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Mine water pollution in Scotland: nature, extent and preventative strategies

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Abstract

Scotland was one of the world's first industrialised countries, and has therefore also been one of the first countries to experience wholesale post-industrial dereliction. Water pollution arising from abandoned mines, particularly abandoned coal mines, is second only to sewage as a source of freshwater pollution nation-wide, and in many coalfield catchments it is the pre-eminent source. Most of the pollution is due to net-alkaline ferruginous waters emerging from deep mines. Scrutiny of records from 80 deep mine discharges reveals that iron concentrations in these waters are only likely to exceed 20 mg/l, and the pH to be below 6.5, where the discharge emerges within 0.5 km of the outcrop of the shallowest mined seam. The bulk of mature near-outcrop mine water discharges in Scotland have < 50 mg/l total Fe, and concentrations > 100 mg/l are only likely where a marine bed lies within 25 m of the worked seam. Where the nearest marine bed is more than 80 m above or below the seam, then the total iron will be less than 4 mg/l, and in most cases less than 1 mg/l. Net-acidic mine waters are far more rare than net-alkaline waters in Scotland, and are most commonly associated with unreclaimed spoil heaps (bings). Both net-alkaline and net-acidic discharges have detrimental effects on the hydrochemistry and biological integrity of receiving waters. Scotland has recently pioneered the use of pre-emptive pump-and-treat solutions to prevent mine water pollution, and has also experienced the successful introduction of passive treatment technology for both abandoned and active workings.

Keywords: Acidity; Alkalinity; Abandoned; Biology; Coal; Drainage; Geology; Mine; Pollution; Rebound; Scotland; Water

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1. Introduction

Scotland has a long history of mining, with the earliest records of coal mining in the 12th century. The locations of the main Scottish coalfields are shown on Fig. 1. Scottish coal production peaked in 1913 at an annual total of approximately 44 000 000 t (Beveridge et al., 1991). Throughout the 20th century, the Scottish coal industry has been in long-term decline, and at the time of writing, the annual production rate is only 6 000 000 t, most of which is from opencast sites, with only one deep coal mine (Longannet, in Fife) still in operation. The decline of the coal mining industry has led to widespread abandonment of dewatering arrangements, leading to significant problems of ground- and surface-water pollution and other impacts (Henton, 1981; Robins, 1990). Although much less widely worked than coal, abandoned workings for lead (Temple, 1956), oil

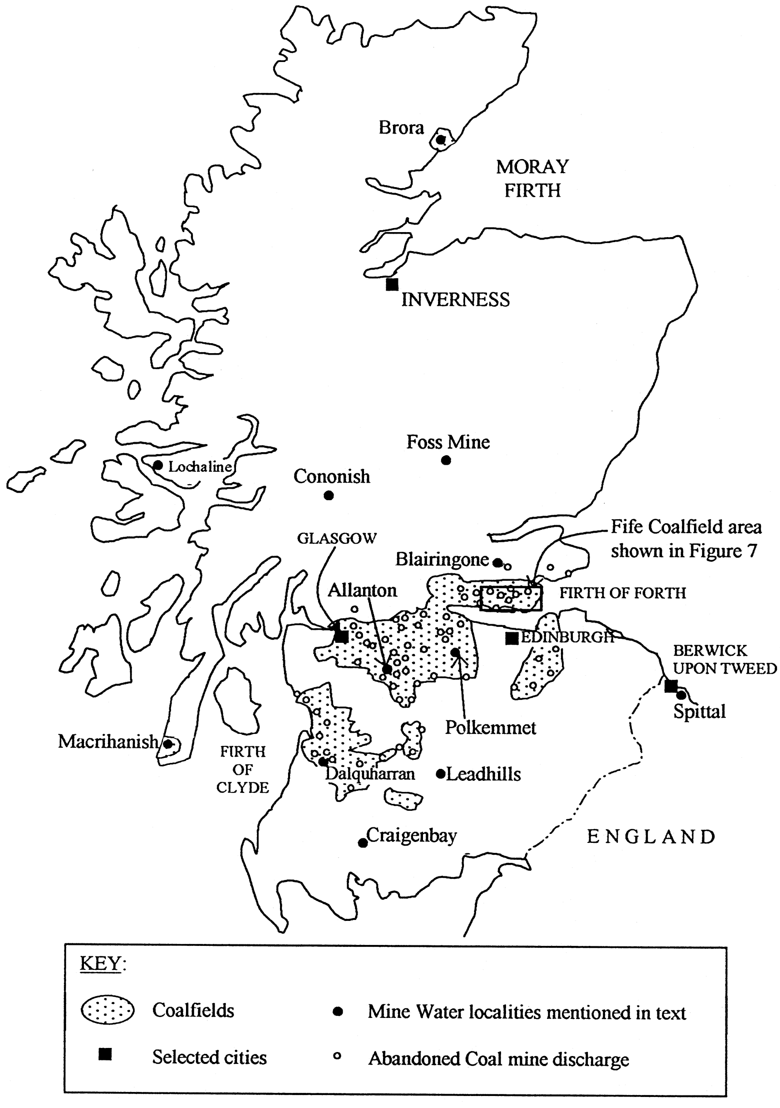

Fig. 1. Map showing the locations of major Scottish coalfields, abandoned coal mine discharges, and specific localities mentioned in the text.

shale (Carruthers et al., 1927), brick clay and fire clay have also been implicated in water pollution (Carter, 1994; Schmolke, 1998). Active non-coal deep mining is currently restricted to the glass sand mine at Lochaline and the barite mine at Foss (Fig. 1), of which only the latter works pyritic strata with the potential to produce pollution problems similar to those found in the coalfields. If the new gold mine at Cononish (Fig. 1) ever enters full production (Parker et al., (1989), it may also intersect strata with the potential to generate acidic and/or metalliferous discharges.

In this paper, the nature and extent of water pollution from abandoned mines in Scotland is assessed. Emerging strategies for preventing and/or remediating mine water pollution are then briefly summarised. Lessons drawn from these experiences are then identified, in the hope that other countries which are currently in an earlier phase of their mining industry can learn from the post-abandonment problems and solutions encountered in Scotland.

2. The nature of Scottish mine waters

Although the term ‘acid mine drainage’ remains entrenched in the literature, it is nevertheless the case that only a small proportion of polluting mine waters are truly acidic. Many mine waters contain seriously polluting concentrations of iron, yet have a circum-neutral pH (Banks et al., 1997). This is certainly the case in Scotland, where the vast majority of problematic discharges from mines have both a circum-neutral pH and an excess of alkalinity over acidity. Such waters are termed ‘net-alkaline’ (Hedin et al., 1994; Younger, 1995a). There are some important exceptions, however, in which the acidity of the mine water exceeds the total alkalinity (resulting in a ‘net-acidic’ water sensu, Hedin et al., 1994; Younger, 1995a). It must be emphasised that alkalinity and acidity are not mutually exclusive properties of an aqueous solution. Alkalinity is defined as the capacity of a given water to neutralise strong acid to a specified end-point (usually the bromcresol green–methyl red colour change at pH 4.5). This capacity is almost wholly afforded by the bicarbonate content of the water in the pH ranges relevant to mine waters. In contrast, the acidity of a given water is its capacity to neutralise strong alkali to a specified end-point (usually the phenolphthalein colour change at pH 8.3). Acidity thus defined owes little to the pH of the water, for even at low pH the proton activity is usually negligible compared with the activities of iron, manganese, aluminium, zinc and other hydroxide-forming metals. Hedin et al. (1994) describe total acidity as comprising the sum of the ‘proton acidity’ (represented by pH) and the ‘mineral acidity’ due to the metals listed above. The importance of distinguishing between net-alkaline and net-acidic mine waters lies in the relative ease of treatment process for the former (Hedin et al., 1994; Younger, 1995a, 1997b), and in the greater severity of environmental impacts which can be anticipated with the latter (Jarvis and Younger, 1997).

