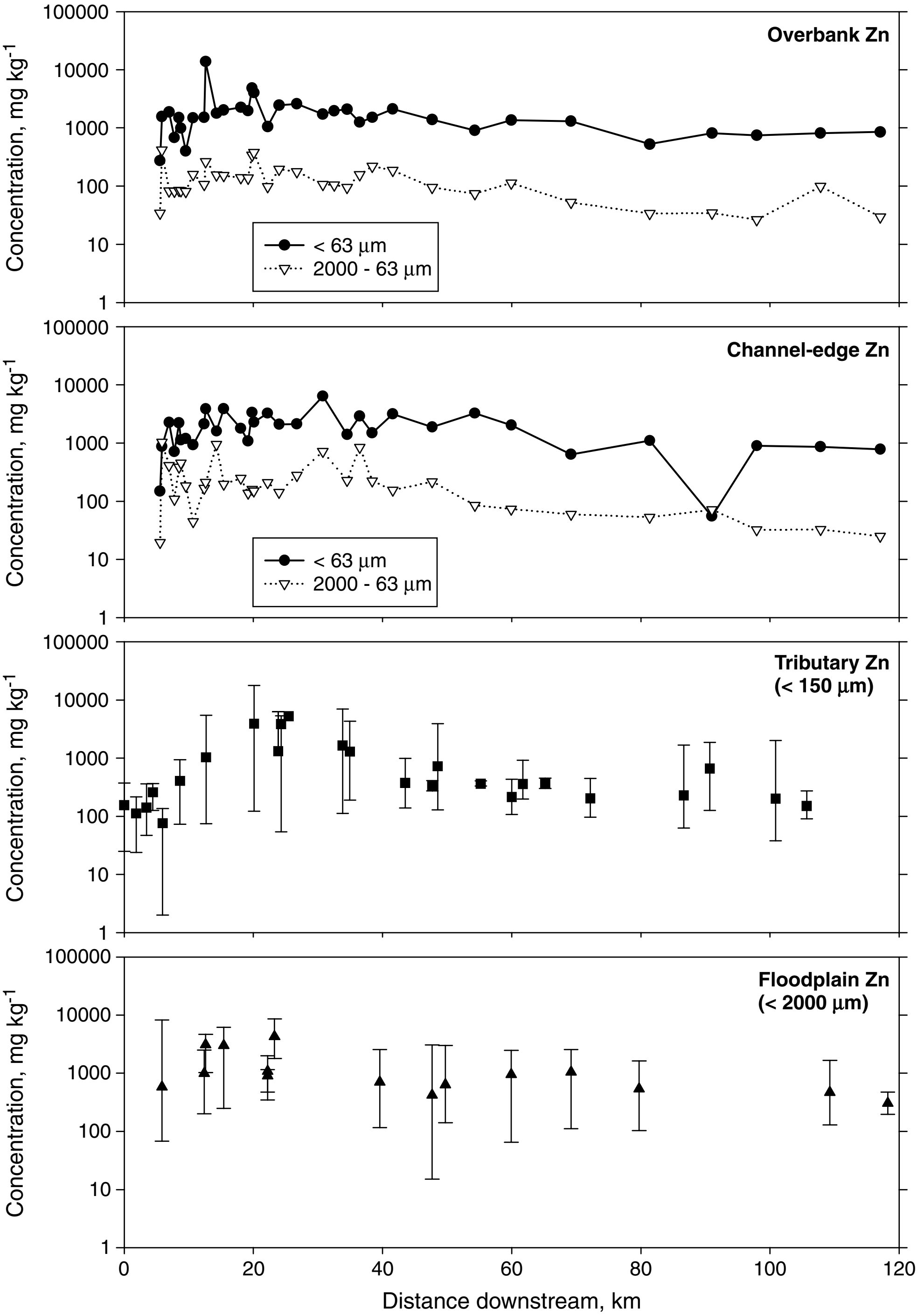

Figure 5. Zn concentrations in autumn 2000 flood sediments compared with tributary stream and floodplain Zn values (mean, maximum and minimum concentrations are shown)

