CHANGES IN FLORA DOWN A STREAM SHOWING A ZINC GRADIENT

P. J. SAY & B. A. WHITTON

Department of Botany, University of Durham, Durham DH1 3LE, England

Received December 21, 1979

Keywords: zinc, gradient, benthic, blue-green alga, diatom, chrysophyte

Abstract

An account is given of the chemistry and floristic composition of stream sites in a small catchment (1.2 km^2) with extensive waste from disused lead mines in the upper part of the catchment. One stream sequence provided a gradient of aquatic zinc levels from very high ($\bar{x}$ = 25.6 mg l^{-1} after passing through a filter) to relatively low ($\bar{x}$ = 1.2 mg l^{-1}). There was a negative correlation between the number of photosynthetic species present in a reach and the logarithm of the concentration of zinc. The flora at the site with the highest level of zinc was nevertheless comparatively rich, with 25 species, as opposed to a maximum of 41 species in any reach with elevated zinc. A reach in an unpolluted tributary had 61 species, 11 of which were absent at all other reaches. A discussion is included of the extent to which the various floristic changes observed are likely to be a direct result of changes in zinc levels rather than of correlated changes such as flow regime.

Introduction

There are many accounts of streams and rivers carrying elevated levels of zinc (e.g. Jones, 1958; Alicke, 1974; Pasternak, 1973) and the influence of this zinc on plants has been reviewed recently (Whitton, 1980). Such waters may show a much reduced flora and fauna and hence be regarded as an extreme environment in the sense of Brock (1969). Brock (1978) has shown just how great a contribution to microbial ecology has been made by research on one particular extreme, the thermal spring. Sites showing a clear gradient from high to low temperatures have proved especially valuable, and Brock was able to make general statements on changes in types and numbers of species, standing crop and primary production. No other gradient in streams has received the same intensive study, so we looked for situations where a stream showed a steady decrease in zinc downstream from the source without at the same time showing too many other types of change. The present paper summarizes the results of a study on Gillgill Burn, Cumbria, the best example of such a stream that we could find. This stream lies in the Northern Pennine Orefield, an area with a long history of lead and zinc mining (Dunham, 1948).

Zinc is relatively soluble and tends to persist at high levels in mine waters long after the closure of mining operations (Jones, 1958). It is however impossible to separate completely the influence of zinc from that of other potentially toxic substances leaching from old wastes; in particular, elevated levels of cadmium occur at the same time as those of zinc, though at considerably lower levels. Similar difficulties probably occur in all studies of gradients carried out in the field. For instance, Brock (1978) pointed out various factors which also tend to change on passing down a thermal gradient. Studies on a gradient of decreasing zinc are however more complicated in that the zinc can not be lost entirely to the surrounding environment. The decrease may occur due to dilution, precipitation or uptake by the biota. If a significant component of the zinc originally in solution becomes precipitated, it may be difficult to establish just what is the contribution of this latter to any observed changes in the biota.

Study area

Gillgill Burn rises approximately 1.5 km to the east of Nenthead village in the Alston Moor area of the Northern Pennine Orefield (Fig. 1). Its source is not far from Kilhope Head, the highest point in the area (644 m), which lies on the Cumbria–Durham county boundary. Two small springs arise near the base of dumps of coarse waste material associated with a large complex of disused mine workings. The uppermost one, designated the source of the main stream, emerges at 609 m. Three further tributaries join Gillgill Burn before it enters the R. Nent at an altitude of 427 m. The total catchment area of the stream and its tributaries is 1.2 km^2.

The extensive area of mineral deposits in the Nent Valley occurs in strata belonging to the Carboniferous Lime-

Hydrobiologia 76, 255-262 (1980). 0018-8158/80/0763-0255$01.60.

stone Divisions. The small valley of Gillgill Burn forms a recognisable section through the strata belonging to the Upper Limestone Group or Millstone Grit Series. The sequence of rocks exposed by the stream is dominated primarily by beds of shale, although these alternate with several well developed belts of sandstone. At the bottom of the stream a large stratum of limestone is exposed which corresponds to the Great Limestone; above this there are only a few very thin limestones. The sandstones include siliceous and micaceous types. The shales have associated thin seams of coal and contain much iron. They tend to fracture easily and form a very unstable substratum. Mineralisation of both the sandstone and the limestone can occur, and in this area the chief mineral is sphalerite, although some galena does occur as well. The sphalerite has been shown to contain both iron and cadmium in solution (Dunham, 1948).

The stream runs for 1.5 km from its source to its entry into R. Nent. It never exceeds 2 m in width, and typically is just over 1 m wide. The rate of vertical drop for the first 400 m is only moderate, but after that it increases, and there are a number of small waterfalls. The substratum varies. In the upper part it consists of small cobbles and pebbles of mineral rock from the waste dumps, accompanied by varying proportions of sand-sized particles. Further downstream there are some stretches of exposed sheet bedrock, but for the most part the substratum consist of sandstone boulders, together with gravels and sand from the fractured shale.

The terrain surrounding the stream in the higher parts is rugged fell and upland pasture, with occasional exposed waste dumps connected with the old mine workings. Further downstream the stream is bordered by meadow pastures and a few planted trees of *Picea abies* (L.) Karst. The latter form a dense copse just above the village. There are several cottages beside the stream for the last 200 m.