Table 1 gives representative chemical analyses for major mine water discharges in Scotland. These figures are derived from analytical records of the University of Newcastle and the Scottish Environmental Protection Agency (SEPA). Samples were analysed by both organisations in accordance with US Public Health Association standard methods of analysis, principally using ion chromatography for the anions and a combination of atomic absorption spectrophotometry and inductively coupled plasma spectroscopy (optical and mass-based) for the cations. The final column of Table 1 (‘net acidity’) indicates whether the water is net-acidic or net-alkaline, for it represents the difference between the total acidity and the alkalinity. Consequently, negative values of ‘net acidity’ correspond to net-alkaline waters, whereas waters with positive ‘net acidity’ are truly net-acidic.

Scrutiny of Table 1 correctly implies that the bulk of Scottish mine waters are net-alkaline, and that these net-alkaline mine waters are predominantly associated with flooded deep mine workings (underground workings accessed by shafts and/or adits). Indeed, the only supposed deep mine water which is net-acidic is the Brora No 1 discharge, and in this particular case, it remains possible that the source of the water has been

Table 1
Representative chemical analyses of selected Scottish mine waters (from University of Newcastle and SEPA archives)

Name	Abb.[a]	Source[b]	Grid ref.	pH	Cond. (μS/cm)	Temp (°C)	Total Fe[c]	Fe^{2+}	Fe^{3+}	Mn	Al	Zn
Lathallan Mill	L	S	NO 465063	6.1	820	11.3	10.8	10.8	< 0.01	0.7	0.04	0.07
Star Road	S	S	NO 296025	6.5	470	11.4	4.02	3.4	0.62	0.5	0.2	0.02
Kames No 1	K	S	NO 685262	5.8	945	–	14	–	–	2	0.02	0.07
Blackwood	BL	S	NS 803432	7.2	420	9	0.7	< 0.01	0.7	0.3	0.2	0.01
Cairnhill	CA		NS 627234	7.6	1960	18	6.7	4.5	2.2	4	1.1	0.05
Brora No 1	B	S	NC 898042	3.6	–	–	7.9	–	–	1	11.2	0.4
Macrihanish	M	S	NR 649208	6.1	–	–	60	–	–	4.7	6.8	0.3
Michael Colliery	Mi	PS	NT 336962	6.9	10 500	17	34	–	–	1.5	0.7	0.01
Frances Colliery	F	PS	NT 309938	6.9	19 350	16	12	–	–	1.1	1.10	0.01
Cuthill No 1	CU	A	NS 990682	5.5	1990	–	37	–	–	0.86	0.1	0.09
Douglas	D	A	NS 867356	6	1350		40	–	–	2.3	0.04	0.08
Pool Farm	PF	A	NS 987542	5.6	355	–	8	–	–	1.7	0.02	0.06
Elginhaugh	E	A	NT 317670	5.7	780	13.8	93	91	2	11.5	0.6	0.4
Pennyvenie No 3	P	A	NS 487066	6.9	1750	14.3	0.3	0.3	< 0.01	0.5	0.15	0.05
Baads Bing east	BE	H	NT 005612	2.8	3350	–	550	340	210	6.3	80	0.4
Baads Bing west	BW	H	NT 002610	3.5	620	–	6	5.5	0.5	0.9	2.4	0.07
Randolph Bing	R	H	NT 303957	3.7	2800	–	43	–	–	24.5	258	0.8

	Abb.[a]	Source[b]	Grid ref.	Ca	Mg	Na	K	SO_4	Cl	Alk.[d]	Ac.[e]	Net-ac.[f]
Lathallan Mill	L	S	NO 465063	87	41	16	6	214	35	182	20.8	−161
Star Road	S	S	NO 296025	61	21	13	12	53	34	173	10	−163
Kames No 1	K	S	NO 685262	130	60	9	8	247	9	232	29	−203
Blackwood	BL	S	NS 803432	75.5	26.8	17	12	37	30	265	3	−262
Cairnhill	CA		NS 627234	385	88	28	72	1346	23	80	27	−53
Brora No 1	B	S	NC898042	125	18	72	20	340	123	0	91	91
Macrihanish	M	S	NR 649208	46	20	26	8	51	57	0	154	154
Michael Colliery	Mi	PS	NT 336962	312	318	1304	78	1713	2662	410	67	−343
Frances Colliery	F	PS	NT 309938	160	320	4290	60	1240	5880	162	30	−132
Cuthill No 1	CU	A	NS 990682	345	97	75	15	932	40	247	68	−179
Douglas	D	A	NS 867356	180	73	11	12	595	14.5	190	75	−115
Pool Farm	PF	A	NS 987542	66	27	7	4	240	26	98	18	−80
Elginhaugh	E	A	NT 317670	256	188	16	23	1100	21.5	207	192	−15
Pennyvenie No 3	P	A	NS 487066	58	42	302	24	142	21	854	2	−852
Baads Bing east	BE	H	NT 005612	407	32	19	7	3077	16	0	2420	2420
Baads Bing west	BW	H	NT 002610	84	36	10	3	304	10	0	190	190
Randolph Bing	R	H	NT 303957	229	115	26	6	2475	103	0	1566	1566

[a] Abb. = abbreviation used on Figs. 3 and 4.
[b] Source: S = flooded shaft; A = abandoned adit; PS = pumping shaft (until 1995); H = spoil heap (bing).
[c] All concentrations mg/l excepy Alk., Ac., and Net-ac., which are in mg/l as $CaCO_3$.
[d] Alk. = alkalinity.
[e] Ac. = acidity.
[f] Net-ac. = net-acidity.

misclassified and that it is actually spoil drainage. The other three net-acidic waters in Table 1 (Randolph Bing, Baads Bing East and Baads Bing West) are definitely spoil heap drainage waters. (‘spoil heap’ is synonymous with ‘mine waste rock pile’, to which the colloquial term ‘bing’ is applied in Scotland). The impression given by Table 1, that most net-acidic waters are associated with mine spoil heaps, while net-alkaline waters are characteristic of flooded deep mines, is borne out by the experience of more than 80 mine water discharges around the country (Younger, 1995b).

Table 2
Summary of mine water volumes by type in Scotland (updated after Younger, 1995b)

Type of ferruginous mine water	Predominant source	Total flow in Forth catchment (Ml/day)	Total flow in Clyde catchment (Ml/day)	Overall total flow in Scotland (Ml/day)	Total iron loading entering Scottish rivers (kg/day)
Net-alkaline	Abandoned deep mines	≥ 150	≥ 45	≈ 200	2500
Net-acidic	Spoil heaps (bings)	≈ 2.5	≈ 1	≈ 4	1000

Both net-alkaline and net-acidic mine water discharges share in common elevated iron concentrations, which are responsible for most of the environmental impact of these discharges. This is because precipitation of large quantities of ferric hydroxide on the beds of receiving streams smothers the benthos, precluding photosynthesis and thus removing the base from the food chain. Table 2 summarises the abundance of these two principal mine water types in Scotland, revealing that at least three tonnes of iron are carried into the streams of central Scotland by abandoned coal mine discharges each day, leading to widespread problems of benthic smothering.