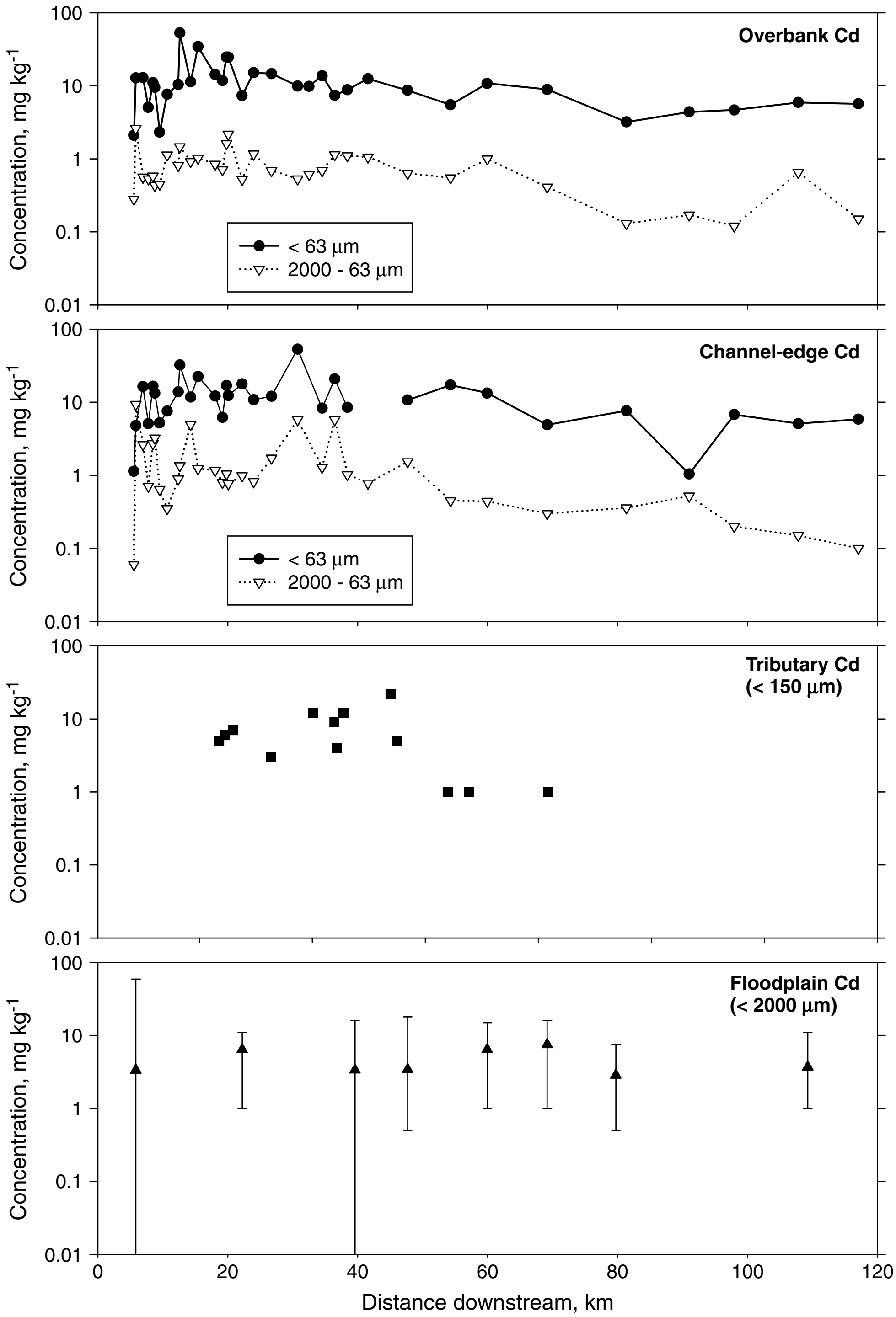

Figure 6. Cd concentrations in autumn 2000 flood sediments compared with tributary stream (based on single samples) and floodplain Cd values (mean, maximum and minimum concentrations are shown)

Beck, Grinton Gill and Cogden Gill, all of which were formerly sites of extensive mining and processing activities. Further high Cd and Zn concentrations 34 km from the source may reflect the input of contaminated sediment from Marske Beck.

Metal concentrations fall and become less variable approximately 40 km downstream, as sediment from uncontaminated tributaries in the Vale of York is introduced into the main river. There are, however, several relatively small reaches of the lower Swale where elevated metal concentrations were found. The first of these, located 45 km from the source of the Swale (approximately 10 km downstream of Marske Beck), is believed to be due to the reworking of contaminated sediment from upstream tributary and trunk river sources, because there are no mining affected tributaries in this reach. The second peak, located at 80 km, can also be attributed to similar sources of contaminated sediment and not local tributary inputs of metal contaminants.

Silt and clay-size fraction. In the <63 μm size fraction, elevated concentrations of Cd, Pb and Zn were found at 6 km downstream, just below Swinner Gill (Figures 4–6). Here, metal levels are significantly higher in the trunk stream than those measured in the tributary but are similar to those measured in historical floodplain sediments in the reach, which seem to have been the primary source of contaminants deposited during the autumn 2000 floods in this part of the Swale. At 12 km, metal concentrations rise to 32 mg kg^{-1} Cd, 8000 mg kg^{-1} Pb and 4500 mg kg^{-1} Zn following the input of metal waste from Gunnerside Beck. Immediately downstream of Gunnerside, Pb concentrations rise to 26 000 mg kg^{-1} with the input of extremely contaminated material from Barney Beck. High metal concentrations at 25 and 35 km relate to inputs from Arkle Beck, Grinton Gill and Cogden Gill and Marske Beck. In this part of the upper Swale, metal concentrations in the silt and clay-size fraction display very similar trends to the sand-size fraction, although concentrations are significantly higher (up to 50 mg kg^{-1} Cd, 10 000 mg kg^{-1} Pb and 6000 mg kg^{-1} Zn). Downstream of Colburn Beck and Skeeby Beck (approximately 50 km from the source) metal concentrations again rise with Cd exceeding 17 mg kg^{-1}, Pb reaching 4500 mg kg^{-1} and Zn exceeding 3000 mg kg^{-1}. Two smelt mills were located in Skeeby Beck, and significant quantities of contaminated material appear to have been washed into the Swale during the autumn floods. However, metal levels initially rise upstream of Skeeby Beck in a reach that has no contaminated tributaries, indicating that the source of this material must be upstream.