Climatic records are available for a meterological station 12 km from Gillgill Burn (Moorhouse, at 500 m altitude: data from Meterological Office, Bracknell, Berkshire). The mean precipitation for the years 1972-1975 was 1782 mm, with November to January the months with the most rain and May and June the driest months. The upper part of Gillgill Burn is often frozen in winter.

Armitage (in press) reported a survey of benthic invertebrates at sites in the catchment of the River Nent, including three from Gillgill Burn; two of these correspond exactly to sites in the present study.

Methods

Location of sites and sampling programme

Gillgill Burn and its four tributaries were gridded initially into sixty 10 m reaches located at 50 m intervals along the streams. Analyses of water from each of these 10 m reaches showed that many had rather similar water chemistries, especially those on the lower tributaries. The final sampling programme was based on 30 reaches, with 19 lo-

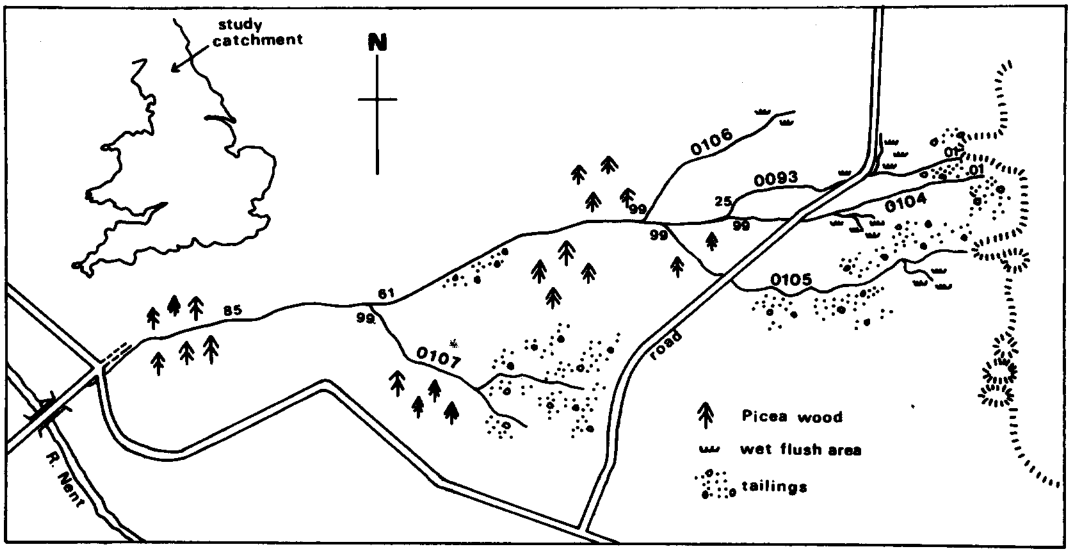

Fig. 1. Map of catchment of Gillgill Burn.

cated on the main stream, eight on a tributary also draining the main area of mineral waste and one each on the last 10 m of the other three tributaries. Reference to the main stream and each of the tributaries is made by a 4-digit number through the rest of this account; individual 10 m reaches on each stream are allocated a further 2-digit number (Fig. 2). The principles used for numbering streams and reaches for data held on computer file at Durham University have been described by Whitton, Diaz & Holmes (1976).

It was difficult to recognize the exact limit of the main stream as opposed to the bank, but an attempt was made to follow the conventions introduced by Holmes & Whitton (1977) for macrophytes in a much larger body of water. The 'river' was regarded as that part of the substratum submerged for more than 85% of the year, as opposed to the 'bank' which is submerged for more than 40% but less than 85% of the year. In the small streams described here a small difference in interpretation could determine whether or not a particular species was included in the flora of a reach. In practice the decision to include a species was often based on whether it was truly submerged at the time of collection rather than trying to establish the exact limit of the main stream. This is probably less important in a survey of micro-algae than it would be for one of large, long-lived macrophytes.

Five surveys of water and phytobenthos were made: 22 September 1973, 1 April 1974, 4 June 1974, 22 August 1974, 1 October 1974. These were all made at periods when subjective estimates of stream flow were 'medium' or 'moderately low'; 'very high', 'high' and 'very low' flows were avoided.

Sampling and analysis of water

The methods and variables measured have been described previously (Say, Diaz & Whitton, 1977). The fraction studied was that passing through a No. 2 Sinta (sintered) glass funnel.

Sampling of phytobenthos

Samples were taken from each reach with the objective of obtaining not only a complete floristic list for each day but also a subjective estimate of the relative proportions of each species. Estimates were made in the field of the relative amounts of macroscopically recognizable species such as the liverwort *Scapania undulata,* and also of the physiognomically distinctive algal communities present. A mixed collection from the various communities was taken with the objective of preserving the communities in approximately the proportions that occurred in the stream. In addition a minimum of six samples of approximately 1 cm^2 area was taken from each reach, including at least one type