It is important to note that all of the mine water discharges referred to in Tables 1 and 2 are 'mature' discharges, in the sense that they have been flowing for several decades. For in the early years after a flooded deep mine first begins to overflow to the surface environment, it is quite possible for the discharge to be net-acidic and to have very elevated concentrations of iron and other ecotoxic metals. Younger (1997b) has recently discussed the temporal changes in the quality of deep mine water discharges following the completion of post-abandonment flooding (the so-called 'first flush' effect), and has shown that abandoned coal mine discharges in Scotland can have iron concentrations as high as 1400 mg/l in the first few decades following emergence, but that no discharges older than 40 years exhibit iron concentrations greater than 30 mg/l. Details of these types of temporal changes in Scotland can be found in the detailed paper by Wood et al. (in press) and are further exemplified by Robb (1994), Robins and Younger (1996) and Marsden et al. (1997). In the remainder of this paper, the focus will be on long-term regional patterns of mine water quality associated with 'mature' mine water discharges, rather than on the 'first flush' so recently documented in the literature.

As with any other groundwaters, the mine waters listed in Table 1 can be classified according to their major-ion chemistry, using standard geochemical plotting techniques. Piper or trilinear diagrams provide a method of graphically comparing water analysis. Analyses of calcium, magnesium, the sum of sodium and potassium, sulfate, chloride, and the sum of bicarbonate and carbonate are plotted. The central part of the diagram is a combination of the cation and anion fractions. A further description of these plots is given in Freeze and Cherry (1979). Fig. 2 is a Piper diagram (see Younger, 1995a for source references) on which the mine waters of Table 1 are seen to occupy a variety of fields. The waters from Star Road, Macrihanish and Blackwood all plot in the '$Ca\text{-}HCO_3$ facies' field, which is characteristic of shallow, fresh groundwaters in most of Scotland's potable supply aquifers (cf. Robins, 1990). The majority of the remaining waters are clustered towards the apex of the main 'diamond' of the Piper diagram, in the field of '$Ca\text{-}SO_4$ facies'. This is the typical plotting position of most UK abandoned coal mine waters (see Younger, 1994), with the high sulfate arising from oxidation of ferrous sulfide (pyrite, FeS_2, which is commonly disseminated within the coal-bearing strata), and the elevated calcium concentrations coming from dissolution of calcite and other minerals (neutralisation reactions provoked by the acidity arising from the pyrite oxidation process).

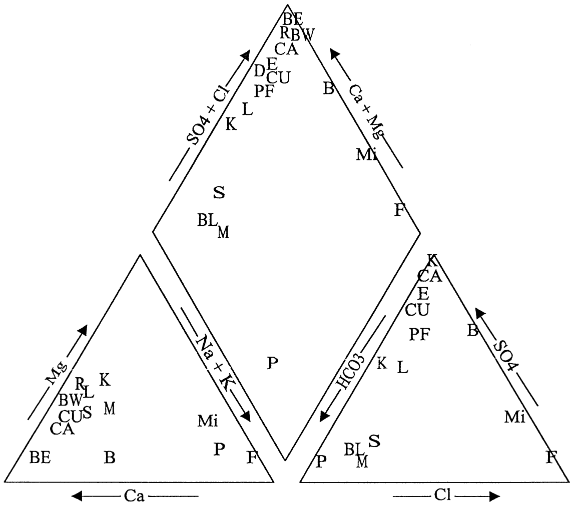

Fig. 2. Piper diagram showing the hydrochemical affinities of the samples listed in Table 1, in which the abbreviations of site names used on this plot may be found.

A few mine waters plot in fields which are ‘unusual’ (at least in the mine water context):

- The pumped mine waters from the Michael and Frances collieries in Fife (see Fig. 7) lie in the field of Na-Cl dominated waters, suggesting a strong marine influence on their quality, which Younger et al. (1995) have argued is consistent with the ingress of sea water into the undersea workings of these mines.
- The Brora No 1 discharge (see Fig. 1 for location) shows an intermediate composition between the Ca-SO_4 and Na-Cl facies. Given the coastal location of the Brora mine, it is reasonable to ascribe the Na-Cl element also to sea water ingress. The most unusual of all of the mine waters is the Pennyvenie No 3 discharge, which plots in the field of Na-HCO_3 facies. This facies is most typical of meteoric groundwaters which have undergone processes of ion exchange, in which an initial, ‘fresh’ Ca-HCO_3 groundwater loses its Ca^{2+}, but gains Na^+, by means of the exchange of dissolved and sorbed fractions within the aquifer (Freeze and Cherry, 1979). This process is typically associated with relatively deep groundwaters, which are accessing strata which have not been vigorously flushed by recent recharge. For instance, Younger (1998a) has noted the existence of similar ion-exchanged waters at depths of > 150 m in the partially-flooded coal workings of the Durham coalfield (in northern England, some 150 km southeast of Pennyvenie). As far as is known, this is the first time such waters have been identified in a Scottish mine, and the occurrence is somewhat surprising in view of the shallow setting of the Pennyvenie discharge (which emerges from an adit). Deep circulation of the mine water prior to emergence is a possible explanation, though examination of abandonment plans suggests that this is somewhat improbable in this case.

One drawback of the Piper diagram for mine water applications is its failure to take account of the balance of acidity and alkalinity which dominates the practical interpretation of mine water analyses for remedial design purposes. A classification scheme which avoids this drawback was devised by Younger (1995a). The waters listed in Table 1 are plotted according to this classification on Fig. 3. This plot immediately reveals the net-alkaline nature of most of the discharges. It is also clear which of the net-alkaline discharges are weakly so (Elginhaugh, Cairnhill and Pool Farm), which has strong implications for remediation planning: weakly net-alkaline discharges will probably require some additional buffering to allow rapid precipitation of metals in a treatment system, whereas strongly net-alkaline discharges require only aeration and sedimentation (Hedin et al., 1994; Younger, 1995a). It is notable that all of the net-acidic discharges shown on Fig. 3 plot very close to the x-axis. This is an artefact of the definition of alkalinity, for all waters with pH of 4.5 or below are automatically classed as having zero alkalinity, forcing them to lie along the x-axis. The relative displacement of net-acidic mine waters towards the left-hand axis also has implications for remediation design, since the waters with very high sulfate should be most amenable to treatment by ‘sulfidisation’ methods, such as the use of compost-based wetlands (Younger, 1997a).

