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Water Pollution Problems and Solutions

Water is one of our most important natural resources, and there are many conflicting demands upon it. Skilful management of our water bodies is required if they are to be used for such diverse purposes as domestic and industrial supply, crop irrigation, transport, recreation, sport and commercial fisheries, power generation, land drainage and flood protection, and waste disposal. An important objective of most water management programmes is the preservation of aquatic life, partly as an end in itself and partly because water which sustains a rich and diverse fauna and flora is more likely to be useful to us, and less likely to be a hazard to our health, than one which is not so endowed. To meet this objective, it is necessary to maintain within certain limits factors such as water depth and flow regimes, temperature, turbidity and substratum characteristics, and the many parameters which contribute to the chemical quality of the water. In waters which receive waste discharges, whether by design or by accident, one or more of these variables may come to lie outside the limits which can be tolerated by one or more of the species which live there, and consequently the biological characteristics of the water are altered.

The biologist's role in the monitoring and control of water pollution is to detect and accurately to describe these alterations, to elucidate as precisely as possible the mechanisms by which they are brought about, and to seek to understand the qualitative and quantitative relationships between pollution and its biological consequences. He or she may also need to be aware of the application of biological processes in the control or amelioration of pollution, and of the serious consequences for public health which water pollution threatens. Finally, he or she must be able to offer constructive advice to other specialists—chemists, engineers, administrators and legislators—who share the responsibility for managing our water resources.

All of these topics will be discussed in the following chapters, but first it might be useful to gain some idea of the nature and scale of the problems posed by water pollution.

1.1 The Scale of Water Pollution

Water pollution, like other environmental concerns, has been the focus of widespread public interest for about three decades now, and this interest seems to be increasing. While this has many obvious benefits, it sometimes can appear that the public perception of water pollution, as manifested for example by political debate and the activities of pressure groups, does not always accord with the scientific reality. This can lead to ill-advised or cost-ineffective actions, including legislation and regulation, in an attempt to deal with perceived or publicised problems which may, in fact, be less serious than others which are less well publicised or less easy for the educated layman to understand. It is therefore important to gain some idea of the real nature and extent of water pollution.

Britain may perhaps fairly be taken as a representative example of a developed country, and is one of the few countries, even in the developed world, where adequate information is available to undertake a general survey. In fact, national surveys of water quality have taken place at regular intervals since 1958; they currently take place once every five years, the most recent one for which data are available being in 1990 (NRA, 1991). Of approximately 40000km of main river surveyed in England and Wales, 65.3% was classified in 1990 as 'good'; 23.4% as 'fair'; 9.5% as 'poor'; and 1.6% as 'bad'. (The basis of these classifications, and the applications of the survey data, are described and discussed in more detail in Chapter 6.) Thus approximately 35% of the total length of rivers in England and Wales could be said to be significantly influenced by pollution, and about 12% of the total seriously so. Bad as this may seem, it does in fact represent a considerable improvement of the situation as recorded in earlier surveys 30 or so years ago (see Chapter 6), which perhaps gives some confidence that the application of the principles and techniques outlined later in this book is of some use!

The distribution of the more seriously polluted rivers throughout the country is, of course, by no means even; the worst situations tend to be found in and around the larger conurbations and industrial areas. However, the common perception of pollution as being caused primarily by industry is not correct. Although this may once have been true, the most recent survey data clearly indicate that today other sources, particularly agriculture, require much more attention than they sometimes receive.

This is most easily seen by referring to a report on water pollution incidents which occurred in England and Wales in 1991 (NRA, 1992). Approximately 28000 incidents were reported to the NRA in 1991, a number which has increased fairly steadily since records began in 1981, when about 12000 incidents were reported. This increase is probably misleading. An 'incident' may arise through accidental, negligent or illegal discharge of wastes to water; or through failure, for whatever reason, of waste treatment processes causing them to exceed their discharge limits. The apparent increase in incidents is probably largely accounted for by the increasingly strict regulation and monitoring of known sources of pollution, and by increased public awareness and willingness to report incidents which in earlier times probably went unnoticed. Nevertheless, and allowing for the fact that about 20% of the incidents reported were unsubstantiated or had no significant effect, over 22000 significant incidents did occur, of which 386 were categorised as 'major'. Of the significant incidents recorded, roughly 28% had causes related to the sewage and water treatment industry itself; 23% related to oil discharges; 13% originated from farms; 12% from industrial sources; and 22% from other sources such as road accidents or leaching of contaminated water from waste dumps.

These figures are probably representative of most Western countries in a similar state of economic and industrial development as Britain, but some idea of the scale of water pollution problems in developing countries can be obtained from Brinkhurst's (1993) account of his experiences in China:

> "It is hard to imagine what horrors are associated with the gross levels of water pollution that an aquatic biologist encounters in the Third World. I have visited the People's Republic of China twice attempting to collect aquatic oligochaetes from clean water. The existence of clean-water species in a group of so-called indicator organisms such as the oligochaetes will be mentioned below, but it is sufficient to say that they were nowhere to be found. Reports exist of normal communities of benthos along the Sino-Soviet border from work done during a previous era of cooperation between China and the USSR. Otherwise, the wide rivers, shown on maps of the middle regions of China, usually are reduced to a thin trickle in the middle of a wide valley. The Gobi Desert surges towards Beijing at an accelerating pace. Only the widths of the bridges and the large areas of dry river bed remain as testimony to the former size of these rivers. The water is sometimes jet black, sometimes rainbow-hued with chemicals, or it is steaming with heat. Even springs among the limestone hills of Guilin contain world-wide 'indicator' species, reflecting upstream contamination not alleviated by a spell underground."

