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Groundwater management problems in abandoned coal-mined aquifers: a case study of the Forest of Dean, England

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Summary

An examination has been made of groundwater related problems experienced in the Forest of Dean since abandonment of the major collieries in 1965. Careful planning prior to abandonment of collieries can reduce the number of poor quality discharges, and so substantially limit surface water pollution. Small-scale mining activity continuing after major collieries have been abandoned can have a serious hydrogeological effect by removal of *in situ* coal from drainage barriers designed to promote free drainage of the mines. In association with the deterioration of lined river channels which retard surface water infiltration, this disruption of subsurface can result in a drainage significant loss of summer base-flow from surface rivers.

Two case histories show that safe disposal of wastes to voids in mined Coal Measures aquifers is possible. Prediction of the hydrogeological behaviour of the mined aquifer is, however, difficult because of the possibility of unrecorded workings, random collapse and associated ponding, and uncertainty over the hydrological behaviour of the coal barriers. Direct investigation of the groundwater flow regime using boreholes and water tracing techniques is recommended.

Introduction

The Forest of Dean is an area of outstanding natural beauty incorporating a National Forest Park, and lies between the Rivers Severn and Wye in the County of Gloucestershire, England (Fig. 1). The hydrogeology of the area has been extensively affected by coal mining which commenced in the seventeenth century and is still active today. Deep workings and free drainage levels still transmit water in large quantities, and extensively affect the groundwater regime in the Coal Measures aquifer. In this paper we describe the significance of the mining activity for present day management of the water resources of the area, including an assessment of the previous effects of waste disposal based on available historic data.

Study area

The Forest of Dean forms a dissected plateau surface covering some 85 km^2, rising from 120 m AOD in the south to 220 m AOD along its northern margin. More resistant rocks to the east and west form somewhat higher ridges. The area is drained by three streams, the Cannop Brook (the major stream draining south), Cinderford Brook and Blackpool Brook (Fig. 1), all of which flow in deeply incised valleys. Much of the area is covered by mature deciduous and mixed deciduous/coniferous woodland. The soils are well drained over the more arenaceous rocks but tend towards gleys on the shales. The long term average precipitation is 860 mm p.a., with a winter maximum. Evapotranspiration estimated for the River Severn catchment south of Bewdley (GR SO78607535) is 470 mm p.a. The area is extensively used for recreation, including camping, walking, natural history, coarse and game fishing and boating.

Geology

The Coal Measures in The Forest of Dean are of Upper Carboniferous age and are underlain by rocks of the Carboniferous Limestone sequence (Fig. 1). They are folded into an elongate north–south asymetric basin with steeper dips on the eastern flank of the north–south axis. In all there are 22 coal seams of varying thickness in the coal measures which are divided into three major stratigraphic subdivisions, the Supra Pennant, Pennant and Trenchard Groups. The Trenchard Group forms the base of the Coal Measures and comprises shales, sandstones, grits and conglomerates. There is only one major coal seam, the Trenchard Seam, which attains a thickness of 1.4 m, and was worked only in the south. The Pennant Group consists of massive sandstones with subordinate shales, and includes three seams of workable thickness. The Coleford High Delf Seam, 1.0 m to 1.5 m thick, is the most important seam in the coalfield, and is overlain by the thinner Whittington and Yorkely Seams, the Whittington being restricted to the southern half of the Basin. Within the Pennant Group lies the Cannop Fault Belt, an 8 km long zone of fracturing embracing up to 25 faults which trends west of north along the Cannop Valley (Fig. 1). To the west, and also affecting the Pennant rocks, is the