Metal concentrations fall at *c*. 60 km, where the unmineralized Scorton Beck joins the Swale. It is probable that contaminants are diluted by the introduction of sediment with low metal concentrations. Concentrations of Cd, Pb and Zn increase again at 70 km, with levels rising to 5 mg kg^{-1}, 2000 mg kg^{-1} and 1000 mg kg^{-1}, respectively. This increase is likely to be a result of contaminant metal remobilisation during the flood event. There are no inputs from contaminated tributaries along this reach of the river, and observed concentrations are similar to those observed in local floodplain sediments, indicating that bank erosion was the probable source of this material. A pronounced reduction in metal concentrations is evident at *c*. 80 km, with Cd falling to 1 mg kg^{-1}, Pb to 100 mg kg^{-1} and Zn to 50 mg kg^{-1}. This may result from the input of large amounts of uncontaminated material from Bedale Beck. Downstream of the River Wiske and Sikes Beck (*c*. 90 km) in the lower reaches of the river, Cd concentrations remain at *c*. 5 mg kg^{-1} and Pb and Zn concentrations stabilize at approximately 1000 mg kg^{-1}.

Contaminant metal concentrations in overbank flood sediment

Sand-size fraction. Two distinct peaks (at 6 and 12 km) of approximately 300 mg kg^{-1} Pb and 400 mg kg^{-1} Zn are evident in the upper 15 km of the river (Figures 4 and 5). These relate to the remobilization of contaminated floodplain material downstream of Swinner Gill and the introduction of mining waste from Gunnerside Beck. The Cd concentrations peak at 2·6 mg kg^{-1} downstream of Swinner Gill but do not significantly increase downstream of Gunnerside Beck (Figure 6). At *c*. 20 km, Pb concentrations increase to *c*. 5000 mg kg^{-1} as a result of pollution from Barney Beck. The Cd (2·2 mg kg^{-1}) and Zn (400 mg kg^{-1}) concentrations at this site are also elevated. As observed in channel-edge sediments, metal concentrations initially rise and then fall rapidly downstream of metal inputs. There is a relatively small rise in metal concentrations at 25 km, which is attributable to the influx of contaminated material from Arkle Beck, Grinton Gill and Cogden Gill.

A lower but more sustained peak in metal concentrations is evident between 35 and 45 km downstream, resulting partly from mine waste introduced from Marske Beck, but also from the downstream movement of metal-enriched material from the upper Swale. Upstream, as opposed to local, contaminant sources are believed to be responsible for high Pb and Zn concentrations approximately 60 and 110 km downstream, as both occur downstream of uncontaminated tributaries (Scorton Beck and Birdforth Beck, respectively).

Silt and clay-size fraction. Contaminant metal concentrations observed in the silt and clay-size fraction of autumn 2000 flood sediments from the Swale are significantly higher than those recorded in the sand fraction (Figures 4–6). In the uppermost reaches of the River Swale, elevated metal concentrations associated with remobilized floodplain sediments downstream of Swinner Gill (6 km) are again clearly evident (13 mg kg^{-1} Cd, 2000 mg kg^{-1} Pb and 1500 mg kg^{-1} Zn). Very high metal levels downstream of Gunnerside Beck (53 mg kg^{-1} Cd, 7500 mg kg^{-1} Pb and 14000 mg kg^{-1} Zn) show that this is an important source of contaminated sediment in the River Swale. However, metal concentrations, after initially rising, fall rapidly downstream of each tributary input, as observed in the channel-edge material. Metal concentrations increase markedly at *c*. 20 km principally as the result of inputs from Barney Beck, but also from processing mills located in Summer Lodge Beck (16 km).

At *c*. 25 km significantly elevated Cd, Pb and Zn concentrations (15 mg kg^{-1}, 10000 mg kg^{-1} and 3000 mg kg^{-1}, respectively) are associated with the input of contaminated material from Arkle Beck, Grinton Gill and Cogden Gill. Metal concentrations decline until *c*. 40 km where the influx of contaminated material from Marske Beck and the remobilization of floodplain material combine to produce very high metal levels along this part of the Swale (14 mg kg^{-1} Cd, 7100 mg kg^{-1} Pb and 2100 mg kg^{-1} Zn). Concentrations of Cd and Pb are again relatively high in flood sediments between 60 and 70 km downstream, with levels comparable to those found in floodplain sediments in this reach of the Swale, suggesting that this material is probably an important source of contaminants. A decrease in metal concentrations occurs at 80 km, which may be due to the input of uncontaminated material from the uncontaminated Bedale Beck. Metal concentrations increase between 90 and 110 km, and stabilize at approximately 5 mg kg^{-1} Cd, 1000 mg kg^{-1} Pb and 800 mg kg^{-1} Zn. There are no mineralized tributaries between 100 and 118 km and relatively high metal concentrations are likely to be caused by the reworking of historically contaminated floodplain material through bank erosion.

Grain size of flood sediment

Overbank and channel-edge flood sediments in the Swale catchment are dominated by sand-sized material (2000–63 μm). This confirms previous grain size analysis by Walling *et al.* (1998) in the Yorkshire Ouse catchment, who showed that material with a diameter of greater than 63 μm comprises between 87 and 63% of overbank sediment collected close to the channel. The proportion of silt and clay in the autumn 2000 flood sediment is broadly similar to that reported by Walling *et al.* (1998), although there is greater variability between sites (Figure 7). In overbank sediment, the <63 μm fraction comprises between 1% and 39% of the total, with a mean value of 12%. Channel-edge deposits contain between 0·8% and 56% silt and clay sized material, with a mean value of 9%.

The proportion of flood sediment comprised of <63 μm material, particularly in channel-edge deposits, is generally higher in the lower reaches of the Swale than in the upper parts of the catchment. This is likely to reflect the introduction of silt and clay-sized material from tributaries such as Bedale Beck, the River Wiske and Cod Beck in the Vale of York that drain intensively farmed areas underlain by Triassic sedimentary rocks. The proportion of <63 μm sediment is also relatively high downstream of mined tributaries such as Swinner Gill, Gunnerside Beck, Barney Beck and Marske Beck.