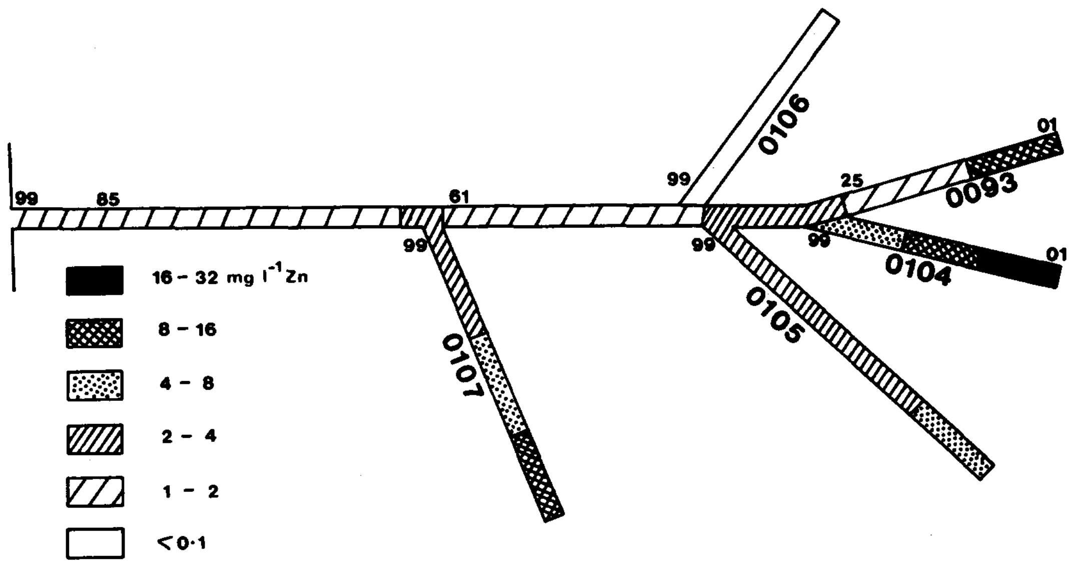

Fig. 2. Diagrammatic representation of Gillgill Burn and its tributaries to show the changes in mean concentrations of zinc and locations of reaches.

of each visually distinctive algal community. The information from these various samples was later combined to allocate a score to each species on a 5-point scale, with 5 = very abundant, 4 = abundant, 3 = frequent, 2 = occasional, 1 = rare. For much of the following paper, the data have been simplified to a presence/absence format, but comments on the abundance of various species are based on the full records which are held on computer file.

Each sample was collected both live and preserved with 3% formalin. The live materials were transported in a cooled thermos flask and stored in the laboratory at 8°C and 500 lux until microscopic study was finished. All records for diatoms in Table 3 are for cells with typical (healthy) chloroplasts at the time of collection, even though the frustules were cleaned later to aid identification.

Taxonomy

Most species were identified to the specific level, but for a few genera the various forms are listed only according to width categories (Whitton, Holmes & Sinclair, 1978; Whitton, Diaz & Holmes, 1979). The reason why we have retained the generic name *Hormidium* (rather than *Klebsormidium)* has been given by Say, Diaz & Whitton (1977). The authorities for many of the species in Table 3 are given by Whitton, Holmes & Sinclair (1978). The following is a list of those which are not: *Schizothrix delicatissima* W. et G. S. West; *Caloneis lagerstedtii* (Lagerstedt) Cholnoky; *Pinnularia appendiculata* (Ag.) Cl.; *Eunotia tenella* (Grun.) Hustedt; *Neidium alpinum* Hustedt; *Eunotia septentrionalis* Östrup; *Oscillatoria pseudogeminata* G. Schmid; *Pinnularia viridis* (Nitzsch) Ehr. var. *sudetica* (Hilse) Hustedt; *Caloneis bacillum* (Grun.) Mereschkowsky; *Navicula minima* Grun.; *Scapania undulata* (L.) Dum.

Results

Water chemistry

The results are summarized in Table 1 and correlation coefficients between zinc and other variables are given in Table 2. Information on the levels of zinc in individual reaches is included in Table 3. The highest level of zinc recorded on any particular day was in each case found in reach 0104/01. The best approach to a gradient from high to low zinc levels in one stream sequence could be found by moving from the top of 0104 down to its junction with 0093 and from there to the bottom of the main stream just before it joined the River Nent. 22 of the 30 reaches studied are included in this sequence(Table 3). There were however several slight rises in zinc on passing down the main stream adjacent to areas of exposed ore; the levels soon dropped again.

Plants

The distribution of photosynthetic plants in reaches of the Gillgill Burn catchment is shown in Table 3. 90 species

Table 1. Water chemistry during 5 surveys of 30 stream reaches in catchment of Gillgill Burn (all elements as mg l^{-1}).

