CHAPTER 2

STUDY AREA: THE RIVER SWALE CATCHMENT AND ITS MINING HISTORY

2.1. THE RIVER SWALE CATCHMENT

2.1.1. General characteristics

The River Swale is the northernmost tributary of the Yorkshire Ouse with its headwaters located in the eastern Yorkshire Dales, from where it flows in an easterly direction (Figure 2.1). After passing through the major settlements of Richmond and Catterick, the river flows 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 River Swale catchment contains four distinct zones of relief; two distinct upland areas, a piedmont zone and a lowland zone. The northern Pennine uplands are located in the north and west of the catchment, reaching a peak of 716 m above ordnance datum at the summit of Great Shunner Fell. These uplands form a large plateau, which is dissected by the narrow valleys of the River Swale and its tributaries. The Swale flows eastwards from this zone, through the formerly glaciated valley of Swaledale, and into the flat, topographically-low Vale of York. The North York Moors form a final zone of high relief in the north east of the catchment, separated from the Pennines by the Vale of York.

Total annual rainfall patterns vary considerably within the Swale catchment. Rainfall of up to 1800 mm yr^{-1} falls in the headwaters, the lower parts of Swaledale receive up to 1300 mm yr^{-1}, and between 600 and 800 mm yr^{-1} falls in the lowlands of the Vale of York. The North York Moors in the north east of the catchment receive approximately 1000 mm yr^{-1} (data from the National River Flow Archive).

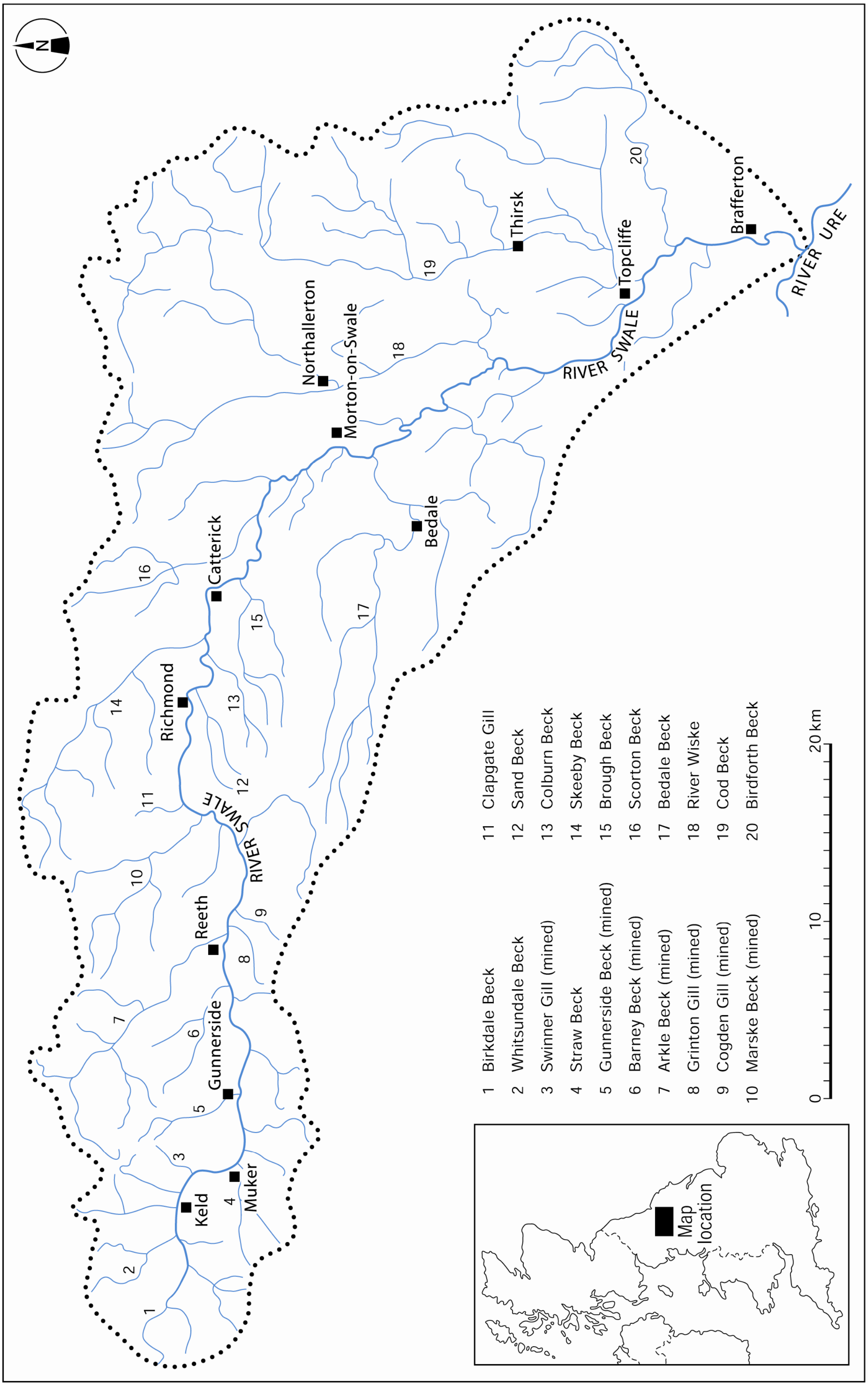

Figure 2.1: The River Swale catchment, showing drainage network and major tributaries

Present day land use within the Swale catchment is predominantly agricultural. Pastoral activities are predominant in Swaledale, with sheep grazing on the lower quality moorland and permanent grassland in the upper and mid-dales. Cattle are grazed on better quality grassland on the valley floors and lower slopes. Arable agriculture dominates the higher quality land in the low-lying Vale of York. Commercial and industrial activities other than tourism are generally confined to the larger centres of population such as Richmond, Catterick, Thirsk and Northallerton, and are unlikely to have a significant impact on the Swale system. Limestone is extracted from Barton and Forcett Quarries, situated to the north of Richmond, and sand and gravel is extracted from alluvial deposits and the river channel from six quarries in the piedmont zone (Environment Agency, 1997).

2.1.2. Catchment geology

The River Swale catchment is underlain by a series of Carboniferous, Permian and Triassic rocks resting on Lower Palaeozoic basement beds (Scrutton, 1994) (Figure 2.2). The basement rocks are succeeded by a massive limestone formation known as the Great Scar Limestone. The Dinantian limestones, shales and sandstones, formerly known as the Yoredale Series, that overlay this formation outcrop in the valleys of the upper Swale and its tributaries (Dunham and Wilson, 1985). The Dinantian rocks can be subdivided into a number of distinct geological units, principally the Hawes, Gayle, Hardrow Scar, Simonstone, Middle, Five Yard, Three Yard and Underset Limestones and the Underset Chert (Dunham and Wilson, 1985).

The Dinantian units are in turn overlain by a series of Namurian sandstones, shales and limestones, formerly known as the Millstone Grit Formation, which outcrop on higher ground in the upper Swale catchment (Dunham and Wilson, 1985). A number of distinct geological units have been identified within the Namurian units, principally the Main Limestone, the Main Chert, the Little Limestone, the Richmond Chert, the Crow Limestone and Crow Cherts (Dunham and Wilson, 1985). Together, the Dinantian and Namurian beds make up the Askrigg Block formation.

The rocks of the Askrigg Block are overlain by a series of Permo-Triassic limestones, mudstones and sandstones (formerly the New Red Sandstone), which outcrop in the piedmont and lower reaches of the Swale, downstream of Richmond (Scrutton, 1994).