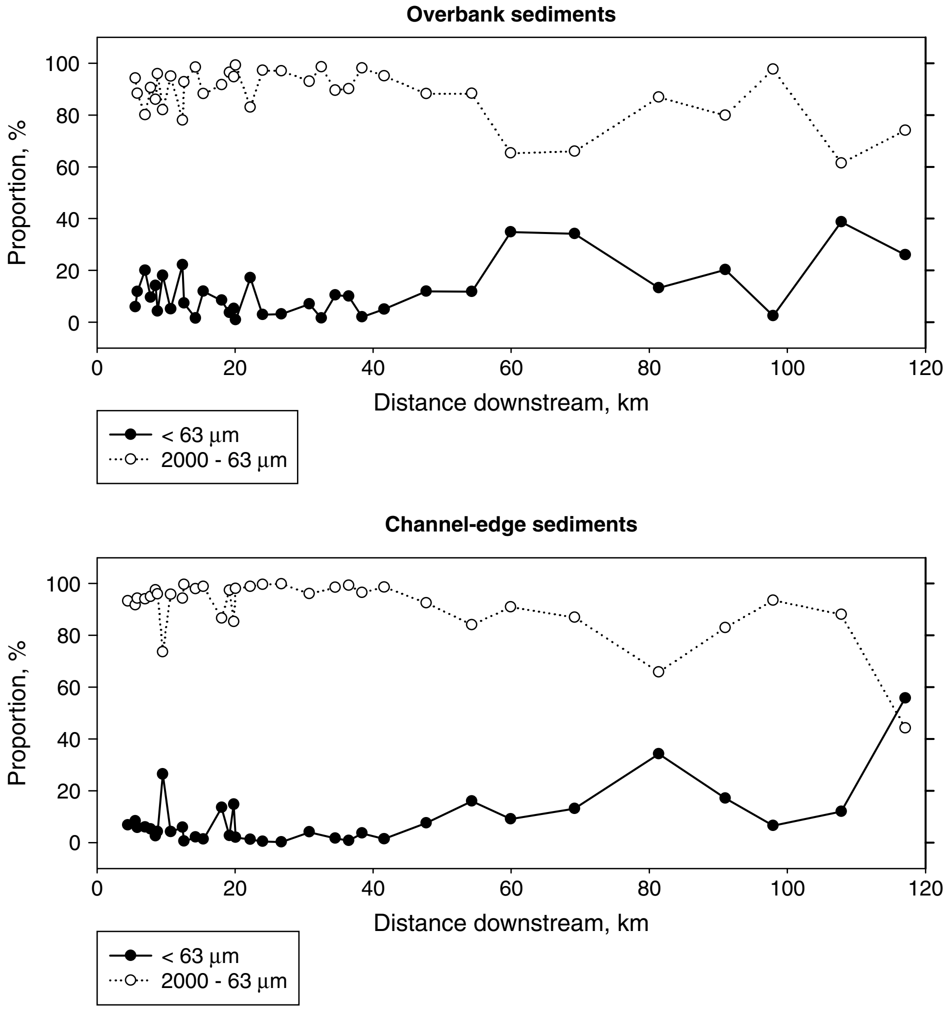

Figure 7. Proportion of 2000–63 μm and <63 μm material in autumn 2000 flood sediments

IDENTIFYING SOURCES OF CONTAMINANT METALS IN SWALE FLOOD SEDIMENTS

Metal analysis of fine grained (<150 μm) stream sediments collected by the British Geological Survey during the late 1980s and early 1990s (British Geological Survey, 1992, 1996) showed that historical metal mining and ore processing caused the severe contamination of many tributaries in the upper part of the Swale catchment (Figures 4–6). Metal concentrations were particularly high in Gunnerside Beck, Barney Beck and Arkle Beck, all of which contained a number of smelting and grinding mills as well as mine sites. Very high metal concentrations in Swale flood sediments immediately downstream of these tributaries show that large amounts of highly contaminated material were introduced into the River Swale during the severe autumn 2000 floods. The highest concentrations of heavy metals, however, are generally found in tributary sediments, indicating the significance of dilution by cleaner sediment within the trunk river in controlling metal levels.

The other major source of contaminated metals during the autumn 2000 floods was historically contaminated floodplain sediment. In the upper 40 km of the Swale, mean metal concentrations (especially Pb) in mineralized tributaries and at contaminated sites on the Swale floodplain are very similar (Figures 4–6). It is likely that both contributed to the high concentrations of contaminant metals found in the autumn 2000 flood sediment deposited in the upper Swale. In the lower two-thirds of the Swale (40–120 km), however, mean metal concentrations in contaminated floodplain sediments consistently exceed levels found in tributary streams. Elevated metal concentrations within the autumn 2000 flood sediments in the middle and lower parts of the Swale (especially in the sand fraction) are therefore attributed largely to the reworking of historically contaminated floodplain material.