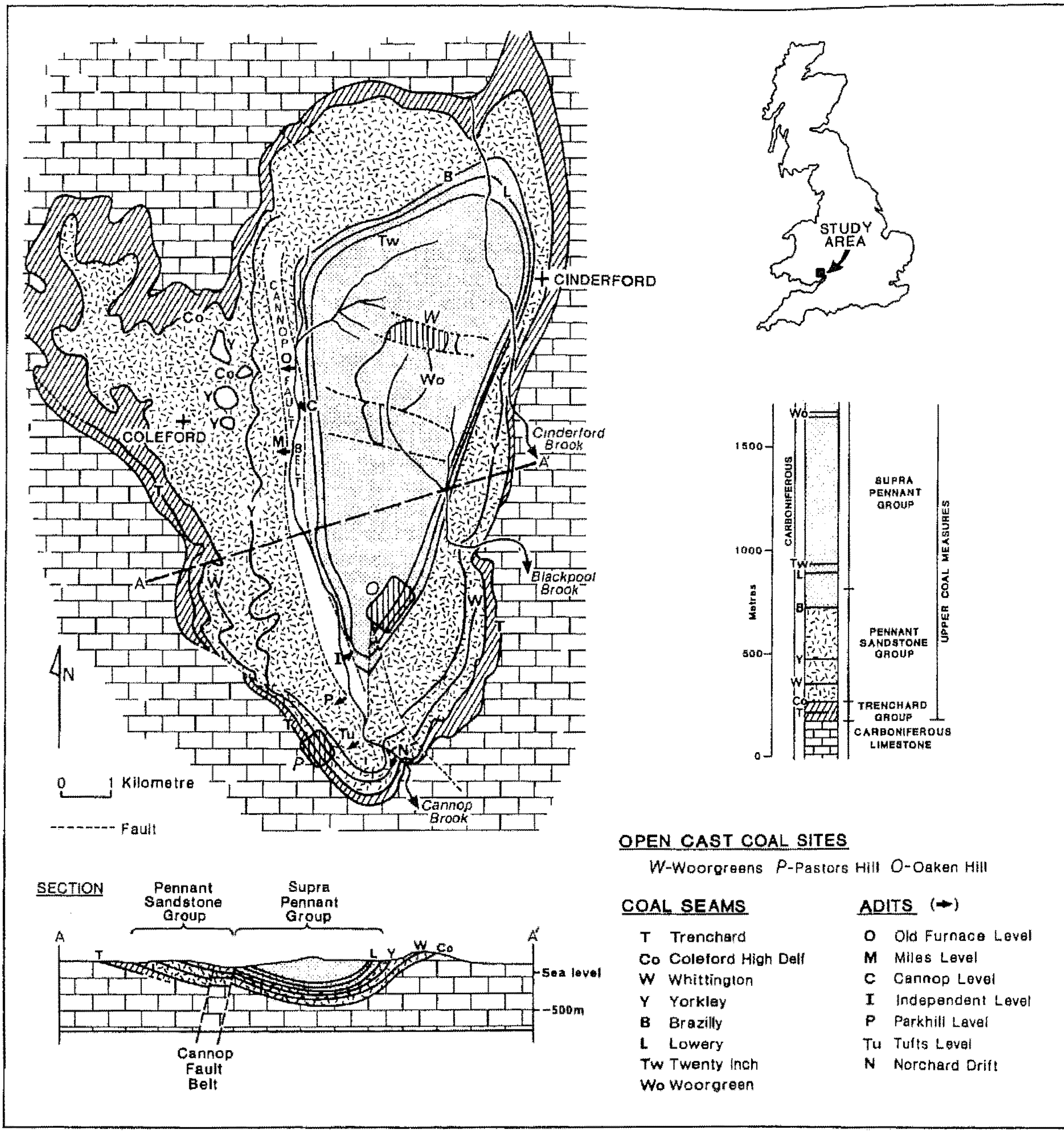

FIG. 1. Geology of the Forest of Dean Coalfield, including locations of open-cast sites, major groundwater discharges from adits and surface streams.

Ridge Anticline, a shallow north–south asymetrical plunging fold with gentle dips on its western flank and steep dips on its eastern flank. The Supra Pennant Group overlies the Pennant Group and outcrops in the centre of the basin. It consists of shales, sandstones and coals divided into two stratigraphic units, a shaly lower division 91 m thick in which there were eight workable coals, and an upper division which contains thick sandstones and subordinate coals.

Coal mining history of the Forest of Dean

Prior to the seventeenth century, coal mining activities were limited to outcrop areas only, and necessitated no form of artificial drainage. It was not until the late eighteenth century when workings were much deeper and more extensive that free drainage levels were needed to drain the workings. These low gradient, cross-measure levels were driven from a low point in the valley floor into the hillside until the level intersected the coal seams. Groundwater drained by gravity to the surface, where it discharged into the nearest water course. Many of these free drainage levels still function today. The area of coal mined from one adit was regulated, the area being termed a gale (Hart 1953). Barriers of intact coal were left around the boundaries of each gale to prevent the ingress of groundwater. The system of gales defines mining concessions, and is the basis for drainage and documentation in this and other coalfields (Ashley 1930; Forrest 1920).

From the early 1900s, coal in the deep part of the basin, below river level was mined from five large collieries reaching a depth of −400 m AOD The Coleford High Delf seam was removed over extensive areas, but despite the retention of coal barriers to direct groundwater flow into the free drainage levels, pumping requirements were high. The mines were therefore closed between 1959 and 1965 when the ratio of volume of water raised per ton of coal was about 40 to 1. All deep basin workings are now abandoned and have become flooded. The underground mining of coal continues today only in the outcrop areas of the Pennant Group, where four small mines are located. Recently, however, opencast mining has also been undertaken.

Environmental problems directly relating to mining activity

Deep barrier removal

Abandoned coalmines are widely recognized as having prolonged detrimental effects on surface water quality due to the development of substantial point discharges of acidic and ochreous mine drainage waters (Porges *et al.* 1966; Emrich & Merritt 1969, Ahmad 1974) but the good management of a coalfield during its closure period can help to minimize these environmental problems.

