

1 **Synoptic monitoring as an approach to discriminating between point**
2 **and diffuse source contributions to zinc loads in mining impacted**
3 **catchments**

4 V.J. Banks* and B. Palumbo-Roe

5 British Geological Survey, Keyworth Nottingham, NG12 5GG, UK

6 *Corresponding author

7

8 **Abstract**

9 One of the global legacies of industrialisation is the environmental impacts of historic
10 mineral exploitation. Recent national initiatives to manage the impacts on ground and
11 surface waters have driven the need to develop better techniques for assessing
12 understanding of the catchment-scale distribution and characterisation of the relative
13 contribution of point and diffuse contaminant sources. The benefits of a detailed,
14 multidisciplinary investigation are highlighted through a case study focused on the
15 Rookhope Burn, a tributary of the River Wear, which falls within a significantly mine
16 impacted area of the North Pennines Orefield, UK. Zinc (Zn) has been identified as
17 the contaminant of concern within this catchment, which is judged by the
18 Environment Agency to be at risk of failing to achieve good water quality status in the
19 context of the Water Framework Directive. The results of synoptic flow monitoring
20 and sampling for chemical determinations of major and trace elements have been used
21 to calculate mass balances of instream and inflow chemical loads in the Rookhope
22 Burn. Despite a dominant impact on the water quality from a mine outburst
23 (especially Zn [1.45 to 2.42 mg/l], Fe [2.18 to 3.97 mg/l], Mn [3.69 to 6.77 mg/l], F
24 [3.99 to 4.80 mg/l] and SO₄ [178 to 299 mg/l]), mass balance calculations combined
25 with geological mapping have facilitated the identification of significant, previously
26 unknown, subsurface contributions of Zn contaminated groundwater (with Zn
27 concentrations in excess of 0.4 to 0.9 mg/l and 0.18 to 0.36 mg/l) to the Burn. The
28 subsurface contributions exhibit spatial correspondence to mine workings with
29 associated mineral veins and adits, or to points of suspected karst groundwater
30 resurgence. These findings reiterate the challenges posed in decision making with

31 respect to remediation, in this case in the context of the management of significant
32 subsurface contributions.

33

34 **Keywords:** mine water, diffuse pollution, zinc, hydrogeology, conceptual models.

35

36 **1. Introduction**

37

38 In many industrialised countries the majority of mining environmental problems are
39 legacies of the past¹. The recognition of the extensive nature of the environmental
40 impacts, which threaten local ecosystems and human health has driven initiatives for
41 remediation, e.g. the USGS Abandoned Mine Lands Initiative^{1, 2} and the UK
42 recognition of the impact of historic metal sites in the context of the Water
43 Framework Directive (2000/60/EC³). Releases of polluting substances that cannot be
44 easily traced back to a discrete contaminant source are referred to as diffuse
45 pollutants. Diffuse source water pollution from current and historic mining activities
46 can severely impact the water quality especially with regards to acidification and
47 metal loading^{4, 5 6, 7}. This has particular relevance in the context of the Water
48 Framework Directive (2000/60/EC), which aims to achieve “good status” for all
49 surface waters (ecological [physico-chemical, biological, specific pollutant and
50 hydromorphological] and chemical components) and groundwaters (quantitative and
51 chemical components) by 2015. In order to implement effective mine water
52 management programmes the extent and distribution of diffuse sources of
53 contaminants is required⁸. Determining the nature and extent of the diffuse
54 contributions within a catchment can be difficult and requires a multidisciplinary
55 approach². If it was possible to identify a homogeneous catchment the impact of both

56 point and diffuse contaminant loading would be cumulative and the signature of point
57 source loading would be spiked, whereas that of diffuse loading would be incremental
58 (Figure 1). In practice, catchments are not homogeneous and the contaminant loading
59 may be subject to a combination of point and diffuse inputs, non-conservative
60 behaviour, as well as dilution where the stream passes through contaminant-free
61 stretches of the catchment. Consequently, more complex contaminant loading patterns
62 result. An added variable is that of seasonality, which results from variations in
63 groundwater residence times.

64

65 This paper addresses the difficulty of discriminating between diffuse and point source
66 impacts of historical mining of lead-zinc mineralization on the water quality in the
67 context of the Rookhope Burn, a southerly flowing tributary of the River Wear, North
68 Pennine, UK. Sources of contaminated drainage have been identified through reviews
69 of earlier work on the catchment ⁹⁻¹¹ and through synoptic monitoring and chemical
70 analysis. The results of the analyses have been interpreted in the context of the
71 geological setting and used to determine the importance of individual sources of
72 contaminated drainage and identify the existence of natural attenuation processes
73 within the catchment.

74

75 The Northumbria River Basin District Management Plan ¹² identified the Rookhope
76 Burn as being at risk of moderate ecological status. The secondary groundwater body
77 that underlies the catchment has been identified as being at risk from mines and
78 minewater pressures.

79

80 Data published by ^{9, 10, 13}, together with historic water quality data provided by the
81 Environment Agency indicate that the key contaminant of concern within the
82 Rookhope catchment is Zn. Zn is of particular concern in the context of its
83 environmental impact, especially in the aquatic environment, owing to its toxicity to
84 aquatic biota. This is acknowledged in its “specific pollutant” designation in the
85 European Water Framework Directive (2000/60/EC). The current UK EQS
86 (Environmental Quality Standard) for Zn ranges from 0.008 to 0.125 mg/ l, the higher
87 value reflecting the beneficial effect of hardness (EC Dangerous Substances Directive
88 76/464/EEC, Table 2b). The maximum point source contribution of Zn to the
89 Rookhope Burn (2.42 mg/l) is comparable with peak concentrations determined in
90 other mining-affected watercourses, e.g Lapus River catchment northwestern
91 Romania ¹⁴, South Korea ¹⁵, but do not reach the concentrations reported in run-off
92 waters monitored in Cabezo Rajao, in Southeast Spain ¹⁶. However, it should be
93 noted that concern with respect to the impacts of Zn being over estimated has
94 encouraged further research with respect to the EQS in the context of zinc’s “specific
95 pollutant” status ^{17, 18}, which allows due consideration of natural background and
96 bioavailability concentrations in the determination of the EQS.

97

98 **2. The Rookhope Catchment**

99

100 Situated towards centre of the North Pennines Area of Outstanding Natural Beauty
101 designation, the Rookhope catchment exemplifies the mining industrial heritage of the
102 area. The source of the catchment lies within grouse moorlands at an elevation of
103 approximately 600 to 540 m OD. Below this, the area is characterised by a relatively
104 treeless landscape primarily given over to hill farming. The catchment bears the scars

105 of abandoned quarries and mine workings, including: numerous mounds of rock and
106 mine waste; remnants of open vein workings; remnants of former mill buildings;
107 disused shafts, and areas of former leats (artificial water channels). Settlement is
108 largely focused on the areas of Rookhope and Eastgate with additional isolated
109 farmsteads. Many of the farms were also once utilised for mining, for example Wolf
110 Cleugh and Lintzgarth (Table 2).

111

112 The catchment is underlain by mineralized Dinantian (Brigantian and Asbian)
113 limestones, capped by Namurian sandstones and mudstones of the Yoredale Group ¹⁹
114 (Table 1). Strata are almost horizontal, with a slight regional dip to the east. The
115 Stainmore and Alston formations comprise sequences of limestone, mudstone,
116 siltstone and sandstone, with occasional developments of seat earth and coal. The
117 limestones are typically only a few metres thick and become increasingly common
118 towards the base of the Stainmore Formation. The Great Limestone is up to 15 m
119 thick and the Alston Formation is dominated by thick limestones. Mineralization is
120 hosted by faults, which are typically normal and of limited vertical throw, and by
121 local occurrences, associated with the limestone, of horizontal mineral replacement
122 referred to as flats. Primary minerals include galena, quartz, and siderite with traces of
123 sphalerite, pyrite, and localised chalcopyrite. Secondary minerals include: limonite,
124 psilomelane, cerrusite, malachite and occasionally azurite. Where flats have formed,
125 significant quantities of fluorite, galena and calcite together with some quartz and
126 chalcedonic silica may be present.

127

128 Superficial deposits comprise: glacial till below ~370 m OD; river terrace deposits
129 associated with the River Wear; ribbons of alluvial deposits associated with all of the
130 river valleys, and blanket peat, which caps the higher ground ²⁰. Anthropogenic
131 deposits, including mine waste and construction materials associated with both mining
132 and railway construction, are also evident throughout.

133

134 The Rookhope catchment comprises an area in the order of 37 km² and the southerly
135 flowing stream contributes a discharge ranging from 100 to 2300 l/s to the River Wear
136 at Eastgate (Figure 2). Rainfall and temperature vary with altitude. An annual
137 effective rainfall of ~1000 mm has been calculated for Eastgate with monthly
138 effective rainfall varying between 53 and 116 mm. The hydrograph for the Rookhope
139 Burn is flashy, i.e. there are frequent, rapid, short term changes in stream flow and the
140 stream responds rapidly to runoff events. A desk study and reconnaissance visits have
141 contributed to the development of a conceptual model of the hydrogeology of the
142 catchment. Four hydrogeological zones that reflect the underlying geology have been
143 identified: [1] upland peat capping the interbedded shales and sandstones with an
144 interbedded limestone (Upper Felltop Limestone) at the lower end of the zone; [2]
145 interbedded shales and sandstones with an interbedded limestone (Lower Felltop
146 Limestone); [3] Till capped bedrock, including the Great Limestone, characterised by
147 the presence of dolines (shake holes), which is indicative of karstic void forming
148 processes, and [4] more resistant Alston Formation bedrock characterized by a
149 number of waterfalls, for example Turn Well (NY94882 39868). The presence of
150 mudstones encourages surface run-off, which may recharge underlying sandstones
151 and then re-emerge as springs and the presence of dolines facilitates fast flow to the
152 stream, thereby further contributing to the flashiness of the hydrograph.

153

154 Although previously worked during a number of phases that are likely to date back to
155 at least the Roman period, the majority of the lead mines were exploited during the
156 period 1692 to 1882 ²¹ (Table 2 ^{22, 23}). More recently, driven by the need for high
157 quality fluorspar for steel-making, fluorspar has been the principal mineral to be
158 exploited in the catchment. Fluorspar mining continued until 1999, when the Grove
159 Rake Mine (Figure 2, Table 2) closed. Frazer's Grove Mine comprises four
160 underground mines: Frazer's Hush, Rake level/Firestone Incline workings, Grove
161 Rake and Greencleugh ^{13, 9, 10, 13} have contributed significantly to the understanding of
162 Frazer's Grove Mine hydrogeology and hydrochemistry. Further descriptive detail of
163 the mine is provided in these references. Sixteen main centres of former mining have
164 been identified within the catchment (Figure 2, Table 2). The driving of mine drainage
165 adits to dewater the mines was common practice in the North Pennines and this had
166 the effect of altering the local hydrogeological regime ²⁴. Of particular note in the
167 context of the inputs to the Rookhope catchment are the Boltsburn and Tailrace
168 Levels.

169

170 The Tailrace Level extends from its portal (NY91624 42779) to Frazer's Grove Mine
171 via Rispey Shaft (NY91117 42739) and Wolfcleugh Old Pumping Shaft (NY90168
172 43230), a distance of approximately 2850 m. It is suspected that not all of the adits
173 that were associated with the Tailrace Level have been recorded and that there are
174 likely to be additional connections between some of the mining areas. This level
175 drains abandoned mine workings with a component of surface run-off entering the
176 level via crown holes ^{9, 9, 10, 13} demonstrated that two thirds of the Frazer's Grove
177 water-make comes from the Great Limestone aquifer with the remaining one third

178 from the Firestone Sill and surface inflows. They carried out underground and surface
179 sampling of waters from Frazer's Grove prior to and during groundwater rebound
180 following cessation of pumping, and established that the chemistry of the groundwater
181 is stratified, reflecting the influence of variations in the bedrock geology (Table 1).
182 Three waters were characterised: Type I associated with the Firestone Sill, comprising
183 moderately mineralized Ca-HCO₃-SO₄ waters with less than 4 mg/l Zn; Type II
184 associated with the Great Limestone, comprising highly mineralized Ca-SO₄ water
185 with up to 40 mg/l Zn, and Type III associated with the deepest workings, comprising
186 mineralized Ca-HCO₃-SO₄ water with up to 13 mg/l Zn and an increasing Cl content
187 and temperature with depth. The cessation of pumping after closure of Frazer's Grove
188 mine (1998) resulted in the water table rising above the aquifer and discharging mine
189 water with peak Zn concentrations as high as 35.6 mg/l via the Tailrace Level (Figure
190 2), the lowest surface discharge point at 364 m OD.

191

192 Boltsburn Level (Table 2) at 332 m OD is not directly connected to Frazer's Grove
193 Mine. It was sampled during the monitoring of rebound at Frazer's Grove Mine ¹⁰ and
194 was considered to have a chemistry typical of Great Limestone groundwater, but with
195 variable Fe concentrations (1 – 10 mg/l).