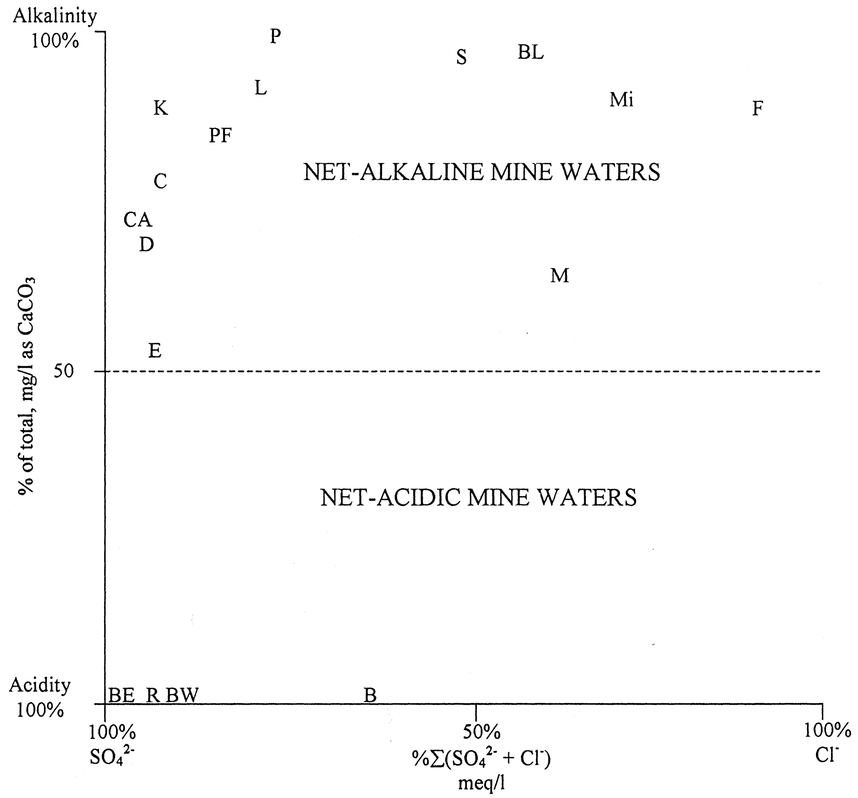

Fig. 3. Scottish mine waters (as listed in Table 1) plotted on the hydrochemical classification diagram originated by Younger (1995a).

3. Geological controls on mine water quality

As implied in the foregoing discussion, the geological setting of a mine water discharge can be expected to exert some influence on its water quality. If this can be shown to be the case, then the long-term water quality of mine water discharges (after the 'first flush') can be adequately predicted from some geological features which can be readily measured on published geological survey maps. It has been hypothesised that the two most important geological features are:

- The distance from the mine-water discharge point to the closest outcrop of the 'most-closely associated coal seam' (MCACS), which is defined here as the shallowest seam in which extensive workings were made by the relevant mine. While it might seem necessary to consider the relative topographic positions of the discharge and the MCACS outcrop, it has been found in practice that very few discharges occur up-dip from the lowest MCACS outcrop point: the vast majority of discharges lie down-dip from the MCACS outcrop. The reason why distance to MCACS outcrop might be expected to control water quality is that discharges distant from the outcrop are less likely to be prone to active oxidation of pyrite near the discharge, whereas discharges on the seam outcrop might reflect active oxidation of pyrite nearby.
- The thickness of strata between the MCACS and the nearest 'marine bed' in the sequence. (This 'marine bed' might be a shale with a marine fossil assemblage, a brackish-water

shale containing *Lingula* sp., or a marine limestone). A number of earlier workers (e.g. Caruccio and Ferm, 1974; Morrison et al., 1990; Younger, 1994) have noted that the pyrite content of marine-influenced coal-bearing strata tends to be higher than that of strata which accumulated under terrestrial conditions. Consequently, oxidation of 'marine beds' and adjoining coals can be expected to result in more severe pollution than would be the case with terrestrial strata (Caruccio and Ferm, 1974).

These hypothetical controls have been tested against the limited data available from SEPA for mature Scottish mine water discharges. The interpretations given below are necessarily based on sparse data, due to the fact that there are only approximately 100 known mine water discharges in Scotland, and not all of these are well-characterised hydrochemically. For this reason, the observations offered below cannot be regarded as definitive, but they are nevertheless interesting for the possibility they offer of bringing some order to the apparent chaos of mine water quality variations.

Fig. 4 shows that total iron concentrations of mature Scottish mine water discharges may only exceed 20 mg/l where the discharge emerges within 0.5 km of the outcrop of the MCACS. The comparable relationship for pH is shown on Fig. 5. pH variations show a less clear cut relationship with distance to MCACS outcrop; this may be because of the multiplicity and power of buffering processes compared with the limited processes which can trap iron as a solid phase. Nevertheless, Fig. 5 reveals that pH values below 6.5 in mature mine water discharges can only be expected within 0.5 km of the MCACS outcrop.

Both Fig. 4 and Fig. 5 reveal that there is a considerable degree of variability in water quality amongst those discharges lying within 0.5 km of the MCACS outcrop. It is interesting to speculate whether some of this variability can be explained by the thickness of strata between the MCACS and the nearest 'marine bed' in the sequence. Fig. 6 examines this proposition for total iron. While it is clear that the bulk of mature near-outcrop mine water discharges in Scotland have total iron of less than 50 mg/l, the few data points available do suggest that total iron in excess of 100 mg/l is likely only where the marine bed is within 25 m of the MCACS. It would also appear (again from sparse data) that where the nearest marine bed is

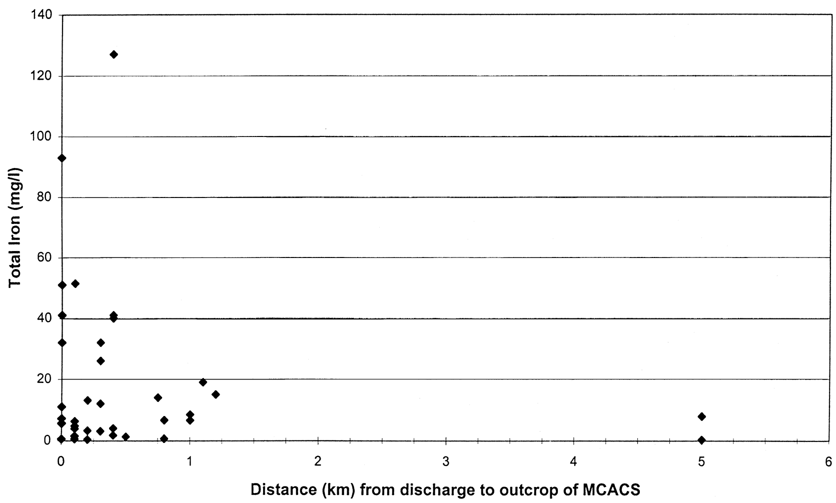

Fig. 4. Total iron in mature Scottish mine water discharges as a function of distance to the outcrop of the 'most closely associated coal seam' (MCACS).

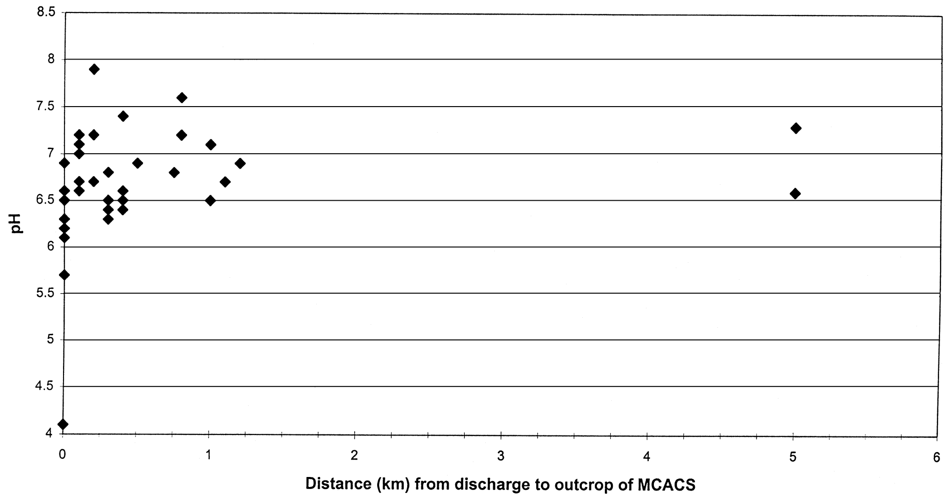

Fig. 5. pH in mature Scottish mine water discharges as a function of distance to the outcrop of the MCACS.

more than 80 m above or below the MCACS, then the total iron would be less than 4 mg/l and in most cases less than 1 mg/l.