Brinkhurst goes on to surmise that similar scenes are to be witnessed in Eastern Europe; certainly, such information as has become available since 1990 (Carter and Turnock, 1993) indicates that the situation there is extremely bad and still deteriorating. Elsewhere in the world, such limited information as exists on a country-by-country basis does little to counter his pessimism (see, for example, UNEP, 1991).

Yet the experience of Britain and some other of the more fortunate countries of the world shows that it is possible to combine economic and industrial development, increased population and the concomitant demands on water resources, with actual improvement of the conditions of the aquatic environment from the dreadful state which we know existed after our own industrial revolution. What is required is the understanding and application of the relevant scientific and technical principles, combined with an appropriate legislative framework and, of course, preferably an informed and sympathetic climate of public opinion. Those scientific principles most likely to fall within the domain of the biologist form the subjects of the succeeding chapters; but perhaps the best introduction to the scope of the problems to be faced, and some of their solutions, is to look at some case studies.

1.2 Metalliferous Rivers

In many parts of the world, rivers have become contaminated with heavy metals such as zinc, lead and copper as a result of mining and associated activities. In Britain, three areas of the country are particularly well known because they contain a number of metalliferous rivers: one is in the south-west of England, one is in West Wales and one is in the North Pennine Orefield in northern England. Although these areas were once major centres for the extraction and processing of metal and mineral ores, within the last hundred years or so the mining activities have declined considerably, or ceased altogether. These areas never became major population centres, and were never subject to the intensive pollution pressures of modern urban and industrial society. The effects of the mining activity are still detectable, but these effects have not been compounded and complicated by those of other forms of pollution associated with modern development. For this reason, they offer the opportunity to investigate the impact of an important group of industrial pollutants—heavy metals—on waters which are relatively unaffected by the pressures which have more recently been unleashed on water bodies in more densely-populated areas. They have therefore been extensively studied, and provide a good illustration of the biological effects of pollution, of the methods which may be used in studying these effects, and of the questions which biologists seek to investigate and answer about polluted waters. The following account is largely based upon the review of Green (1984). Mance (1987) also discusses some studies of metalliferous rivers.

Ecological studies on metalliferous rivers in West Wales began about 70 years ago, and have continued, intermittently, ever since. Carpenter (1922, 1924) observed that fewer invertebrate species occurred in these rivers at stations close to the lead mines, and that the differences in abundance of invertebrates appeared to be due to lead in the mine effluents rather than to physical differences in the river bed or any other parameter of water quality. Certain invertebrate groups (Platyhelminthes, Mollusca, Crustacea, Oligochaeta and many Insecta) were always absent from the most heavily polluted sites, but some insect species such as *Cloeon simile* (Ephemeroptera), *Simulium latipes* (Diptera) and *Velia currens* (Hemiptera) appeared to be tolerant of elevated lead concentrations. Following the closure of a mine and the cessation of pollution, Carpenter (1926) described a process of recovery. The first stage was the establishment of a restricted fauna consisting almost entirely of insect larvae on a substratum bearing a limited covering of algae and bryophytes. Oligochaetes, molluscs, platyhelminthes, crustaceans and many insect species remained absent. Subsequently, the encroachment of chlorophyceous algae was accompanied by an increase in invertebrate species diversity, with oligochaetes, turbellarians, caddis larvae and other insects becoming established. In the final stage of recovery, macrophytes were established in physically-suitable areas and there was a large increase in the numbers of invertebrate taxa present, including molluscs, and the development of fish populations. This process of recovery which occurred following the closure of a mine could also be observed in reverse (Carpenter, 1926) when a mine which had been closed for some years was subsequently reopened. The same stages of succession could also be observed contemporaneously in successive reaches of a polluted river with increasing distance from the source of pollution (Carpenter, 1924). The toxic agent responsible for these changes was at first assumed to be lead, particularly dissolved lead rather than the particulate component of the mine effluents. Carpenter (1925) investigated the toxicity of dissolved lead salts to fish, but at the concentrations of lead found in the river water, lead salts alone were less toxic than the river water. This indicated that the mine effluents contained some additional toxic agent, and zinc was soon identified as being an important factor.

During the decades following Carpenter's early investigations, advances in techniques of taxonomy, ecological sampling and chemical analysis provided more detailed information on the effects of metal pollution in upland rivers. Jones (1940a, b) studied the Rivers Ystwyth and Rheidol, also in Wales, and confirmed the general pattern described by Carpenter. In the Ystwyth it became clear that zinc, rather than lead, was the most abundant toxic agent; by 1958 lead levels had declined markedly but zinc levels remained high (Jones, 1958). This probably occurred because zinc is more soluble than lead, and because the pattern of mining activity in the area tended to result in the fairly efficient removal of lead and silver from the ores, whereas waste material dumped in and around the mines remained rich in zinc. Between 1940 and 1958, there was no substantial increase in the number of species found in the Ystwyth. Molluscs, crustaceans, oligochaetes and leeches were still absent. Among the insects, the fauna remained restricted but *Rhithrogena semicolorata* (Ephemeroptera), *Simulium* spp. (Diptera), and the stoneflies *Leuctra* spp. and *Nemoura* spp. were fairly numerous. Caseless caddis larvae were more numerous than cased caddis larvae.