In the case of the Lowery Seam (Supra Pennant Group) in the Forest of Dean, deep basin mining left only one major coal barrier 20 m wide, running east–west across the centre of the main basin (Fig. 2A) which has therefore divided the the basin into two units. However in the NW the seam was too thin to extract, and a substantial area was left unmined downdip of the outcrop. On abandonment, the main east–west barrier remained intact, causing ponding of water in the northern workings. These now discharge through the Cannop Level (whose workings were protected to the east by a minor barrier), and many ferruginous springs around the outcrop zone. These springs are caused by discharge through the unmined zone in response to the hydraulic head generated by ponding behind the main barrier, which retards flow to the south and the lowest possible discharge point. In the southern unit, coal removal was more complete and mined water discharges only from the Independent free drainage level (Mean long-term flow rate 10 l/s). The proportion of baseflow in the Cannop Brook derived from the Supra Pennant Group is relatively low (approximately 9% estimated from a survey of summer low flow conditions) due to the high proportion of shales in this group. The overlying clayey stagnogley soils retard recharge, and vertical leakage through the shales is also small. Thus, these ferruginous mine discharges are readily diluted by the large baseflow from the Pennant Series, and the water quality of the surface stream remains good (Fig. 3).

In the Coleford High Delf Seam (Pennant Group), there are five separate mine units separated by coal barriers up to 55 m thick (Fig. 2b). However, prior to abandonment these were pierced, allowing the development of an integrated groundwater flow from north to south. Thus only a single minewater discharge point occurs at the lowest adit entrance, the Norchard Drift, which has a mean long term discharge rate of 200 l/s. Whilst the Cannop Brook downstream of this large discharge has a poor quality (Fig. 3), the total length of river affected is small compared with that which would have been expected had the coal barriers remained intact, and overflow had occurred at many separate locations. It is also of interest to note that there has been a progressive improvement in the quality of the Norchard Drift discharge over the nineteen year period since abandonment (Fig. 4). This quality improvement accords well with the model of Cairney & Frost (1975), who suggested that static conditions minimize the rate of production of iron pyrites oxidation products. Thus, it is suggested that initially there was a period of flushing in the Coleford High Delf Seam as the abandoned mined voids became flooded, but more stable groundwater conditions then followed, leading to a reduction of pyrites oxidation. At present, the annual average water level flucuation in the abandoned Cannop Colliery shaft just north of the Old Furnace Level (Fig. 2b) varies between 8 and 15 m. Continued oxidation in this annually inundated zone may limit further water quality improvement at the Norchard

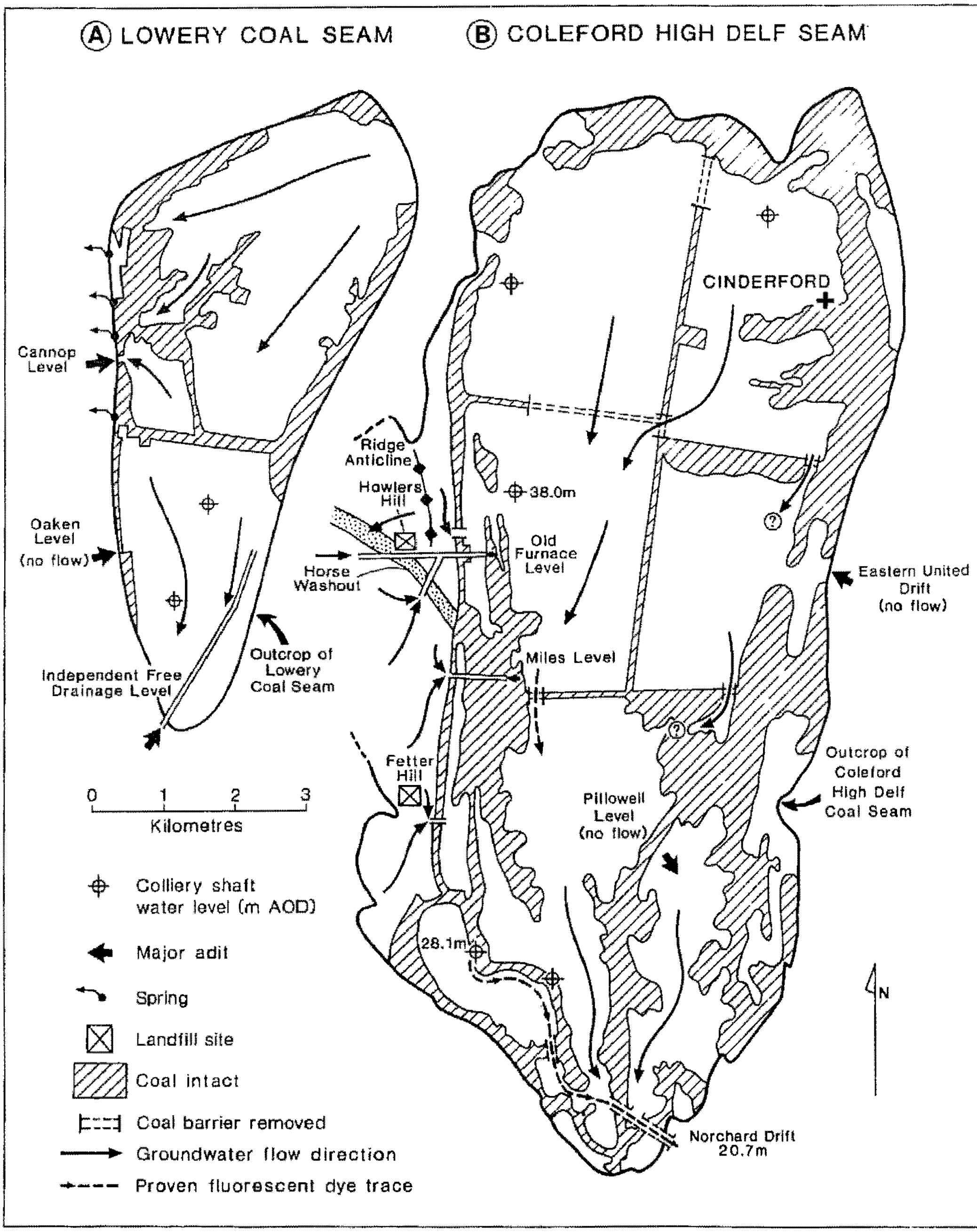

FIG. 2. Extent of mining, coal barriers and groundwater flow in the Lowery (A) and Coleford High Delf (B) coal seams, based on mine plans.