Though the confidence in these interpretations is necessarily limited by the scarcity of data, it is worth noting that recent work on the English and Welsh coalfields (which have larger data sets) has revealed the same patterns (Younger and Adams, 1999).

4. Impacts on surface water quality

Table 2 provides an estimate of the total quantity of water flowing from abandoned mines in Scotland. The quantity is substantial; indeed it is approximately the same magnitude as the total amount of ground water abstracted for public and private supply purposes in Scotland (Younger, 1995b). In terms of the environmental impact of these mine water discharges, the following facts are pertinent:

- In the Forth catchment (i.e. the freshwater drainage system feeding the Firth of Forth; Fig. 1) discharges from abandoned mines have been the single greatest cause of freshwater pollution since approximately 1994, accounting for some 37% of freshwater pollution (Younger, 1997b). The primacy of mine waters as a pollution source in this catchment was attained as rolling programmes of improvements in sewage discharges gradually reduced the impacts from that source.
- In terms of the entire country (which obviously includes many thousands of square kilometres with no mining history), sewage is the primary cause of surface water pollution (33%), but mine waters are the second greatest single cause at 22% (Marsden et al., 1997).
- Abandoned mine waters are responsible (either solely or in combination with other pollution sources) for the degradation of approximately 480 km of streams and rivers in Scotland (D. Holloway, SEPA, written communication 1998).

Obviously, thorough documentation of the hydrochemical and biological impacts of Scottish mine waters nationwide is beyond the scope of this paper. However, it is feasible to illustrate the nature and scale of the impacts through the example of a single sub-catchment. Fig. 7 shows the catchment of the River Ore, a major tributary of the River Leven, which drains into the Firth of Forth on the east coast of the Fife peninsula. The River Ore has a mean flow near its mouth of approximately 1.9 m^3/s. Some seven deep-mine

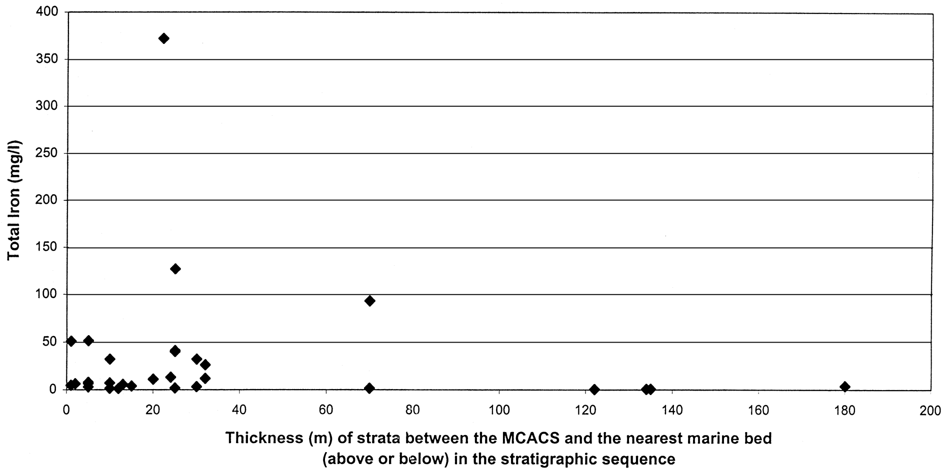

Fig. 6. Proximity to a marine bed as an explanation for variations in total iron concentration between mature Scottish mine water discharges which all lie within 0.5 km of the outcrops of their MCACSs.

Table 3
Mean pH, conductivity, and total iron concentrations in mine waters and river waters plotted on Fig. 7, with BMWP scores for selected river sites upstream (u/s) and downstream (d/s) of major mine water discharges[a]

No. on Fig. 7	Grid reference	Name	Mine water samples					River water quality samples		
			pH	Conductivity (μS/cm)	Iron (total) (mg/l)	BMWP score u/s	BMWP score d/s	pH	Conductivity (μS/cm)	Iron (total) (mg/l)
1	NT 125947	Blairenbathie	6.5	2000	2.0	75	0			
2	NT 170955	R. Ore at Lochore						8.0	312	< 0.1
3	NT 173952	Lochfitty Burn u/s conf.						7.2	439	< 0.1
4	NT 189953	W. Colquhally	6.6	2657	7.3	30	25			
5	NT 201949	R. Ore at Bow Bridge						7.4	793	1.0
6	NT 204949	Minto No. 2	6.8	3012	11.1	42	24			
7	NT 218955	R. Ore at Bowhill Br.						7.4	969	1.5
8	NT 218948	Cardenden	7.3	1930	1.6					
9	NT 219950	Den Burn at Cardenden						7.4	886	1.6
10	NT 223956	Parson's Mill	6.5	1842	37.0	43	25			
11	NT 232962	Kirk Burn u/s conf.						6.8	1120	15.0
12	NT 233961	New Carden	6.7	826	3.0					
13	NT 243963	R. Ore at Cluny Br.					48	7.5	1057	1.9
14	NT 294971	R. Ore at Thornton						7.7	1048	1.4
15	NT 236984	Kinglassie	6.9	3035	12.5					
16	NT 303983	Lochty Burn u/s conf.						7.9	1383	2.6
17	NT 306990	Balgonie Bing	4.3	2508	62.0					
18	NT 330997	R. Ore Balfour Mains						8.0	1176	1.2
19	NT 303957	Randolph Bing	3.1	2800	370.0					
20	NT 315960	Lappie Burn d/s Rand.						4.8	1500	11.0
21	NT 309938	Frances Colliery	6.9	19 350	12.0					
22	NT 336962	Michael Colliery	6.9	10 500	34.0					

[a] Data from SEPA archives.