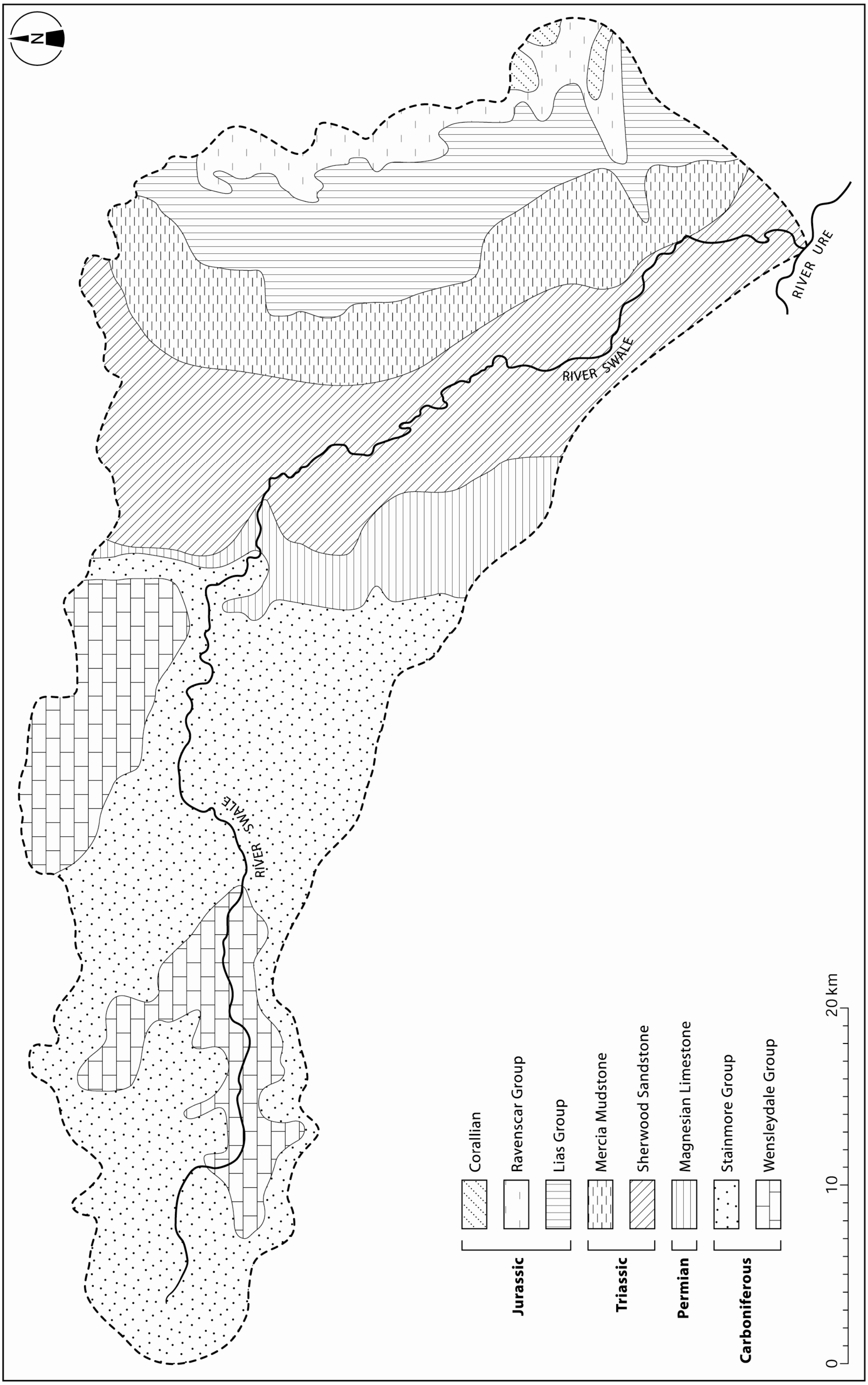

Figure 2.2: Geology of the Swale catchment (simplified from BGS 1:250,000 scale solid geology maps sheets 53N 02W [Humber-Trent] and 54N 02W [Tyne-Tees])

These beds are in turn overlain by the lower Jurassic rocks of the Lias, Ravenscar and Corallian groups, which outcrop in the north east of the catchment (Scrutton, 1994).

2.1.3. Mineralisation

The heavily mineralised rocks of the Askrigg Block form the southern part of the Northern Pennine Orefield (Dunham and Wilson, 1985). The upland tributaries of the River Swale cross the most heavily mineralised zone in the southern part of the Northern Pennine Orefield (Figure 2.3) (Dunham and Wilson, 1985). Lead, zinc, barium and fluorine-rich fluids associated with the concealed Wensleydale Granite were introduced into brittle Carboniferous strata during the late Carboniferous or early Permian (Ixer and Vaughan, 1993). Four principal types of ore body are associated with this mineralisation:

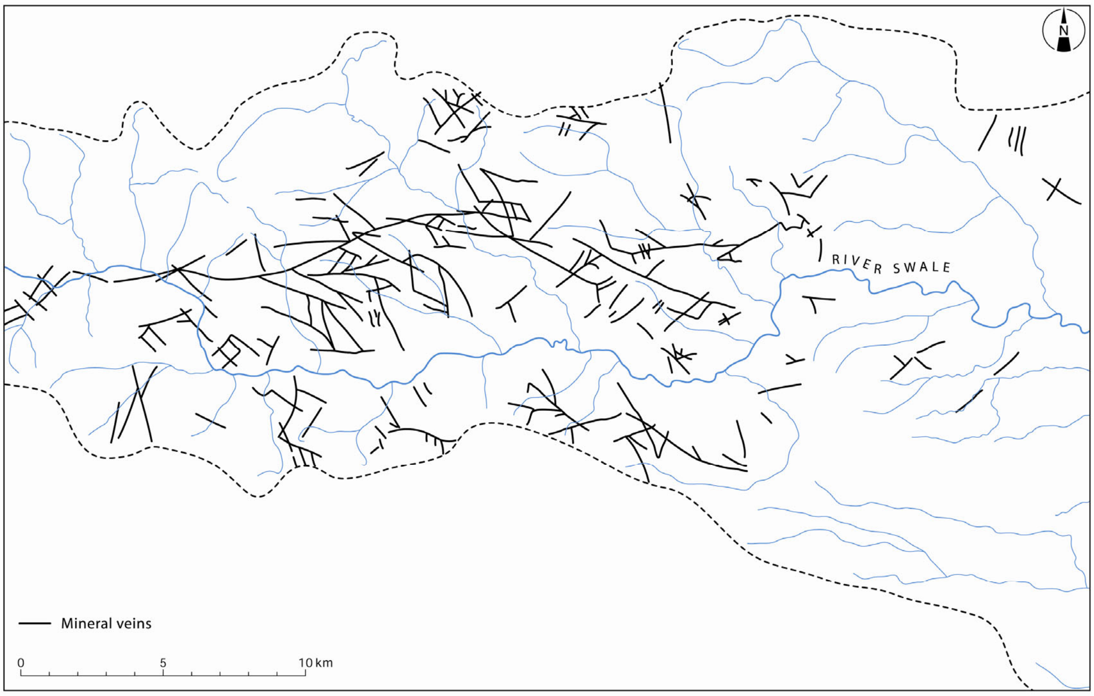

Figure 2.3: The distribution of mineral veins in the Swale catchment (adapted from Raistrick, 1975)

1. Veins: large ribbon-like mineral deposits emplaced in fissures in brittle limestones and cherts
2. Scrins: mineral deposits in vertical or steeply dipping fractures
3. Pipes: vertical replacement deposits formed in limestones at the intersection of two fractures

4. Flots, floats or flats: replacement deposits parallel to the bedding plane, usually associated with a larger vein system

(Dunham and Wilson, 1985; Ixer and Vaughan, 1993).

Productive ore bodies are generally confined to the strata between the Richmond Chert and Underset Limestone (principally the Main Limestone), the Middle Limestone, the lowest sandstones of the Millstone Grit Formation, and the uppermost part of the Great Scar Limestone (Dunham, 1959; Dunham, 1988). In Swaledale, ore bodies are generally oriented in an east/west or south-east/north-westerly direction, in horizontal or gently inclined Dinantian and Namurian rocks (Dunham and Wilson, 1985; Scrutton, 1994).

The Swaledale mineral veins are comprised of several metalliferous sulphide ores, principally:

1. Galena (PbS): the primary ore of the Northern Pennine Orefield, occurring as bands parallel to the walls of the vein, thin layers along the bedding planes of limestones, and in the matrix of many veins and flots.
2. Sphalerite (ZnS): the second most abundant sulphide ore in Swaledale veins.
3. Copper sulphides: constitute less than 0.1 % of the total mineral veins. Chalcopyrite ($CuFeS_2$) is relatively abundant in the Middleton Tyas area, north of Richmond.
4. Bravoite ($[Fe, Ni, Co]S_2$), pyrite and marcasite (FeS_2): occur in small amounts in veins and flots.

(Dunham and Wilson, 1985).

In addition to the metal sulphides, several gangue minerals have also been identified in Swaledale deposits:

1. Fluorite (CaF_2): generally very abundant, but constitutes only a small part of the mineral veins in the Gunnerside Beck and Barney Beck area.
2. Baryte ($BaSO_4$): abundant in most veins, sometimes with intergrown crystals of galena.
3. Witherite ($BaCO_3$): abundant in Swaledale, and identified as the primary gangue mineral in the Sir Francis, Surrender, Friarfold and Old Rake veins.

4. Calcite, Aragonite ($CaCO_3$): very abundant, often interbedded with other gangue and sulphide minerals.
5. Dolomite ($MgCO_3.CaCO_3$): commonly found adjacent to limestone bedrock.
6. Barytocalcite ($BaCO_3.CaCO_3$): a very rare mineral recorded in the Blakethwaite and Lownathwaite mines by Bradley (1862) and found in spoil from Sir Francis Level, Gunnerside Beck.

(Dunham and Wilson, 1985).

2.1.4. Catchment geochemistry

Detailed hydrogeochemical and stream sediment surveys have been carried out in the upper Swale catchment by Ineson and Al-Badri (1980; 1981). A variety of common and trace elements were analysed using a combination of X-ray fluorescence, atomic absorption spectrophotometry, colourimetry, and flame photometry. The pattern of elements observed in stream waters was found to strongly reflect underlying lithology, with elements falling into calcareous, siliceous and mixed (both calcareous and siliceous) populations (Ineson and Al-Badri, 1980). Significant ($+2\sigma$) anomalies of metals such as Pb and Zn were observed in streams draining mineralised areas around the villages of Reeth and Gunnerside, with the highest values recorded in waters downstream of former lead smelting and dressing sites (Ineson and Al-Badri, 1980).

A similar pattern was observed in stream sediments collected in upper Swale. Lower Silesian (Namurian) sandstones outcropping to the north and west of Reeth are shown by a zone of Si enrichment observed in samples from this area (Ineson and Al-Badri, 1981). A large anomaly in Pb, Zn, Ba, F and V concentrations was observed in the Gunnerside Beck-Arkengarthdale area, which was likely to be derived from the Old Gang and Surrender vein system (Ineson and Al-Badri, 1981). A large Sr anomaly was also observed in stream sediments from this area, although this pattern was not reflected in hydrogeochemical samples. The origin of this anomaly has not been explained (Ineson and Al-Badri, 1981).

A more extensive geochemical survey of stream sediments throughout the Swale catchment has been carried out by the British Geological Survey (1992; 1996). These data suggest that there are several distinct geochemical zones within the catchment. The uppermost reaches of Swaledale are characterised by anomalies of Bi, Co, Ga, Li, Mo, Nb, P, Sb, Sn, V, Y, Zn and Zr. The mined tributaries further down Swaledale are characterised by Ag, Ba, Cd, Mn, Ni, Pb, Sr and Zn anomalies. Elevated concentrations of Ca and Cu can be observed in the Richmond area, while the Vale of York is characterised by higher levels of Ca and Mg (British Geological Survey, 1992; 1996).