On the basis of some toxicity tests, the absence of fish, molluscs and crustaceans was ascribed to the presence of toxic metals in the water, but the scarcity of flatworms, and the absence of leeches and oligochaetes was thought to be due to the unfavourable characteristics of the substratum. By 1980, little further improvement had occurred. Brooker and Morris (1980) recorded more species than were found in 1958, but much of the increase was apparently due to the fact that some groups of animals earlier identified to genus, particularly chironomids and simulids, were identified to the species. Paradoxically, the association of particular metal levels with the biological characteristics of the water is becoming more difficult. For example, it is now known that high levels of calcium to some extent protect animals from the toxic effects of heavy metals, whereas low levels can, quite apart from any influence of heavy metals, themselves act as limiting factors.

A great deal more is now known about the influence of purely physical factors on the patterns of distribution of invertebrate species. Therefore it is less easy than it might earlier have appeared to interpret the available biological data solely in terms of the measured heavy metal levels. Nevertheless in the nearby river Rheidol, where metal levels are lower, the invertebrate community is distinctly richer. Whereas Carpenter (1924) recorded 29 species, Laurie and Jones (1938) recorded 103 following a distinct reduction in the metal levels some years earlier; Jones (1949) recorded 130 species, though molluscs and crustaceans were still absent. Brooker and Morris (1980) recorded 134 species.

Elsewhere in Britain and in other parts of the world, metalliferous rivers similar to those in Wales have been widely studied, though rarely over such a long period of time. In south-west England, Brown (1977) studied the River Hayle which is contaminated with zinc, copper and iron. Metalliferous rivers in the North Pennine Orefield have received some attention (e.g. Armitage, 1980). Examples from North America include the studies of Sprague *et al.* (1965) on rivers polluted with copper and zinc; and of Gale *et al.* (1973) on rivers polluted with zinc and lead. Zinc-polluted rivers in Australia have been investigated by Weatherley *et al.* (1967). The river South Esk in Tasmania, which contains cadmium, zinc, copper, iron and manganese, has been investigated by Thorp and Lake (1973), Tyler and Buckney (1973) and Norris *et al.* (1982). There are, of course, many other rivers polluted with heavy metals, but in most of these the effects of heavy metal pollution are compounded or modified by substantial inputs of organic matter and/or other industrial pollutants. Based on his review of investigations relating to rivers polluted solely or predominantly by heavy metals without these other complicating factors, Green (1984) drew attention to the following general points.

In rivers polluted by heavy metals, the invertebrate fauna is affected by the elimination, or numerical reduction, of certain species. If the input of pollution ceases, the invertebrate fauna gradually recovers with the passage of time. A similar process of recovery can be observed with increasing distance from a source of pollution, as the concentration of pollutants decreases. The nature of the recovery is a gradual increase in the numbers of species and in the numbers of individuals found in the water. Taxa which are universally affected by metal mining and associated activities are Mollusca, Crustacea, Platyhelminthes and Oligochaetes. Some groups, however, appear to behave inconsistently in response to metal pollution. One such group is the larvae of caddis flies (Trichoptera). In the Rheidol and Ystwyth, for example, Jones (1940b) noted the absence of cased caddis larvae from polluted stations, whereas carnivorous, caseless species such as *Rhyacophila dorsalis* and *Polycentropus flavomaculatus* were present. In laboratory experiments, no evidence was found that the concentration of dissolved metal found in the rivers was lethal to cased caddis species, and in fact some species were able to construct their cases, in the laboratory, from particles of solid mine waste. This suggested that metals may exert indirect effects on some species in the field, possibly related to the effects of the metal on the food source of the caddis larvae.

An alternative explanation, of course, may be that sublethal toxicity rather than lethal toxicity plays some part in the elimination of species. Animals may be able to survive, for a short period of time, exposure to levels of metals similar to those found in the rivers, but may be unable to complete their entire life cycles under these conditions. In some cases, however, caddis larvae appear actually to become more abundant than expected in the polluted stretches of metalliferous rivers (Norris *et al.,* 1982; Sprague *et al.,* 1965; Weatherley *et al.,* 1967). Commonly, reduced predation pressure from fish has been suggested as a possible reason for this. There is also some inconsistency in the reported response of another important insect group, the Ephemeroptera (mayflies), to metal pollution. Some invertebrate groups which are commonly reduced or absent from polluted waters appear to be affected by alterations to the physical characteristics of the river bed which are caused by the particulate matter in mine effluents, rather than by the toxic action of the metals themselves. Oligochaetes, platyhelminths and leeches are possible examples.

Another form of stream-bed alteration which may have profound effects is the development of excessive algal growth, as reported in some metalliferous rivers in northern England (Armitage, 1980). One hypothesis to account for this process is that the metals, by removing herbivorous invertebrates, allow the establishment of an unusually luxurious algal mat on the river bed, which in turn interferes with the normal patterns of distribution of animals which are not themselves directly affected by the metal. Algal growth may, of course, be enhanced in rivers with substantial inputs of plant nutrients or organic matter, so this particular phenomenon may not be universal. However, there is evidence (see Chapter 4) that organic matter can afford some protection to aquatic species from the toxic effects of metals, so the outcome in any individual case may be difficult to predict. Indeed, no two rivers are exactly similar in their physical, chemical andbiological characteristics, and the interactions of living organisms with one another and with their physical environment are so complex that whatever general pattern emerges, it will inevitably be subject to significant variations of detail according to the precise local circumstances.