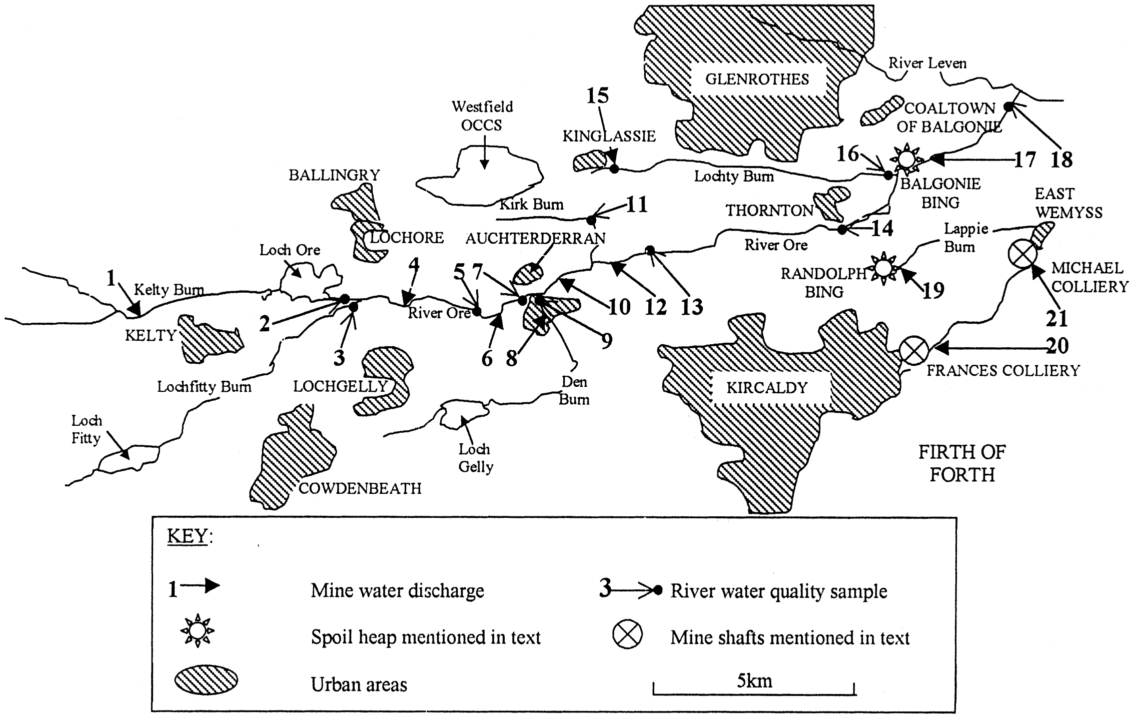

Fig. 7. Map of the River Ore catchment, Fife, Scotland, showing the locations of mine water discharges and river water quality sampling points listed in Table 3. This figure should be examined side-by-side with Table 3 to gain an appreciation of the cumulative effects of the mine water discharges on the overall quality of the River Ore.

discharges and one spoil heap discharge (Balgonie bing) flow into the Ore and its tributaries (Table 3). The flow rates and iron concentrations of most of these discharges have been previously described by Henton (1979) and Robins (1990), but the overall impacts on the River Ore have not hitherto been reported.

Coal mining in the Ore catchment was undertaken from at least the 16th century until September 1967, when the last deep mine (Minto; see Table 3 and Fig. 7 for location) closed, and dewatering was ceased. Some 9 years later, in December 1976, mine waters began to flow into the River Ore and its tributaries, beginning first at the most easterly discharge points (New Carden, Kinglassie), with the more westerly points (most dramatically at Minto) commencing to flow by the start of 1977 (Jackson, 1981). Although the National Coal Board were well aware at the time that the discharges were emerging from their recently-closed mines, they felt able to conclude that:

> "it is difficult to suggest an alternative without involving the NCB in tremendous expenditure, e.g. preparing, maintaining and emptying large settlement lagoons" (Jackson, 1981).

Henton (1979) has described the iron concentrations and flow rates of the Ore mine water discharges in the first few years after their initial emergence. Flow rates of all of these discharges remain at approximately their 1977 levels at the time of writing, as do iron concentrations for all but two of the discharges (Blairenbathie and New Carden), where the total iron has halved over the intervening two decades to current steady levels as reported in Table 3. The current effects of the mine water inputs on the quality of the River Ore can be appreciated by simultaneous examination of Table 3 and Fig. 7. The total mineralisation of the River Ore (as represented by specific electrical conductance) rises from a mean of 312 μS/cm upstream of the highest minewater discharge to approximately 1400 μS/cm above the confluence with the River Leven. Effectively, this means that the River Ore is transformed from a viable water resource in its upstream reaches to a river which would no longer be suitable for public supply abstractions downstream of the mine water inputs. This situation is likely to persist indefinitely, as none of the treatment options available at reasonable cost will result in an overall lowering of total mineralisation. Effectively, the mining history of East Fife has permanently removed the River Ore from the water resources available for human use.

In terms of ecology, the most important single influence of the mine waters entering the Ore is the smothering of the benthos with iron hydroxides. Mean total iron in the River Ore increases from less than 0.1 mg/l upstream of the mine waters to more than 1 mg/l near the confluence with the Leven. Given the mean flow rate at this point of approximately 1.9 m^3/s, the mean iron loading of the River Ore is approximately 160 kg/day. Time series data held by SEPA show that peak total iron concentrations in the range 2–4 mg/l tend to coincide with peak flows, in January or February each year. There are thus times in the winter when the total iron loading of the River Ore exceeds 0.5 t/day. Such elevated iron loadings result in a significant impoverishment of the benthic invertebrate population of the river. In terms of biological quality, the species diversity and total numbers of individual benthic invertebrates present in the Ore decrease markedly between samples taken upstream and downstream of major mine water discharges (Table 3). The measure of biological quality used in Table 3 is the biological monitoring working party (BMWP) score. The BMWP score is a single number that gives an overall weighted assessment of the numbers and biodiversity of benthic macro-invertebrate communities. BMWP scores are widely used in the UK to index the 'biological health' of streams. Basically, the higher the BMWP score, the more 'healthy' (i.e. the less affected by physical or chemical stresses) is the stream. For a more extended discussion of the derivation and use of BMWP scores in mine water impact assessment, the reader is referred to the recent paper by Jarvis and Younger (1997). Suffice it to note here that the raw species diversity and abundance data used to derive these BMWP scores were collected between 23 and 25 September 1998, by means of standard 3-min kick samples at the sites marked on Fig. 7, with care being taken wherever feasible to sample the full range of instream habitats (pool, riffle, etc.) present at each site. At the upstream end of the Ore system, above the Blairenbathie mine water discharge, a BMWP score of 75 is recorded. No value downstream of this point ever approaches such a relatively high value. The remaining biological sampling points reveal recovery of the BMWP score between successive mine water inputs to approximately 30–40, before the next discharge downstream effectively halves the score to the mid-twenties once more. Similar BMWP score variations were recorded downstream of mine water discharges in the nearby Durham coalfield of NE England by Jarvis and Younger (1997). Bearing in mind that there are a further 460 km of Scottish streams affected by mine waters outside the Ore catchment, it is to be expected that similar faunal impoverishment will be widespread in the former mining districts.

In the Clyde catchment, a further nuance of abandoned mine water problems occurred in 1971, when disposal of liquid wastes by injection into abandoned underground mine voids led to a serious pollution incident. Rebounding mine waters carried the liquid waste back to the surface and into a nearby river, which was thereby devastated for many kilometres downstream (Henton, 1974).

Degradation of the water quality and biological status of recipient water courses is not the only problem associated with abandoned mine waters in Scotland. In Allanton, north Lanarkshire (for location see Fig. 1), mine water rebound following the closure of the Kingshill No. 1 Colliery around 1970 culminated in surface discharges commencing around 1985. While the bulk of post-rebound discharge emerged from the Allanton shafts, a substantial amount of ferruginous water emerged in a housing estate that had been constructed before the mine closed. This ferruginous water has caused clogging of local surface water drains, resulting in the occasional backing-up of storm water during wet periods, causing flooding of properties (C. Schmolke, personal communication, 1998).