variable	detection limit	means recorded for any one reach		extremes recorded in any survey					
		minimum	maximum	minimum	reach where recorded	date	maximum	reach where recorded	date
temperature (°C)	0.1	7.3	10.8	3.8	0093/01	1. 4.74	15.0	0093/43	4. 6.74
O.D.$_{420\ nm}$	0.005	0.005 -	0.048	0.002	0104/01	4. 6.74	0.084	0093/11	22. 9.73
conductivity (µs cm^{-1})		125.3 -	208.4	83.3	0104/57	4. 6.74	300.0	0104/01	19.10.74
pH	0.1	6.2 -	7.3	5.7	0093/01	19.10.74	7.8	0093/99	22. 8.74
total alkalinity (mg l^{-1} $CaCO_3$)	1.0	6.0 -	41.5	2.0	0093/01	19.10.74	47.0	0093/99	19.10.74
Na	0.1	3.2 -	19.6	2.7	0104/01	4. 6.74	52.0	0104/85	1. 4.74
K	0.05	0.6 -	1.5	0.1	0104/57	19.10.74	2.6	0093/01	22. 9.73
Mg	0.05	1.7 -	5.2	1.26	0104/43	19.10.74	6.8	0093/01	22. 9.73
Ca	0.05	8.5 -	21.1	5.4	0104/43	19.10.74	31.0	0093/04	19.10.74
Al	0.05	<0.05 -	1.41	<0.05	0106/99	22. 9.73	2.13	0093/01	22. 8.74
Mn	0.005	0.028 -	1.02	<0.005	0093/47	22. 9.73	2.01	0093/08	4. 6.74
Fe	0.02	0.06 -	2.94	<0.02	0093/64	22. 8.74	7.4	0093/11	4. 6.74
Cu	0.005	<0.005 -	0.012	<0.005	26 reaches	various	0.014	0093/01	19.10.74
Zn	0.005	0.024 -	25.6	0.050	0106/99	22. 8.74	30.2	0104/01	22. 9.73
Cd	0.0003	0.001 -	0.060	0.001	0106/99	19.10.74	0.060	0104/01	19.10.74
Pb	0.003	0.031 -	2.06	0.007	0106/99	22. 8.74	3.7	0104/01	22. 8.74
PO_4-P	0.01	<0.01 -	0.056	<0.01	5 reaches	various	0.12	0093/95	4. 6.74
NH_4-N	0.01	0.01 -	0.43	<0.01	20 reaches	various	0.81	0093/95	19.10.74
NO_3-N	0.01	0.07 -	0.75	<0.01	12 reaches	various			
SO_4-S	0.2	0.7 -	6.6	0.6	0093/25	19.10.74	4.03	0104/01	22. 8.74
Si	0.1	1.72 -	2.61	1.1	0093/25	22. 8.74	3.2	0093/01	22. 8.74
F	0.05	1.05 -	3.2	1.0	0093/99	22. 8.74	4.0	0093/01	22. 9.73
Cl	1.0	10.0 -	21.5	5.3	0093/08	22. 9.73	52.8	0104/85	4. 6.74

Table 2. Correlation coefficients between zinc and other variables of water chemistry for 30 stream reaches in catchment of Gillgill Burn. (All except Ca and NH_4-N significant at P = < 0.001)

Cd	+ 0.942	Ca	− 0.155
Al	+ 0.844	NH_4–N	− 0.208
Pb	+ 0.809	Cl	− 0.249
Mn	+ 0.686	OD_{420}	− 0.307
F	+ 0.651	Na	− 0.559
Cu	+ 0.494	pH	− 0.641
SO_4–S	+ 0.438	total alkalinity	− 0.676
conductivity	+ 0.334		

were recorded from sites with elevated zinc levels ($\bar{x}$, ⩾ 1.2 mg l^{-1}). A few of these species were present only on a sample day when zinc levels were below average and a few might possibly have been washed into the mainstream from uncontaminated sites in the catchment. However the great majority of the species are certainly part of the normal flora of this stream. 25 species were taken from the reach (0014/01) with the highest level of zinc. This compares with 61 species from 0106/99, the lowermost reach of an unpolluted tributary. There is also a general trend for the numbers of species to increase with decreasing zinc levels on passing down the main zinc gradient, but the effect is not very marked. The relationships between numbers of species and zinc levels are summarised in Table 4.

Discussion

Mining in the immediate area of Gillgill Burn ceased in 1921, but the main stream and three of its tributaries still carry higher levels of zinc, and to a lesser extent, also cadmium and lead. The principal sources of these metals are drainage waters from the surrounding mine tips, which contain appreciable quantities of sphalerite and some galena. The reaches with the highest levels of zinc also tended to carry elevated levels of aluminium and manganese (Table 2). The sources of these two elements are probably the weathering of associated sandstone or shale in the case of aluminium, and accessory gangue minerals such as dolomite, which has bee shown to carry manganodolomite in this area (Dunham, 1948). The high levels of Na and Cl sometimes found were due to the use of road-salt in winter.

Although there are minor rises and falls in the levels of zinc present on passing downstream, nevertheless the stream sequence 0104-0093 provides a good example of stream showing a gradient from high to low zinc (Table 3). The reduction in zinc levels on passing downstream is due at least partly to dilution by water from 0106 and seepage from the surrounding peaty soil. No estimate has so far been made of the role of precipitation in reducing the levels of zinc present: there is no obvious coating of any white or grey mineral deposit on the surfaces of rocks, *Scapania* leaves or algae. There is however a conspicuous deposit of sediment rich in iron oxide between reaches 0093/11 and 0093/25; presumably this 'traps' some zinc. There is probably also considerable binding of zinc to loose masses of eroded peat just above 0093/11. Order of magnitude estimates of stream flow, plant standing crop and possible levels of zinc accumulation together indicate that biotic uptake can be responsible for only a very small percentage of the observed drop in zinc levels. It seems probable that dilution and perhaps also cation-exchange on loose peat are the main agents responsible.

In any discussion of the influence of zinc on changes in floristic composition on passing downstream, it is obviously important to consider correlated changes. With the data available, there is no way of separating the influence of zinc from that of highly correlated chemical variables such as cadmium and lead (Table 2). The physical factor which seems most likely to play some role in determining species distribution on passing downstream is flow, and in particular the tendency for parts of the upstream reaches to become dry under conditons of very low flow.