2.1.5. Glacial history and Holocene development

The Yorkshire Dales have been glaciated on a number of occasions throughout the Pleistocene. The most recent of these events occurred at the end of the Devensian (18,000 – 13,000 years BP). During this period, high relief areas in the Yorkshire Dales acted as centres of snow accumulation and ice generation (Raistrick, 1926). This ice flowed down river valleys such as Swaledale, Wensleydale, Wharfedale and Airedale, and joined the major ice sheet in the Vale of York (Raistrick, 1926; Howard and Macklin, 1998). The deposition of glacial moraines severely impeded drainage, resulting in the development of Lake Humber. The moraine deposits were breached approximately 11,000 years BP. Lake Humber gradually drained, allowing a river system with flanking levees to develop over fine-grained lacustrine deposits (Gaunt *et al.*, 1971; Gaunt, 1981). This coincided with forest regeneration in the Swale catchment (Blackham *et al.*, 1981). River channels became deeply incised until a gradual rise in sea level resulted in a phase of fluvial alluviation in the Vale of York around 8500 years BP (Gaunt *et al.*, 1971).

The fluvial development of the Yorkshire Dales during the Holocene can be characterised by alternating periods of incision and aggradation, linked to climatic variations, and, over the last thousand years, human disturbances such as deforestation and increased cultivation (Macklin *et al.*, 2000). This has caused the development of pronounced terrace sequences in upland areas of catchments such as the Swale and Wharfe (Taylor and Macklin, 1997; 1998; Howard *et al.*, 1999; Taylor *et al.*, 2000). In contrast, aggradation and sediment storage are likely to have dominated the Holocene development of lowland reaches of the Swale and adjacent catchments (Taylor *et al.*, 2000).

2.1.6. Fluvial geomorphology

In the upper reaches of the Swale, a narrow, high-gradient channel flows through a narrow valley (Figure 2.4). A number of prominent bedrock exposures can be observed on the

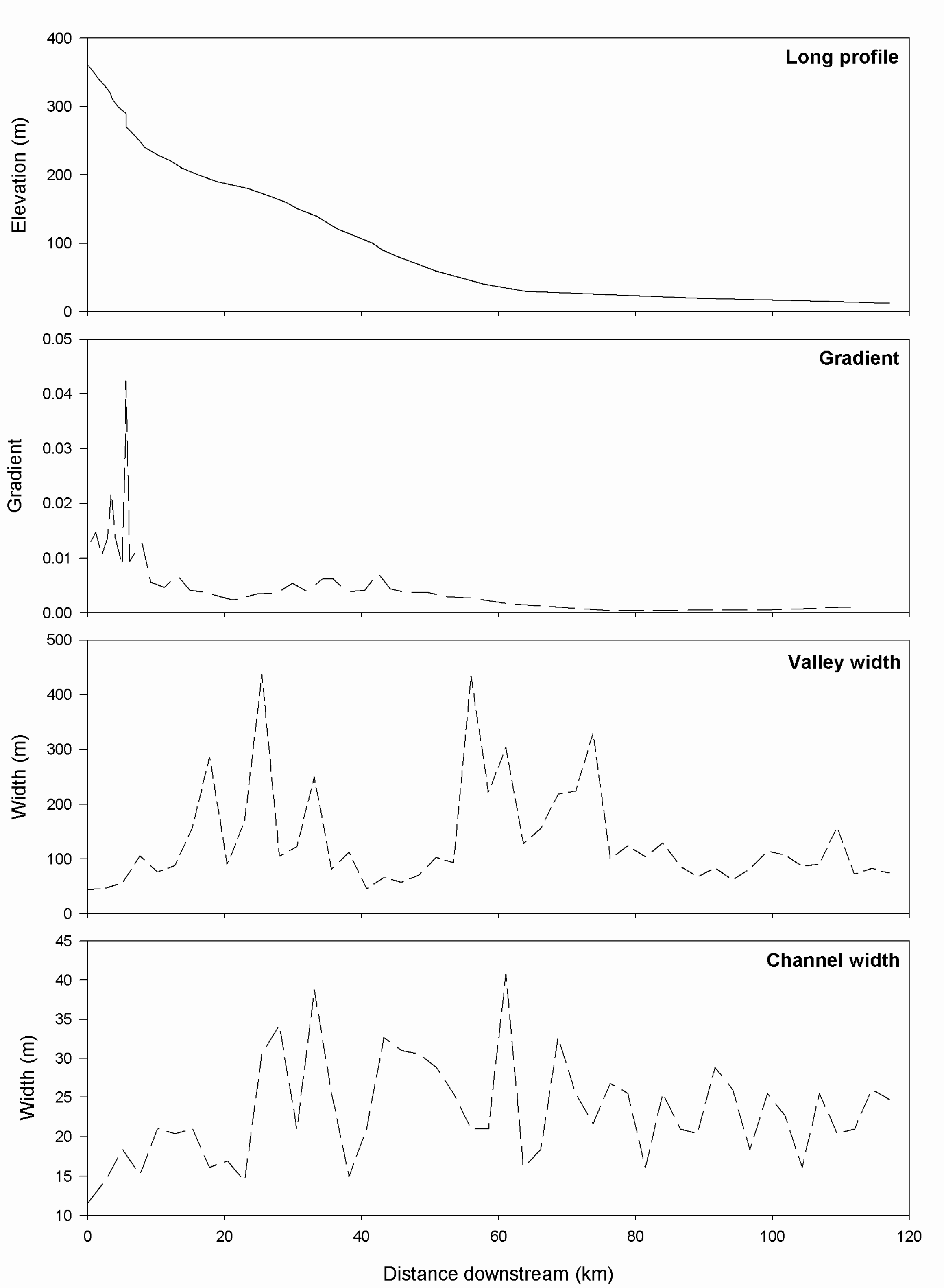

Figure 2.4: Geomorphological characteristics of the River Swale (measured from OS 1:10,000 scale Landline data). Valley width is defined as the maximum width of the floodplain and adjacent terraces

valley sides, and similar outcrops in the channel have caused the formation of several small waterfalls. Extensive floodplain deposits can be observed further downstream, as the river enters the wide, formerly glaciated U-shaped valley of Swaledale. These conditions continue for until approximately 40 km downstream, where the channel widens and the river enters a narrow, steep-sided valley. The Swale leaves the narrow reach approximately 15 km further downstream, as it enters the piedmont zone. The valley widens considerably and channel gradient decreases in the topographically flat Vale of York.

Fluvial development over the past several hundred years has been dominated by variations in flood frequency and magnitude (Longfield and Macklin, 1999; Merrett and Macklin, 1999). Longfield and Macklin (1999) reconstructed changes in flood magnitude and frequency in the Ouse catchment from instrumental records of flood events at York maintained since 1878. Five distinct periods (1878-1903, 1904-1943, 1944-1968, 1969-1977 and 1978-1996) of differing flood frequency and magnitude and associated sediment flux were identified within the record (Table 2.1). These variations are likely to be linked to variations in atmospheric circulation patterns and land use changes which occurred during the 119-year record (Longfield and Macklin, 1999). Flood frequency and magnitude both appear to have increased during the twentieth century, with the most severe floods occurring in the last 25 years (Longfield and Macklin, 1999). Westerly circulations appear to be the dominant driving force behind smaller floods, while cyclonic conditions are likely to be the major climatic cause of larger events. Sediment fluxes have varied during the study period, largely as a response to land use changes and increased flood frequency and magnitude. Fluxes occurring over the last 25 years are likely to be the highest since the cessation of metal mining at the end of the nineteenth century (Longfield and Macklin, 1999).

Merrett and Macklin (1999) used lichenometric dating of coarse flood deposits to reconstruct fluvial response patterns to extreme flooding in the Yorkshire Dales. Three periods of enhanced flood magnitude have been identified in the geomorphic record (Merrett and Macklin, 1999) (Table 2.2). The first of these occurred between 1750 and 1800, and was characterised by increased valley floor aggradation. The second, smaller increase in flood magnitude occurred between 1850 and 1900. This period was characterised by incision throughout the Yorkshire Dales, with the exception of parts of

Table 2.1: Flood frequency and magnitude in the Yorkshire Ouse basin, reconstructed from instrumental records (after Longfield and Macklin, 1999)

Period	Frequency and magnitude	Sediment flux	Flood generating conditions
1878-1903	Low	High due to metal mining	Westerly and Cyclonic
1904-1943	Low	Low	Westerly
1944-1968	High	High due to moorland drainage	Westerly
1969-1977	Low	Low	Cyclonic
1978-1996	High	High due to changes in farming practices	Cyclonic

Table 2.2: Flood frequency and magnitude in the Yorkshire Ouse basin, reconstructed from flood deposits (after Merrett and Macklin, 1999)

Period	Frequency and magnitude	Fluvial Response
1600-1750	High (but few flood units)	Aggradation
1750-1800	High	Increased valley floor aggradation
1800-1850	Low (but many flood units)	Incision
1850-1900	High	Aggradation in heavily mined reaches
1900-1940	Low	Incision
1940-1990	High	

Swaledale, where metal mining increased sediment supply. The final period occurred between 1940 and 1990, which was characterised by extensive drainage in upland moorland catchments and a resulting increase in flood magnitude and sediment supply. Flood frequency and magnitude declined between the periods of enhanced flooding, resulting in decreased sediment supply and widespread incision. Deposits from these periods are generally finer than those from periods of enhanced flooding, since flood competence would have decreased along with magnitude (Merrett and Macklin, 1999).

These variations in the frequency and magnitude of large floods generally agree with those reconstructed from instrumental records by Longfield and Macklin (1999).