At the village of Leadhills (Fig. 1), in Scotland's Southern Uplands, post-abandonment changes in mine stability led to a serious threat of flooding (Schmolke, 1998). Prior to August 1991, an old drainage adit known as the Gripps Level drained some 23 Ml/day of water from abandoned lead mines. A roof fall in the Gripps Level at that time halted the discharge, and led to the impoundment of a vast volume of mine water in the old workings. A head of 25 m built up behind the roof fall, and eventually water began to emerge from old airshafts along the Level. More alarmingly, a large tension crack opened up in the hillside, and this also began to yield water. The risk of a catastrophic failure of these newly-flooded workings remains, posing a substantial risk to life and property downstream of the mine site (Schmolke, 1998).

Sudden failure of a roof fall which has been impounding mine water has already occurred at another village, in this case lying immediately south of the Scottish border at Spittal, near Berwick Upon Tweed (see Fig. 1). At approximately 0.00 h on 24 June 1998, water suddenly began to surcharge the main storm sewer in the main street of the coastal village of Spittal. The flow of water was violent, flipping heavy covers off access chambers and quickly flooding the street to a depth of approximately 1 m. Of course the water did not restrict itself to the street, but also burst into 19 homes. Apart from the normal water damage associated with flooding, the unfortunate residents soon discovered that their properties were being stained by the deposition of iron hydroxide. Chemical analysis of a sample obtained in the early hours of 25 June revealed the flood water to have a pH of 5.9, with 1.4 mg/l each of iron and manganese, 920 mg/l of SO_4, and a specific electrical conductance of 1690 μS/cm. The water also carried much silt, and fragments of coal, sandstone and shale. The flow continued as a torrent for approximately 17 h, then declined over a period of only 30 min to leave a trickle in the bottom of the storm sewer by 17.30 h on 25 June. The total volume of water released in the 17-h period is estimated to have been at least 60 Ml. Subsequent CCTV inspection of the storm sewers in the town revealed a connection to an old stone-arched adit portal, buried beneath made ground. A manuscript in local archives records a 'coal drift' in this position, which had been abandoned in 1820. All of the evidence suggests that a substantial head of mine water stored behind a barrier of roof-fall debris finally exceeded the strength of the barrier approximately 178 years after mine closure.

5. Preventative strategies

Just as Scotland has been one of the first industrialised countries to experience the full array of post-industrial pollution problems, so it is beginning to lead Europe in the development of practical solutions to these problems. The former state mining corporation British Coal [and its predecessor, the National Coal Board (NCB)] was always reluctant to accept responsibility for pollution from abandoned mines, for the law extant during most of its life [the Control of Pollution (Scotland) Act 1974] specifically exonerated any mine owner who 'permitted' water pollution from abandoned mine workings. This exoneration clause has now been removed from Scottish law with effect from 1 January 2000. On 31 October 1994, the regulatory duties of British Coal were vested in a new public body, the Coal Authority, which has already done much, in anticipation of the change in the law, to remediate pollution at sites long-neglected by British Coal, and to prevent further mine water outbreaks in sensitive catchments (Parker, 1997). These activities have all been undertaken in collaboration with the Scottish Environmental Protection Agency (SEPA) and its predecessor bodies, and usually with the active participation of local government agencies. In the paragraphs which follow, all of the major Scottish experiences in mine water remediation to date are briefly catalogued, providing interesting examples of what may be deemed ‘best practice’ for these sorts of problems.

In mid-1994, prior to the formation of the Coal Authority, the last few Scottish coal mines were threatened with either closure or privatisation. Along the East Fife coastline, the former Frances colliery (Fig. 7) had been under care and maintenance for nine years, preserving access to substantial undersea reserves of coal which might feasibly have been an attractive option for the privatised coal industry in future years. However, to maintain access to Frances colliery, it had been necessary to maintain pumping of mine water not only at Frances colliery (9 Ml/day), but also at the nearby Michael colliery (24 Ml/day; see Fig. 7). While both of these pumped discharges were ferruginous (see Tables 1 and 3), they were disposed of directly into the sea (Firth of Forth), where their biological impact was minimal (although the Michael discharge sustained an unsightly orange plume in the Firth). In common with various other mine sites around the UK (see Younger, 1993), British Coal had failed to find an early buyer for Frances colliery, and in the early autumn of 1994 the decision was taken to close the mine without further delay. Given the abundant evidence for the pollution risk associated with mine abandonment in the Ore catchment nearby (Fig. 7, Table 3), the Forth River Purification Board (a predecessor of SEPA) threatened British Coal with a legal injunction requiring continuation of pumping, and commissioned an urgent study of the probable environmental consequences of the cessation of dewatering from the Frances and Michael shafts. Details of the findings of this study have been published by Younger et al. (1995). Essentially, the application of state-of-the-art mine water rebound modelling techniques (since described in detail by Sherwood and Younger, 1997) led to the prediction that cessation of dewatering at the coastal pits would eventually lead to uncontrolled mine water discharges in the coal outcrop areas inland, totalling approximately 18 Ml/day. The principal receptors for these discharges were predicted to be the River Ore (which is already heavily stressed by mine water discharges as recounted above) and the River Leven (which has hitherto been unaffected by direct mine water discharges). On the basis of these predictions, the Forth River Purification Board refused to agree to a cessation of pumping at Frances and Michael unless British Coal proposed a satisfactory pollution prevention strategy. After delicate negotiations, British Coal eventually agreed to allow mine water rebound to proceed only until the water level in the coastal shafts reached 56 m below sea level, after which further rebound would be prevented by renewed pumping, with the pumped water being treated and disposed to the sea to standards set by SEPA. The agreement signed by British Coal (and subsequently bequeathed to the Coal Authority upon the demise of British Coal) also provided for the drilling of observation boreholes in the onshore coalfield during the rebound process, to allow checking of the predictions over water rise. At the time of writing, these boreholes are being installed by the Coal Authority, who are also making preparations for the pump-and-treat scheme.

Another pump-and-treat scheme to prevent river pollution has been installed south of the Forth, at Polkemmet colliery (see Fig. 1 for Location). This scheme put an end to 11 years of speculation over the likely consequences of uncontrolled mine water rebound in the extensive workings around Polkemmet. The cessation of dewatering at Polkemmet occurred in contentious circumstances in the bitter aftermath of the 1984–1985 national miners' strike (Younger, 1995b), and no provisions were made at the time for monitoring or control of future mine water rebound. In 1995, SEPA requested that the newly-established Coal Authority investigate the status of mine water recovery in the area. Boreholes were drilled into the Polkemmet workings, revealing that the water was only 20 m below the lowest likely surface outflow point (Sadler and Rees, 1998), and that it was rising sufficiently rapidly that discharge into the River Almond could be expected by the spring of 1998. Sampling of waters in the boreholes allowed geochemical modelling of the possible impacts of uncontrolled discharges to the River Almond, suggesting that iron loadings in excess of 36 kg/day would enter the river, seriously damaging aquatic habitats

(Chen et al., 1999). In the light of such predictions, the Coal Authority agreed to collaborate with SEPA in developing a strategy to prevent the pollution of the River Almond (Marsden et al., 1997). Further sampling of mine waters rising through the workings revealed that the waters furthest from the seam outcrop had the lowest concentrations of iron (echoing the results presented in the foregoing discussion on geological controls on mine water chemistry). On this basis it was decided that pumping from the deeper parts of the workings would yield a water more amenable to low-cost treatment (Sadler and Rees, 1998). Pumping was therefore recommenced at Polkemmet shaft in early 1998, approximately 12 years after it had originally been terminated. The rise in water levels was halted, and treatment of approximately 8.6 Ml/day of mine water containing 5–10 mg/l total iron (by aeration, flocculation and sedimentation) resulted in a discharge of acceptable quality into the nearest stream, and the successful prevention of the pollution of the River Almond (Sadler and Rees, 1998).