The numbers of species tend to increase with decreasing levels of zinc, but the difference between the top and bottom of the main stream is only slight in view of the marked drop in mean zinc levels (from 25.6 to 1.5 mg l^{-1} Zn). The relatively long lists of species for the reaches with the highest zinc levels may be swollen slightly because it is especially difficult here to delimit the main stream from surroundings which are submerged less frequently. The inclusion of 'bank' species for downstream reaches would extend considerably species totals due to the presence of many bryophytes submerged only intermittently. While there is only a slight overall increase in species on passing downstream, there are marked differences in numbers between reaches with similar zinc levels. These probably reflect the diversity of microhabitats in any particular reach. Armitage (in press) also noted that the substratum played an important role in determining numbers of animals (individuals, not species) at zinc polluted sites. For instance, 0093/29 (Armitage's G2) supported a relatively abundant fauna (44 animals per metre width), whereas in

Table 3. Species present in 30 stream reaches in catchment of Gillgill Burn. The reaches are presented in a sequence which is a compromise between one based on geographical location on passing downstream and one based on mean zinc levels. The 1-5 scale indicates the numbers of occasions a particular species was found during the five surveys.

reaches	0104/01	0104/15	0104/29	0104/43	0093/01	0093/04	0093/08	0104/57	0104/71	0104/85	0104/99	0105/99	0107/99	0093/29	0093/32	0093/40	0093/43	0093/47	0093/50	0093/61	0093/64	0093/68	0093/74	0093/85	0093/88	0093/95	0093/99	0093/11	0093/25	0106/99
Zn $\bar{x}$	25.6	20.8	18.9	9.2	9.2	9.8	8.6	6.2	4.7	4.8	4.6	5.0	3.4	1.9	2.6	2.1	1.9	1.6	1.5	1.5	1.7	1:7	1.7	1.6	1.5	1.5	1.8	1.3	1.2	0.064
min.	18.0	18.0	17.9	3.5	6.2	7.7	7.2	4.4	3.8	4.1	3.7	4.3	2.8	0.9	1.6	1.8	1.3	1.4	1.2	1.3	1.4	1.2	1.3	1.4	1.3	1.3	1.5	1.0	0.8	0.050
max.	30.2	27.8	20.8	18.9	13.4	14.0	14.2	10.6	5.9	6.2	6.1	6.4	4.1	2.5	3.2	2.7	2.7	2.0	1.8	1.7	2.1	2.1	2.1	1.7	1.7	1.6	2.2	1.3	1.9	0.093
s.d.	4.5	4.0	1.4	6.2	2.7	2.4	2.5	2.5	0.8	0.9	1.1	0.9	0.53	0.64	0.8	0.4	0.5	0.24	0.23	0.18	0.26	0.34	0.33	0.16	0.14	0.14	0.28	0.22	0.49	0.017
geographical sequence	+	+	+	+				+	+	+	+			+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		
total species	25	16	21	25	31	29	23	29	20	22	22	25	25	41	31	25	38	31	22	38	24	34	33	39	30	37	28	35	39	61
total records	62	44	55	57	75	54	42	63	46	60	56	70	71	93	71	58	86	76	79	78	94	91	107	106	86	116	83	78	80	131
records per species	2.48	2.75	2.61	2.28	2.41	1.86	1.82	2.17	2.30	2.72	2.54	2.80	2.84	2.26	2.29	2.32	2.26	2.45	3.59	2.05	3.91	2.67	3.24	2.71	2.76	3.13	2.96	2.22	2.05	2.14
taxon																														
Schizothrix delicatissima	3																													
Synechococcus sp. >6 ≤8 µm	1																													
Synechococcus sp. >8 ≤18 µm	4																													
Synechococcus sp. >16 ≤32 µm			1																											
Caloneis lagerstedtii	2																													
Pinnularia appendiculata	1					1																								
Eunotia tenella					5	1	1																							
Neidium alpinum			2	2				2																		2				
Pinnularia borealis			1	2				2																						
Euglena mutabilis	5	3	4	1		1			1			1	1																	
Frustulia rhomboides var. saxonica				1	2	1	1	2	1															1						
Eunotia septentrionalis						1																								
Ochromonas sp. >8 µm					1																									
Dinobryon sp.								1		1																				
Synura uvella								2	1						1															
Euglena sp. >32 µm						1			1					1																
Aphanocapsa sp. >1 ≤2 µm					1																					1	1			
Phormidium sp. >1 <2 µm							1							1		1	2						1							
Closterium tumidum								2		2				1			1					1								
Plectonema gracillimum					1					1	5			1	2					1										5
Microthamnion strictissimum		2	4	4	4	3		1	1					3							1							3	1	
Oscillatoria pseudogeminata	2		1		1	1					1			1		1				1								1		
Phormidium sp. >2 ≤4 µm	2			1		2		1			3	1		1	1				1	1		1	3			3	1		2	
Stichococcus sp.		1				1	1	1					1	2			2												1	
Microspora sp. >8 µm				1			1		2	4			2	1	1	1								2				2	2	
Characium sp.				1	1	1	1	1		2			1	2		1		1		2	1					2			1	
Hormidium fluitans							1		1	3	3	3		1								1	1							
Ankistrodesmus sp.	1				3	1		1			1			1			1			1				1						1