196

197 **3. Methodology**

198

199 Synoptic flow monitoring and sampling for chemical determinations of major ions
200 and trace elements was carried out, including both instream sampling points along the
201 Rookhope Burn and tributary inflow sites (locations of potential contaminant

202 discharge to the Rookhope Burn). The British Geological Survey database of mine
203 adits informed the identification of potential point source contributions. Monitoring
204 and sampling were carried out in May 2007, June 2007 and January 2008. The visits
205 were scheduled to coincide with different hydrological conditions and the sampling
206 points were chosen using topographic maps, aerial photographs and field investigation
207 in order to cover the stream stretches upstream and downstream of visible mine water
208 discharges, or at the confluence of major tributaries. In practice it was difficult to
209 predict the stage of the river owing to the flashiness of the river hydrograph. It was
210 considered that the May 2007 visit was the closest to baseline conditions, whilst the
211 June 2007 visit coincided with the tail effect of a storm event. Immediately prior to
212 the commencement of monitoring, there was a groundwater outburst from an
213 abandoned mine shaft at Wolfcleugh (NY91059 42828; point 7, Figure 2), which had
214 a marked impact on the chemistry of the Rookhope Burn.

215

216 Water pH, temperature, Eh and conductivity were measured in the field using a Water
217 Quality Multiparameter meter. Alkalinity was determined by titration immediately
218 after sample collection, using a Hach digital titrator with H₂SO₄ (0.16 N or 1.6 N) and
219 bromocresol green indicator. Samples for chemical analysis were filtered in the field
220 using a disposable 0.45 µm cellulose-acetate cartridge filter and collected in
221 polyethylene bottles. Chemical analyses were carried out in the laboratories of the
222 British Geological Survey. Major and trace elements of 1% HNO₃ field-preserved,
223 filtered samples were determined by ICP-AES (Varian Vista Axial). Fe (II) was
224 determined by colorimetric analysis of 2–2 dipyrityl spiked samples. The major
225 anions Cl, SO₄, NO₃ and F were determined by ion chromatography (Dionex DX-

226 600). Duplicate samples and blanks using cleaned field equipment were included at
227 each sampling event for quality control.

228

229 Discharge was determined for each sampling point, during each of the sampling
230 campaigns, using the velocity-area method ²⁵. A Columbia 2 Digital Stream Meter,
231 an impeller-type flow meter, was used to measure stream velocity. In order to achieve
232 consistency, on each occasion monitoring was carried out at pre-determined
233 monitoring positions (marked by posts in the river bank) and at each monitoring point,
234 where the stage allowed it, the velocity was determined at the same distances across
235 the channel. Discharge was derived from the mean of the values calculated using the
236 mid-section and mean-section formulae. Inevitably there are problems associated with
237 this type of monitoring. The variability in discharge is, in part, attributed to the form
238 of the river bed, which is occupied by significant volumes of mine and rock waste
239 through which groundwater flow bypasses the flow monitoring. This is particularly
240 evident in places where the watercourse bifurcates around islands of rock and at low
241 stages, water can be seen draining from the rock islands to the channel, on one or both
242 sides of the island.

243

244 Contaminant loadings were determined utilizing an approach comparable with that of
245 ⁵. At each instream or inflow measuring point the contaminant load was calculated
246 from the product of the discharge and contaminant concentration. The contaminant
247 load distribution along the study stream helped to identify sources and sinks along the
248 Rookhope Burn, based on an assumption that the load at the end of a stream segment
249 includes the load from the point upstream plus the contribution from all surface and

250 subsurface inflows along the stream segment. Increases in load between instream
251 sites, were attributed to a source associated with the monitored stream segment. If the
252 instream contaminant load decreased between sites, a sink (chemical, biological or
253 physical attenuation of metal load) was assumed to be responsible for the removal of
254 contaminant load, except in locations where this was associated with a reduction in
255 discharge. The cumulative instream load, as defined by ⁵, was determined at the base
256 of the catchment by calculating the sum of the increases in loads entering the stream.
257 This provides a minimum estimate of the total load of contaminant added to the
258 stream. The cumulative instream attenuation was, similarly, defined as the sum of all
259 the negative values of change in load.

260

261 **4. Results**

262

263 **4.1 Discharge**

264 Discharges of inflow and instream sampling points are reported in Tables 3 and 4.
265 Figure 3, which summarises the flow monitoring in the Rookhope Burn stream,
266 demonstrates that there is not a simple linear increase in discharge down the channel.
267 Two stretches of rapid increase in discharge are notable, namely between sample
268 points 9 and 11 (4890 m to 4960 m downstream of the head of the catchment, Figure
269 2) and between sample points 19 and 21 (7155 m to 7400 m). The only obvious
270 contributions to these two stretches comprise, respectively, groundwater drainage
271 from the Tailrace Level (sample point 10) and the surface water contribution from
272 Bolts Burn (sample point 20), but the volumes derived from adding these
273 contributions to the upstream discharge do not fully account for the increase in

274 discharge in these stretches. Additionally, the data suggest that there have been losses
275 in discharge between monitoring points 21 and 24 (except in June 2007, during the
276 tail end of the storm event).

277

278 Following the first monitoring visit (May 2007) it was suspected that worked mineral
279 veins were forming flow paths for previously unrecognised groundwater contributions
280 to the Rookhope Burn. To explore further the nature of the contribution in the stretch
281 between sample points 9 and 11, flow monitoring was carried out in August 2007 at
282 closely spaced intervals across the fault/ mineral vein associated with the Tailrace
283 Level (point 10, Figure 2, Table 5). Giving due allowance for the variability that
284 results from the flow monitoring technique described above, the discharge
285 measurements indicate a groundwater contribution to the stream immediately
286 downstream of the Tailrace Level. Examination of the historic maps, geology map
287 and aerial photographs established that this increase is associated with a point that
288 aligns with a series of mine workings, immediately to the east of the surface
289 expression, of the northeast to southwest-trending mineral vein with which the
290 Tailrace Level is associated. Comparable with the discharge from the Tailrace Level,
291 the groundwater contribution was characterised by lower temperature, pH, electrical
292 conductivity and total dissolved solids and higher dissolved oxygen concentration on
293 the northern side of the channel (Table 5). Examination of historic records indicated
294 that the increase in discharge downstream of Bolts Burn, between sample points 19-
295 21, was likely to be mine water from an adit that was driven into Red Vein from the
296 south bank of the river, immediately downstream of Bolts Burn. Subsequent
297 investigation in this area identified the presence of a drainage adit at NY93778 42712,

298 with minimal discharge (0.486 l/s on 11 May, 2009), which was insufficient to
299 account for the increased discharge between sample points 19 and 21.

300

301 **4.2 Hydrogeochemistry**

302

303 4.2.1 Inflows

304 To assist with the interpretation of the contaminant loading in the catchment
305 consideration has been given to the geochemistry of the contributing waters, which
306 include: minewater; seepages from the mine waste; the Rookhope Burn water quality,
307 and contributions from other adits and surface waters (Tables 3 and 4). The
308 minewaters were classified as Ca-HCO₃-SO₄ water, from: the mine water outburst at
309 Wolfcleugh (sample point 7), Tailrace Level (sample point 10) and Boltsburn Level
310 (sample point 18). These waters were found to be near neutral (pH 6 to 7), highly
311 ionized, with elevated concentrations of: Ca (27-125 mg/l), Mg (5 to 20 mg/l), K (6 to
312 8 mg/l at the outburst), HCO₃ (73 to 234 mg/l), SO₄ (16 to 299 mg/l) and F (1 to 5
313 mg/l). Ca:Mg weight ratios in the mine waters were generally high (>6). They were
314 characterized by Zn concentrations in the range 0.04 to 2.42 mg/l, the higher
315 concentrations being associated with the mine water outburst (sample 7). Sample 7
316 was also found to be enriched with Mn (3.69 to 6.77 mg/l). When compared with the
317 minewater types defined by ¹³, they appear to fall within the Type III category, but
318 were generally more dilute. Water from other adits (sample points 26 and 29, Figure
319 2) comprised dilute Ca-HCO₃ and Ca-HCO₃-Cl water with neutral to slightly alkaline
320 pH values and lower concentrations of Ca, Mg and SO₄. The Ca:Mg ratio was found
321 to be marginally higher than that of the minewaters (~7.5). These waters were also

322 characterised by lower concentrations of F and Zn than the mine waters. Their
323 chemistry suggests that the discharge from these adits is largely surface water
324 drainage through the unsaturated zone.

325

326 Seepages from the mine waste heaps at Wolf Cleugh (sample point 27) and the
327 tributary receiving the drainage from the area of spoil heaps to the west of Rookhope
328 Burn at Rookhope village (sample point 28) exhibited different chemistries. Sample
329 point 28 had elevated Zn (0.67 - 0.92 mg/l), Pb (0.13 - 0.32 mg/l) and SO₄ (138 -
330 143 mg/l) concentrations. The seepage at sample point 27 appears to have been
331 diluted by surface water, exhibiting lower concentrations of these determinands. F
332 was relatively elevated in both samples (1.89 mg/l in sample point 28, and 1.70 mg/l
333 in sample point 27). Both sample points were dry during the baseflow sampling in
334 May 2007. Surface waters from the tributaries: Brecken Sike, Rispey Sike, Redburn
335 and Bolts Burn (sample points: 4, 12, 15 and 20) exhibited lower ionic strength and
336 comprised Ca-Na-Mg-Cl-SO₄ waters. The surface waters exhibited lower Ca:Mg
337 ratios and Zn concentrations ranging from 0.01 to 0.06 mg/l.

338

339 4.2.2 Rookhope Burn

340 Water chemistry of the samples obtained from the synoptic monitoring of the
341 Rookhope Burn is reported in Table 4. The analyses for the May 2007 sampling
342 campaign are considered to be the closest to the stream base flow conditions and are
343 plotted in Figure 4 against distance from the headwaters of Rookhope Burn to its
344 confluence with the River Wear at Eastgate. Sample inflow chemistries are also
345 shown. The plots for F, HCO₃, SO₄, Ca and Mn all exhibit a significant increase in

346 concentration between sample points 6 and 9, which are attributed to the input from
347 the Wolfcleugh mine water outburst described above. Downstream, the concentration
348 of these determinands decreased to the proximity of sample point 11, where it levelled
349 out (except for a slight increase in Ca and alkalinity) between sample points 11 and
350 13, before a general decrease again in the direction of Eastgate. A second decrease
351 occurred downstream of sample point 13 and appears to be coincident with the
352 outcrop of the Great Limestone in the bed of the river. Fe concentrations (mainly
353 reduced) were higher in the headwaters of the catchment, whereas, upstream
354 concentrations of Zn were in the order of 0.15 - 0.68 mg/l, but increased steeply in the
355 stretch between sample points 6 and 9 respectively, reaching ~1 mg/l in sample 9 in
356 May 2007, immediately downstream of the mine outburst at Wolfcleugh. Between
357 sample points 9 and 11 the Zn concentration decreased substantially to 0.42 -
358 0.21 mg/l. Between sample points 11 and 13 there was a levelling of the
359 concentration of Zn, before a further progressive decrease downstream to Eastgate
360 (0.09-0.11 mg/l).

361

362 These results indicate that the major changes in the Rookhope Burn stream chemistry
363 occurred at, or immediately downstream of, the location of the mine water outburst at
364 Wolfcleugh. More subtle variations along the catchment point to additional
365 contributions from: mineralized groundwater, seepages from mine waste, surface
366 water and to the influence of changes in the bedrock geology. Along the majority of
367 the length of the Rookhope Burn concentrations of Zn exceeded the EQS (aquatic life-
368 standards quoted for salmonid and the more sensitive cyprinid life), calculated on the
369 basis of the hardness of each sample, during the May 2007 sampling campaign.
370 Exceptions were the headwaters of Rookhope Burn (sample point 1) and the point

371 immediately downstream of Grove Rake Mine (sample point 3), which did not exceed
372 either of the EQS Zn values. However Zn concentrations were above the EQS value
373 for salmonid fish life in the subsequent monitoring campaigns. From sample point 6
374 (upstream of the mine outburst) to sample point 19 (downstream of Boltsburn Level)
375 all of the water samples in the burn were above the threshold value for cyprinid life
376 related to the water hardness. The remaining stretch of Rookhope Burn, to its
377 confluence with the River Wear, had Zn concentrations above the EQS value for
378 salmonid fish life.