ENVIRONMENTAL IMPLICATIONS OF CONTAMINATED FLOOD SEDIMENTS

The elevated levels of metal contamination recorded in overbank and channel-edge sediment deposited along the River Swale during the autumn 2000 floods present a potential risk to ecosystem (both natural and agricultural) and human health. This risk is, however, difficult to quantify in the Swale valley as it is presently unknown what proportion of the sediment-accumulated metals is taken up by plants, ingested by grazing animals and enters the food chain. With the River Swale's relatively high pH, it is unlikely that contaminated channel-edge sediments deposited during the autumn 2000 floods would adversely affect water quality. There may, however, be localized problems in some of the mineralized tributaries that drain catchments with siliceous lithologies, which have low stream water pH. The same is not true for contaminated sediment deposited on the Swale floodplain, especially where receiving (accreting) floodplain sites already have high metal concentrations. All of the floodplain (overbank) sample sites were in agricultural land use; predominantly grazing in Swaledale and arable in the Vale of York. Identifying the degree of Cd, Pb and Zn contamination is, however, not a straightforward task, primarily because of the lack of consensus among UK environmental regulatory agencies over what constitutes appropriate threshold values. Furthermore, contamination thresholds also vary depending on land use, and on physical and chemical soil characteristics.

In the case of the River Swale floodplain, which has soils contaminated by mining activities, it could be argued that the guidelines set out by the Inter-Departmental Committee on the Redevelopment of Contaminated Land (ICRCL) in 1990 on '*The aftercare of metalliferous mining sites for pasture and grazing*' are appropriate. Using the maximum action trigger concentrations (values not to be exceeded for use as specified) for grazing livestock for Cd (30 mg kg^{-1}), Pb (1000 mg kg^{-1}) and Zn (3000 mg kg^{-1}), only two sample sites have Pb values (in the <2000 μm size fraction) that exceed this level and none of the sample sites have Cd or Zn values that lie above action trigger concentrations (Figure 8). This position is, however, somewhat misleading in that the Swale floodplain is a semi-natural system that has been receiving contaminant metals produced by mining activity for many hundreds of years and has not been 'restored', and the land use has not changed significantly over this period. Using ICRCL guidelines for permitted metal levels used in the aftercare of mining sites for assessing contamination in floodplain environments is therefore probably not appropriate. If soils in the Swale floodplain (regardless of whether they are already contaminated) are considered as being agricultural, then MAFF's 1998 *Code of Good Agricultural Practice for the Protection of Soil* guidance concentrations (in terms of material being added to soil) are Cd 3 mg kg^{-1}, Pb 300 mg kg^{-1} and Zn between 200 and 300 mg kg^{-1} (pH dependant). Taking these values, 18%, 60% and 35–70% of floodplain sites sampled in the River Swale received sediment with concentrations of Cd, Pb and Zn, respectively, that exceeded MAFF guidelines (Figure 8). To set the risk in a European context, using the Dutch action (formerly C or danger) value for soil pollution (Cd 12 mg kg^{-1}, Pb 530 mg kg^{-1} and Zn 720 mg kg^{-1}), none of the sites would be of real concern with respect to either Cd or Zn. However, 35% of sites have received Pb in flood sediments where the danger value has been surpassed and the feasibility of removal or burial of contaminated material would be recommended (Department of Soil Protection, 2000).

Whichever of these trigger or signal values are used, there is clear evidence that the autumn 2000 floods resulted in significant and widespread contamination of floodplain soils in the Swale valley. The standard nitric acid based digestions used in this study, and which are widely used in the assessment of contaminated land in the UK, do not throw light on the chemical speciation, notably the bio-availability, of metals in flood