Drift outlet. Whilst initial iron levels have fallen exponentially, halving over an approximately 5.5 year period, in the future this decline will be less rapid and the concentrations will stabilize at a lower but still significant level.

Shallow barrier removal

Shallow barriers are those associated with free drainage levels, including the boundary barriers between adjacent gales. In the unsaturated zone

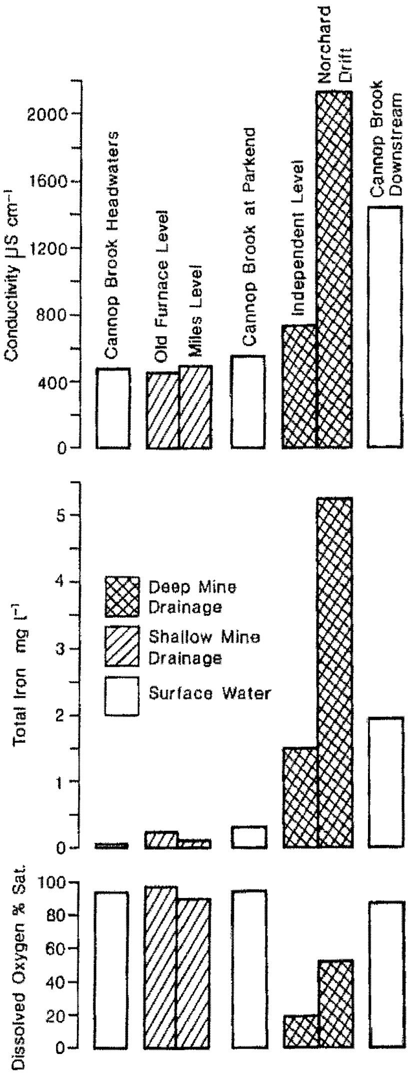

FIG. 3. Conductivity, total iron and dissolved oxygen for mine drainages and the Cannop Brook. Figures are best available long term averages for the period 1974 to 1984.

above these levels, percolation is predominantly vertical in the fractured Pennant sandstones, but is impeded by the seat earth clays underlying the coal seams, which have a very low permeability 12.0×10^{-8} m/s Shubert 1980; Rehm *et al.* 1980). Whilst these may be excavated in the major haulage roadways to provide adequate roof clearance, they remain undisturbed in the extensive galleries from which coal extraction occurs. Thus flow is directed downdip on the surface of the seat earth, and is concentrated by the network of abandoned roadways into small streams with discharges up to 5 l/s (Fig. 5). The downdip flow is however diverted laterally by the barriers of unmined coal remaining in the floors of the along-measures roadways leading to the cross-measures free drainage levels. This water, therefore, discharges to the surface rather than penetrating further downdip into the now abandoned deep basin workings below river level.

Present day abstraction of coal from these barriers has necessitated their piercing to facilitate mine drainage, and in some cases they have been totally removed. Direct observation at several sites shows that water has been diverted from the free drainage levels into the deep basin, as illustrated in Fig. 5. Furthermore, removal of coal from beneath the free drainage level at one site has caused subsidence and fracturing in the Pennant Sandstone, resulting in vertical leakage from the bed of the free drainage level. This amounts to 3 l/s additional recharge which may generate a correspondingly greater quantity of poor quality water at the discharge from Norchard Drift outfall. However, the reduction of summer baseflow in the Cannop Brook due to this diversion of groundwater is a more serious environmental problem. The dependance of the summer baseflow in Cannop Brook on the discharge of shallow mine drainage waters is clearly demonstrated in Fig. 6. Reduction of this flow could seriously affect the amenity value of the recreation areas in the headwaters, and reduce the viability of the coarse and game fisheries. The effect would be particularly serious in the Cannop Ponds, where the Old Furance Level supplies 59% of the summer baseflow, and drains two coal mines where barriers are actively being extracted.

The water from the shallow free drainage levels is of good quality because it is derived primarily from the Pennant sandstones and has limited contact with the pyritiferous shales and coals (Fig. 3). Reduction of the free drainage inflow could, therefore, reduce the dilution available for poorer quality mine drainage from the deep basin. This is of greatest importance at the Independent Level which is tributary to the Cannop Brook upstream of an extensive fishery.