379

380 4.2.3 Zinc Load

381 The hydraulic data, which indicate gaining and losing reaches in the stream, have
382 been combined with chemical measurements to derive Zn loads in Rookhope Burn in
383 order to assess the impact of these reaches on the stream water quality. Figure 5
384 illustrates the spatial variation in Zn concentrations and the Zn load along the
385 Rookhope Burn and Table 6 summarises the gains and losses in Zn load at the 11
386 stream segments defined by sample locations in the stream. The Zn load profiles
387 differ from the concentration profiles in that they display two distinct peaks in load.
388 The greatest increase occurs between sample positions 9 - 11 (upstream and
389 downstream of the Tailrace Level respectively, ~4890 m and 4960 m downstream of
390 the head of the catchment), in May 2007 and January 2008. In June 2007 the Zn load
391 contribution in the stretch between sample points 6 and 9, located upstream and
392 downstream of the Wolfcleugh mine water outbreak was the largest in the Rookhope
393 Burn. The second loading peak entered Rookhope Burn in the stretch between sample
394 positions 16-19 and 19-21, respectively, in May - June 2007 and January 2008.

395

396 For the river stretches characterised by an increase in the metal load, mass balance
397 calculations have been made between the net changes in instream load and the inflow
398 loads measured along the same stretches in order to further elucidate the relative
399 influence of inflows on the stream. The inflow source contributing to stretch 6-9 is the
400 Wolfcleugh mine water outburst (sample point 7) with a Zn load of 85 mg/s in May
401 2007 (Zn 2.42 mg/l), 294 mg/s in June 2007 (Zn 2.34 mg/l) and 10 mg/s in Jan 2008
402 (Zn 1.45 mg/l). Water from this inflow point source contributes to 66 to 82 % of the
403 total Zn load in May and June 2007, but only the 3.5 % in January 2008. For this
404 stream segment, the difference between the net change in instream load and the inflow
405 load of Wolfcleugh mine water outburst leaves a negative balance of -60 mg/s in May
406 and June 2007 and -20 mg/s in January 2008. This denotes that the measured inflow
407 load entering stretch 6 - 9 is greater than the net change in load measured for the
408 stream segment, indicating a possible removal of Zn through physical or chemical
409 processes. Field evidence of ochre precipitation in the immediate vicinity suggests
410 that Zn mass is lost by chemical precipitation/ adsorption. Commonly observed Fe
411 oxy-hydroxide and SO₄ mineral precipitation downstream of the river's confluence
412 with SO₄ Fe(II) rich- mine drainage is generally associated with a decrease in
413 dissolved concentrations of trace metals, including Zn, due to adsorption on the Fe
414 mineral precipitates^{26, 27}.

415 In contrast, along stretches 9 - 11 and 16 - 19 the gains in Zn load in the stream cannot
416 be attributed only to the sampled inflows. The only inflow in stretch 9 - 11 was
417 Tailrace level (sample point 10) with a Zn load of: 10 mg/s in May 2007 (Zn
418 0.29 mg/l); 4 mg/s in June 2007 (Zn 0.07 mg/l), and 0.8 mg/s in January 2008 (Zn
419 0.04 mg/l). The balance indicates an unsampled Zn inflow of: +50 mg/s in May

420 2007; -0.7 mg/s in June, and +302 mg/s in January 2008. Similarly, Boltsburn level
421 (sample point 18) alone cannot account for the increased load in stretch 16 - 19 where
422 a balance of unsampled Zn inflows of: +30 mg/s in May 2007; +65 mg/s in June 2007
423 and + 8 mg/s in January 2008 have been determined. The results suggest a significant
424 inflow of subsurface Zn-rich water to the stream that contributes to the Zn loading in
425 these areas.

426

427 The greatest apparent net Zn load losses occur along the stretches 13 - 16 and 21 - 23
428 (except in June 2007). Cumulative Zn loads at Eastgate (Table 7), at the downstream
429 end of the study catchment, ranged from 130 mg/s to 360 mg/s through the 3 sampling
430 events, with instream cumulative attenuation along the study stream ranging between
431 80 and 140 mg/s. The sampled visible inflow loads accounted for 75 to 85 % of the
432 cumulative instream Zn load in May and June 2007, but only 6 % in January 2008.

433

434 **5. Discussion**

435

436 The most significant impact on the water quality of the Rookhope Burn that has been
437 identified during the course of this study is the point source contribution of mine
438 water from the outburst at Wolfcleugh. The National Grid Reference (NY391059
439 542828) of the location of the outburst indicates that it is situated on Rispey Vein. The
440 elevation of the shaft was estimated to be ~375 m OD, which places it marginally
441 above the Tailrace Level ~365 m OD at river level. This suggests that there was a
442 collapse of the underground workings, resulting in a blockage somewhere
443 downstream of Rispey Vein causing an increase in pore water pressures and

444 consequential outburst of minewater. Remedial measures, which entailed capping the
445 shaft and feeding the discharge into an outlet channel, were carried out at some point
446 between the June 2007 and January 2008 monitoring visits. Coincidental with this, the
447 discharge from the outburst of mine water at Wolfcleugh appears to have reduced
448 (35 l/s in May 2007; 126 l/s in June 2007 and 6.8 l/s in January 2008). During the
449 monitoring period the chemistry also appears to have ameliorated (Table 3), with
450 reductions in the concentration of SO₄, F, Fe, Mn and Zn. The synoptic monitoring
451 commenced in the order of five months after the outburst occurred. During the period
452 prior to the outburst it is likely that the stratification of the water chemistry in Grove
453 Rake Mine described by ¹³ and ^{9, 10} and attributed to the geological influences on the
454 geochemistry was disrupted as a consequence of the build up of pore water pressure,
455 squeezing water into previously unconnected areas of the mine workings. Upon the
456 release of this pressure, the stratification would have been further disturbed,
457 facilitating the release of more acidic mine water with the acidity being attributed to
458 its contact with pyritic shales, as seen in Grove Rake Mine. It is possible that the
459 apparent improvement in the water quality represents the re-establishment of
460 stratification in the mine water. Further monitoring is required to determine more
461 conclusively whether this is the case. The discharge data indicate that the engineering
462 works have confined the flow from the outburst, which appears to have resulted in an
463 increased contribution to the Rookhope Burn via the bed of the stream.

464

465 Known point sources, suspected to contribute Zn loading to the stream via drainage
466 adits include the discharge from the Tailrace and Boltsburn levels. Comparison of the
467 analyses determined during this study (0.29 mg/l and 0.06 mg/l respectively during
468 the baseflow conditions in May 2007) with those reported by ¹⁰ indicate that the

469 chemistry of the water was similar. The Tailrace Level is known to receive a surface
470 water contribution ¹⁰. Nevertheless, the significant reduction in Zn and SO₄
471 concentrations after the May 2007 sampling suggest improvements in the quality of
472 the groundwater contribution (Table 3), with reductions in electrical conductivity,
473 alkalinity, F and Mn also being evident. Furthermore, the postulated blockage
474 associated with the outburst is thought to have affected the discharge from the
475 Tailrace Level (34 l/s in May 2007; 61 l/s in June 2007 and 19 l/s in January 2008).
476 The improvement in the groundwater chemistry and reduction in discharge appear to
477 be responses to the reduction in head brought about by the release of minewater via
478 the mine outburst and subsequent remedial engineering. The chemistry of the
479 discharge from the Boltsburn Level also showed an improvement during the
480 monitoring period; however the improvement was more variable than, and not as
481 progressive as, that of the discharge from the Tailrace Level, suggesting that the
482 variation represents seasonality of the water quality.

483

484 Further to the known point source contributions, this work has identified two
485 previously unidentified sources of contaminated groundwater, which are suspected to
486 emanate from the bed of the river and contribute 15 to 25 % of the cumulative Zn load
487 in the Rookhope Burn during the May and June 2007 sampling. These subsurface
488 contributions, however, become dominant in January 2008 when approximately 95%
489 of the Zn load entered the stream through these zones. Analysis of the discharge data
490 and Zn loading indicate the presence of one such zone between sampling positions 9
491 and 11, where a contribution in the vicinity of the Tailrace Level is suspected.

492 A second point occurs between sampling positions 16 and 19. The focus for this input
493 has not been established. Mineral veins cross the stream downstream of the Boltsburn

494 Level, but closely spaced analysis of the physico-chemical conditions carried out in
495 May 2009 failed to locate the ingress. As the calculation of the Zn load uses the
496 discharge data, any error in the measurement, or calculation of discharge would
497 impact on the calculation of the Zn load. The potential for some loss of flow to the
498 bed of the river, where it comprises a significant thickness of boulders cannot be
499 entirely precluded. Whilst the accuracy of the discharge cannot be verified, a relative
500 increase in discharge was observed on each occasion. Furthermore, subtle increases in
501 the pH, alkalinity, Ca and Mg between sample points 16 and 19 suggest another
502 source of groundwater. Additionally, the concentration profiles for F and SO₄ during
503 base flow sampling (Figure 4) indicate dilution as a consequence of this input. The
504 geological setting of these points suggests that the increased discharge is attributable
505 to the karst hydrogeology in this area. A number of shake holes (dolines) have been
506 identified to the south of the river (centred on NGR NY93338 42874 and NY93489
507 42828) in the stretch between sampling locations 16 and 19. The dolines are situated
508 in an area where there is a thin cover of glacial till, close to the feather edge of the
509 sandstones and mudstones, which cap the Great Limestone. Thus it is likely that
510 recharge via the dolines occurs and indicates the presence of a mature karst system
511 that resurges to the Rookhope Burn via the easterly dipping Great Limestone. The
512 lower concentrations of SO₄ in this water indicate less contact with the mineralization
513 and this is reflected in the lower Zn concentration, when compared with the
514 concentration from the Tailrace Level and from farther upstream.

515

516 Whether the contributions in the stretches between sampling locations 9 - 11 and 16 -
517 19 should be classified as point or diffuse sources has been the subject of considerable
518 discussion. Using the approach presented in the introduction these are clearly point

519 source contributions, however at a closer scale the detail of the point of the emissions
520 has not been fully resolved, particularly in the zone between sampling locations 17
521 and 19, where it is suspected that the contribution occurs over a zone in the river bed,
522 which might be considered a diffuse input.

523

524 Analysis of the Zn loading has also established the existence of Zn sinks. The greatest
525 apparent net Zn load losses occurred along the stretches 13 - 16 and 21 - 23 (except in
526 June 2007). The reduction in the Zn load between points 13 and 16, downstream of
527 the Tailrace Level, was associated with a significant decrease in the Zn concentration
528 in the river (Figure 5), which is likely to be a consequence of attenuation by chemical
529 precipitation of Zn. The reduction in flow suggests that significant dilution is unlikely.
530 The decrease in load determined between points 21 and 23 also coincides with a
531 measured decrease in discharge (in May 2007 and January 2008). It is difficult to tell
532 whether this reflects flow loss below the bed of the river, or unmeasured flow in the
533 stream sediments. It is also possible that there are karstic losses from the bed of the
534 river to the Great Limestone.

535

536 Seepage water (sample positions 27 and 28) emanating from waste heaps,
537 characterised by elevated SO_4 , Pb, Zn and F, is considered to be representative of
538 diffuse contaminant sources in the catchment.

539

540 F has been shown to be a good indicator of mining impacted groundwater in other
541 catchments²⁸ and the evidence from this work suggests it to be a good indicator in the
542 Rookhope catchment. From Table 4 it can be seen that elevated F concentrations are

543 associated with both point (mine water) and diffuse (mine waste-derived) inputs. The
544 concentration of F (0.20 to 4.48 mg/l) in the Rookhope Burn increases steadily down
545 the catchment, suggesting diffuse contributions, in the mining impacted area, with
546 local, spiked point source contributions that are locally masked by the minewater
547 contribution from the outburst at Wolfcleugh. The increased loading in a downstream
548 direction indicates the F to be more dispersed and conservative than Zn (Figure 6).
549 SO₄ shows a similar, dispersed contribution, which is comparable with that observed
550 by ⁵. Locally there is a reduction in the F load associated with a reduction in the
551 discharge determined for sample point 23. This may be indicative of karstic losses of
552 stream water to the bed of the river, as hypothesised above.

553 The measured concentrations indicate that F might also be a contaminant of concern.
554 Whilst the WHO guideline for drinking water quality is 1.50 mg/l ²⁹, ³⁰ suggested that
555 F concentrations in the river environment be limited to 0.5 mg/l, based on the toxic
556 effects on invertebrates and fish in soft waters with low ionic content. Toxicity was
557 concluded to be related to water hardness however, and with increased hardness safe
558 levels of F could be increased to 1.0 to 1.5 mg/l ³⁰. The guideline values are lower
559 than the concentrations determined in the vicinity of the Tailrace Level and during
560 baseflow conditions throughout much of the Rookhope Burn downstream of Grove
561 Rake. Further research is required to understand the ecological impacts.