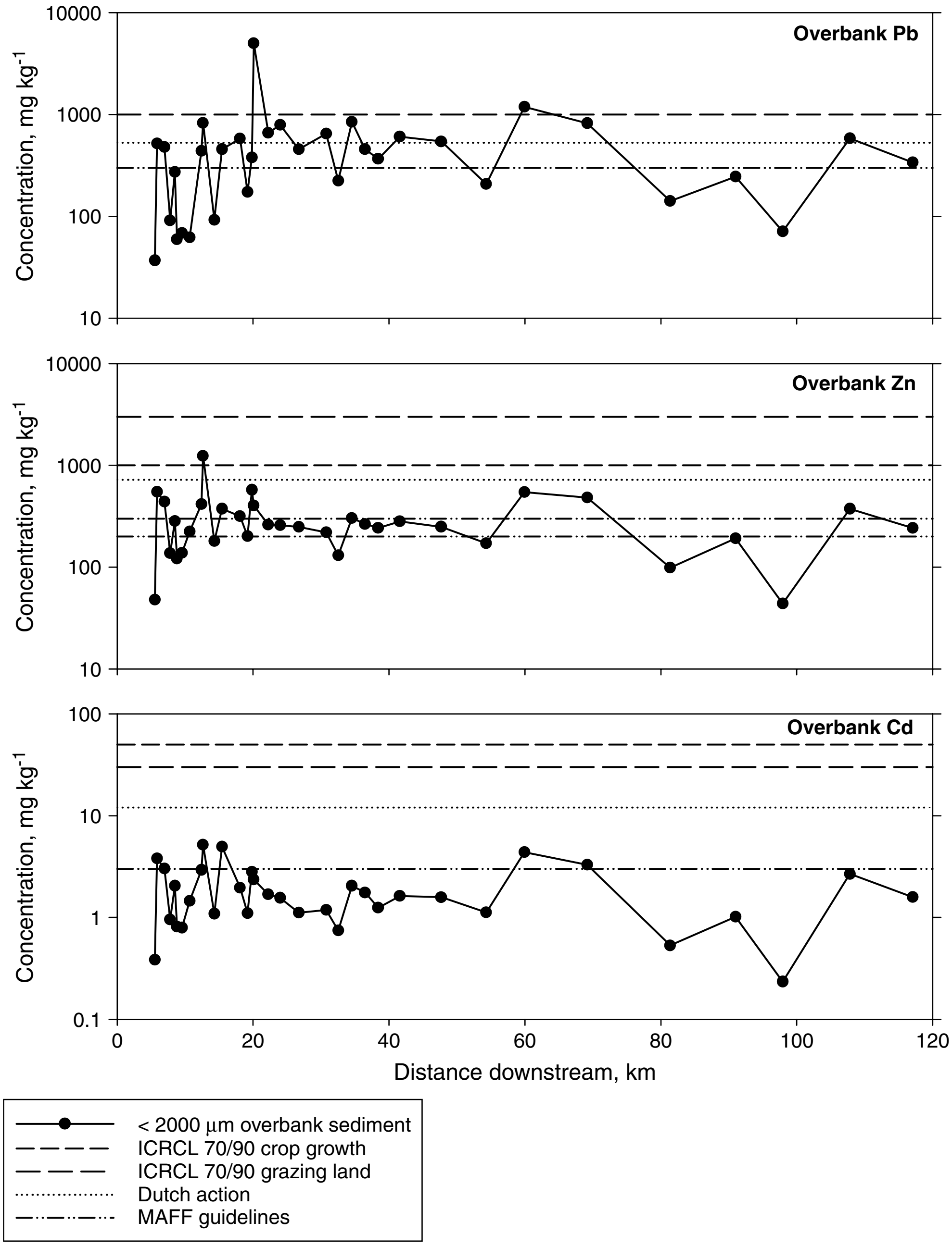

Figure 8. Heavy metal concentrations in <2000 μm autumn 2000 flood sediment compared with British and European standards (MAFF guidelines for Zn are 200 mg kg^{-1} between pH 5·0–7·0 and 300 mg kg^{-1} at pH >7·0. Both are displayed because sediments from the Swale catchment range from pH 5·0 to pH 11·5)

sediments. Follow-up studies are required to further evaluate the chemical and physical forms of sediment-associated metals. This should include the use of sequential extraction procedures, which have proved to be powerful techniques for highlighting differences in the mobility and reactivity of contaminant metals in river sediments (e.g. Macklin and Dowsett, 1989).

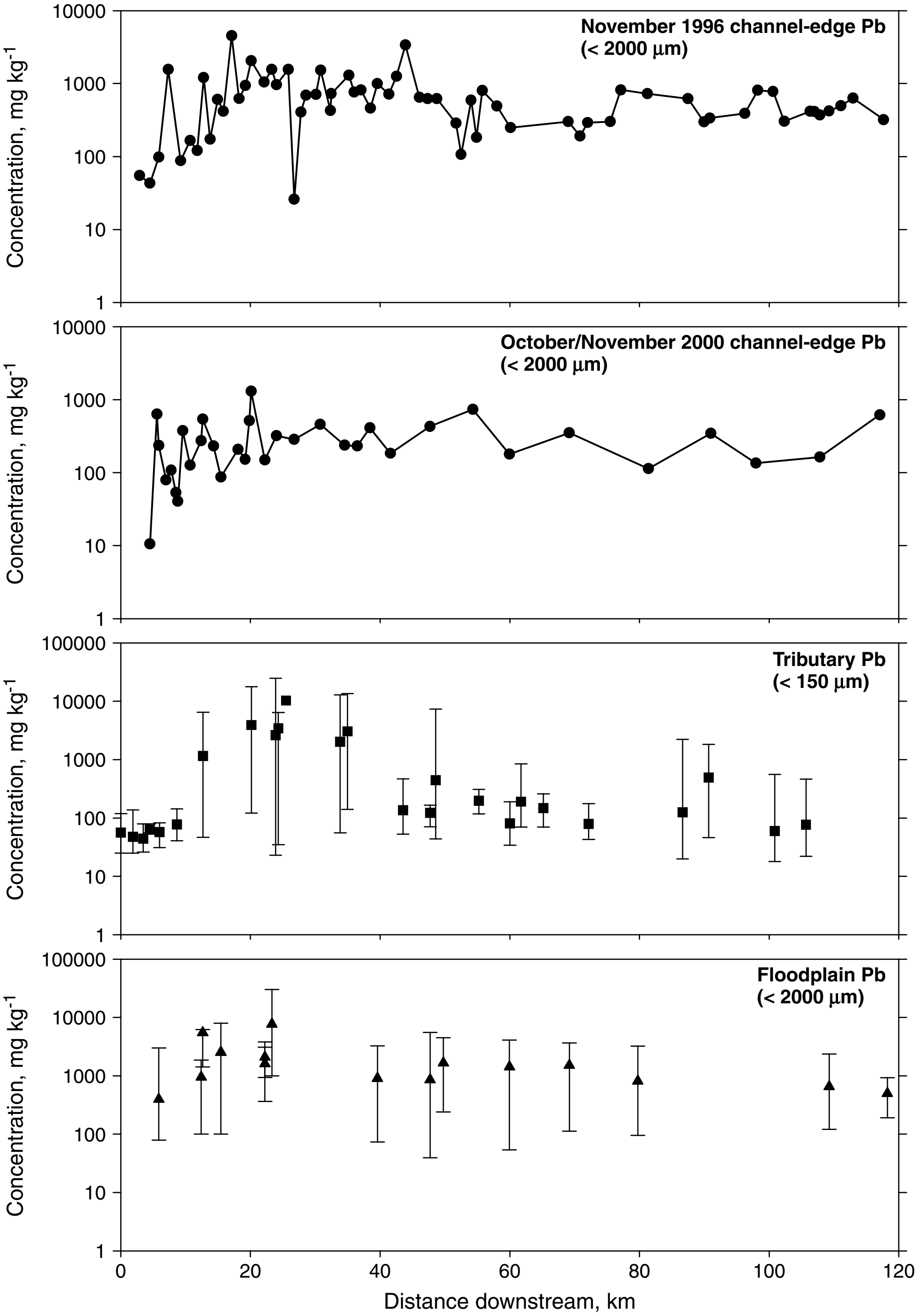

Figure 9. Pb in 1996 (Gamesby, 1997) and 2000 channel-edge sediments compared with tributary stream and floodplain Pb values (mean, maximum and minimum concentrations are shown)