One major difficulty in studying the effects of pollution in the field and in drawing from them conclusions of general applicability is that it is usually impossible, in any individual case, to compare what is happening in the polluted river with what would have been happening had the river not been polluted. Most commonly, surveys of polluted rivers consist of contemporaneous observations of different sites along a river or within a river system at different distances from the source of pollution. However, it is well known that, even in the complete absence of pollution, the biological characteristics of different points within a river system vary widely according to the physical and chemical conditions prevailing at the different locations. The precise relationships between the biological community and its physical environment are not well understood, and it is therefore extremely difficult to distinguish the consequences of pollution from the response of the community to natural variations in its physical environment. The RIVPACS system (see Chapter 3) represents a recent development towards a solution of this difficulty. Nevertheless, it would be very interesting to have available for study two physically and chemically identical rivers, of which one was polluted (preferably with a single pollutant). In practice, such a pair of rivers probably does not exist, although attempts have been made on a limited scale to approach this situation experimentally. However, a pair of rivers which approaches this ideal as closely as we may reasonably hope is to be found in the North Pennine Orefield in northern England, and may be used as a case study.

1.2.1 The Rivers East and West Allen

The Rivers East and West Allen in Northumberland, England, lie within the North Pennine Orefield. They flow roughly northwards for approximately 18 kilometres before joining to form the River Allen, itself a tributary of the South Tyne (Figure 1.1). The rivers drain adjacent valleys which were heavily exploited for a variety of metal and mineral ores, particularly during the eighteenth and nineteenth centuries. After the early years of the present century, mining activity declined rapidly and virtually ceased in 1946. Sporadic mining for fluorspar took place at the Beaumont mine at the head of the East Allen until 1979, and a very limited amount of mining continued intermittently at Barneycraig on the West Allen until 1981; since that time no activity has been recorded in either valley. Until the end of the nineteenth century, mining in the Allendales was dominated by the production of lead ore. The West Allen mines, in particular, produced substantial quantities of zinc ore, but this seems to have been simply discarded prior to 1899, being

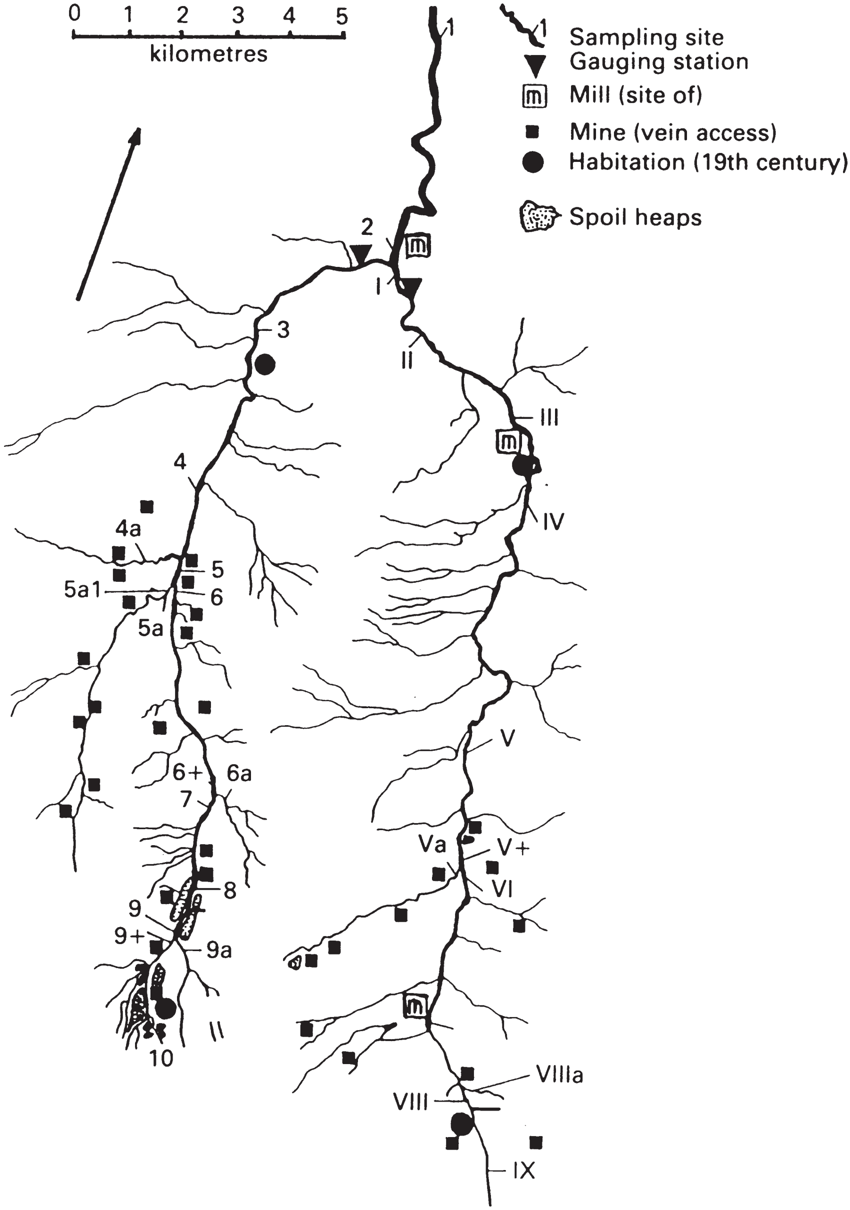

Figure 1.1 Map of the Rivers East and West Allen, showing sampling stations, derelict mines and workings, and remaining spoil heaps. After Green (1984)

returned as backfill to disused shafts or left in surface spoil heaps. Although the East Allen mines produced far greater quantities of ore than those on the West Allen, the zinc-bearing veins are almost entirely confined to the West Allen. Moreover, in the East Allen valley most of the waste material was removed when the mines closed, while on the West Allen there remain extensive areas of spoil heaps and derelict land associated with mining activity. As a result, the River West Allen today contains considerably higher levels of zinc than the East Allen. A comparative study of these two physically-similar and geographically-adjacent rivers therefore provides a valuable opportunity to study the ecological effects of zinc.