562

563 **6. Conclusions**

564

565 Zn has been identified as the key contaminant of (ecological) concern in the
566 Rookhope catchment, where it generally exceeds the EQS values for salmonid and

567 cyprinid life. Synoptic sampling and contaminant load calculations have demonstrated
568 that Zn primarily reaches the stream via point sources of mine water. Zn sinks gave
569 also been identified. This may be particularly important in the context of any future
570 changes in the catchment either as a consequence of climate change, or anthropogenic
571 influences. In considering remedial target measures to achieve “good status” further
572 work is required to determine the actual ecological impacts of the levels of
573 contamination that have been identified. F has been shown to be a good indicator of
574 the contribution of dispersed contamination to the Rookhope Burn. The measured
575 concentrations indicate that F might also be a contaminant of concern with values >
576 1.5 mg/l during baseflow conditions throughout much of the Rookhope Burn
577 downstream of Grove Rake.

578

579 High resolution water monitoring, in conjunction with a good conceptual model, can
580 be used to discriminate between point and diffuse sources and subsequently assess the
581 implications of their distribution. In this case study, building on the work of earlier
582 authors^{9, 10, 13}, this has facilitated the characterisation of the five most significant
583 source contributions of Zn to the Rookhope Burn: the known contributions via
584 drainage adits (Tailrace Level and Boltsburn Level); previously unknown sources of
585 mine water entering via the bed of the stream; suspected karst groundwater resurgence
586 to the bed of the stream, and the mine water ingress via a recent mine water outburst.
587 The remedial measures for the outburst incorporated a permanent drainage discharge
588 to the Rookhope Burn, which will also comprise a long term point source contribution
589 of Zn to the stream. Nonetheless, the results of the synoptic sampling and the work of
590¹⁰ indicate that the quality of the Burn is likely to ameliorate with time.

591

592 The triggering of the outburst raises the question of the stability of the underground
593 workings and the risk of designing remediation schemes for a single point, which
594 could be made obsolete in the event of a comparable outburst elsewhere in the
595 catchment. Furthermore, the mine water contribution to the bed of the river highlights
596 the difficulty in designing remedial schemes for mine water contamination,
597 demonstrating the need for more detailed understanding of the hydrology associated
598 with abandoned workings.

599

600 The results from this research highlight the need for an iterative approach to such
601 studies, as the interpretation of the results of the synoptic sampling and analysis has,
602 in part, relied upon an untested, conceptual understanding of the hydrogeology of the
603 catchment. For example, the explanation for the increase in the Zn loading between
604 sampling points 16 and 19 could be underpinned with dye tracing, via the dolines
605 located at NGR NY93338 42874 and NY93489 42829, in order to confirm the
606 existence of karst flow paths in the stretch between sample points 16 and 19.

607

608

609

610 **Acknowledgements**

611 The Environment Agency is thanked for assistance with synoptic monitoring reported
612 here, as are Dr Ben Klinck, Dr Simon Chenery and visiting researchers: Arek
613 Bauerek, Karol Kuras and Natalia Vera de Fernandez. Chemical analyses were carried
614 out by staff in the laboratories of the British Geological Survey.

615 This paper is published with the permission of the Executive Director of the British
616 Geological Survey (NERC).

617

618 References

- 619 1. B. G. Lottermoser, *Mine Wastes Characterization, Treatment, Environmental Impacts.* ,
620 Second edn., Springer., 2007.
- 621 2. B. A. Kimball, Church, S.E. and Besser, J.M. , Proceedings 7th International Conference on
622 Acid Rock Drainage (ICARD). St Louis MO. American Society of Mining and Reclamation
623 (ASMR), 2006.
- 624 3. EnvironmentAgency, *Water Framework Directive Programme. River Basin Characterisation 2*
625 *Project. Risk Assessment Technical Method: Diffuse mines and minewaters pressures on*
626 *ivers.*, 2007.
- 627 4. B. S. Caruso, Ward, R.C., *Environmental Management* 1998, **22**, 225-243.
- 628 5. B. A. Kimball, Runke, R.L., Walton-Day, K. and Bencala, K.E., *Applied Geochemistry*,
629 2002, **17**, 1183-1207.
- 630 6. W. M. Mayes, Gozzard, E., Potter, H.A.B. and Jarvis, A.P., *Environmental Pollution*, 2008,
631 **151**, 165-175.
- 632 7. K. Mighanetara, Braungardt, C. B., Rieuwerts, J. S., Azizi, F. , *Journal of Geochemical*
633 *Exploration*, 2009, **100**, 116-124.
- 634 8. A. Jarvis, Fox, A., Gozzard, E., Hill, S., Mayes, W. and Potter, H. , in *IMWA Symposium*
635 *2007: Water in Mining Environments*, , ed. R. Cidu, and Frau, F. , Cagilari, Italy., 2007.
- 636 9. K. Johnson, Younger, P.L. , in *Proceedings of the 7th International Mine Water Association*
637 *Congress*, , Katowice, Poland, 2000, pp. 271-279.
- 638 10. K. Johnson, Younger, P.L., in *Mine water hydrogeology and geochemistry.*, ed. P. L. a. R.
639 Younger, N.S., 2002, pp. 347-363.
- 640 11. P. L. Younger, in *Fluorspar in the North Pennines.* , ed. R. A. Fairbairn, The Friends of
641 Killhope. 2003, p. 132.
- 642 12. Environment Agency, *Water for life and livelihoods. River basin planning: summary of*
643 *significant water management issues. Northumbria River Basin District.* , 2009.
- 644 13. P. L. Younger, *Applied Geochemistry* 2000, **15**, 1383 - 1397.
- 645 14. G. Bird, Macklin, M.G., Brewer, P.A., Zaharia, S., Balteanu, D., Driga, B. and Serban, M.,
646 *Environmental Geochemistry and Health*, 2009, **31**, 741-758.
- 647 15. J.-Y. Lee, Choi, J-C and Lee, K-K. , *Environmental Geochemistry and Health*, 2005, **27**,
648 237-257.
- 649 16. M. C. Navarro, Perez-Sirvent, C., Martinez-Sanchez, M.J., Vidal, J., Tovar, P.J. and Bech, J. ,
650 *Journal of Geochemical Exploration* 2008, **96**, 183-193.
- 651 17. J. A. B. Bass, Blust, R., Clarke, R.T., Corbin, T.A., Davison, W., de Schampelaere, K.A.C.,
652 Janessen, C.R., Kalis, E.J.J., Kelly, M.G. Kneebone, N.T., Lawlor, A.J., Loftis, S.,
653 Temminghoff, E.J.M., Thacker, S.A. Tipping, E., Vincent, C.D. Warnken, K.W. and Zhang,
654 H., *Environmental Quality Standards for trace metals in the aquatic environment.* SC030194,
655 2008.
- 656 18. S. D. W. Comber, Merrington, G., Sturdy, L., Delbeke, K. and van Assche, F. , *Science of the*
657 *Total Environment*, 2008, **403**, 12-22.
- 658 19. B. Young, in *Northumbrian rocks and landscape. A field guide.* *Yorkshire Geological*
659 *Society.*, ed. C. Scrutton, 1995, p. 219.

- 660 20. D. J. D. Lawrence, Arkley, S.L.B., Everest, J.D., Clarke, S.M., Millward, D., Hyslop, E.K.,
661 Thompson, G.L. and Young, B., *Northumberland National Park Geodiversity Audit and*
662 *Action Plan. British Geological Survey Commissioned Report CR/07/037N.* , 2007.
- 663 21. K. C. Dunham, *Geology of the Northern Pennine Orefield. Volume 1 - Tyne to Stainmore.*,
664 Second edn., British Geological Survey, NERC., 1990.
- 665 22. R. A. Fairbairn, *Weardale Mines*, 1996.
- 666 23. K. C. Dunham, in *Friends on the Northern Lead Dales. An anthology of The Friends of*
667 *Killhope.*, ed. B. Chambers, The Friends of Killhope. , Editon edn., 2002, p. 134.
- 668 24. H. K. Jones, Morris, B.L., Cheney, C.S., Brewerton, L.J., Merrin, P.D., Lewis, M.A.,
669 MacDonald, A.M., Coleby, L.M., Talbot, J.C., McKenzie, A.A., Bird, M.J., Cunningham, J.
670 and Robinson, V.K. , *Physical properties of minor aquifers in England and Wales.* WE/00/4,
671 Environment Agency R&D Publication 68., 2000.
- 672 25. E. M. Shaw, *Hydrology in Practice.* , Third edn., 1999.
- 673 26. S. Rose, Ghazi A. M. , *Environmental Geology* 1997, **36**, 364-370.
- 674 27. J. M. a. N. Bigham, D.K., *Reviews in Mineralogy and Geochemistry*, 2000, **40**, 351-403.
- 675 28. D. J. Bove, Walton-Day, K. and Kimball, B.A., *Geochemistry: Exploration, Environment*
676 *Analysis* 2009, **9**, 125-138.
- 677 29. WorldHealthOrganisation., *Fluoride in Drinking-water.* WHO/SDE/WSH/03.04/96, 2004.
- 678 30. J. A. Camargo, *Chemosphere*, 2003, **50**, 251-264.
- 679
- 680

FIGURE CAPTIONS

Figure 1. Hypothetical plots of cumulative Zn load from point and diffuse contaminant sources.

Figure 2. Location plan of Rookhope catchment showing the sampling points.

Figure 3. Discharge along the Rookhope Burn with indicated sampling point numbers.

Figure 4. Instream and inflow total dissolved element concentrations versus distance from Rookhope Burn headwaters to the River Wear (May 2007 sampling).

Figure 5. Instream and inflow concentrations and load of Zn versus distance in Rookhope Burn.

Figure 6. Load profiles of F and SO₄ in Rookhope Burn.

TABLE CAPTIONS

Table 1: Stratigraphical context.

Table 2: Centres of mining within the Rookhope Catchment.

Table 3: Sampling point location, major ion and trace element concentrations, field measurements and discharges of inflows in Rookhope catchment.

Table 4: Sampling point location, major ion and trace element concentrations, field measurements and discharges of Rookhope Burn.

Table 5: Discharge and field measurements determined south, mid and north channel in the vicinity of the Tailrace Level (NY 91631 42732) on 11 August, 2007.

Table 6: Summary of changes in Zn load at the 11 stream segments defined by sample locations in Rookhope Burn.

Table 7: Cumulative instream Zn loading, instream attenuation and cumulative measured inflow contributions to the total Zn load in Rookhope Burn.