Other geomorphological investigations indicate that the Swale catchment is extremely sensitive to the effects of extreme flooding. Flash floods frequently occur in upper Swaledale, transporting large amounts of material down the valley. A particularly large event occurred in 1883, when the river rose by an estimated 9.4 metres at Keld, depositing and estimated 1000 tons of sediment per acre in some areas (Pounder, 1989). Lichenometric dating of terrace deposits cut into an alluvial fan at the base of Whitsundale Beck in upper Swaledale suggests that the lowest units were formed during a major flood in 1899, when the nearby bridge over the river was destroyed (Pounder, 1989). The small fan that has developed from the mouth of Great Ash Gill is also thought to have formed during this flood (Pounder, 1989). Similar investigations in Shaw Beck, Arkengarthdale, reveal a series of coarse terrace units associated with large historic flood events (Newson and Macklin, 1990; Macklin, 1997; Merrett and Macklin, 1998). Lichenometric dating suggests that these units were formed between 1795 and 1976, although the majority of deposits are likely to be associated with large events that occurred in 1828, 1846 and 1866 (Merrett and Macklin, 1998; Merrett, 2001).

The particularly large storms associated with Hurricane Charley in August 1986 led to the creation of new flood deposits in Shaw Beck. 116.5 mm of rain fell in Arkengarthdale between 1700 on 25th August and 1500 on 26th August (Newson and Macklin, 1990). This caused a small reservoir situated at the head of Shaw Beck to fail, sending a flood wave with an estimated peak discharge of 23.4 m^3s^{-1} down the valley (Newson and Macklin, 1990). This broke through spoil tips associated with the disused Stang Mine, and transported several thousand tonnes of waste up to 300 m downstream (Macklin, 1997). In wider areas of the valley, the pre-flood channel was infilled and the floodplain was buried in up to a metre of coarse sediment. At narrower zones, however, older alluvium was stripped out and localised incision occurred (Newson and Macklin, 1990). Large amounts of coarse material were also transported in Gunnerside Beck during this event (Pounder, 1989).

Several recent studies have investigated patterns of contemporary bank erosion in the Swale catchment. Work by Grove and Sedgwick (1998) and Lawler *et al*. (1999) suggests that bank erosion rates are relatively low in upstream and downstream reaches, and are high in middle reaches of the river. This increase in erosion rate corresponds to the active piedmont zone, where stream power is high and the banks are easily erodible (Grove and Sedgwick, 1998). Lower rates of erosion in upland reaches may be attributable to low stream power and therefore little entrainment of particles from the banks (Lawler *et al.*, 1999). Mid-bank erosion rates display a distinct seasonality, particularly in the upper catchment, peaking between December and March as a response to the loosening of material by freeze-thaw activity and subsequent entrainment during more frequent high flow events (Grove and Sedgwick, 1998). Bank top and toe erosion rates show less seasonality, as a result of thermal buffering by vegetation and stream water, respectively (Grove and Sedgwick, 1998). In addition to these studies, a river habitat and corridor survey were undertaken as part of the River Swale Regeneration Project during summer 1999. 500 m sections of the River Swale were surveyed using standard Environment Agency techniques (River Swale Regeneration Project, 2001). Statistical analysis of the resulting data set indicates that the majority of bank erosion occurs adjacent to areas of rough pasture, suggesting that grazing on the river bank increases erosion rates.

Floodplain and channel sedimentation patterns in the Swale catchment have also been investigated by Walling *et al*. (1998b; 1999b). These studies suggest that mean annual sedimentation rates, inferred by ^{137}Cs dating of floodplain sediment cores, are generally low in the upper Swale (Walling *et al.*, 1998b). Sedimentation increases markedly in the piedmont zone, before decreasing slightly in the lower reaches of the Swale (Walling *et al.*, 1999b). A similar pattern is displayed by total annual floodplain sediment, although channel sediment storage patterns increase steadily with distance downstream (Walling *et al.*, 1998b). These data were used to calculate total annual storage of sediment for the Swale as a whole. A total sediment load of 61,566 t yr^{-1} is delivered to the system, compared to a mean suspended sediment load of 42,352 t yr^{-1}. This suggests that approximately 31 % of the total sediment budget of the Swale system is lost to floodplain and channel storage each year (Walling *et al.*, 1999b).

A composite fingerprinting procedure has been used by Walling *et al*. (1999a) and Owens *et al.* (1999) to reconstruct suspended and floodplain sediment provenance in the River Swale catchment. The results of this procedure indicate that the amount of sediment derived from each bedrock type is proportional to the area that the bedrock underlies (Walling *et al.*, 1999a). The proportion of material derived from each geological sub-basin displays some variation over the last *c*. 100 years, possibly as a result of changes in land use and climatic fluctuations (Owens *et al.*, 1999). The fingerprinting procedure was also used to identify the type of material derived from each source area. Relatively limited areas of cultivated land appear to contribute more sediment to the fluvial system than the uncultivated land that dominates the catchments (Walling *et al.*, 1999a). This is reflected in the high amount of material from topsoil sources that is observed in overbank deposits. In addition to this, the proportion of material derived from subsoil and channel bank sources has increased over the last few decades, indicating that land use and climatic changes are influencing both the type and source of sediment in the fluvial system (Owens *et al.*, 1999).

2.2. METAL MINING IN THE SWALE CATCHMENT

2.2.1. The history of lead mining in Swaledale

The earliest evidence of lead mining in Swaledale comes from the Hurst Mine, where a pig of lead inscribed with the name of the Roman Emperor Hadrian (AD 117-138) was discovered, along with a number of wooden tools (Raistrick and Jennings, 1965). However, it is likely to have been occurred since before the Roman period, although no evidence of pre-Roman workings has been located. However, this may be due to the reworking of old sites by later miners (White, 1998). It is likely that early organised mining in Swaledale ended during an uprising by the Brigantes tribe in AD 155 (Collingwood and Myers, 1937), although it may have continued until the end of Roman occupation in the 5th century AD.

There are no records of mining over the next four hundred years, and it is likely that most mines were abandoned (Raistrick and Jennings, 1965). Lead extraction resumed after the Danish conquest of northern Britain in the 9th century, from established sites such as the Old Gang (*Ald Gang*) mines between Gunnerside Beck and Barney Beck. Small scale mining continued after the Norman Conquest, although it is unlikely that any new prospecting occurred (Raistrick and Jennings, 1965).

Mining became important from the 12th century, when lead from Swaledale was used in the construction of large buildings such as Waltham, Rievaulx and Clairvaux Abbeys (Raistrick and Jennings, 1965). Extraction during this time was tightly controlled by the monasteries, which issued leases to miners and collected royalty payments. Output gradually increased until the Henry VIII dissolved the monasteries in England and Wales between 1536 and 1540. Lead was stripped from church roofs and sold cheaply; approximately 500 tonnes was removed from Rievaulx Abbey alone (Morrison, 1998). This severely depressed market prices and caused many larger mines to close. Speculative mining increased greatly, as those who had taken over monastic land sold extraction rights to small groups of miners (Raistrick and Jennings, 1965). In approximately 1540, John Leland noted that '*The men of Sualdale be much usid in digging Leade Owre* [from the] *great Hills on each side of Sualdale*', suggesting that small-scale mining was commonplace at this time (Fieldhouse and Jennings, 1978).

By the time of the Industrial Revolution in the late eighteenth century, lead extraction had become more organised. Large commercial enterprises such as the London Lead Company leased significant areas of land and commenced industrial scale mining operations with systematically worked shafts and levels (Raistrick and Jennings, 1965). Mines dating from this period were primarily located in Gunnerside Beck, Barney Beck and Arkle Beck, with smaller numbers located in Swinner Gill and Marske Beck (Figure 2.5). Many of the mines were relatively short lived, producing several hundred tonnes of lead ore before being abandoned. Others, such as Surrender Mine in Arkengarthdale, the Old Gang mines in Barney Beck and Grinton Liberty mine in Cogden Gill, were operative for almost one hundred years and produced tens of thousands of tonnes of lead. Output from Swaledale remained high until the late nineteenth century, when increased competition from abroad effectively ended the British lead mining industry (Raistrick and Jennings, 1965).

2.2.2. Mining and processing techniques

Early mines employed small open pits and shallow shafts and trenches to extract material from veins outcropping at or near the surface. As technology developed during the eighteenth century, deeper shafts and horizontal levels were also employed to extract ore bodies (White, 1998). In addition to this, a technique known as hushing was also used to locate and extract lead ores. In this method, a reservoir was constructed above the area likely to contain lead ore. The reservoir was then breached, releasing a torrent of water that removed the surface soil, exposing the underlying bedrock and mineral veins (Gill,