Chromulina sp. >8 µm	1		2	1			1	1						1	1															1
Synura sphagnicola					1									1														1	1	
Lyngbya sp. >1 ≤2 µm							1	1				1				1	1	1										1	1	
Lyngbya sp. >2 ≤4 µm	1					1					1	1	2	1	1	1	1	2		2		2	4			3	1	2		1
Pinnularia viridis var. sudetica	2	5	3	3	3	1		3	5	4	1			2			1			2		3	4	1				2	2	1
Caloneis bacillum	3	2	4	2	1	1	1	2		2		4	1	1		1	1				1			1		2	3	1	1	1
Eunotia exigua	2	2	2	3	4	1	1	3	2	5			2	1	2		2	1		1	4		1	1				2	2	1
Pinnularia subcapitata	5	2	4	3	2		3	4	3	5	3	2	3	3	2		1		2	1			4	1					1	2
Cylindrocystis brebissonii	5	4	5	5	5	4	5	4	4	5	4	5	2	4	5	2	2	4	4	1	5	2	2	2	1	2		1	5	3
Cosmarium subarctoum	2	5	3	3	2	4	5	5	5	4	5	3	5	4	3	3	2	3	3	2	5	4	5	3	1	3		1	4	1
Hormidium rivulare	5	5	4	3	5	5	2	4	4	4	5	5	5	5	5	5	5	5	5	5	5	4	5	4	5	5	5	3	5	4
Mougeotia sp. >8 µm	4	3	2	3		2	3	3	1	2	3	3		1	2		2	2	2	3	5	4	3	4	1	5	1	1	1	1
Mougeotia sp. >8 ≤12 µm	1	3	2	3	4	3	3	3		2	2	2	4	3	5	2	1	1	1	1	5	5	3	4	4	4	4	1	2	1
Ulothrix moniliformis	2		3	1	1	1	1	1	2		1	3	4	5	2		2	1		1		2	4	2		1		4	4	4
Chlamydomonas sp. >8 µm	5	3	2	5	2	2	2	3		3	2	1	3	4	2		2				3	2			1	4	1	3	2	3
Pseudanabaena catenata	2	2	1	2	3	1	2		4	1	1		3	2	3	3	5	2	2	2	1	3	4	3	1	5	3	1	1	2
Navicula minima	1	1		2	3	3	1	2	1			3						1				1	1		1				2	2
Hormidium flaccidum	1						1								2			1	4	1		1	1		1		1			1
Pinnularia viridis		1	4	2	3	3	4	2	2	2		1	1				1									1		2		2
Chamaesiphon polymorphus			1		3	2				1	3	4	1	3	4	5	5	5	5	5	5	5	5	4	5	5	5		3	5
Roya obtusa				2				4	4	4		3	3	3	2	1	2	1		1	5	2	1			1		2	2	1
Homoeothrix varians					5	1					5	5	5	4	3	5	5	5	5	3	5	4	5	5	5	4	3		4	4
Phormidium sp. >1 µm				1				1					3															1		1
Oscillatoria sp. >4 ≤6 µm					1							1			1															1
Stigeoclonium tenue					2						3	4	2	4	3	2	5	5	5	3	5	5	4	5	4	5	5	1	2	1
Achnanthes sp.					1																							1	1	1
Navicula sp.					1				1		1													1				1	1	1
Verrucaria sp.					3	4				1						2	3	4	4	1	4	4	4	5	5	5	5		2	4
Scapania undulata					1					2	2	2	5	5	2	5	5	5	5	5	5	5	5	5	5	5	3		5	5
Hydrurus foetidus												4	5	4	4	4	4	5	5	5	5	4	5	5	4	4	3	1	1	4
Plectonema boryanum											1				1	1	3			1		2				1			1	
Chrysonebula holmesii												4	1	3	4	5	4	5	5	5	5	4	5	5	5	4	5			2
Achnanthes minutissima								1				4	4	2		1	3	3	5	3	5	1	3	3	4	5	5	2	2	2
Phormidium mucicola														4	3	2	3	4	5	4	5	4	5	5	4	4	5			
Staurastrum punctulatum														2	1	2	1	3	5	2	5	5	1	3	4	5	3	1	1	1
Clastidium setigerum														1					2											
Pleurocapsa sp. >4 ≤8 µm														1			1			1										
Chlamydomonas sp. >8 µm														2			1							1				1	1	1
Meridion circulare															1		1	1					3	3	4	5	5	1	1	3
Cymbella sp.															1		1					1						1		1
Aphanocapsa sp. >2 ≤4 µm														1	1	1	1	1		1		1							2	1
Surirella ovata																	2	1		2		2	4	2	1	4	4	1		3
Gongrosira incrustans																	'	1		1		1		2	1		1			1
Synedra rumpens																		1	1	2	1	2	5	5	2	3	5			4
Fragilaria capucina (twisted)																		1		1	3	2		2	4	1	1			
Cymbella ventricosa																		1	3	1			3	3	1	1	1			1
Fragilaria sp.																				1			2	1						
Diatoma hiemale var. mesodon																				2			3	1	4					4
Gomphonema parvulum																						1		2	1	2	1			2
Nitzschia amphibia																								3	1	2				
Navicula cryptocephala var. veneta																								3	1	2				1
Oscillatoria sp. >8 ≤12 µm																								1	2	3				1
Fragilaria vaucheriae																								1						2
Oscillatoria sp. >6 ≤8 µm																										2			1	3
Nitzschia sp.																											3			
Draparnaldia mutabilis																												4		
Closterium moniliferum																												1		3
Closterium rostratum																												2		1
Closterium ralfsii																												2		1
Closterium subulatum																												1		2
Zygnema sp. >16 ≤24 µm																													2	
Calothrix parietina																													2	
Microspora amoena																														5
Synedra ulna																														4
Tabellaria flocculosa																														4
Ceratoneis arcus																														3
Mougeotia sp. >16 ≤24 µm																														2
Gomphonema sp.																														2
Pinnularia maior																														3
Penium sp.																														3
Netrium digitus																														2
Spirogyra sp. >24 ≤32 µm																														2
Homoeothrix sp. (not H. varians)																														1