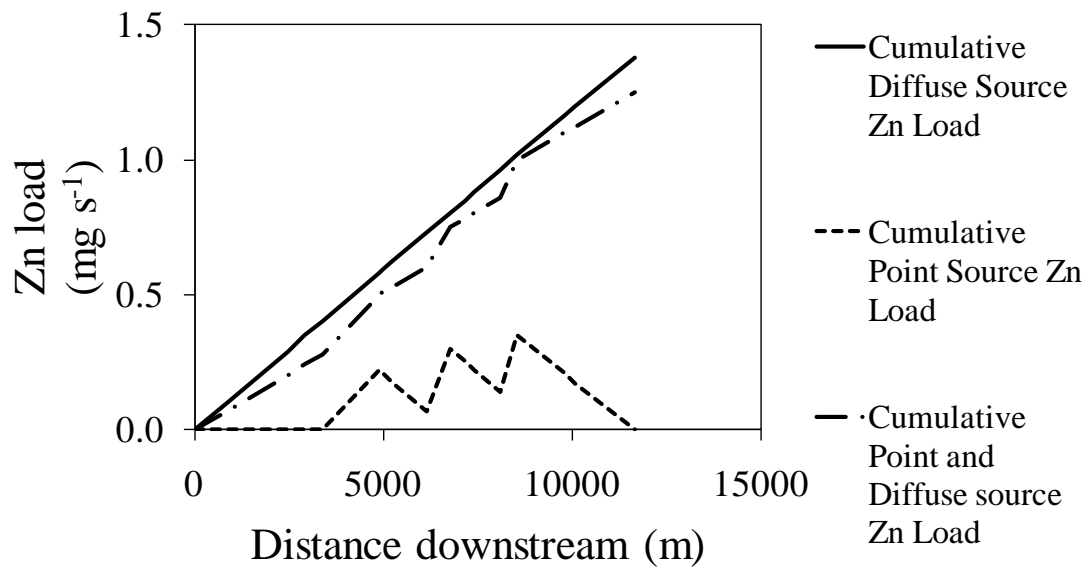


Figure 1

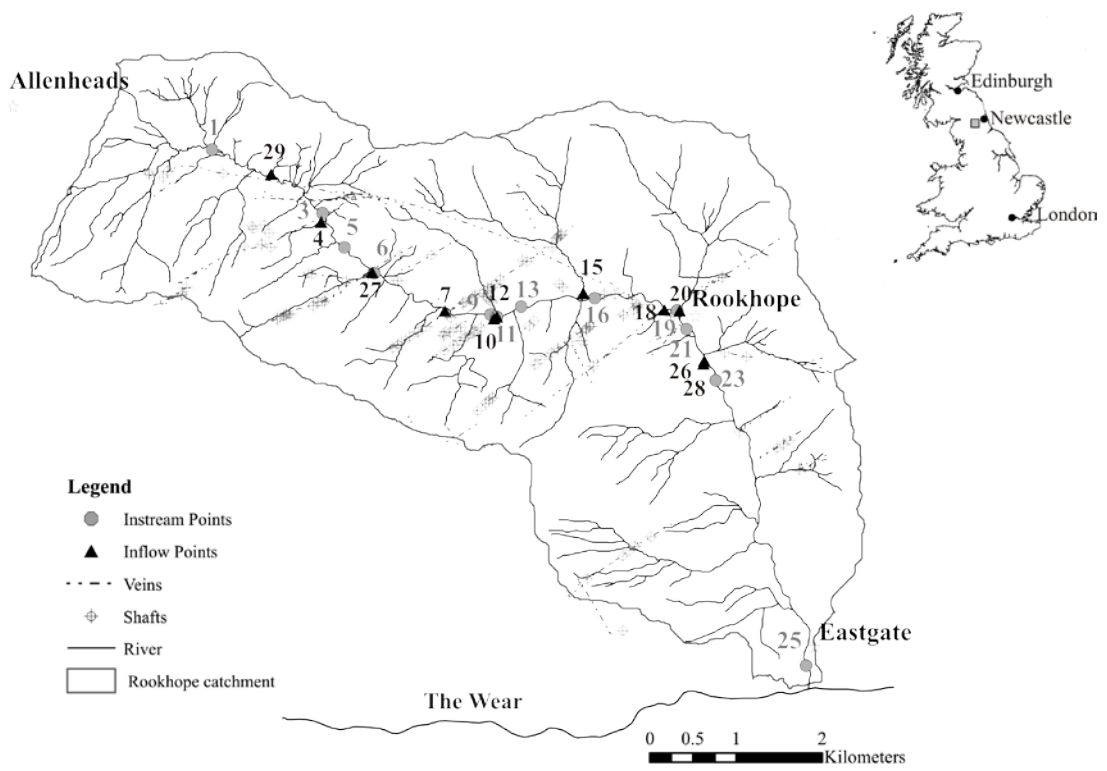


Figure 2

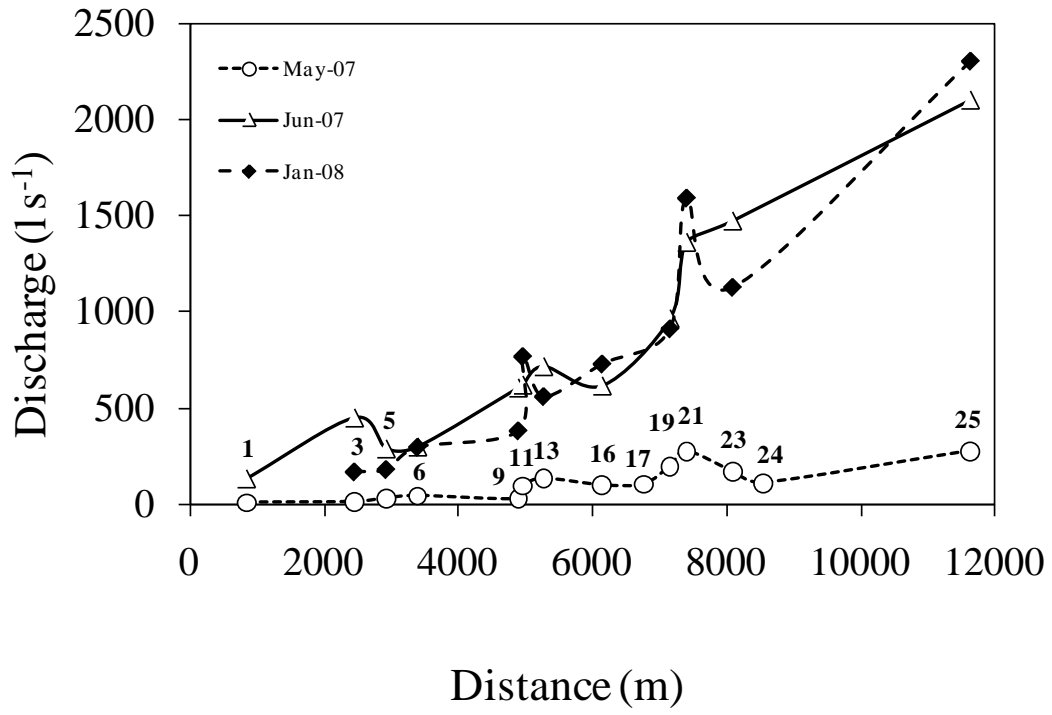


Figure 3

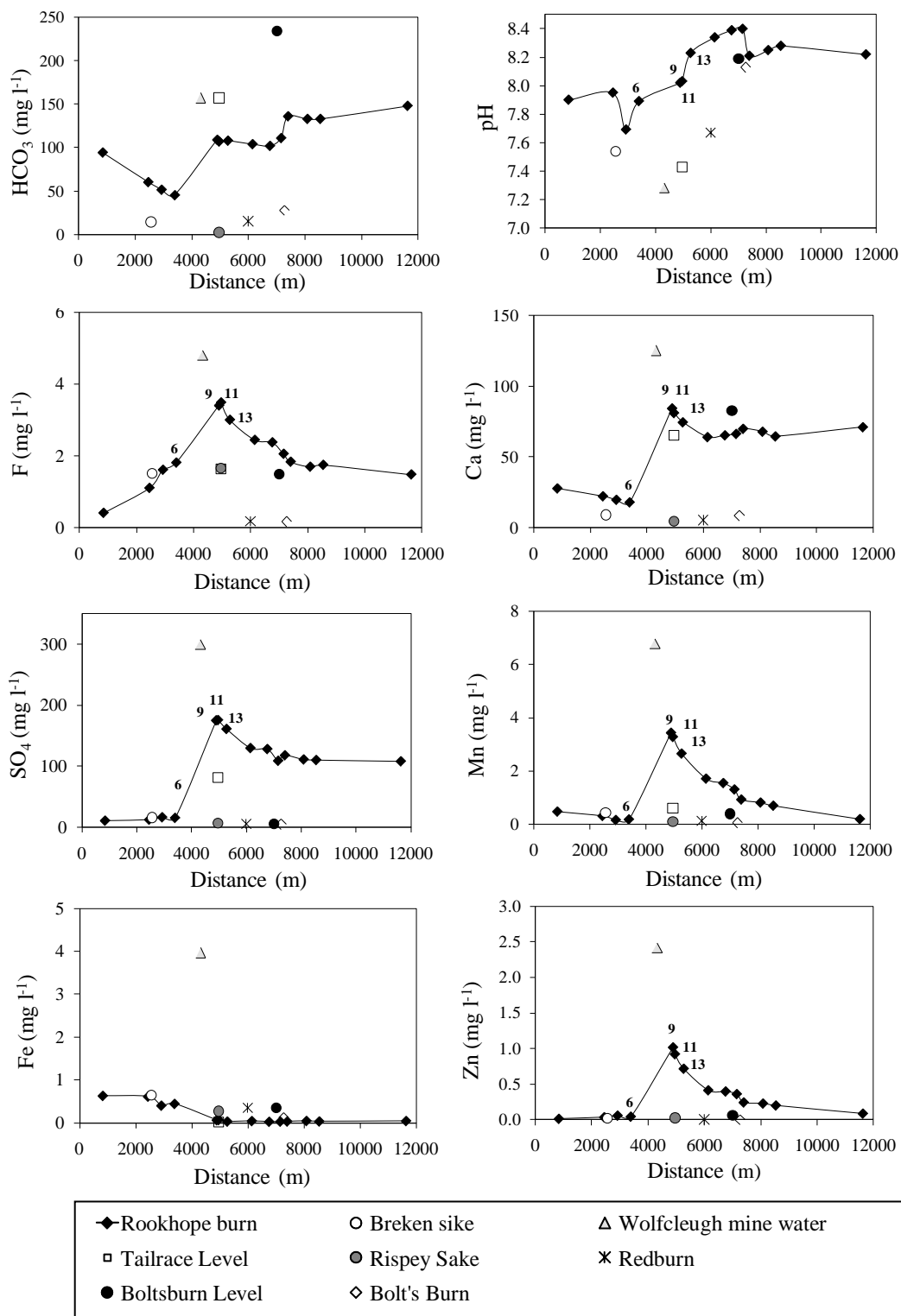


Figure 4

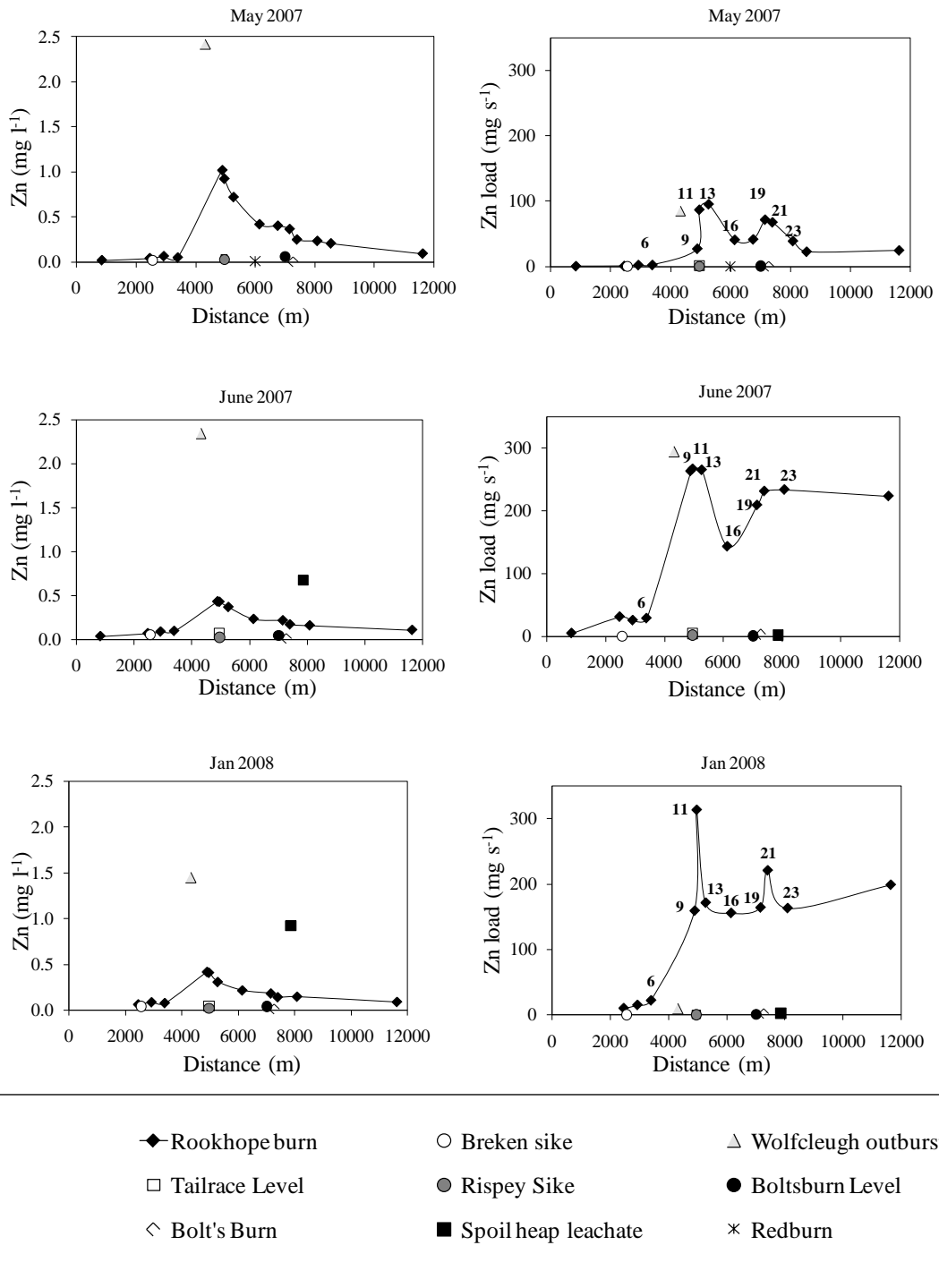


Figure 5

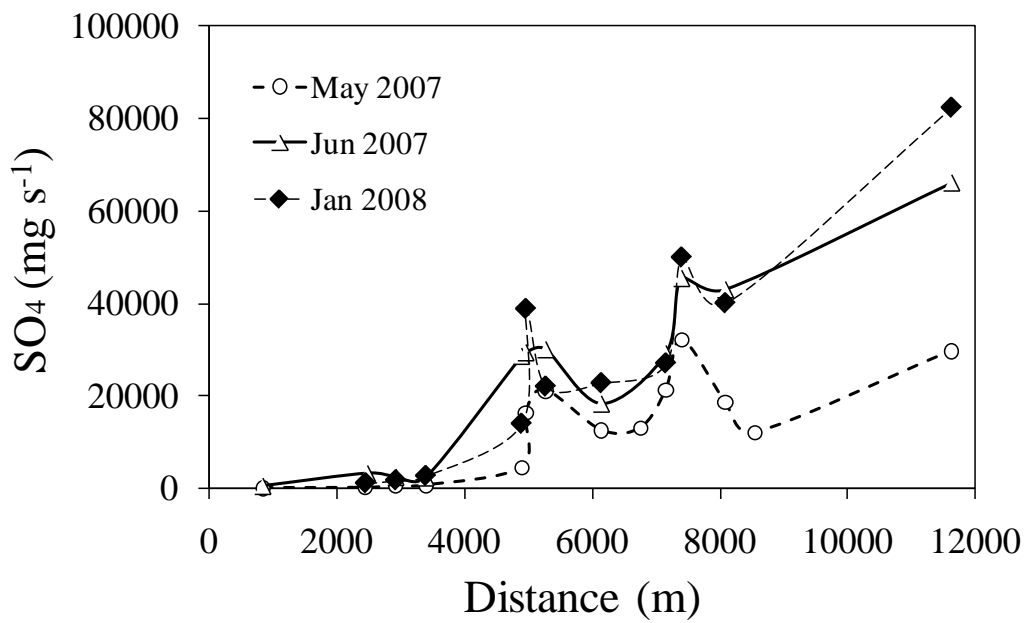
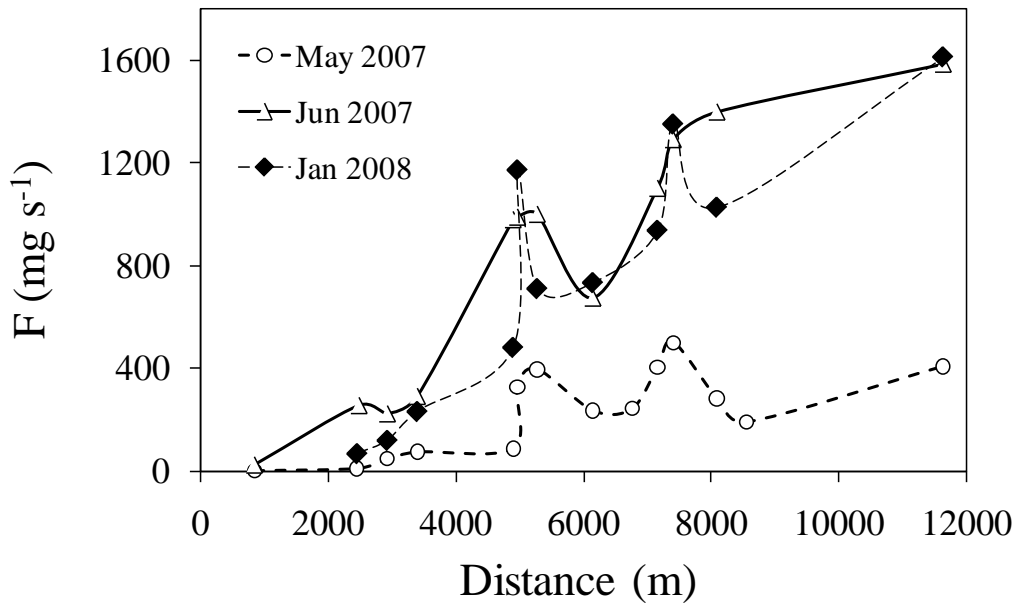


Figure 6

Table 1

| Group | Formation | Member |
|--------------|------------------|-------------------------|
| Yoredale | Stainmore | Grindstone Sill |
| | | Upper Felltop Limestone |
| | | Sandstone |
| | | Lower Felltop Limestone |
| | | High Grit Sill |
| | | Low Grit Sill |
| | | Crag Limestone |
| | | Firestone Sill |
| | | Little Limestone |
| | | Great Limestone |
| | Alston | Four Fathom Limestone |
| | | Three Yard Limestone |
| | | Five Yard Limestone |
| | | Scar Limestone |
| | | Tynebottom Limestone |
| | | Jew Limestone |
| | | |

Table 2

| Mine area/ name | National Grid Reference | Date of operation, where known | Description/ References. |
|---|--------------------------------|--|---|
| Frazer's Hushes | 388222 544469 | Early | Hushes (water flushed workings) for iron-rich flats associated with the Lower Felltop Limestone. |
| Frazer's Hush and Greencleugh Mines/ Greencleugh Vein and Red Vein | 388833 544438 | Recent | Worked for fluorspar. Connected underground with Groverake Mine (Young in Scrutton, 1995). Greencleugh Vein joins Red Vein at 389978 544174, which crosses Boltsburn Vein at 393592 542820 and continues in a southeasterly trend. |
| Frazer's Grove Mine | 389559 544153 | Particularly active between 1880 and 1900, closing in 1903 and 1999. | Early working of iron ore flats associated with the Lower Felltop Limestone. Subsequent working for galena and fluorspar. (Carruthers and Strahan, 1923). Reopened and comprised four separate mines: Frazer's Hush, Rake Level/ Firestone Incline workings, Incline workings, Grove Rake and Greencleugh (Johnson and Younger, 2002; Younger 1999). Originally referred to as a Grove Rake Mine. Levels flooded. |
| Breckon Sike Level | 389112 543608 | | Associated with West Groverake (Dunham, 1990). Open cast workings quarried for iron in the Upper and Lower Felltop limestones. |
| Wolf Cleugh New Vein | 390849 542945 | | Greenwell's Level worked for lead, Hawk Sike for iron. |