Post-abandonment collapse

On abandonment of a colliery, expansion and extrusion of the seat-earth clay underlying the coal, together with settlement of the roof, gradually reduces the mined void. A tracer experiment was conducted in the flooded Coleford High Delf workings of the Flourmill Shaft (Fig. 2). Five kilograms of sulphorhodamine B dye (Durham Chemicals Ltd) were injected at the base of the shaft, which was choked by fallen debris. The dye was flushed into circulation using 28 m^3 of water, and was detected after 7.5 days at the Norchard Drift outfall, a straightline distance of 3.5 km from the injection shaft. The tracer breakthrough curve shows remarkably little dispersion, the

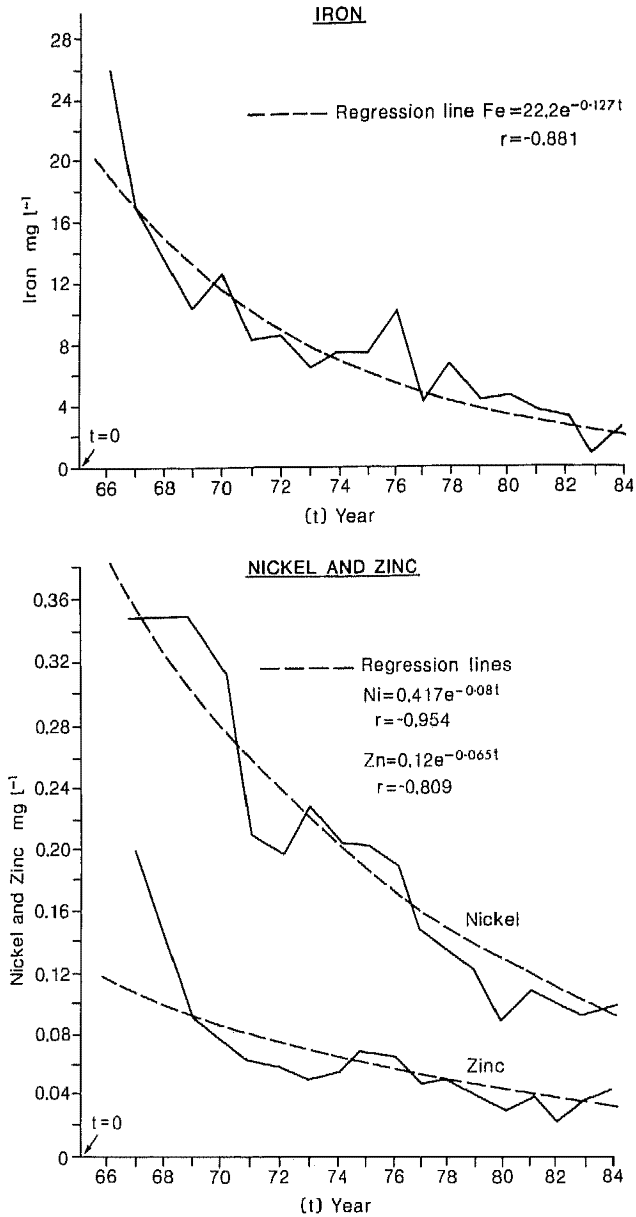

FIG. 4. Mean Annual total iron, nickel and zinc concentrations at the Norchard Drift for the period from commencement of discharge in 1966 to 1984.

dye pulse duration at the Norchard Drift being only 1.3 days, suggesting non dispersed 'plug-flow' (Aldous & Smart, in preparation). This suggests that flow is concentrated into a major conduit, probably developed along the lines of the main haulage roadways, rather than more dispersed flow occurring throughout the laterally extensive mined void. This situation is similar to that observed in the unsaturated zone (see below), and is supported by the lack of open voids when workings in the Yorkely seam were penetrated at 75 m below the surface (1 m AOD) by a borehole drilled in the saturated zone for resource evaluation by Severn Trent Water Authority. In fact, the unlined hole was closed by seat earth extrusion at this level 9 months after completion.