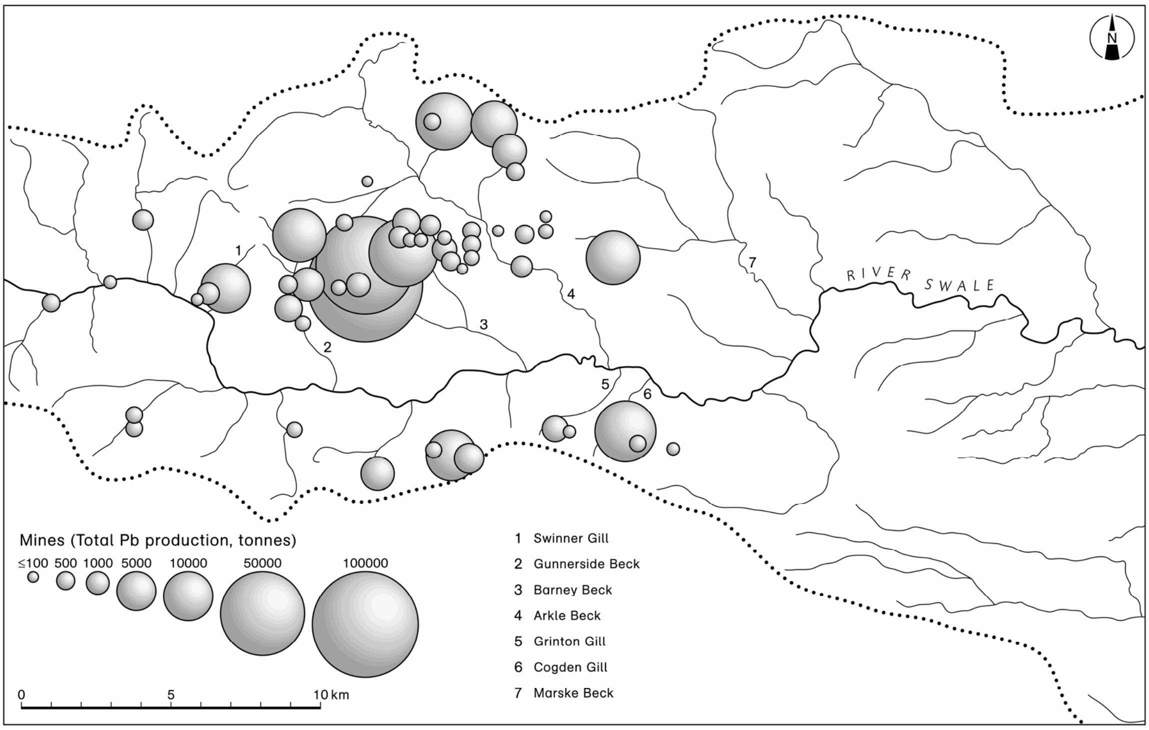

Figure 2.5: Location and output (c. AD 1700-1900) of Pb mines in Swaledale

2001). Once located, the veins were worked using simple quarrying techniques, with hushing being used to periodically remove debris from the working area. The use of this technique was particularly prevalent in Arkengarthdale and Gunnerside Beck, where it was employed until the early nineteenth century (Gill, 2001). Evidence of these hushes still dominates the present day landscape in these tributaries (Plate 2.1).

When extracted, the lead ore was processed in Swaledale using a multi-stage process. The first stage was known as dressing (Figure 2.6). The raw material from the mine, known as *bouse*, was tipped into a *bouse team*, where ore was loosened from gangue material with the aid of water (Plate 2.2) (Gill, 2001). The mixture was washed through a grate, and finer material was collected. Coarser ore-bearing material was then separated from gangue, and crushed by hand or with the aid of water powered rollers (Plate 2.3) (Jennings, 1963; Morrison, 1998). A density separation process was then used to remove the heavy lead particles from the lighter gangue minerals and country rock (White, 1998). The mixture was agitated in a *hotching tub*; a water-filled wooden box in which a sieve was suspended. The larger pieces of ore were collected from the top of the sieve, while the finer material, known as *smitham*, was allowed to settle at the base of the tub. The light gangue material was skimmed off the top of the smitham and discarded, while the

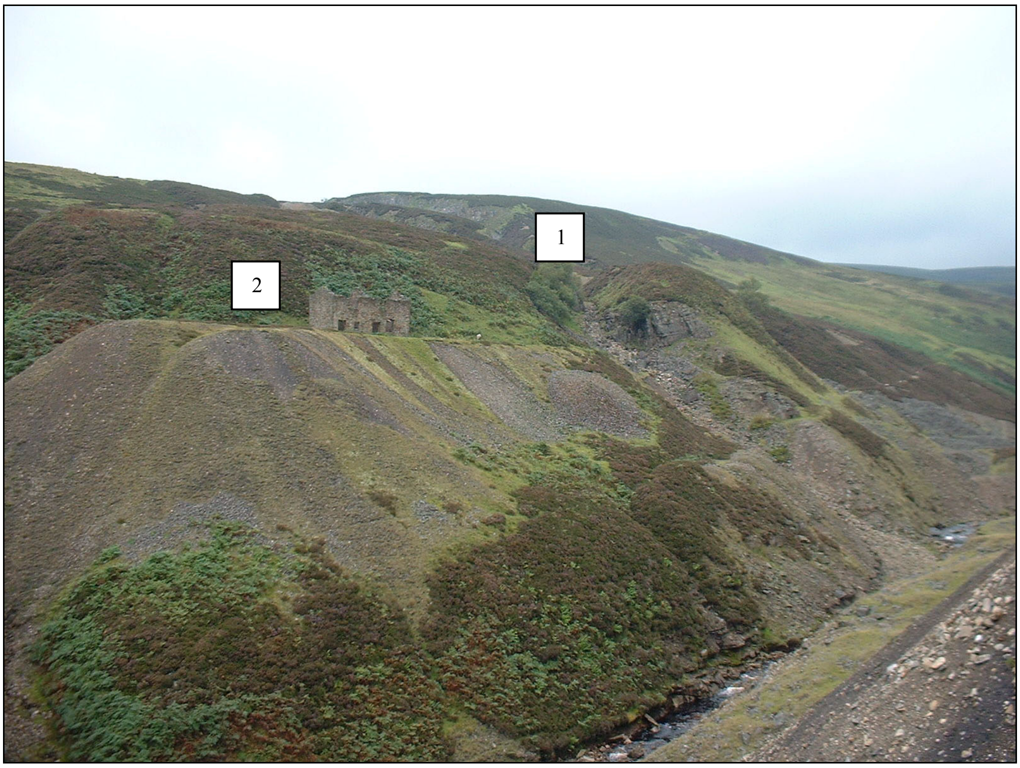

Plate 2.1: North Hush (1) and Priscilla Level (2), Gunnerside Beck

Plate 2.2: Bouse teams, Old Gang Company dressing floor, Sir Francis Level, Gunnerside Beck. Water was channelled behind the structures (1) and through each individual bouse team (2)

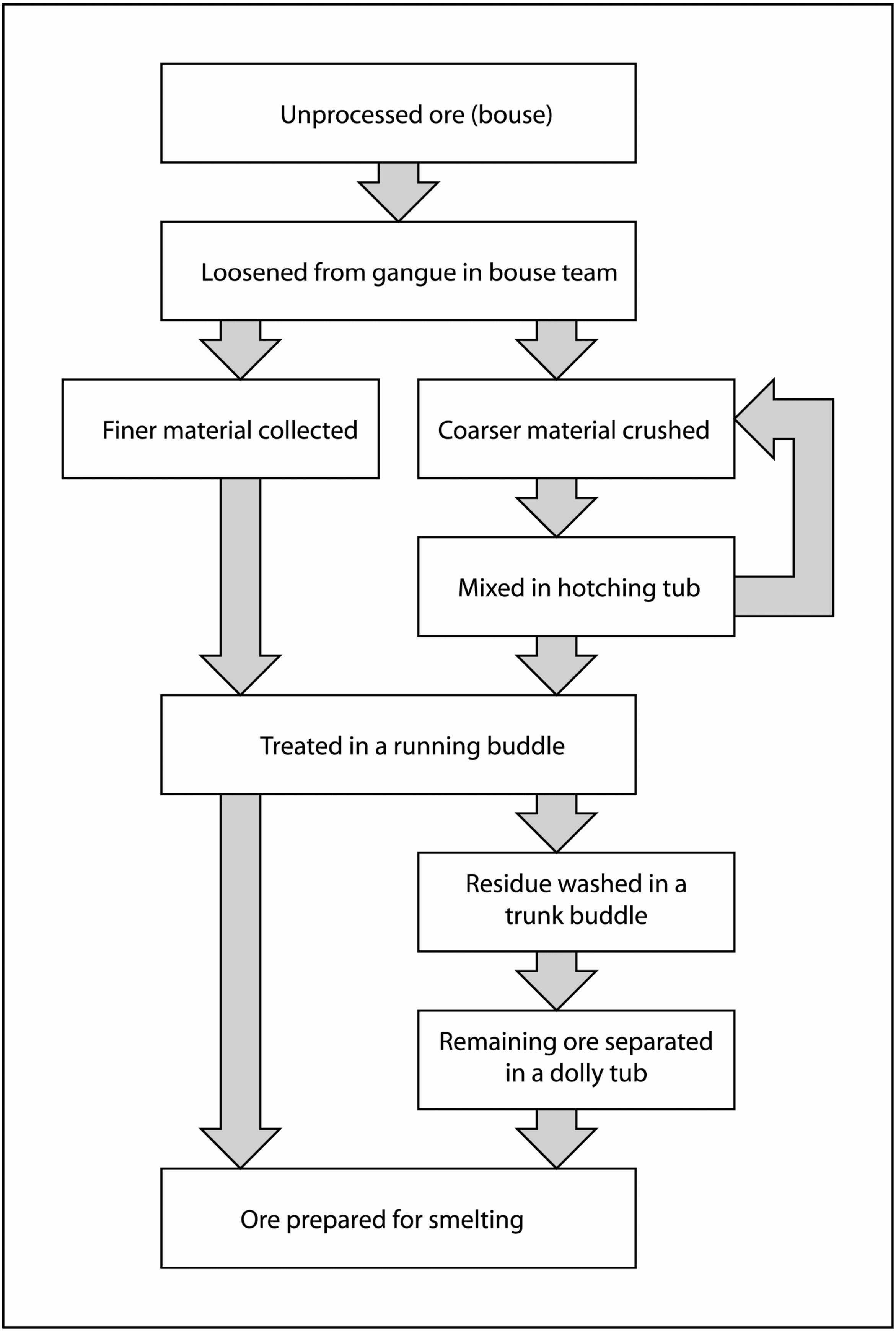

Figure 2.6: The ore dressing process employed in Swaledale lead mines

Plate 2.3: Water-powered crusher, Bunton Level, Gunnerside Gill (from Morrison, 1998)

heavy ore at the bottom was collected. Pieces of ore attached to rock fragments formed a middle layer, and were again crushed in order to separate the ore (Gill, 2001).