| Wolf Cleugh Old Vein (Thorny Slitt Level) | 390139 543272 | Late 1700s, 1818-1846, 1901-1912 | Worked for lead, primarily from the Little Limestone and White Hazle. Subsequently worked for fluorspar. |
| Rispey Vein, Shaft and Mill | 391090 542800 | 1889 Smelt mill constructed | Exploited for lead and iron carbonate, the ore coming from both the Little and Great limestones (Dunham, 1990; Fairbairn, 1996). Weardale Lead Company built Rispey Mill (Dunham, 2002). |
| Scarsike Veins (Tailrace Water Level). | 391631 542732 | | East and West Scarsike Veins were worked for lead. The Tailrace Water Level was driven from a level of 364 m OD in Scarsike Vein, then turns north west and continues as a crosscut via Rispey Engine and Wolfcleugh shafts to Groverake Whimsey Shaft (a total distance of 2.8 km). Dunham (1990) reported that it was understood to be partially blocked between Wolfcleugh and Groverake mines. |
| Straitlegs (Straightleggs) Vein and Level | 392060 542880 | | Level driven south from the burn to the vein (not shown on the current 1: 50 000 scale geology sheet) (Dunham, 1990; Fairbairn, 1996). |
| Redburn Mine | 392328 543621 | | North-eastern end of Rispey Vein. Barren ironstone trials adjacent (Fairbairn, 1996). |
| Lintzgarth Arch | 392448 542979 | Built in 1737 | Remnant of the former Lintzgarth Mill, which was and incorporated a silver refining furnace (Fairbairn, 1996). |
| Fulwood Mine | 392568 542537 | | Worked for the ironstone flats associated with the Great Limestone (Fairbairn, 1996). |
| Boltsburn Mine | 393679 542802 | Boltsburn West Level driven in the early 1800s. | Worked primarily for fluorspar, but early workings for lead. Vein crosses the Rookhope Burn. |
| Brandon Walls Vein | 394652 541118 | Dates at least to 1662 (Fairbairn, 1996) | Mined for lead ore and ironstone. Ironstone was worked in the Great Limestone on both sides of the valley at Brandon Walls Iron Mine (394777 541231) and Hanging Walls Mine. |
| Stotfield Burn Mine | 394302 542377 | 1863 to 1887, 1914, 1950s. | Worked for lead and then fluorspar (Weardale Lead Company). |
| Captain's Cleugh Mine | 395295 541063 | Early iron. Lead 1850 to 1858. | The shaft (395295 541063) was worked for iron ore in the Great Limestone. Subsequent lead production noted by Dunham (1990) and Fairbairn (1996). |