A similar closure of workings is also observed in the

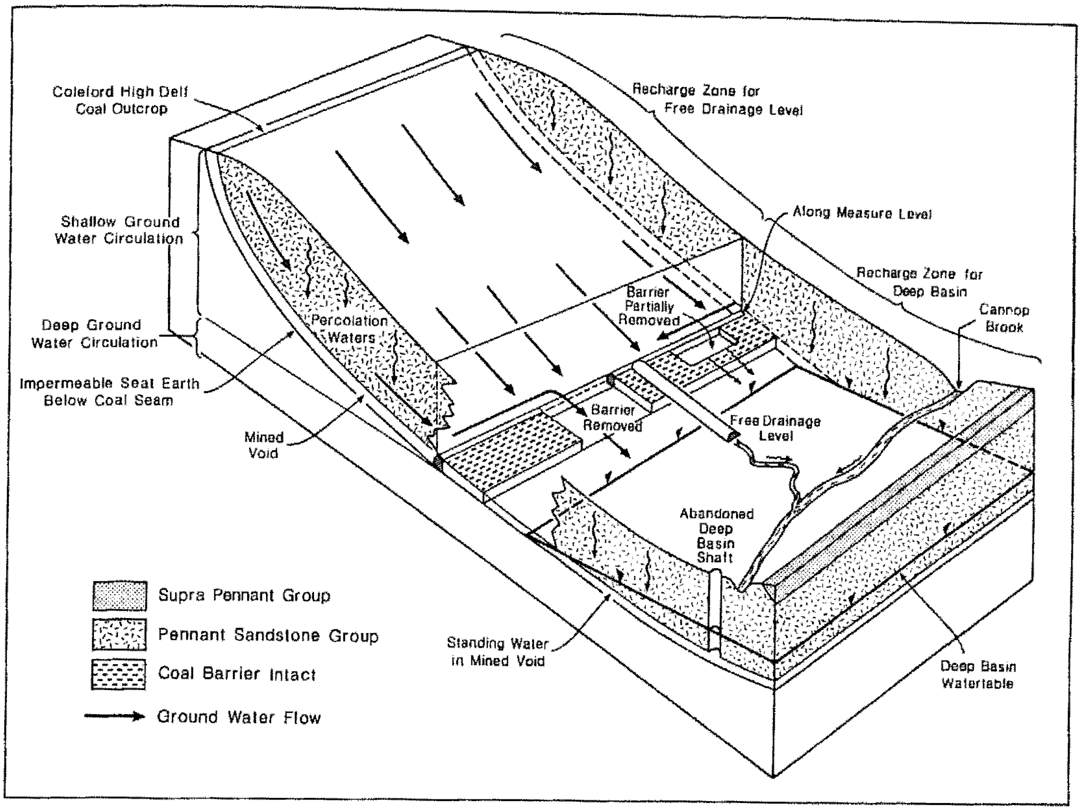

FIG. 5. Schematic block diagram illustrating the hydrological function of shallow coal barriers, and the effects of their removal.

unsaturated zone. Direct exploration has demonstrated that few extensive workings greater than 10 years old are open, although some main roadways are still accessible after 125 years. The latter serve as the major drainage routes, and have streams with discharges of several litres per second, with sufficient competence when flowing down-dip (4°–5°) to erode the seat–earth (Fig. 7). This prevents complete closure of the roadway. The walling of many main roadways with sandstone blocks was also common, and this retards both roof subsidence and entry of the seat-earth. In these cases, and for the cross-measures drainage levels, spalling and roof collapse are the main closure mechanisms. Localized collapses can leave open voids in the adjacent roadway. In the cross-measures levels, such collapses are particularly frequent at the intersection with the coal seams, where the collapses cause substantial ponding. This is the case for Tufts Level, where access beyond the Yorkely Seam is prevented by an extensive collapse. In Bixslade Upper Level, the ponding is over 5 m deep with water emerging over and from between foundered sandstone blocks. Such ponding may divert flow to an adjacent free drainage level, as occurred at Parkhill Level (37 m AOD) (Fig. 1), where pit water leaked from the Pastorshill Open Cast Site into a higher adjacent workings of Tufts Level (46 m AOD) contary to the expected direction of free flow. The probable flow direction in abandoned workings cannot therefore be simply deduced from the geology and mine plans, because free vadose flow will be progressively replaced after abandonment by pressure flow caused by ponding in the mine voids.

The roadway behind such collapses initially becomes flooded, in some cases to above roof level. Through time, ferruginous deposits (ferric hydroxides), seat-earth and rock waste transported in the slow moving ponded water behind the blockage will substantially reduce the void volume. These sections of ponded workings could represent an environmental hazard if catastrophic failure of the blockages occurs, releasing sediment and large volumes of ponded ferruginous mine waters. Henton (1983) reported such a sudden release at Dalgharren, Ayrshire, where a section of prime salmon river was destroyed overnight by waters with a pH of 3.5 and iron content of