The resulting fine material was then treated in a *running buddle*. This consisted of a shallow wooden or stone channel with a sloping floor. Material from the hotching tub was placed at the top of the channel and raked against the flow. Lighter gangue materials and the finest pieces of ore were washed out of the buddle into slime pits for settling (Raistrick and Jennings, 1965). The largest pieces of ore remained at the head of the buddle, from where they were collected. The remaining mixture of gangue and small pieces of ore was collected from the foot of the buddle (Gill, 2001). This buddle-foot material, along with material from the slime pits, was repeatedly washed in a *trunk buddle* until no more gangue could be separated, and then treated in a *dolly tub* (Morrison, 1998). The remaining material was slowly agitated in this bucket-like, water-filled device (Gill, 2001). This allowed heavy ore particles to settle at the base of the tub, from where they were collected, while lighter materials remained in suspension.

The ore produced in the dressing process was then smelted to produce lead. During this process, galena (lead sulphide) was initially converted into lead oxide and sulphur dioxide by heating in an oxidising atmosphere (Equations 2.1 to 2.4). During the Mediaeval period, small wind-blown furnaces known as bales were used in this stage of the smelting process, over eighty of which have been located in the Swale catchment (White, 1998). These were replaced by larger and more efficient ore-hearths in the 1570s. An ore-hearth was a small bellows-driven blast furnace in which the ore was mixed with a fuel such as peat or charcoal. The bellows were often driven by a water wheel, allowing the smelt process to be more closely controlled. Both pure lead and a mixture of lead oxide and sulphate, known as grey slag, were collected from the hearth, while sulphur dioxide gas was released through a chimney or flue (Equations 2.1 to 2.4) (Gill, 2001).

$$2PbS + 3O_2 = 2PbO + 2SO_2 \tag{2.1}$$

$$2PbO + PbS = 3Pb + SO_2 \tag{2.2}$$

$$2PbS + 4O_2 = 2PbSO_4 \tag{2.3}$$

$$PbS + PbSO_4 = 2Pb + 2SO_2 \tag{2.4}$$

The grey slag was then introduced into a reducing atmosphere to produce pure lead (Equations 2.5 to 2.7). This was achieved in a slag hearth, in which the mixture of lead oxide and sulphate, along with poor quality ores, was combined with carbon fuel in the form of peat or coal. Pure molten lead and glassy black slag were tapped off, while a mixture of sulphur dioxide and carbon dioxide gases was released through a flue (Equations 2.5 to 2.7). The black slag was often crushed and re-processed to extract any remaining lead (Gill, 2001).

$$2PbO + CO = 2Pb + CO_2 \tag{2.5}$$

$$PbSO_4 + 2CO = Pb + SO_2 + 2CO_2 \tag{2.6}$$

$$2PbO + C = 2Pb + CO_2 \tag{2.7}$$

Dressing floors and smelters were often located close to the mines, with several situated in Gunnerside Beck, Barney Beck, Arkle Beck, Marske Beck and Cogden Gill (Figure 2.7).

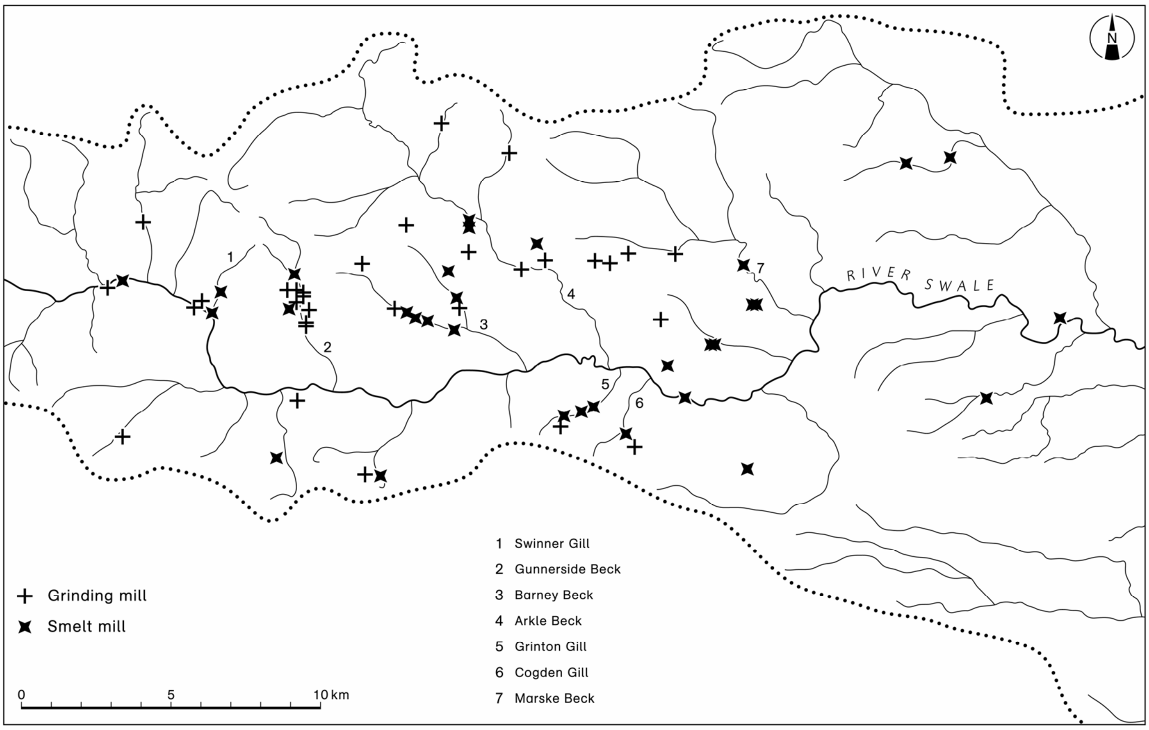

Figure 2.7: Location of smelters and dressing floors in Swaledale

Ores were often transported from mines operated by the same company to a single processing area. For example, the AD Lead Mining Company, which operated mines in Swinner Gill, Gunnerside Beck and Barney Beck, ground and smelted the ores at Surrender Smelt Mill in Barney Beck (Plate 2.4) (Gill, 2001).

The processing of lead ore was a relatively inefficient process. Statistics compiled by Hunt (1848a; 1848b) suggest that only 60 – 70 % of Pb was recovered from the galena, which typically contains 86.6 % Pb. This means that a significant proportion of the total Pb extracted in the catchment is likely to have been discarded on spoil tips or released directly into the river system.

Plate 2.4: Surrender smelt mill, Barney Beck

2.2.3. Mining production records

Early mine production records are frequently incomplete or inaccurate, although those available for Swaledale are amongst the most complete in the United Kingdom (Gill, *pers. comm.*). A detailed reconstruction by Gill (unpublished) includes all surviving details of recorded lead production from all the mines in Swaledale from 1684 to 1913. These records indicate that, by the time the industry had ended, mines in Swaledale had produced over 350,000 tonnes of lead. However, this is almost certainly an underestimate, as the production records are far from complete.

Dunham and Wilson (1985) made tentative production estimates based on geological evidence and mining records for three major sub-divisions of the Swaledale mining area: the heavily mineralised North Swaledale Mineral Belt, the Richmond area, and South Swaledale and parts of northern Wensleydale (Tables 2.3 to 2.5). Although there are still likely to be some uncertainties with these estimates, they suggested that total lead production in Swaledale was at least 550,000 tonnes (Dunham and Wilson, 1985). Lead output was dominated by the Old Gang mines located in Barney Beck, whose production accounts for 65 % of the total output (Figure 2.8). Other large mining operations in Arkle

Table 2.3: Recorded and estimated lead production (after Dunham and Wilson, 1985)

Area	**Period**	**Recorded output (tonnes)**	**Estimated additional output (tonnes)**	**Total (tonnes)**
North Swaledale	1696 - 1913	339,612	215,000	554,612
South Swaledale	1851 - 1893	46,192	84,000	130,192
Richmond	1864 - 1874	1305	1016	2321

Table 2.4: Recorded production of lead metal and concentrates in the North Swaledale Mineral Belt (after Dunham and Wilson, 1985; Fieldhouse and Jennings, 1978)

Mining group	**Years**	**Lead metal (long tonnes)**	**Concentrates (long tonnes)**
A.D. Old Gang - Lownathwaite	1696-1700	2200	3750
A.D. Mines	1786-1913	148,251	220,253
C.B. Mines	1783-1912	65,724	96,886
Hurst	1852-1890	9340	13,375

Table 2.5: Recorded production of lead metal and concentrates in the South Swaledale mining zone (after Dunham and Wilson, 1985)

Mining group	**Years**	**Lead metal (long tonnes)**	**Concentrates (long tonnes)**
Grinton	1775-1893	2431	4031
Oxnop – Summer Lodge	1817-1872	1081	1550
Mukerside, Whitaside, Ellerton	1861-1896	577	791