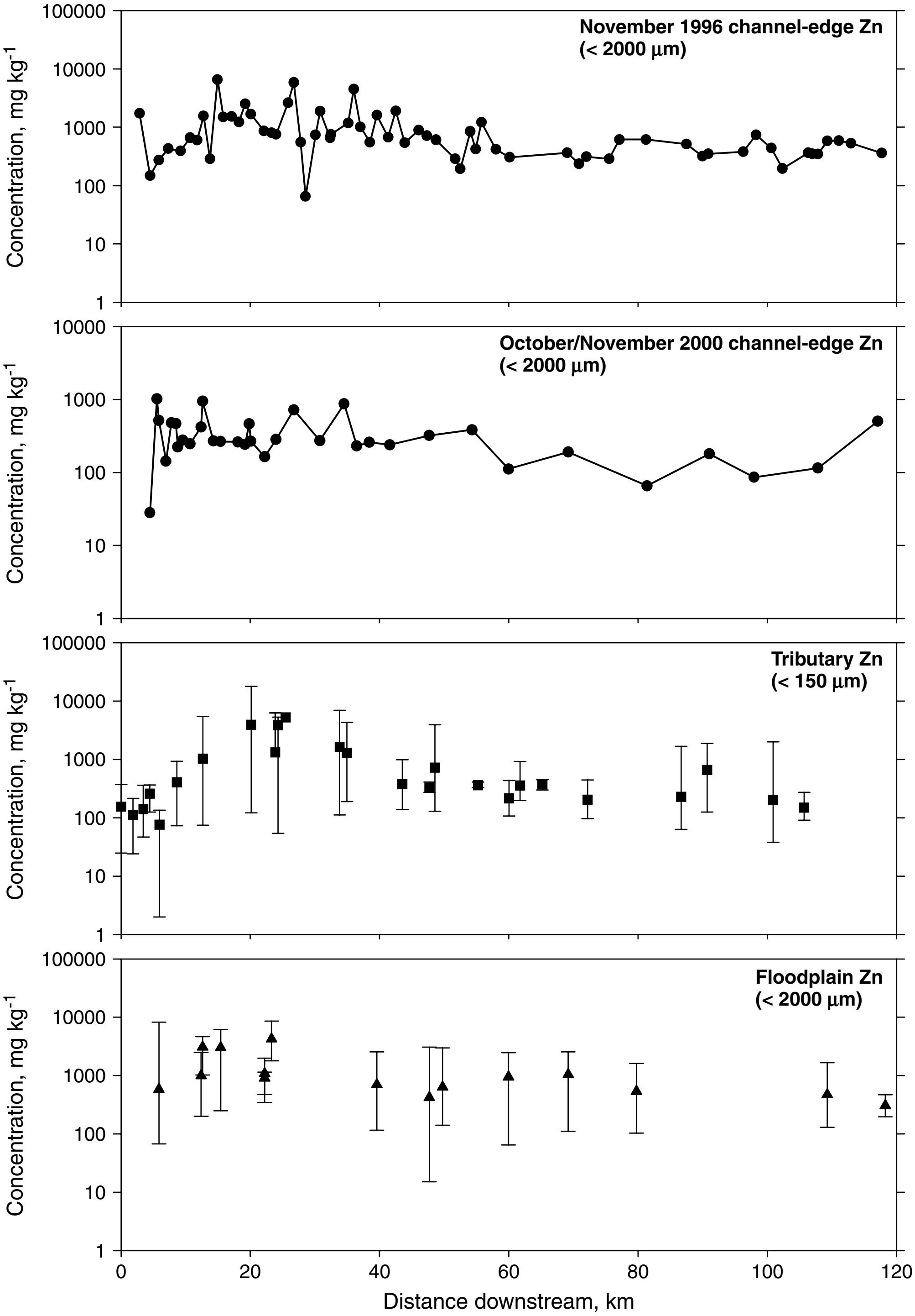

Figure 10. Zn in 1996 (Gamesby, 1997) and 2000 channel-edge sediments compared with tributary stream and floodplain Zn values (mean, maximum and minimum concentrations are shown)