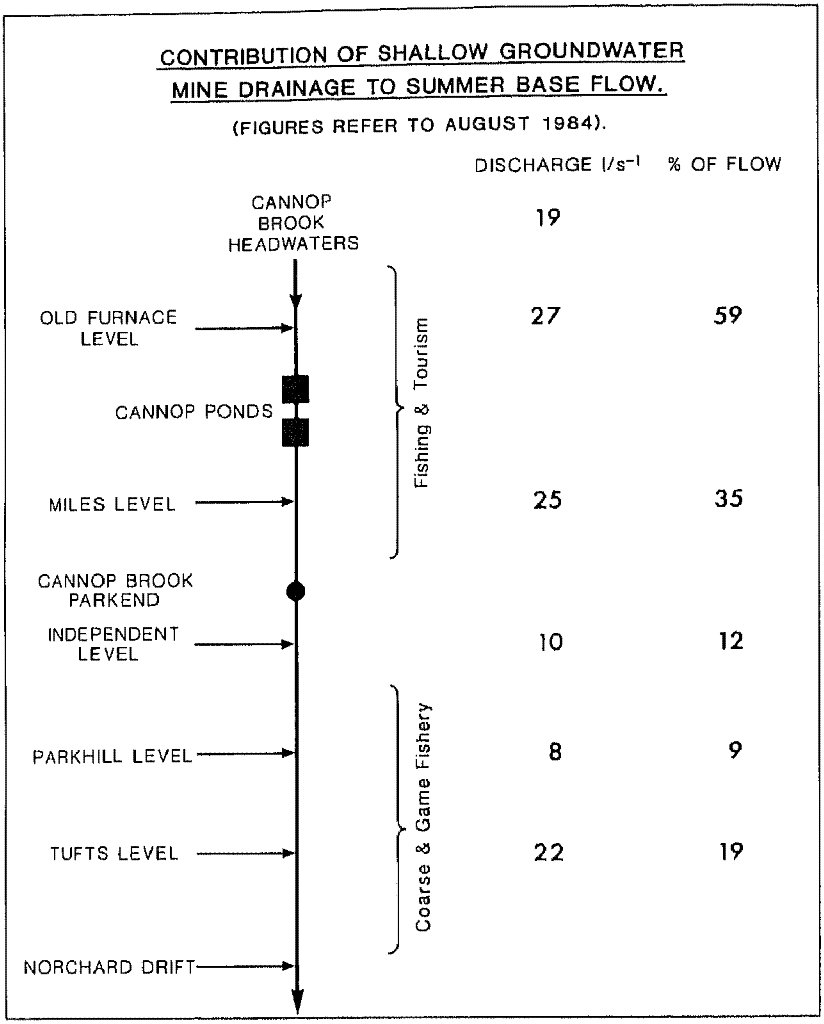

FIG. 6. Contribution of shallow groundwater mine drainage to summer baseflow in the Cannop Brook for August 1984.

1000 mg/l. In the Forest of Dean, a similar event occurred during mining at Tufts Level, where water burst out from behind a collapse. More recently, in April 1984, a deep seated earthquake measuring 3.3 on the Richter scale with an epicentre near Knighton, S Wales (some 75 km distance) affected the area. The discharge from Tufts Level was being monitored at this time, and following the shock there was a sudden decrease in flow of about 4 l/s. This was followed by a slow return to the original discharge, aided by rodding of the Yorkely Seam collapse, to increase flow to a trout hatchery. There were no changes in the sediment content or chemistry of the water. This example demonstrates the potential instability of such collapses in the abandoned workings, although it did not result in a catastrophic release.

Environmental problems indirectly relating to mining activity

Deterioration of lined channels

During development of the deep basin mines, sections of the surface rivers were lined to prevent infiltration into the mine workings and so reduce the cost of drainage pumping. The problem of infiltration from rivers was most severe in the Pennant Sandstone which had been fractured as a result of mining subsidence, and was also traversed by the Cannop fault belt (Fig. 8). The Cinderford and Blackpool Brooks, therefore, were lined along their entire length traversing the Pennant Sandstone with concrete

FIG. 7. Free drainage in mine workings abandoned in 1956. Closure of the adjacent mined galleries by swelling of the seat earth has occurred, and the stone retaining walls on both sides of the roadway have collapsed. Seat earth is being eroded by the small stream keeping the roadway open, below the intact Pennant Sandstone roof.

channels, both cast *in situ* and of block construction. The problem was particulary severe at Cannop Colliery, and much of the adjacent Cannop Brook was similarly lined. Downstream, the Cannop Ponds had been constructed to provide power for the iron furnaces at Parkend and were probably sealed with seat-earth, so additional lining was therefore not necessary.

Since abandonment of the large collieries, there has been deterioration of the concrete structures due to further differential subsidence and also due to vehicular damage during timber extraction. The channel linings have been extensively cracked and in places walls and floor have foundered. At several points it is possible to observe loss of water from streams, and at medium to low flows, for example, the Blackpool Brook is completely lost within the Pennant outcrop. Of the 9.5 km of lined channel in Fig. 8, 50% is currently damaged. The overall extent of leakage from these channels is not known, but as stated above, any loss of summer baseflow in the Cannop Brook could be serious. This problem of infiltration from surface streams will increase as further sections of lined channel deteriorate.

Problems may also arise if poor quality surface water contaminates good quality groundwater following channel deterioration. This has occurred at Pastors Hill, where a small surface stream has been periodically contaminated by effluent from a large intensive pig farm established in 1981 and subsequently ammoniacal nitrogen concentrations in the surface water during pollution events have reached 17.5 mg/l, with much lower values at other times. Prior to the pig farm expansion, the groundwater quality at Tufts Level which drains mineworkings underlying the small surface stream had been good (Table 1), but subsequently ammoniacal nitrogen levels became much more variable, and occasionally reached very high values (maximum 5.0 mg/l). It was found that a section of culvert conducting surface water from the vicinity of the pig farm had foundered following a collapse in the underlying workings of the Trenchard Seam. The stream was wholly captured into the workings, and the water discharged into Tufts Level, giving rise to the observed pollution. During the transmission through the workings there was little or no attenuation of the pollution, but dilution occurred on mixing with the much greater flow in the level.