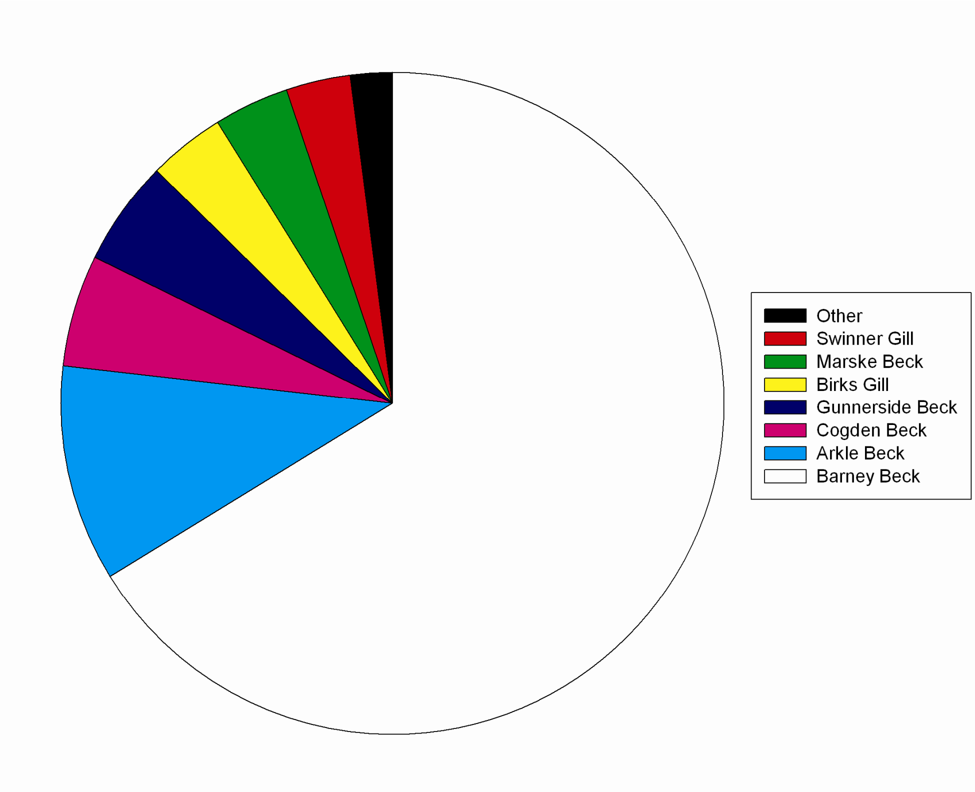

Figure 2.8: Total Pb production by tributary (based on data from Gill, pers. comm.)

Beck, Gunnerside Beck, Grinton Gill, Cogden Gill and Marske Beck account for much of the remaining lead production.

Small amounts of other minerals such as fluorite, baryte and copper were also extracted within the Swale catchment. Copper ores may have been extracted in the Richmond area from as early as 1454, with later periods of extraction occurring during the mid-eighteenth and mid-nineteenth centuries. Production is likely to have ceased by 1879, by which time upwards of 6600 tonnes had been extracted (Dunham and Wilson, 1985). Relatively small quantities of fluorite and baryte were produced (*c.* 2500 and 35,000 tonnes, respectively), often through the reworking of old spoil tips in the early twentieth century (Dunham and Wilson, 1985). As the lead mining industry declined, small amounts of silver were recovered from the galena concentrates produced from a number of mines in the North Swaledale Mineral Belt. The amount of silver contained in the ore was very small (typically less than 4 oz Ag per tonne Pb), and had previously been regarded as uneconomical to extract (Dunham and Wilson, 1985).

2.3. THE IMPACT OF METAL MINING ON THE RIVER SWALE SYSTEM

2.3.1. The potential impacts of mining and processing

As stated in Section 2.2.2, the mining and processing techniques employed during the eighteenth and nineteenth centuries were relatively inefficient, and introduced large quantities of contaminated material into the environment. Water was an intrinsic part of the process, being employed to expose ore seams, drive crushing and smelting mills, and to sort ore from gangue material. Many dressing floors had their own supply of water diverted from a nearby stream or reservoir (Raistrick and Jennings, 1965). Once it had been used in the dressing process, the water was discharged into the nearest stream. This caused considerable pollution in the River Swale at the time, as described in a contemporary account:

> '[Mining is] *detrimental to the spawn by impregnating the water with filth, poisonous minerals, and particles of lead. This for so many miles in its descent so pollutes and discolours the river with its thick dirty mud, that it gives it very much the appearance of the washings of the turnpike road after a heavy shower of rain.*'
>
> (Whitaker, 1823).

It is inevitable that much of the polluted sediment described by Whitaker (1823) was deposited on the floodplains and within the channels of both mined tributaries and the River Swale itself. Therefore, these floodplain and channel sediments are a potential source of contaminants to the contemporary fluvial system.

A large number of predominantly fine grained spoil and slag tips from mining and processing operations can still be observed in upland parts of the catchment. Large amounts of sphalerite, fluorite, baryte and witherite remain in the tailings heaps throughout the mined tributaries, along with appreciable amounts of galena. Geochemical investigations have revealed relatively high concentrations of Pb, Zn, Ni, Cu, Ba and F in mine spoil samples from throughout the catchment (Dunham and Wilson, 1985). Slag tips, such as those that can be observed at the Surrender smelt mill (Plate 2.4), are also likely to be highly contaminated. Geochemical investigations of Derbyshire slags dating from the Mediaeval period and the Industrial Revolution reveal that they are dominated by calcium, boron and lead compounds (Maskall *et al.*, 1996; Gee *et al.*, 1997). This is likely to be the case for similar deposits in Swaledale. The largely unvegetated spoil tips and slag heaps are therefore likely to remain a source of a range of contaminants through physical and chemical weathering and runoff processes.

2.3.2. Investigations of floodplain contamination

A number of studies of spatial and temporal patterns of floodplain contamination in the River Swale catchment have been carried out. These investigations reveal a long history of contaminated sediment deposition and storage in floodplains throughout the catchment. For ease of presentation, results from these studies have been grouped into upland (0 – 35 km downstream), piedmont (35 – 70 km downstream) and lowland zones (70 – 120 km downstream).

2.3.2.1. Upland contamination patterns

At Keld, in the upper reaches of the Swale, contamination is focussed on intermediate mining-age terraces that have now been abandoned through incision (Sedgwick, 2000). The highest terraces are uncontaminated, suggesting that they were not inundated while mining took place, while the present floodplain is less contaminated due to the deposition of cleaner sediment during frequent periods of post-mining inundation (Sedgwick, 2000). Metal concentrations exhibit a distinct down-profile variation. Sediments are uncontaminated below a depth of approximately 25 cm. Above this, Pb concentrations reach a peak of 1400 mg kg^{-1} at approximately 20 cm depth. Concentrations remain elevated at approximately 400 mg kg^{-1} in the upper part of the profile (Sedgwick, 2000).

A series of floodplain cores taken further downstream by Brennan and Macklin (reported in Macklin *et al.*, 1994) display a similar pattern. The first core, located just upstream of Gunnerside Beck, shows maximum Pb concentrations of approximately 1500 mg kg^{-1} at a depth of 70 cm. It is likely that this material was deposited during the peak of mining activities in the area during the 1850s and 1860s (Macklin *et al.*, 1994). In the second core, taken downstream of Gunnerside Beck, two large peaks in Pb concentration can be observed. The first, at a depth of 1 metre, shows concentrations of Pb in excess of 8000 mg kg^{-1}. In the second, at a depth of 70 cm, concentrations of Pb reach 6000 mg kg^{-1}. A similar pattern has been observed in a core from a nearby site by Sparks (1998). In a final core, taken downstream of Barney Beck, peak Pb concentrations of 30000 mg kg^{-1} can be observed at a depth of 70 cm (Macklin *et al.*, 1994).

Similar patterns have been observed further downstream in a laterally active reach at Reeth. Contamination is focussed on the lower terrace surfaces that were frequently inundated during the mining period. These are no longer inundated due to the construction of a flood embankment after the cessation of mining, preventing dilution with cleaner sediment (*cf.* Lewin *et al.*, 1977). Higher surfaces that were adjacent to the mining-era channel also exhibit elevated metal concentrations (Sedgwick, 2000). Metal concentrations are highest at a depth of between 70 and 80 cm, with Pb reaching 5000 mg kg^{-1}. Pb concentrations remain high further down the profile, at approximately 2000 mg kg^{-1}, and in more recent sediments where concentrations of 1000 mg kg^{-1} can be observed (Sparks, 1998; Sedgwick, 2000).

2.3.2.2. Piedmont contamination patterns

The narrow, confined valley at Lowenthwaite in the piedmont zone has limited floodplain development. Contamination is focussed on high and intermediate terrace units, which were inundated during severe mining-era floods (Sedgwick, 2000). 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).

A different pattern has been observed further downstream, at Brompton-on-Swale, near Catterick. At this site, contamination is focussed on lower terraces that have been regularly inundated since the pre-mining era, with Pb concentrations reaching 3000 mg kg^{-1} (Taylor and Macklin, 1997). Heavy metal concentrations generally decrease towards the present channel and with depth; sediments below 100 cm are uncontaminated (Taylor and Macklin, 1997). Approximately 1.5 km downstream, at Catterick, contaminated sediments form a thin veneer across the floodplain surface (Hudson-Edwards *et al.*, 1999b). Pb concentrations reach a peak of 4500 mg kg^{-1} at depth, and decline closer to the surface.

The highly active piedmont reach at Kirkby Fleetham displays a similar pattern to that of Lowenthwaite, with contamination focussed on higher terrace units that are now protected by a post-mining era flood embankment (Sedgwick, 2000). In areas where this embankment is discontinuous, concentrations decrease with distance from the channel. Pb concentrations reach a peak of *c.* 4000 mg kg^{-1} between 150 and 250 cm depth, and decline towards the surface (Carter, 1998).

2.3.2.3. Lowland contamination patterns

At Morton-on-Swale in the lower reaches of the river, metal concentrations generally decline towards the channel due to the regular deposition of clean sediment on lower terrace units (Sedgwick, 2000). Concentrations are highest on higher terrace units adjacent to an ox bow lake that was active during the mining period. Pb concentrations increase with depth from *c.* 1000 mg kg^{-1} at the surface to 5800 mg kg^{-1} at a depth of 120 cm (Sedgwick, 2000). A similar pattern can be observed further downstream at Maunby, with metal concentrations highest on upper terrace units (Carter, 1998). 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 are uncontaminated (Carter, 1998).