1.2.2 Physical and Chemical Survey

A series of 15 sampling stations was established on the West Allen and its tributaries. A further 12 stations on the East Allen were chosen for

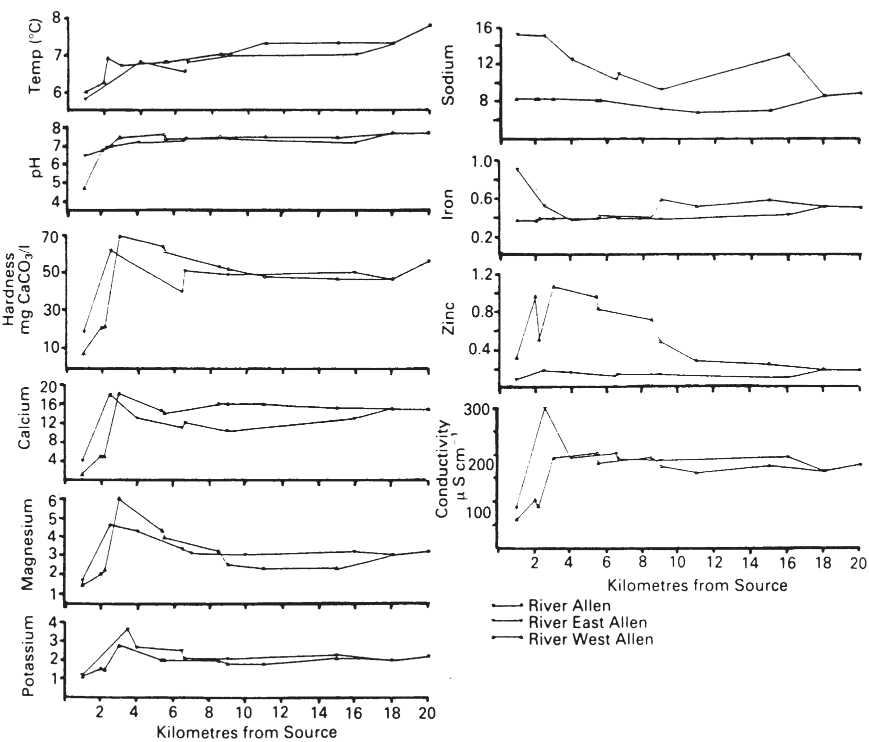

Figure 1.2 Median values of chemical determinands at mainstream sites on the Rivers East Allen, West Allen and Allen, plotted against distance from source (Green, 1984)

Table 1.1 Values of chemical variables for one pair of equivalent sites on the East and West Allen, 1979–80. Data from Abel and Green (1981). (Values as mg l^{-1} unless otherwise stated; ND = not detectable)

	Detection limit	West Allen Site 7		East Allen Site VI	
		Mean	Range	Mean	Range
pH		7.7	6.7–8.6	7.5	5.9–8.8
conductivity (μS cm^{-1})		257	61–460	214	62–330
Ca		33	6–73	38	5–65
Mg		6.39	1.35–13.8	3.9	1.57–13.8
K		2.5	0.5–4.1	2.9	0.8–5.2
Na		9.53	4.5–16	12.75	5.3–23.4
Mn		0.10	0.01–2.0	0.17	0.01–1.0
Fe		0.41	0.01–1.1	0.22	0.01–1.0
Pb	0.1		ND–trace		ND–trace
Cu	0.03	ND		ND	
Co	0.06	ND		ND	
Cd	0.01	ND		ND	
Ni	0.06	ND		ND	
Zn	0.001	1.31	0.45–3.68	0.13	<0.001–0.36

comparative study. The East Allen stations were chosen so that each was broadly similar in physical terms (width, depth, distance from source, substratum characteristics, nature of the surrounding terrain) to a site on the West Allen. Thus sites 7, 6a and 6+ on the West Allen could be considered as ‘equivalent sites’ to VI, Va and V+ on the East Allen (Figure 1.1). Between June 1979 and October 1980, samples for chemical analysis were taken twice monthly from each site. The results are summarised in Figure 1.2. In terms of temperature, pH, conductivity and a wide range of chemical determinands the two rivers are very similar. Zinc levels in the West Allen were consistently up to ten times higher than in the East, placing some stretches of the West Allen among the most heavily zinc-polluted rivers and the East Allen at the upper end of the range found among rivers which may be considered unpolluted. Concentrations of toxic heavy metals other than zinc (copper, cadmium, lead, nickel, chromium) fell consistently below the detection limits of atomic absorption spectrophotometry. Some representative data for one pair of equivalent sites are given in Table 1.1, and levels of dissolved zinc for several pairs of sites are compared in Table 1.2. Compared to the soft, acidic Welsh rivers discussed earlier, the Allens are slightly alkaline and harder, though the zinc levels are broadly comparable.