Table 3

| Site | Description | Easting | Northing | Date | Sample Code | T | pH | Eh | Cond | Alk (HCO ₃) | Ca | Mg | Na | K | Cl | SO ₄ | NO ₃ | F | Tot S | Si | Ba | Sr | Mn | Tot Fe | Fe(II) | Al | Zn | Pb | Average | | | | |
|------|--|---------|----------|---------|-------------|------|------|-------|------|----------------------------|------|-------|------|-------|------|-----------------|-----------------|------|-------|-------|-------|-------|-------|--------|--------|-------|-------|-------|-----------|--|--|--|-----|
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Discharge | | | | |
| | | | | | | °C | mV | uS/cm | mg/l | | | | | | | | | | | | | | | | | | | | | | | | l/s |
| 29 | Adit u/s Grove Rake mine | 389050 | 544411 | 27/6/07 | WD229 | 8.5 | 6.59 | 260 | 127 | 94 | 21.5 | 6.91 | 8.10 | 1.77 | 52.4 | 9.15 | 0.03 | 0.22 | 3.50 | 3.54 | 0.033 | 0.072 | 3.10 | 6.04 | 6.00 | 0.013 | 0.051 | <0.0 | 4.51 | | | | |
| 4 | Brecken Sike | 389631 | 543858 | 02/5/07 | WD104 | 14.3 | 7.54 | 390 | 94 | 15 | 8.98 | 2.67 | 3.28 | 0.82 | 4.63 | 16.3 | 0.12 | 1.52 | 5.43 | 0.74 | 0.006 | 0.03 | 0.448 | 0.646 | 0.690 | 0.071 | 0.018 | <0.01 | 0.60 | | | | |
| | | | | 27/6/07 | WD204 | 11.0 | 5.98 | 368 | 46 | 3 | 4.31 | 1.42 | 2.75 | <0.5 | 3.05 | 8.08 | <0.02 | 0.59 | 3.10 | 0.65 | 0.007 | 0.01 | 0.106 | 1.02 | 0.754 | 0.264 | 0.055 | 0.026 | 3.79 | | | | |
| | | | | 28/1/08 | WD304 | 4.5 | 5.35 | 551 | 51 | 59 | 3.44 | 1.19 | 2.61 | 0.65 | 3.47 | 7.47 | 0.28 | 0.44 | 3.09 | 1.13 | 0.008 | 0.01 | 0.075 | 0.497 | 0.458 | 0.145 | 0.039 | 0.010 | 5.45 | | | | |
| 27 | Leachate waste heap on river bank | 390216 | 543275 | 27/6/07 | WD227 | 10.9 | 5.68 | 414 | nd | 10 | 4.53 | 1.16 | 2.78 | 0.584 | 3.31 | 4.63 | 0.231 | 1.70 | 1.92 | 0.875 | 0.006 | 0.008 | 0.030 | 0.728 | 0.522 | 0.450 | 0.094 | 0.127 | nd | | | | |
| 7 | Wolfcleugh mine water outbreak | 391059 | 542828 | 02/5/07 | WD107 | 9.5 | 7.28 | 293 | 785 | 157 | 125 | 20.7 | 8.23 | 8.01 | 11.0 | 299 | 0.17 | 4.80 | 90.7 | 3.17 | 0.012 | 0.34 | 6.77 | 3.97 | 3.930 | 0.411 | 2.42 | <0.01 | 35.00 | | | | |
| | | | | 27/6/07 | WD207 | 9.6 | 6.43 | 293 | 614 | 108 | 98.9 | 18.3 | 8.16 | 6.72 | 11.0 | 256 | 0.64 | 4.36 | 73.2 | 3.02 | 0.011 | 0.28 | 5.21 | 2.83 | 2.541 | 0.463 | 2.34 | <0.01 | 125.75 | | | | |
| | | | | 28/1/08 | WD307 | 8.9 | 6.38 | 321 | 527 | 151 | 79.4 | 13.8 | 7.65 | 5.69 | 13.3 | 178 | 0.69 | 3.99 | 54.8 | 2.67 | 0.011 | 0.25 | 3.69 | 2.18 | 2.100 | 0.291 | 1.45 | 0.010 | 6.67 | | | | |
| 10 | Tailrace Level | 391631 | 542732 | 02/5/07 | WD110 | 8.5 | 7.43 | 434 | 434 | 157 | 65.4 | 10.2 | 8.04 | 3.28 | 11.6 | 81.4 | 0.85 | 1.63 | 24.1 | 2.53 | 0.008 | 0.25 | 0.607 | 0.016 | <0.1 | 0.021 | 0.291 | <0.01 | 33.80 | | | | |
| | | | | 27/6/07 | WD210 | 8.7 | 6.77 | 376 | 241 | 82 | 37.1 | 6.06 | 7.10 | 1.80 | 8.72 | 22.5 | 1.64 | 1.29 | 7.20 | 2.07 | 0.008 | 0.15 | 0.166 | 0.153 | 0.150 | 0.083 | 0.067 | 0.069 | 61.32 | | | | |
| | | | | 28/1/08 | WD310 | 7.7 | 6.29 | 521 | 218 | 73 | 26.9 | 4.62 | 6.15 | 1.50 | 8.98 | 16.2 | 2.19 | 1.04 | 5.81 | 2.06 | 0.007 | 0.11 | 0.163 | 0.103 | 0.093 | 0.057 | 0.042 | 0.046 | 18.65 | | | | |
| 12 | Rispey Sike | 391668 | 542756 | 02/5/07 | WD112 | 14.0 | 6.56 | 445 | 63 | <5 | 4.41 | 1.21 | 3.79 | 1.07 | 5.92 | 6.74 | 0.25 | 1.66 | 2.63 | 1.36 | 0.006 | 0.01 | 0.099 | 0.274 | 0.268 | 0.230 | 0.026 | <0.01 | 0.50 | | | | |
| | | | | 27/6/07 | WD212 | 10.9 | 5.51 | 437 | nd | 10 | 2.02 | 0.844 | 3.10 | <0.5 | 3.27 | 4.29 | 0.11 | 0.38 | 1.80 | 0.80 | 0.007 | 0.01 | 0.217 | 0.848 | 0.671 | 0.321 | 0.023 | 0.042 | 78.32 | | | | |
| | | | | 28/1/08 | WD312 | 5.7 | 4.69 | 540 | 44 | <5 | 1.91 | 0.898 | 3.40 | 0.70 | 5.17 | 4.85 | 0.38 | 0.27 | 2.02 | 1.35 | 0.007 | 0.01 | 0.211 | 0.507 | 0.500 | 0.237 | 0.021 | 0.025 | 8.09 | | | | |
| 15 | Redburn | 392669 | 543032 | 02/5/07 | WD115 | 15.6 | 7.67 | 337 | 85 | 15 | 5.26 | 2.22 | 6.12 | 0.82 | 11.2 | 5.49 | 0.04 | 0.18 | 2.34 | 1.81 | 0.005 | 0.019 | 0.141 | 0.353 | 0.243 | 0.018 | 0.006 | <0.01 | 7.50 | | | | |
| 18 | Boltsburn Level | 393607 | 542837 | 02/5/07 | WD118 | 8.9 | 8.19 | 348 | 529 | 234 | 82.8 | 12.7 | 10.1 | 4.57 | 13.3 | 76.4 | 0.38 | 1.49 | 22.5 | 3.37 | 0.014 | 0.36 | 0.398 | 0.058 | <0.1 | <0.01 | 0.060 | <0.01 | 8.70 | | | | |
| | | | | 27/6/07 | WD218 | 9.8 | 7.34 | 382 | 337 | 113 | 47.0 | 7.74 | 8.73 | 2.73 | 9.97 | 36.9 | 0.94 | 1.40 | 11.0 | 2.67 | 0.011 | 0.22 | 0.151 | 0.325 | 0.170 | 0.020 | 0.047 | <0.01 | 13.73 | | | | |
| | | | | 28/1/08 | WD318 | 7.0 | 6.92 | 423 | 374 | 122 | 48.0 | 7.41 | 9.33 | 2.60 | 17.8 | 37.0 | 1.87 | 1.34 | 11.4 | 2.73 | 0.011 | 0.22 | 0.173 | 0.244 | 0.170 | <0.25 | 0.041 | 0.01 | 14.20 | | | | |
| 20 | Bolts Burn | 393785 | 542828 | 02/5/07 | WD120 | 11.5 | 8.13 | 406 | 91 | 28 | 8.55 | 2.23 | 5.13 | 0.69 | 7.91 | 5.00 | 0.05 | 0.18 | 2.06 | 1.88 | 0.007 | 0.03 | 0.062 | 0.123 | 0.121 | 0.016 | <0.0 | <0.01 | 0.86 | | | | |
| | | | | 27/6/07 | WD220 | 10.4 | 6.97 | 305 | nd | 5 | 3.15 | 1.20 | 4.34 | <0.5 | 6.39 | 4.56 | 0.21 | 0.12 | 1.88 | 1.26 | 0.009 | 0.01 | 0.112 | 0.372 | 0.289 | 0.133 | 0.013 | <0.01 | 221.99 | | | | |
| | | | | 28/1/08 | WD320 | 4.9 | 6.42 | 394 | 48 | 5 | 2.78 | 1.13 | 4.33 | 0.54 | 6.91 | 5.59 | 0.79 | 0.09 | 2.13 | 1.69 | 0.010 | 0.01 | 0.087 | 0.179 | 0.210 | 0.085 | 0.013 | 0.010 | 137.13 | | | | |
| 28 | Discharge from waste heaps- Rookhope village | 394067 | 542244 | 27/6/07 | WD228 | 12.0 | 7.69 | 233 | 410 | 64 | 65.0 | 10.7 | 3.40 | 1.10 | 4.04 | 138 | 0.11 | 1.89 | 40.3 | 0.80 | 0.020 | 0.10 | 0.603 | 0.498 | 0.455 | 0.111 | 0.675 | 0.325 | 2.46 | | | | |
| | | | | 28/1/08 | WD328 | 2.9 | 7.27 | 282 | 448 | 122 | 64.0 | 10.0 | 3.31 | 1.38 | 5.51 | 138 | 0.14 | 1.88 | 43.3 | 1.12 | 0.016 | 0.09 | 0.422 | 0.299 | 0.370 | 0.055 | 0.922 | 0.132 | 2.58 | | | | |
| 26 | Adit discharge d/s point 28 | 394058 | 542209 | 27/6/07 | WD226 | 9.2 | 7.65 | 299 | 162 | 57 | 25.7 | 3.34 | 3.67 | 1.12 | 4.38 | 16.7 | 1.67 | 0.09 | 3.91 | 1.11 | 0.015 | 0.105 | 0.021 | 0.285 | 0.215 | 0.106 | <0.0 | <0.01 | 12.37 | | | | |
| | | | | 28/1/08 | WD326 | 6.7 | 7.38 | 460 | 158 | 127 | 20.9 | 2.79 | 3.67 | 1.28 | 7.87 | 9.50 | 3.13 | 0.08 | 3.35 | 1.41 | 0.012 | 0.092 | 0.016 | 0.086 | 0.060 | 0.040 | <0.0 | 0.010 | 14.66 | | | | |