Table 4. Relationship between number of species in 30 reaches of the Gillgill Burn catchment and the logarithm of the concentration of zinc in water at the same reach.

			slope ± S.E.	*intercept ± S.E.*
$\log_{10} Zn_{\bar{x}}$	v	species	– 13.7 ± 2.0	36.5 ± 1.4
$\log_{10} Zn_{min}$	v	species	– 14.1 ± 1.9	35.0 ± 1.2
$\log_{10} Zn_{max}$	v	species	– 12.9 ± 2.0	37.6 ± 1.6

0093/25 (G3) the numbers were much less (12 animals per metre width). The substratum of the former is mainly stony and that of the latter is soft peat. The numbers of algal species recorded by us at these two sites were however similar (Table 3).

Although the stream sequence 0104-0093 provides a good example of a zinc gradient, the changes in species totals are neither as pronounced nor as steady as those shown in temperature (hot spring) gradients studied by Kullberg (1968). Sites with elevated zinc levels are known from other areas sometimes to have a very reduced flora. For instance, Say (1978) found only two algae (*Gomphonema parvulum* and *Achnanthes minutissima)* at a site not only highly polluted with zinc (22.8 mg l^{-1}) but also cadmium (0.44 mg l^{-1}) and suspended matter. It does however seem probable that the much higher species total in 0106/99 is due to the near absence of zinc pollution. Eleven species in 0106 were not recorded on any of the 14 reaches of 0093 below the entry of 0106. The potentially toxic influence of zinc at other sites seems especially probable for *Microspora amoena,* which was recorded from 0106/99 in all five surveys, and for *Synedra ulna* and *Tabellaria flocculosa,* which were recorded in four surveys. These species may possibly tolerate elevated zinc levels under other conditions, for Mount (1965) concluded from an experimental study that *Synedra ulna* is highly tolerant of zinc.

While there is only a moderate increase in number of species on passing from high to low zinc reaches on 0104-0093, there is a much more obvious change in species composition (Table 3). Species largely or entirely restricted to sites with the higher zinc levels include *Synechococcus* forms, *Euglena mutabilis* and four diatoms, *Caloneis lagerstedtii, Pinnularia appendiculata, P. borealis* and *Eunotia tenella.* It seems probable that all these species can occur elsewhere in the absence of high levels of zinc (or other heavy metals), but their abundance may in some way be favoured by the presence of zinc. *Euglena mutabilis* is the most widespread plant in highly acidic streams (Hargreaves, Lloyd & Whitton, 1975), and these streams also carry high concentrations of heavy metals. Two other species widespread in 0104-0093, *Eunotia exigua* and *Hormidium rivulare,* are also frequent in acid mine drainages. About eight of the species in 0104-0093 occur all the way down the stream. One of these, *Hormidium rivulare,* is known to show genetic variation with respect to zinc tolerance (Say, Diaz & Whitton, 1977). Among six different populations of *Hormidium* taken from sites within the Gillgill Burn catchment, the higher the level of zinc in the field, the greater the tolerance to zinc shown in laboratory assays (Say & Whitton, 1977). *Stigeoclonium tenue* taken from 0093/01 was also much more resistant to zinc than populations taken from streams not enriched with zinc (Harding & Whitton, 1970).

The extent to which the restriction of species to the downstream part of 0104-0093 is in fact due to the higher zinc levels further upstream can be judged only by comparison with other sites. Experimental transplants of material to upstream sites would establish only whether a particular strain is sensitive and give no indication of the ability of the species to produce resistant strains. At least some of the species restricted to the downstream part of 0093 are however known to occur elsewhere in much smaller streams lacking zinc pollution *e.g. Hydrurus foetidus* and *Surirella ovata.* On the other hand, the presence of intermediate levels of zinc may actually favour the presence of *Hydrurus foetidus* and also of *Chrysonebula holmesii.* Both of these form conspicuous growths in 0093 throughout much of the year, yet elsewhere the former, and usually also the latter, are abundant only when water temperatures are very low. Records of *Hydrurus* were made in the unpolluted 0106/99 on four of the five sample dates, but these were due to the presence of only a few cells. It seems possible that the success in summer of these two gelatinous chrysophytes at intermediate zinc levels is due to reduced competition from other algae or decreased grazing resulting from the presence of the zinc.