At Thornton, another lowland reach of the Swale, metal concentrations are generally uniformly low across the floodplain due to a series of flood embankments that were constructed prior to the onset of industrial mining activities (Sedgwick, 2000). Concentrations are elevated considerably in an area that had no flood protection until the early twentieth century. Pb concentrations are generally uniform at 300 mg kg^{-1} with depth, although the top of the section displays some enrichment. This may be attributable to traffic pollution from a nearby road (Sedgwick, 2000). A slightly different pattern can be observed at Myton-on-Swale, close to the Swale-Ouse confluence. The absence of flood embankments has allowed metal-enriched sediment to form a thin veneer of contamination across the floodplain (Hudson-Edwards *et al.*, 1999b). Peak Pb concentrations of 932 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).

2.3.2.4. Summary of catchment-scale patterns

The previous investigations outlined in sections 2.3.2.1 to 2.3.2.3 show that patterns of floodplain contamination in the Swale catchment are extremely complex. In general, metal concentrations start off high in the upland zone, increase markedly downstream of the major mined tributaries, before gradually decreasing with distance downstream from the mined area. The depth at which peak concentrations occur appears to increase with distance downstream, probably as a result of increasing sediment yield. However, this pattern is not apparent for several lowland sites due to the presence of extensive flood embankments.

Spatial contamination patterns show considerable variability along the length of the Swale, and appear to be strongly influenced by the floodplain morphology of specific study sites. Generally, however, contamination is focussed on higher terraces that were regularly inundated during the mining period.

2.3.3. Investigations of channel sediment contamination

The geochemistry of active fluvial sediments in the River Swale has previously examined by Gamesby (1997), Grove and Sedgwick (1998) and Sedgwick (Sedgwick, 2000) (Figure 2.9). Metal concentrations are low in the headwaters of the Swale, upstream of the mining area. A series of peaks can be observed immediately downstream of mined tributaries such as Swinner Gill, Gunnerside Beck, Barney Beck and Arkle Beck, suggesting that contaminated sediments are remobilised from these streams (Grove and Sedgwick, 1998). Contamination is greatest downstream of the heavily mined Barney Beck, with concentrations of 4500 mg kg^{-1} Pb, 6500 mg kg^{-1} Zn and upwards of 20 mg kg^{-1} Cd observed in channel sediments (Gamesby, 1997; Sedgwick, 2000). Metal concentrations decline sharply after each of these inputs, but remain elevated for a considerable distance downstream of the mining area (Figure 2.9).

The storage of sediment-associated nutrients (Owens *et al.*, 2001) and contaminants (Walling *et al.*, 2003a) in the River Swale has also been evaluated. In these studies, concentrations of Cr, Cu, Pb, Zn, P and 23 PCB congeners were measured in samples of fine grained overbank and channel sediments collected from seven sites between November 1997 and January 1999. Cr and P concentrations were found to be relatively constant along the river, while PCBs were below detection limits (Owens *et al.*, 2001). A Cu anomaly likely to be attributable to Cu-rich Triassic bedrock was observed in the lower reaches of the Swale (Walling *et al.*, 2003a). Pb and Zn concentrations display a marked downstream trend, with concentrations decreasing with distance from the mined area in the upper reaches of the catchment. Channel bed sediment storage is highest in the middle and lower reaches of the Swale; as a result, contaminant storage is also greatest in the

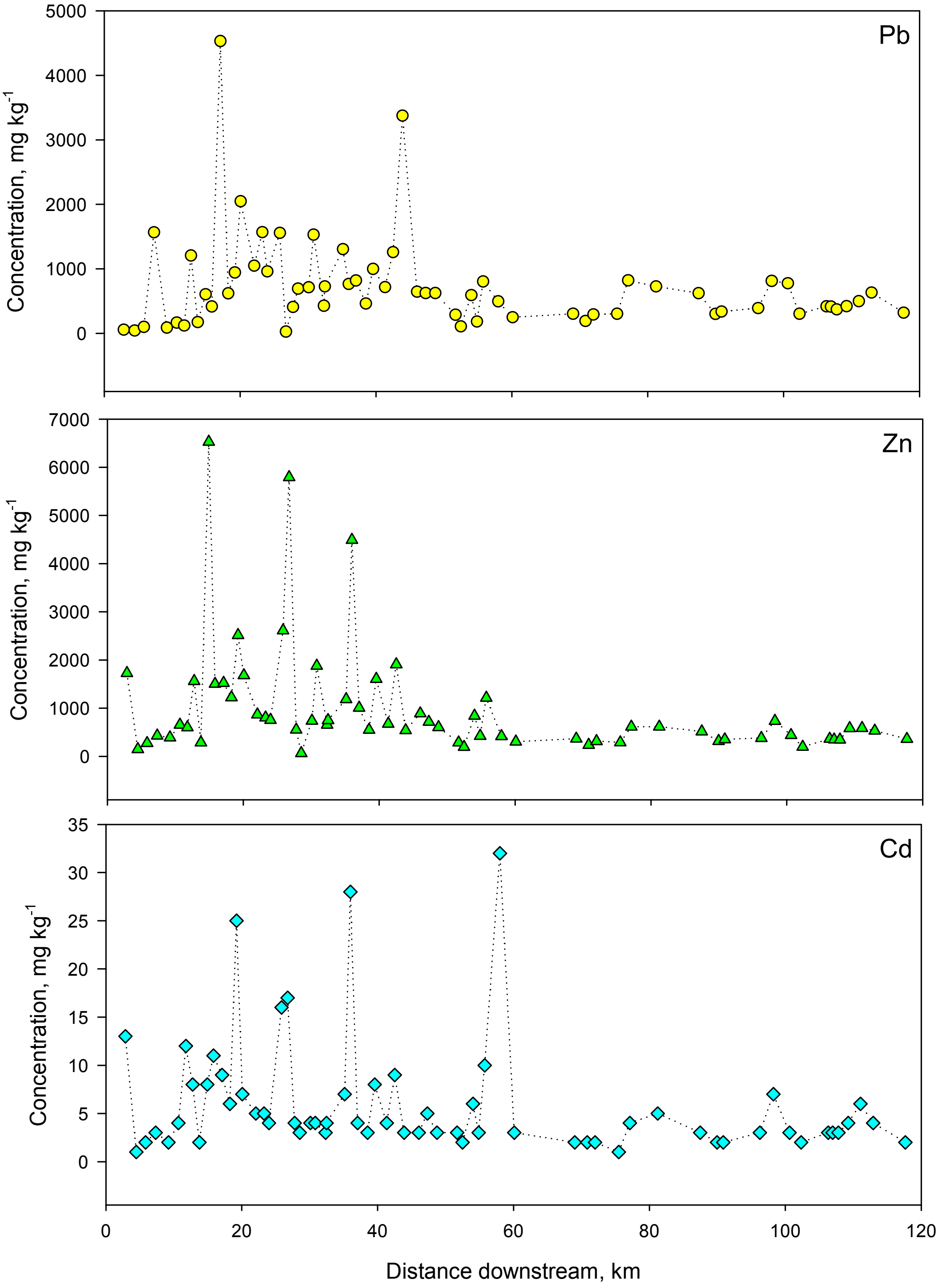

Figure 2.9: Metal contamination in River Swale channel sediments (after Gamesby, 1997; Sedgwick, 2000)

middle and lower reaches. However, Pb and Zn concentrations are generally low in these stretches of the river (Walling *et al.*, 2003a).

Average annual floodplain deposition rates between December 1997 and December 1999 were calculated using Astroturf mats located at four sites along the Swale. Deposition rates were observed to decrease with distance downstream, from 15.7 kg m^{-2} a^{-1} at the uppermost site to 8.6 kg m^{-2} a^{-1} at the site furthest downstream (Walling *et al.*, 2003a). No obvious downstream trends in contaminant content were observed. Annual contaminant flux declines with distance downstream, as a result of the observed decrease in sedimentation rate with distance from the source. Mean annual total deposition flux of contaminants to the Swale floodplain were calculated from direct field measurements during the study period, adjusted using detailed sedimentation rates interpolated from ^{137}Cs-dated floodplain cores (reported in Walling *et al.*, 1998b). These were estimated to be 27.821 t a^{-1} for Pb and 20.018 t a^{-1} for Zn. Channel bed storage of contaminants relative to total downstream flux was found to be low, accounting for only 1.5 % Pb and 1.4 % Zn. In contrast, mean annual floodplain deposition flux was calculated as 95 % of the downstream flux of Pb and 62 % of the downstream flux of Zn. This reflects the position of the source of these contaminants in the upper reaches of the Swale, allowing their loss along much of the length of the river (Walling *et al.*, 2003a). This suggests that the downstream flux of contaminants would be significantly greater in the absence of floodplain storage. Long-term estimates of mean annual floodplain storage are orders of magnitude greater than present fluxes (Walling *et al.*, 2003a).

2.3.4. Summary and required research

Evidence presented in previous studies (Sections 2.3.2 and 2.3.3) suggests that historic metal mining has left a lasting legacy on the Swale catchment. Floodplain sediments along the entire length of the river display a degree of contamination, and some reaches are severely polluted. Contemporary channel and overbank sediments have also been shown to be highly contaminated with heavy metals such as Pb, Zn and Cd. This suggests that contaminants are still being redistributed though the erosion of spoil tips and contaminated floodplain material, which may lead to potentially serious environmental problems.

Although previous investigations have demonstrated that metal-rich sediment continues to be cycled through the system almost 100 years after the cessation of mining, the full impact of historic metal mining has not been fully evaluated. Subsequent chapters will address this by building upon the existing literature to identify patterns of metal distribution in flood sediments, formerly mined tributaries and the floodplain, at a catchment scale. The relative importance of tributaries and floodplain sediments as sources of contaminated sediment will be evaluated, and the long-term significance of metal storage and remobilisation will be assessed.