Table 1.2 Concentrations of filtrable zinc (mgl^{-1}) in river water from equivalent sites on the East and West Allen, 1979–80. Data from Abel and Green (1981). West Allen sites are designated by Arabic numerals, East Allen sites by Roman numerals

West Allen				East Allen			
		Zinc concentration				Zinc concentration	
Site	km from source	Mean	Range	Site	km from source	Mean	Range
10	1	0.24	0.04–0.56	IX	1	0.24	<0.001–0.83
8	3	1.88	0.65–4.15	VII	4	0.19	0.1–0.34
7	5.5	1.31	0.45–3.68	VI	6.5	0.13	<0.001–0.36
6a[a]	5.5	0.09	<0.001–0.33	Va[a]	6.5		0.04–0.49
6+	5.5	0.87	0.09–1.88	V+	6.5		0.11–0.14
5	9	0.51	0.12–1.22	V	9		<0.001–0.23
4	11	0.50	0.04–1.28	IV	13		0.08–0.49
3	15	0.34	0.08–0.80	III	17		0.04–0.31

[a]Denotes tributary site.

1.2.3 Biological Survey

Twenty-three sampling stations on the two river systems were surveyed in May, June and October 1980. In addition certain sites were surveyed at monthly intervals during this period. Five replicate Surber samples (see Section 3.3) were taken on each sampling occasion. The results of the survey indicated that the East Allen is, in biological terms, typical of many upland streams and rivers. The fauna is dominated by insects, with molluscs, crustaceans, oligochaetes and platyhelminths also represented. In all 121 taxa were recorded from the Allens during the survey (this number has since increased considerably, partly through improved taxonomic techniques). As expected, the headwaters of the East Allen are relatively poor in species and numbers of individuals, but the fauna develops rapidly and in its lower reaches the East Allen is a moderately good trout fishery. In contrast the West Allen, though initially similar to the East, receives zinc inputs about three kilometres from its source and the invertebrate fauna is markedly affected; some of the survey results are summarised in Figure 1.3. Within the general pattern of reduced species diversity and numbers of individuals at the zinc-polluted sites, the effects of the zinc on particular invertebrate species could clearly be seen. Four species which were common in the East Allen were entirely absent from the mainstream of the West Allen: *Gammarus pulex* (Crustacea), *Ancylus fluviatilis* (Mollusca), *Taeniopteryx nebulosa* (Plecoptera), and *Hydroptila* sp. (Trichoptera). Several other species were absent from many stations on the West Allen, although present

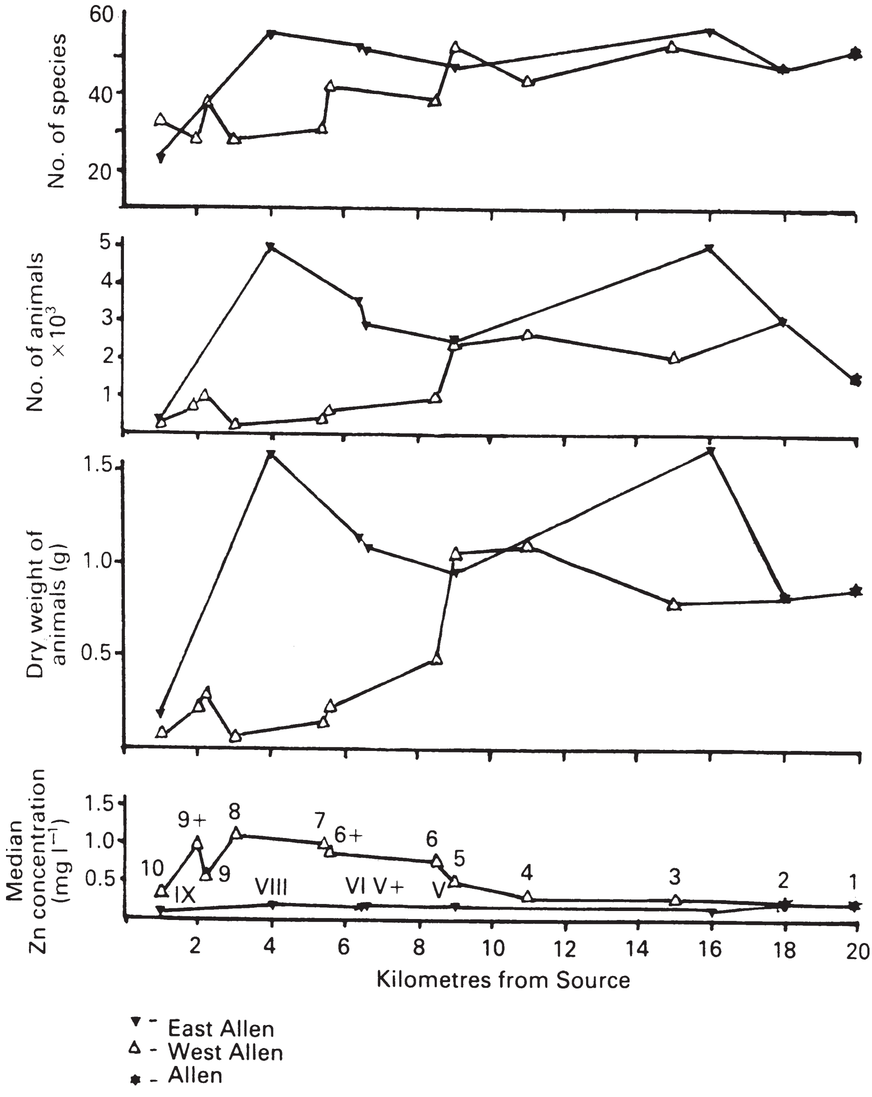

Figure 1.3 Total number of species, total number of animals and the total dry weight of animals collected from each sampling station during May-October 1980 in the Rivers East Allen, West Allen and Allen (Green, 1984)

in the East (Table 1.3). Species found in both rivers were generally present in greatly reduced numbers in the West Allen; Figure 1.4 shows some data for Plecoptera species, and similar patterns were shown by Ephemeroptera, Trichoptera, Coleoptera and Diptera. Moreover, the survey data indicated that the life cycles of some species were altered in the zinc-polluted stretches. For example, nymphs of the stonefly *Amphinemoura sulcicollis* disappeared