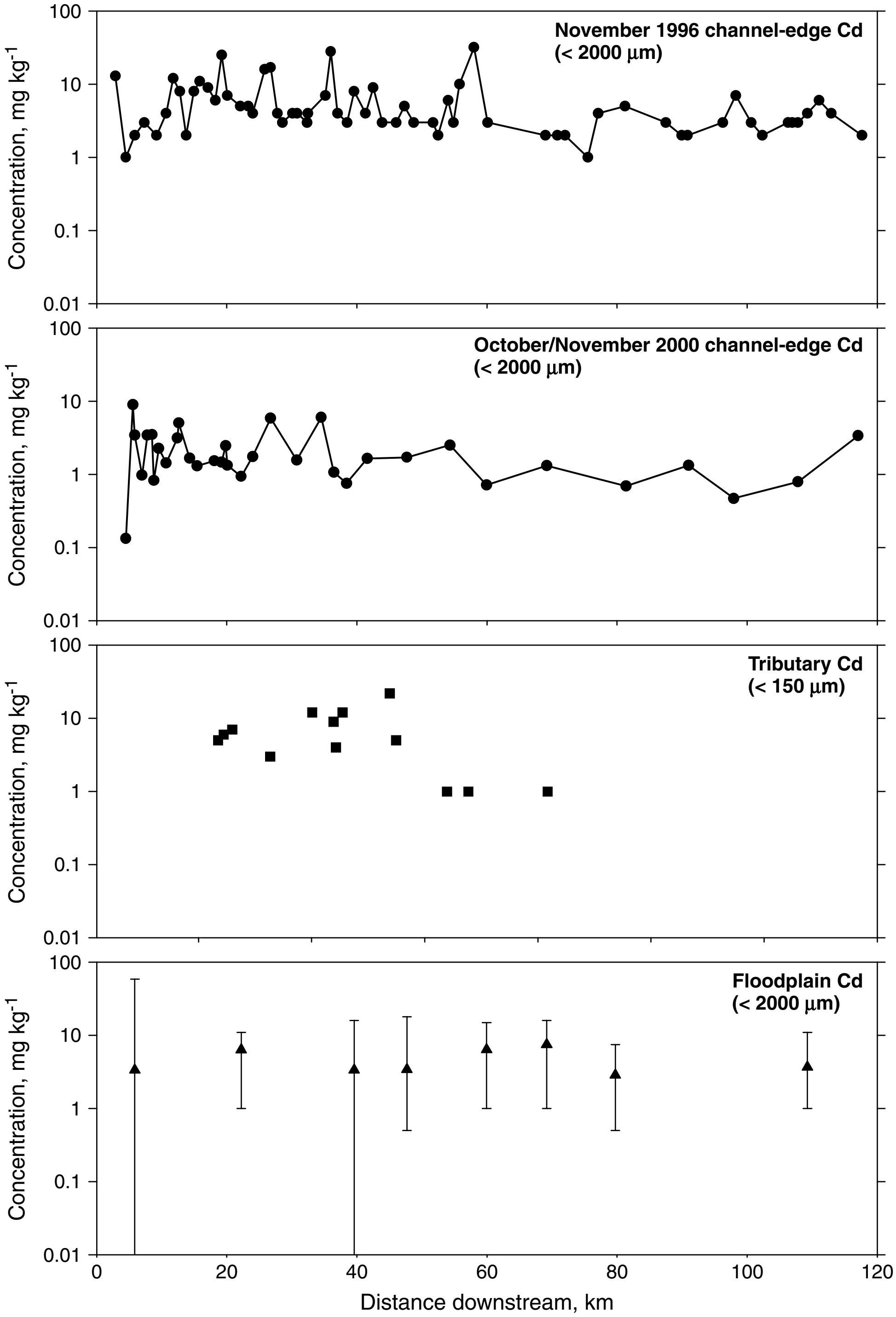

Figure 11. Cd in 1996 (Gamesby, 1997) and 2000 channel-edge sediments compared with tributary stream (based on single samples) and floodplain Cd values (mean, maximum and minimum concentrations are shown)

One of the key questions that arose after the autumn 2000 floods was the extent to which they were unusual. From a hydrological perspective, the October and November 2000 floods were greater than any in the Vale of York since 1947, with rainfall for the September to November period being the highest on record for those months (DEFRA, 2001). With respect to flood-related contamination, we are very fortunate that in the Swale catchment concentrations of Cd, Pb and Zn in channel-edge sediments (<2000 μm) deposited during floods in November 1996 were analysed in detail by Gamesby (1997). Comparison with autumn 2000 channel-edge flood sediments indicates very similar downstream metal distributions in both flood events, but concentrations of Cd, Pb and Zn are very much higher in samples collected in November 1996 (Figures 9–11). It is likely that some of this variation can be explained by slight differences in analytical procedures, but it is very probable that lower metal concentrations in the autumn 2000 flood sediments were the result of dilution by a much greater sediment delivery from uncontaminated parts of the Swale catchment. Nevertheless, in terms of recent floodplain contamination the autumn 2000 floods do not appear to have been an unusual event in the Swale. Indeed, this confirms earlier work by Sparks (1998) and Longfield and Macklin (1999) who demonstrated that sediment-associated metal fluxes in the River Swale over the past 20 years or so are the highest since the end of metal mining in the late nineteenth century.

CONCLUSIONS

River channel-edge and overbank sediments deposited during severe flooding in the autumn of 2000 in the River Swale contain elevated levels of Pb, Zn and Cd. Concentrations are highest in the silt and clay-size fraction and metal concentrations, especially Pb, exceed MAFF guidelines along much of the river. This is particularly pronounced downstream of historically mined areas in the upper reaches of the catchment, although elevated heavy metal concentrations can be observed along the entire course of the river. Contaminated material was derived from both the introduction of metalliferous waste from mined tributary sources and from the reworking of historically contaminated floodplain deposits in the main river.

If the frequency of high-magnitude floods increases as predicted in the coming decades in response to climate change, it is probable that historically mined catchments, such as the Swale, will experience significant flood-related contamination as a result of the reworking of metal-rich floodplain material (cf. Macklin, 1996; Longfield and Macklin, 1999). The deposition of contaminated sediment on UK floodplains, not just more frequent flooding, therefore may be the real threat posed by climate change.

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