nd= not detected

Table 4

| Site | Description | Easting | Northing | Date | Sample Code | T | pH | Eh | Cond | Alk | Ca | Mg | Na | K | Cl | SO ₄ | NO ₃ | F | Total S | Si | Ba | Sr | Mn | Tot Fe | Fe(II) | Al | Zn | Pb | Average Discharge |
|------|---|---------|----------|---------|-------------|----|------|-------|---------------------|------|------|------|------|------|-------|-----------------|-----------------|------|---------|-------|-------|-------|-------|--------|--------|-------|-------|-------|-------------------|
| | | | | | | °C | mV | µS/cm | (HCO ₃) | mg/l | | | | | | | | | | | | | | | | | | | |
| 1 | Rookhope Burn - headwaters | 388362 | 544696 | 02/5/07 | WD101 | 15 | 7.90 | 294 | 194 | 94 | 27.7 | 4.90 | 6.53 | 2.80 | 14.29 | 10.66 | 0.06 | 0.41 | 3.83 | 2.40 | 0.053 | 0.106 | 0.469 | 0.629 | 0.613 | 0.050 | 0.015 | <0.01 | 7 |
| | | | | 27/6/07 | WD201 | 11 | 6.37 | 348 | 48 | 9 | 5.32 | 1.38 | 3.93 | 0.57 | 5.36 | 4.78 | 0.03 | 0.20 | 2.09 | 0.832 | 0.019 | 0.017 | 0.199 | 1.67 | 1.37 | 0.246 | 0.035 | <0.01 | 134 |
| | | | | 28/1/08 | WD303 | 5 | 6.21 | 503 | 76 | 34 | 5.88 | 1.55 | 4.42 | 0.90 | 7.20 | 6.97 | 0.37 | 0.41 | 2.96 | 1.14 | 0.012 | 0.021 | 0.151 | 0.426 | 0.426 | 0.142 | 0.060 | 0.01 | |
| 3 | Rookhope Burn - d/s Grove Rake adit | 389645 | 543961 | 02/5/07 | WD103 | 18 | 7.95 | 413 | 179 | 60 | 22.2 | 4.37 | 6.56 | 2.35 | 12.77 | 12.29 | 0.02 | 1.10 | 4.72 | 0.666 | 0.023 | 0.078 | 0.305 | 0.613 | 0.542 | 0.040 | 0.037 | <0.01 | 11 |
| | | | | 27/6/07 | WD203 | 13 | 7.03 | 299 | 64 | 8 | 6.38 | 1.65 | 4.07 | 0.81 | 5.06 | 7.47 | 0.11 | 0.57 | 2.88 | 0.836 | 0.014 | 0.020 | 0.184 | 0.992 | 0.742 | 0.268 | 0.068 | 0.024 | 450 |
| | | | | 28/1/08 | WD303 | 5 | 6.21 | 503 | 76 | 34 | 5.88 | 1.55 | 4.42 | 0.90 | 7.20 | 6.97 | 0.37 | 0.41 | 2.96 | 1.14 | 0.012 | 0.021 | 0.151 | 0.426 | 0.426 | 0.142 | 0.060 | 0.01 | |
| 5 | Rookhope Burn (intermediate location) | 389900 | 543562 | 02/5/07 | WD105 | 20 | 7.69 | 441 | 177 | 52 | 19.7 | 4.35 | 7.45 | 2.21 | 13.03 | 16.25 | 0.06 | 1.61 | 6.05 | 0.491 | 0.018 | 0.067 | 0.153 | 0.403 | 0.332 | 0.073 | 0.059 | <0.01 | 30 |
| | | | | 27/6/07 | WD205 | 13 | 6.81 | 328 | 61 | 12 | 6.89 | 1.79 | 4.14 | 0.82 | 5.21 | 8.89 | 0.08 | 0.78 | 3.28 | 0.840 | 0.013 | 0.019 | 0.158 | 0.916 | 0.681 | 0.272 | 0.087 | 0.023 | 289 |
| | | | | 28/1/08 | WD305 | 6 | 6.41 | 505 | 88 | 44 | 7.26 | 1.87 | 4.87 | 1.02 | 8.51 | 9.97 | 0.51 | 0.67 | 3.77 | 1.27 | 0.013 | 0.022 | 0.141 | 0.488 | 0.488 | 0.155 | 0.083 | 0.01 | |
| 6 | Rookhope Burn at footbridge Wolf Cleugh | 390241 | 543261 | 02/5/07 | WD106 | 19 | 7.89 | 381 | 166 | 45 | 17.9 | 3.85 | 6.68 | 1.87 | 12.43 | 15.20 | <0.0 | 1.81 | 5.36 | 0.442 | 0.016 | 0.056 | 0.174 | 0.443 | 0.373 | 0.071 | 0.044 | <0.01 | 42 |
| | | | | 27/6/07 | WD206 | 13 | 6.92 | 295 | 67 | 9 | 6.83 | 1.76 | 4.38 | 0.79 | 5.08 | 8.23 | 0.07 | 0.98 | 3.20 | 0.847 | 0.013 | 0.018 | 0.156 | 0.904 | 0.686 | 0.284 | 0.095 | 0.026 | 299 |
| | | | | 28/1/08 | WD306 | 6 | 6.44 | 498 | 83 | 88 | 6.42 | 1.68 | 4.42 | 0.92 | 8.13 | 9.24 | 0.53 | 0.79 | 3.37 | 1.20 | 0.011 | 0.020 | 0.123 | 0.453 | 0.453 | 0.164 | 0.074 | 0.011 | |
| 9 | Rookhope Burn-upstream Tailrace level | 391591 | 542785 | 02/5/07 | WD109 | 17 | 8.02 | 294 | 551 | 109 | 84.4 | 14.8 | 7.94 | 5.78 | 11.04 | 174.45 | 0.13 | 3.40 | 57.1 | 2.05 | 0.015 | 0.240 | 3.44 | 0.066 | 0.118 | 0.038 | 1.02 | <0.01 | 26 |
| | | | | 27/6/07 | WD209 | 11 | 7.23 | 276 | 127 | 32 | 22.0 | 4.74 | 5.06 | 1.79 | 5.89 | 47.40 | 0.30 | 1.62 | 14.3 | 1.20 | 0.013 | 0.064 | 0.877 | 0.869 | 0.690 | 0.269 | 0.435 | 0.026 | 606 |
| | | | | 28/1/08 | WD309 | 7 | 6.63 | 450 | 225 | 83 | 25.7 | 5.19 | 5.73 | 2.35 | 7.05 | 36.85 | 0.61 | 1.27 | 16.3 | 1.68 | 0.011 | 0.081 | 0.975 | 0.578 | 0.544 | 0.163 | 0.419 | 0.01 | |
| 11 | Rookhope Burn-d/s Tailrace level | 391668 | 542756 | 02/5/07 | WD111 | 17 | 8.03 | 385 | 547 | 107 | 81.1 | 14.4 | 7.62 | 5.55 | 11.27 | 174.90 | 0.14 | 3.48 | 55.7 | 2.00 | 0.015 | 0.236 | 3.28 | 0.070 | 0.085 | 0.041 | 0.922 | <0.01 | 94 |
| | | | | 27/6/07 | WD211 | 11 | 7.29 | 270 | 177 | 28 | 22.5 | 4.79 | 4.95 | 1.79 | 5.89 | 47.48 | 0.23 | 1.60 | 14.4 | 1.22 | 0.013 | 0.063 | 0.855 | 0.855 | 0.506 | 0.263 | 0.430 | 0.026 | 621 |
| | | | | 28/1/08 | WD311 | 7 | 6.64 | 432 | 220 | 93 | 25.5 | 5.16 | 5.69 | 2.32 | 9.57 | 50.65 | 1.01 | 1.53 | 16.3 | 1.66 | 0.011 | 0.080 | 0.951 | 0.531 | 0.530 | 0.157 | 0.410 | 0.01 | |
| 13 | Rookhope Burn | 391946 | 542876 | 02/5/07 | WD113 | 17 | 8.23 | 427 | 521 | 108 | 74.5 | 13.7 | 7.93 | 5.18 | 11.17 | 160.40 | 0.20 | 3.00 | 51.5 | 2.05 | 0.015 | 0.230 | 2.66 | 0.034 | <0.050 | 0.039 | 0.718 | <0.01 | 132 |
| | | | | 27/6/07 | WD213 | 11 | 7.37 | 287 | 149 | 25 | 20.9 | 4.42 | 5.05 | 1.68 | 6.00 | 42.06 | 0.21 | 1.40 | 12.8 | 1.20 | 0.012 | 0.060 | 0.741 | 0.810 | 0.712 | 0.246 | 0.370 | 0.028 | 716 |
| | | | | 28/1/08 | WD313 | 5 | 6.87 | 316 | 191 | 54 | 20.6 | 4.15 | 5.31 | 1.87 | 9.42 | 39.48 | 0.86 | 1.27 | 12.5 | 1.50 | 0.011 | 0.064 | 0.699 | 0.441 | 0.440 | 0.149 | 0.307 | 0.01 | |
| 16 | Rookhope Burn | 392799 | 542973 | 02/5/07 | WD116 | 16 | 8.34 | 440 | 455 | 104 | 64.0 | 11.2 | 7.25 | 3.91 | 11.39 | 129.19 | 0.15 | 2.44 | 38.3 | 1.96 | 0.016 | 0.203 | 1.71 | 0.045 | <0.050 | 0.032 | 0.416 | <0.01 | 97 |
| | | | | 27/6/07 | WD216 | 11 | 7.46 | 292 | 140 | 18 | 16.0 | 3.52 | 5.29 | 1.30 | 6.90 | 29.86 | 0.19 | 1.10 | 9.32 | 1.21 | 0.011 | 0.051 | 0.481 | 0.716 | 0.575 | 0.205 | 0.232 | 0.020 | 616 |
| | | | | 28/1/08 | WD316 | 7 | 7.12 | 458 | 168 | 93 | 17.8 | 3.71 | 5.97 | 1.69 | 10.12 | 31.31 | 0.87 | 1.01 | 10.4 | 1.63 | 0.010 | 0.061 | 0.521 | 0.364 | 0.360 | 0.114 | 0.214 | 0.01 | |
| 19 | Rookhope Burn d/s Boltsburn Level | 393756 | 542833 | 02/5/07 | WD119 | 11 | 8.40 | 402 | 447 | 111 | 66.3 | 11.7 | 8.15 | 4.18 | 10.01 | 108.44 | 0.13 | 2.05 | 37.8 | 2.12 | 0.015 | 0.225 | 1.30 | 0.032 | <0.050 | 0.018 | 0.362 | <0.01 | 197 |
| | | | | 27/6/07 | WD219 | 11 | 7.60 | 313 | 150 | 24 | 18.0 | 3.72 | 5.44 | 1.41 | 6.81 | 30.33 | 0.28 | 1.14 | 9.38 | 1.27 | 0.011 | 0.058 | 0.395 | 0.715 | 0.574 | 0.192 | 0.217 | 0.018 | 965 |
| | | | | 28/1/08 | WD319 | 5 | 7.22 | 405 | 173 | 59 | 17.7 | 3.46 | 5.70 | 1.60 | 10.38 | 29.71 | 0.91 | 1.03 | 9.40 | 1.53 | 0.010 | 0.060 | 0.402 | 0.340 | 0.340 | 0.109 | 0.180 | 0.01 | |
| 21 | Rookhope Burn d/s Bolts Burn | 393862 | 542610 | 02/5/07 | WD121 | 11 | 8.21 | 351 | 476 | 136 | 69.9 | 12.6 | 9.52 | 4.18 | 10.93 | 117.45 | 0.31 | 1.83 | 36.1 | 2.39 | 0.015 | 0.278 | 0.924 | 0.035 | <0.050 | 0.012 | 0.245 | <0.01 | 274 |
| | | | | 27/6/07 | WD221 | 11 | 7.59 | 316 | 163 | 29 | 19.3 | 4.13 | 5.50 | 1.37 | 6.85 | 33.43 | 0.47 | 0.95 | 10.1 | 1.34 | 0.011 | 0.076 | 0.322 | 0.612 | 0.526 | 0.168 | 0.170 | 0.020 | 1361 |
| | | | | 28/1/08 | WD321 | 5 | 7.21 | 352 | 179 | 29 | 18.5 | 3.86 | 5.58 | 1.31 | 9.54 | 31.40 | 1.10 | 0.85 | 9.97 | 1.58 | 0.010 | 0.075 | 0.304 | 0.298 | 0.300 | 0.098 | 0.139 | 0.01 | |
| 23 | Rookhope Burn d/s spoil heaps | 394203 | 542016 | 02/5/07 | WD123 | 9 | 8.25 | 358 | 453 | 133 | 67.9 | 11.9 | 9.36 | 3.84 | 10.98 | 110.63 | 0.17 | 1.69 | 33.9 | 2.19 | 0.015 | 0.262 | 0.810 | 0.047 | <0.050 | 0.010 | 0.229 | <0.01 | 168 |
| | | | | 27/6/07 | WD223 | 10 | 7.66 | 324 | 82 | 29 | 18.0 | 3.81 | 5.70 | 1.23 | 6.89 | 29.26 | 0.43 | 0.95 | 9.08 | 1.29 | 0.011 | 0.069 | 0.283 | 0.666 | 0.511 | 0.167 | 0.159 | 0.020 | 1472 |
| | | | | 28/1/08 | WD323 | 7 | 7.24 | 550 | 194 | 141 | 21.6 | 4.38 | 6.01 | 1.67 | 9.83 | 35.56 | 1.11 | 0.91 | 11.5 | 1.73 | 0.011 | 0.087 | 0.307 | 0.268 | 0.270 | 0.082 | 0.145 | 0.01 | |
| 25 | Rookhope Burn at Eastgate | 395248 | 538715 | 02/5/07 | WD125 | 9 | 8.22 | 354 | 480 | 148 | 71.1 | 11.8 | 10.6 | 3.75 | 15.14 | 107.62 | 1.44 | 1.48 | 32.8 | 1.33 | 0.016 | 0.308 | 0.186 | 0.046 | <0.050 | <0.01 | 0.088 | <0.01 | 276 |
| | | | | 27/6/07 | WD225 | 10 | 7.99 | 288 | 191 | 42 | 25.3 | 4.23 | 6.04 | 1.36 | 8.10 | 31.49 | 1.50 | 0.75 | 9.62 | 1.31 | 0.012 | 0.106 | 0.136 | 0.559 | 0.484 | 0.125 | 0.106 | 0.018 | 2099 |
| | | | | 28/1/08 | WD325 | 5 | 7.39 | 376 | 221 | 49 | 24.9 | 4.14 | 6.18 | 1.43 | 11.49 | 35.75 | 2.55 | 0.70 | 10.9 | 1.52 | 0.011 | 0.110 | 0.142 | 0.216 | 0.200 | 0.063 | 0.086 | 0.01 | |

Table 5

| Sample Location | Rookhope Burn Point 9 | +10 m | +20 m | +30 m | +42 m | +52 m | +62 m | Tailrace Level Point 10 | +2 m d/s Tailrace Level | +10 m | Rookhope Burn Point 11 |
|------------------------|-----------------------|-------|-------|-------|-------|-------|-------|-------------------------|-------------------------|-------|------------------------|
| Discharge (l/sec) | 47.6 | 159.4 | 82.8 | 128.1 | 118.6 | 102.8 | 116.8 | 7.8 | 198.8 | 107.9 | 76.8 |
| pH | 7.47 | 7.47 | 7.6 | 7.52 | 7.64 | 7.67 | 7.66 | 6.59 | 7.64 | 7.66 | 7.60 |
| | 7.50 | 7.50 | 7.59 | 7.58 | 7.62 | 7.63 | 7.65 | | 7.64 | 7.66 | 7.61 |
| | 7.51 | 7.51 | 7.59 | 7.59 | 7.61 | 7.65 | 7.63 | | 7.25 | 7.66 | 7.60 |
| Temperature (°C) | 13.0 | 13.9 | 13.9 | 13.6 | 13.6 | 13.4 | 13.4 | 8.8 | 13.3 | 13.3 | 13.2 |
| | 12.9 | 13.9 | 13.8 | 13.6 | 13.4 | 13.4 | 13.3 | | 13.3 | 13.2 | 13.1 |
| | 13.0 | 13.9 | 13.9 | 13.8 | 13.6 | 13.4 | 13.4 | | 10.2 | 13.3 | 13.0 |
| Conductivity (µS/cm) | 102 | 441 | 439 | 0 | 12 | 440 | 440 | 383 | 437 | 405 | 431 |
| | 437 | 440 | 442 | 438 | 430 | nd | 440 | | 438 | 437 | 434 |
| | 438 | 442 | 442 | 443 | 440 | 440 | 440 | | 398 | 437 | 433 |
| Total Dissolved Solids | 51 | 220 | 220 | 0 | 5 | 220 | 220 | 191 | 219 | 203 | 215 |
| | 218 | 220 | 221 | 219 | 215 | 0 | 220 | | 219 | 218 | 317 |
| | 219 | 221 | 221 | 221 | 220 | 220 | 220 | | 199 | 219 | 217 |
| Dissolved Oxygen (ppm) | 9.4 | 9.40 | 8.80 | 9.83 | 8.18 | 9.06 | 9.41 | 8.50 | 9.48 | 9.11 | 9.29 |
| | 9.29 | 9.29 | 9.39 | 9.40 | 9.31 | 9.35 | 9.12 | | 9.65 | 9.59 | 9.20 |
| | 9.30 | 9.30 | 9.31 | 9.21 | 8.99 | 9.18 | 9.28 | | 10.18 | 9.20 | 9.40 |
| | | | | | | 9.22* | 9.14* | | | 8.00* | |
| | | | | | | 9.33 | 9.49 | | | 9.55 | |
| | | | | | | 9.15 | 9.39 | | | 9.66 | |

*Stream bifurcates

Table 6

| Stream stretch | Net change in zinc load May 2007 (mg/s) | Net change in zinc load June 2007 (mg/s) | Net change in zinc load Jan 2008 (mg/s) |
|-----------------------|--|---|--|
| 1-3 | 0.3 | 26 | n/a |
| 3-5 | 1.4 | -6 | 5 |
| 5-6 | 0.1 | 3 | 7 |
| 6-9 | 25 | 235 | 137 |
| 9-11 | 60 | 3 | 155 |
| 11-13 | 8 | -2 | -142 |
| 13-16 | -54 | -122 | -16 |
| 16-19 | 30 | 66 | 8 |
| 19-21 | -4 | 22 | 57 |
| 21-23 | -29 | 2 | -58 |
| 23-25 | -14 | -10 | 36 |

Table 7

| | May 07 | June 07 | Jan 08 |
|---|---------------|----------------|---------------|
| Min cumulative Zn loading (mg/s) | 128 | 358 | 278 |
| Min cumulative Zn attenuation (mg/s) | -104 | -140 | -79 |
| Min cumulative inflow Zn loading (mg/s) | 95 | 306 | 16 |
| Min cumulative inflow Zn loading (% cumul. load.) | 75 | 85 | 5.6 |
| Wolfcleugh mine water outbreak (% cumul. load.) | 66 | 82 | 3.5 |