Table 1.3 Species found along the length of the East Allen, but absent from three or more sites on the mainstream of the West Allen. Data from Green (1984)

Plecoptera:	*Leuctra fusca*
	Siphonoperla torrentium
	Taeniopteryx nebulosa[a]
Ephemeroptera:	*Ecdyonurus venosus*
	Ecdyonurus dispar
	Baetis muticus
	Ephemerella ignita
	Caenis sp.
Trichoptera:	*Hydropsyche instabilis*
	Hydropsyche fulvipes
	Hydroptila sp[a]
Crustacea:	*Gammarus pulex*[a]
Mollusca:	*Ancylus fluviatilis*[a]

[a]Species absent from all sites on the mainstream West Allen.

from the East Allen in July/August as the mature nymphs emerged from the water as adults. Nymphs of the new generation were abundantly reestablished by October; in the West Allen, however, no new nymphs had appeared by October in the more polluted stretches, perhaps because the peak zinc concentrations tend to occur during the summer and have a particularly marked effect on the early life stages. Possibly the limited populations of this and similarly-affected species in the West Allen are restored later in the year by downstream drift from unpolluted tributaries. The results of some further analyses of the survey data are described in Section 3.4.

1.2.4 Zinc Toxicity

The depletion of the invertebrate fauna in the zinc-polluted stretches may be due to the direct toxic action of the zinc; or may arise as a consequence of, for example, the disappearance of an animal's prey species or some other indirect cause. Green (1984) tested the lethal toxicity of zinc to several invertebrate species under conditions similar to those found in the Allens. One way to measure lethal toxicity is to determine the concentration of the poison which will kill half of a sample of animals within a specific period, such as four days—this value is termed the 96-hour median lethal concentration, or 96 h LC50. Methods of measuring toxicity are discussed in detail in Chapter 4. Table 1.4 shows some results. All of the species tested

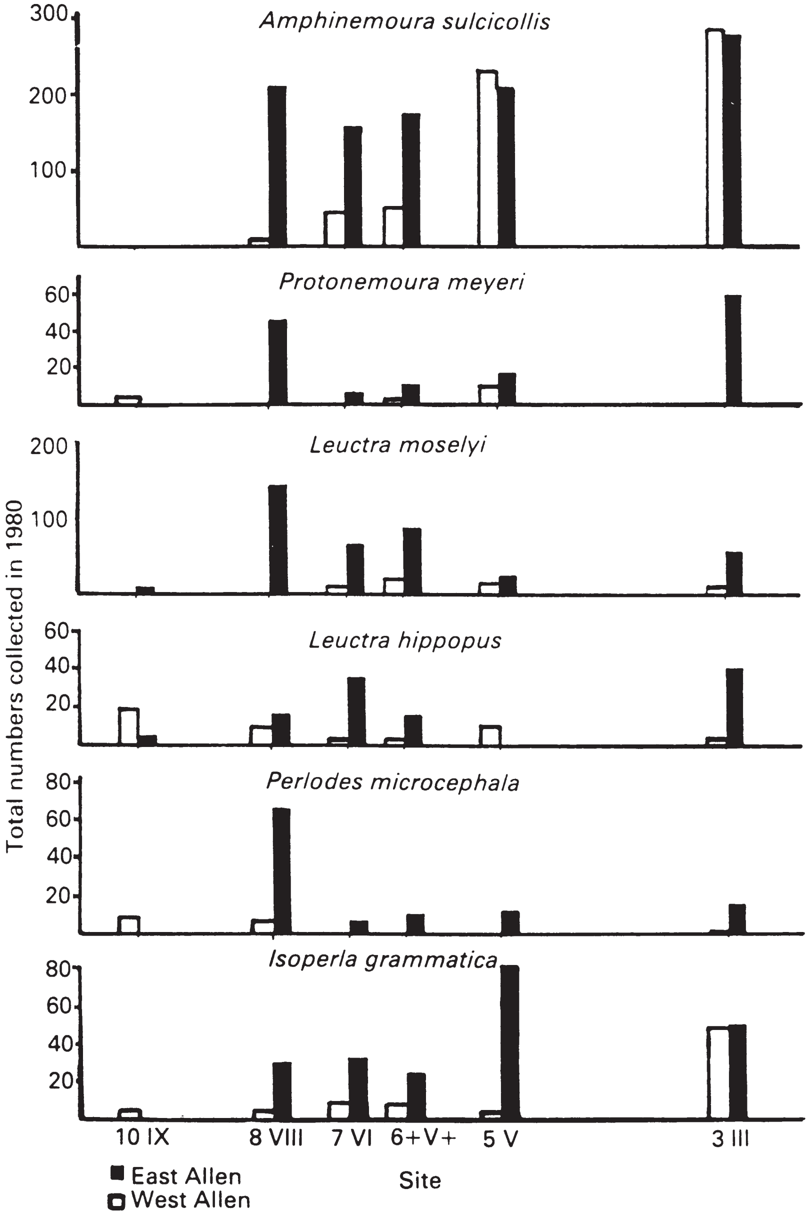

Figure 1.4 Total numbers of selected species of Plecoptera (stoneflies) from 'equivalent sites' on the Rivers East and West Allen during May-October 1980 (Green, 1984)