While some species are apparently much more abundant in the presence of high levels of zinc, the relative contribution of the various major phyla to the species total does not appear unusual for a fast flowing stream draining a peaty catchment. Of 61 species recorded from reaches with $\geqslant$ 3.0 mg l^{-1} Zn, the phyletic composition is: blue-green algae, 17; diatoms, 16; Chlorophyta excluding Conjugales, 11; chrysophytes, 7; Conjugales, 6; Euglenophyta, 2; lichen, 1; bryophyte, 1.

Summary

Streams within a small catchment (1.2 km^2) lying in the Alston Moor Orefield, northern England, provide a good opportunity to study the influence of zinc enrichment on the photosynthetic flora. One stream sequence showed a gradient from very high levels ($x = 25.6$ mg l^{-1}Zn) in water near the source to much lower levels further downstream ($x = 1.2$ mg l^{-1}). 30 reaches (each 10 m long) were sampled at five different occasions over a period of about one year. There was a tendency for the number of species to increase on passing down the zinc gradient, but the effect was not very marked. The flora at the site with the highest level of zinc included 25 species, whereas the maximum recorded in any reach with elevated zinc was 41 species. The change in specific composition on passing downstream was more marked than the overall increase in number of species. The species present only at the higher levels of zinc (>3 mg l^{-1}) and with at least five records (stream and/or date) were *Schizothrix delicatissima, Synechococcus* sp., *Eunotia tenella, Pinnularia borealis* and *Euglena mutabilis.* A reach of an unpolluted tributary just above its entry to the polluted stream had 61 species, 11 of which were never found in reaches with elevated zinc. Among the species restricted to the unpolluted tributaries, those with the most records were *Microspora amoena, Synedra ulna* and *Tabellaria flocculosa.*

Acknowledgments

We are most grateful to the Natural Environment Research Council for a studentship (P. J. S.) Thanks are due to J. R. Carter for aid with identifying diatoms. F. W. Smith spent many hours discussing the geology of the area and the history of its mining. D. Middlemass helped collect samples; T. Brett and J. W. Simon aided in the analysis of water. Measurements of fluoride were made by an Orion specific ion electrode at the laboratory of the Sunderland and South Shields Water Co. B. M. Diaz suggested that we put the data on computer file and gave much help with resolving the problems that resulted; we are also grateful to A. Waugh for his careful checking of various print-outs.

References

Alicke, R. 1974. Die hydrochemischen Verhältnisse im Westharz in ihrer Beziehungen zur Geologie und Petrographie. Clausthaler Geol. Abb. 20, 223 pp.

Armitage, P. D. in press. The effects of mine drainage and organic enrichment on benthos in the River Nent system, (Northern Pennines). Hydrobiologia.

Brock, T. D. 1969. Microbial growth under extreme conditions. Symp. Soc. gen. Microbiol. 9: 15-41.

Brock, T. D. 1978. Thermophilic Microorganisms and Life at High Temperatures. 465 pp. Springer-Verlag, N.Y., Heidelberg, Berlin.

Dunham, K. C. 1948. Geology of the Northern Pennine Orefield. 1. Tyne to Stainmore, 357 pp. Memoirs of the Geological Survey, H. M. Stationery Office, London.

Harding, J. P. C. & Whitton, B. A. 1976. Resistance to zinc of Stigeoclonium tenue in the field and the laboratory. Br. phycol. J. 11: 417-426.

Hargreaves, J. W., Lloyd, E. J. H. & Whitton, B. A. 1975. Chemistry and vegetation of highly acidic streams. Freshwat. Biol. 5: 563-576.

Holmes, N. T. H. & Whitton, B. A. 1977. The macrophytic vegetation of the River Tees in 1975: observed and predicted changes. Freshwater Biol. 7: 43-60.

Jones, J. R. E. 1958. A further study of the zinc-polluted river Ystwyth. J. Anim. Ecol. 27: 1-14.

Kullberg, R. G. 1968. Algal diversity in several thermal spring effluents. Ecology 49: 751-755.

Pasternak, K. 1973. The spreading of heavy metals in flowing waters in the region of occurrence of natural deposits and of the zinc and lead industry. Acta Hydrobiol. 15: 145-166.

Say, P. J. 1978. Le Riou-Mort, affluent du Lot pollué par métaux lourds. 1. Etude préliminaire de la chimie et des algues benthiques. Annls Limnol. 14: 113-131.

Say, P. J., Diaz, B. M. & Whitton, B. A. 1977. Influence of zinc on lotic plants. I. Tolerance of Hormidium species to zinc. Freshwat. Biol. 7: 357-376.

Say, P. J. & Whitton, B. A. 1977. Influence of zinc on lotic plants. II. Environmental effects on toxicity of zinc to Hormidium rivulare. Freshwat. Biol. 7: 377-384.

Whitton, B. A. 1980. zinc and plants in rivers and streams. In: J. O. Nriagu (ed.) Zinc in the Environment, volume II. John Wiley & Sons.

Whitton, B. A., Diaz, B. M. & Holmes, N. T. H. (1976) A computer orientated recording system for plants in flowing waters. (Duplicated report, Department of Botany, University of Durham: copies available on request.)

Whitton, B. A., Diaz, B. M. & Holmes, N. T. H. 1979. A computer orientated numerical coding system for algae. Br. phycol. J. 14:

Whitton, B. A., Holmes, N. T. H. & Sinclair, C. (1978). A Coded List of 1000 Freshwater Algae of the British Isles No. 3 in the Water Archive Manual Series. 335 pp. Department of the Environment, Reading.