For existing mine water discharges, pump-and-treat schemes are rarely likely to be established, because of the costs and risks associated with drilling into and pumping long-flooded workings. Recently, remediation of existing mine water discharges in Scotland has been achieved using passive treatment technology. The first large-scale passive treatment systems for mine waters in the UK were established in England and Wales in 1994 (Younger, 1997a). However, small-scale experiments with wetlands on Scottish mine sites commenced earlier than this, in 1992, with the creation of a reed bed to remove suspended solids from opencast drainage at Lambhill, Fife, and the installation of a small wetland at the foot of a spoil heap (Gilmerton bing) near Edinburgh in 1992 (Carter, 1994). A small reed bed was subsequently installed at Dalquharran mine (Fig. 1), Ayrshire, in 1994, to polish a small quantity of seepage emerging from an impoundment designed to control the release of mine water to the nearby Water of Girvan (Marsden et al., 1997). Former colliery washery lagoons at Allanton, north Lanarkshire, receive a substantial uncontrolled mine water discharge from the shafts of the Kingshill No. 1 Colliery. These lagoons have begun to develop a healthy colony of reeds, and they are functioning as an efficient wetland treatment system, lowering iron concentrations in the mine water from 17 to < 1 mg/l, and raising the pH from 7.2 to 8.2 (Schmolke, personal communication, 1998).

At Blairingone (Fig. 1), in Fife, closure of an opencast mine in 1994 was soon followed by the emergence of a highly ferruginous discharge ($\leq$ 118 mg/l total Fe) from a nearby 19th century mine adit (at Mains of Blairingone). The discharge caused highly visible staining of the bed of the River Devon for a distance of 2 km downstream of the adit. Following negotiations with SEPA, the site owner agreed to divert the adit discharge into a nearby natural wetland, with the intention of achieving iron removal prior to final outflow to the River Devon. Following diversion, the average rate of iron removal within the wetland has been 94%, and final discharge to the river generally has 2 mg/l or less of total iron, so that the River Devon is no longer stained at all. Meanwhile, the iron concentration in the adit discharge has dropped markedly (following the typical ‘first flush’ pattern described by Younger, 1997b), so that the iron concentration entering the wetland is now generally less than 30 mg/l (Marsden et al., 1997).

In the River Ore catchment, steps have recently been taken by the Coal Authority to address part of the pollution problem which has persisted there since 1976. During 1998, an aerobic wetland (similar to those at Dalquharran and Mains of Blairingone) has been constructed at the Minto No. 2 discharge, and it is anticipated that this will effectively trap 13 kg/day of iron that has hitherto flowed into the River Ore. While this represents a little less than 10% of the mean total iron loading in the Ore at its mouth, the local improvements in the appearance and ecology of the River Ore will be considerable. It is conceivable that the success of this scheme will in time provide the impetus for further schemes to address the remaining 90% of the iron loading entering the River Ore, so that the ecological health of most of the river will eventually improve.

All of the examples of full-scale passive treatment listed above are for net-alkaline discharges from abandoned coal mines. The latest developments in passive treatment in Scotland are for net-acidic waters emerging from active workings. At Craigenbay (Fig. 1), Galloway, a roadstone quarry produces an effluent typified by a pH of 3.2, 24 mg/l total iron and as much as 89 mg/l of aluminium. A vertical-flow wetland, in which the mine water is forced to flow through a bed of compost followed by a bed of limestone gravel, has been installed at the site, along with two conventional compost wetland beds (Norton et al., 1998). Although performance data are not yet available for this system, experiences with the same approach in south Wales (Younger, 1998b) give cause for optimism. A similar vertical flow wetland system at pilot scale was also installed in August 1998 at Foss mine (Fig. 1), Perthshire, (an active barite mine) by the author's research team, and initial monitoring results show encouraging rates of removal of iron, aluminium and zinc from the mine water. Significant challenges to the applicability of passive treatment at both Craigenbay and Foss arise from their relatively high altitudes (280 m above sea level at Craigenbay, 730 m above sea level at Foss), which at Scottish latitudes are sufficient to guarantee sub-arctic conditions in the winter months. Apart from the obvious problems of freezing, doubt must remain over the metabolic rates of sulfate-reducing bacteria during the sustained periods of intense cold that commonly occur in the Scottish mountains.

In the special case of spoil heaps, there is some scope for pollution prevention by the relatively simple expedient of land reclamation. Unreclaimed spoil heaps can have serious impacts on receiving watercourses. For instance Fig. 7 and Table 3 illustrate the persistence of very poor water quality in the Lappie Burn, Fife, hundreds of metres downstream of the unreclaimed Randolph bing. Similarly, the Balgonie Bing discharge (Fig. 7, Table 3) has a noticeable detrimental effect on the River Ore, despite the relatively small flow of the bing discharge compared to the river. Experience shows that the volumes of polluted surface runoff are greatest where spoil heaps are unreclaimed (Bayless and Olyphant, 1993). For instance, the Baads bing in west Lothian (Table 1) was extensively reclaimed in 1979/1980, resulting not only in the successful establishment of grass cover and woodland, but also in a substantial reduction in pollutant loadings entering the West Calder Burn (and thence the River Almond). Prior to the reclamation of Baads bing, the West Calder Burn was essentially dead throughout its 11 km length; after reclamation, detectable impacts on the West Calder Burn were restricted to within a few tens of metres of the bing. This dramatic reduction in impacts is reflected in a reduction of two to three orders of magnitude in the iron loadings leaving the bing before and after reclamation. For instance, before reclamation, the mean iron loading from the east discharge was approximately 550 kg/day, and from the west discharge approximately 450 kg/day. Post-reclamation, the corresponding figures are 1 kg/day from the east discharge and 0.2 kg/day from the west.

If the process of reclamation allows sub-soil infiltration into the spoil to continue, a perched groundwater system may be sustained within the spoil, leading to persistent discharges of poor quality water long after reclamation. The remnant discharges from Baads bing appear to be associated with a perched water table, though the consequences are not especially grave in this case. Elsewhere, perched groundwater in otherwise reclaimed spoil causes significant degradation of small streams (e.g. Younger, 1998b).

6. Conclusions

Scotland was one of the world's first industrialised countries, and has therefore also been one of the first countries to experience wholesale post-industrial dereliction. Water pollution arising from abandoned mines, particularly abandoned coal mines, is second only to sewage as a source of freshwater pollution nationwide, and in many coalfield catchments, it is the pre-eminent source. Most of the pollution arises from net-alkaline ferruginous waters emerging from deep mines. Net-acidic water are far less common, being most frequently associated with unreclaimed spoil heaps (bings). Both types of discharge have detrimental effects on the hydrochemistry and biological integrity of receiving waters. Scotland has recently pioneered the use of pre-emptive pump-and-treat solutions to prevent mine water pollution, and has also experienced the successful introduction of passive treatment technology for both abandoned and active workings. All of these experiences are potentially valuable to scientists and engineers in other countries that have not yet reached the senescent state of heavy industry that already obtains in Scotland.

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