Table 1.4 Toxicity of zinc to some invertebrate species. Data extracted from Green (1984). Where two sets of results are given, the results represent the range of toxicity values recorded in replicate tests carried out at different times

Species	Result[a]	
Gammarus pulex	2.0(1.67–2.40)	336 h LC50 0.66 (0.50–0.88)
Baetis rhodani	1.3(0.6–2.9)	
	31(16.3–58.9)	336 h LC50 16.5 (7.5–36.3)
Rhithrogena semicolorata	70(36.8–133)	336 h LC50 52 (34.4–78.5)
	135(71–256)	336 h LC50 68 (45.3–102)
Leuctra moselyi	15.7(9.24–26.7)	
	55(30.6–99)	336 h LC50 17.5 (4.07–75.3)
Amphinemoura sulcicollis	120 h LC50 130 (59.1–286)	
Isoperla grammatica	90(40.9–198)	
Lymnaea peregra	2.6(0.8–8.3)	
Chloroperla tripunctata	No mortalities in 144 h at concentrations >360 mg l^{-1}	
Deronectes depressus	No mortalities in 14 h at concentrations >360 mg l^{-1}	
Limnephilus sp.	No mortalities in 288 h at concentrations >360 mg l^{-1}	

[a] 96 h LC50 values in mg l^{-1} unless otherwise stated.
Values in parentheses are 95% confidence limits.

were either absent from all or part of the West Allen mainstream, or found only in greatly reduced numbers.

Comparing the zinc levels in the water (Table 1.2) with the values in Table 1.4, three groups of animals can be distinguished. First, those such as *Gammarus pulex* and the snail *Lymnaea peregra,* for which the LC50 values are very close to the zinc concentrations found in the river. It is reasonable to conclude that the river water is rapidly toxic to these species, and that any individuals which found themselves in the polluted stretches would quickly die if they were unable to escape speedily to a less polluted area. Second, there is a group of species which appears to be remarkably resistant to zinc. The stonefly *Chloroperla tripunctata,* a caddis fly of the genus *Limnephilus,* and the beetle *Deronectes depressus* withstood concentrations of zinc greater than 360 mg l^{-1} for up to 12 days without any animals dying at all. This suggests that although the possibility of sublethal toxicity cannot be discounted, it is likely that mechanisms other than the direct effect of zinc on the animals are largely involved. Third, there is an intermediate group for which median lethal zinc concentrations are roughly between 10 and 100 times higher than the zinc levels recorded in the river. For this group, indirect effects may also be involved; however, experience with many poisons and animals, particularly fish, which have been more extensively studied, suggests that sublethal toxicity of zinc is likely to be an important factor in the observed ecological status of these species.

Some species were tested on more than one occasion at different times of the year and the median lethal concentrations varied considerably (Table 1.4). In part, this is probably a reflection of the fact that toxicity often cannot be measured, however it is expressed, with great precision. However, it is possible that some species vary in their susceptibility to zinc at different times of the year, according to the stage of the life cycle which they have reached. The effect seems to be particularly marked in the case of the mayfly *Baetis rhodani*. This feature of the results, along with the various aspects of sublethal toxicity and the nature and extent of the indirect effects of zinc, all need to be further investigated before the effects of the zinc on the receiving water fauna can be fully understood.

1.2.5 Some Further Questions

The investigations of the Allens and other metalliferous rivers show that in each case, the effects of the metal on the receiving water fauna are broadly similar. Generally, it is observed that there is a reduction in the number of species present in the polluted areas, together with a reduction in numbers of individuals of those species which are not eliminated altogether. Certain species appear to be particularly sensitive to heavy metals, others apparently more resistant, and the status of some species with respect to metal pollution appears to vary from one location to another. In other words, there is a perceptible general pattern which is subject to variations in detail. It is important to know to what extent the findings of any particular study are of general application, and to what extent they are restricted to, for example, particular geographic regions, or to waters which have particular physical, chemical or biological characteristics. Therefore it is necessary to consider in more detail the ecotoxicological mechanisms which may underlie the observed effects of the metals. By doing this, it will be possible to illustrate some of the biological questions which may arise out of the investigation of a polluted water.

The role of sublethal toxicity is potentially an important area for further investigation. In the river West Allen, the concentrations of zinc which are lethal to several of the affected species are between 10 and 100 times higher than the zinc levels recorded in the water, that is, within the range where sublethal toxicity may be expected. The measurement of sublethal toxicity gives rise to a number of technical and conceptual difficulties, some of which are discussed in detail in Chapter 4. However, some experiments on sublethal effects of zinc on Limnephilid caddis larvae (which are generally absent from the West Allen) were reported by Abel and Green (1981). These experiments showed that feeding rates of the animals, expressed as the quantity of food consumed per day, were reduced by 30% in animals exposed to the levels of zinc consistently recorded in the river water. The same authors claimed that activity levels, expressed as the percentage of time spent swimming by