Waste disposal

Pollution arising from the disposal of industrial wastes into abandoned mine workings have been reported

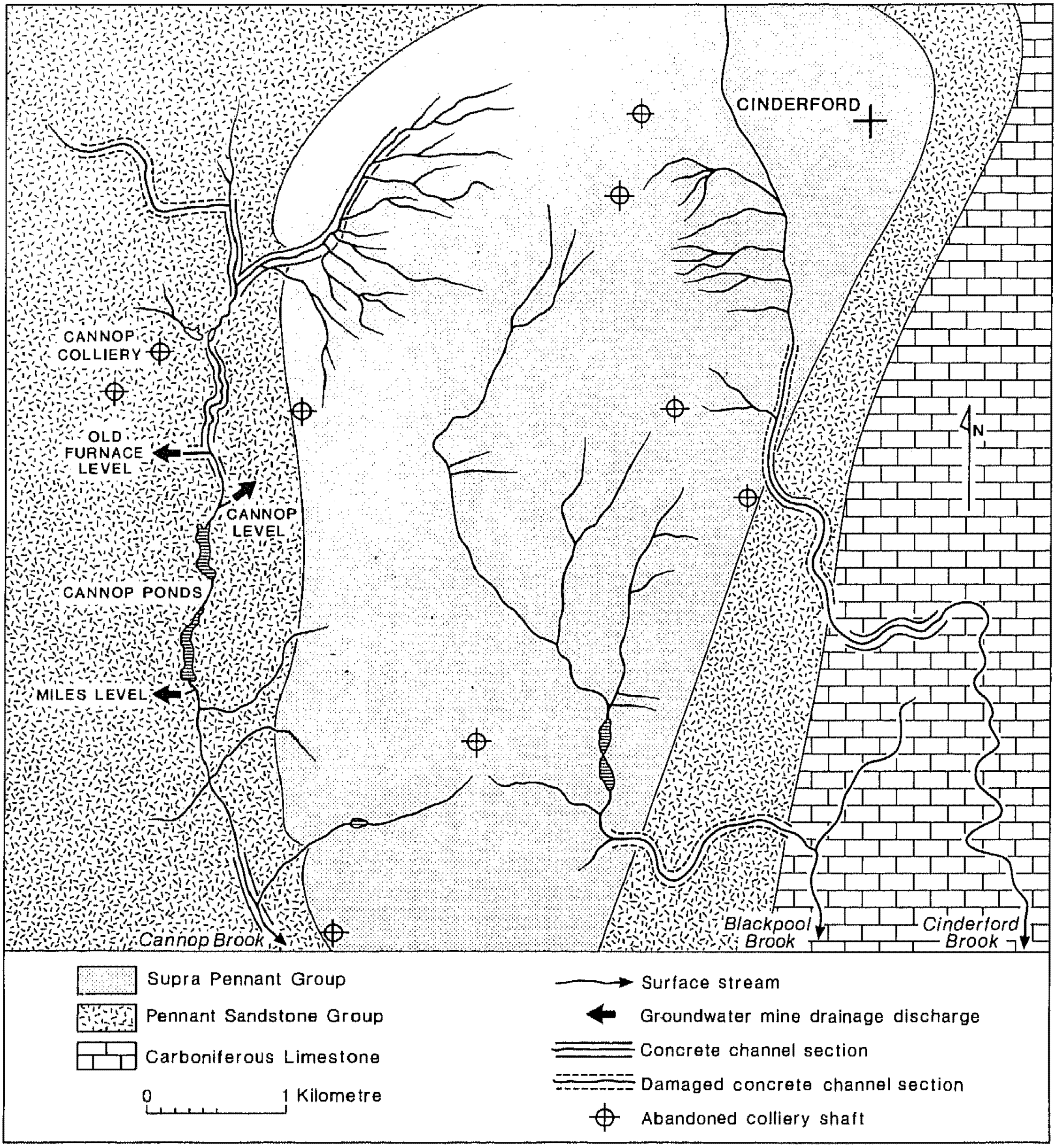

FIG. 8. Integrity and extent of lined channel in the northern part of the Forest of Dean Coalfield.

from other coalfields (Henton 1974). In the Forest of Dean no serious environmental problems have been encountered to date, despite two major waste disposal operations.

At Fetter Hill (Fig. 2b), a disused Pennant Sandstone quarry driven into the valley side was used for waste disposal before closure in 1977 (Carter 1979). Prior to 1963, used tyres, glass cullet and quantities of acidic liquid fruit processing waste were tipped. After this date heavy metal bearing liquids and hydroxide sludges including up to 10 000 mg/l of cadmium, chromium, zinc, nickel, iron and cyanide were disposed of at a rate of 90 000 l per week. In addition organic wastes including methylchloride and trichloroethane were also discharged. The liquid level in the quarry never rose, the waste apparently discharging via fractures in the quarry walls and an adit in the SW corner of the site. Despite a probable

TABLE 1. *Ammoniacal nitrogen concentrations for tufts level before and after establishment of an intensive pig farming unit*

	Pre pig farm 1974–1981				Post pig farm 1981–1984				Mann–Whitney U*
Ammoniacal	n	x	S.D.	max	n	x	S.D.	max	
Nitrogen as N	95	0.01	0.008	0.15	57	0.145	0.632	5.0	†

Units in mg/l.
* Mann–Whitney U differences at 95% confidence level expressed as †.
n—number of samples, x—mean concentration, S.D.—standard deviation, max—maximum value.

connection between the adit and workings in the Coleford High Delf Seam underlying the site, no heavy metal contamination of ground or surface waters was detected (Table 2). It should be noted that this sequence of events occurred before realistic controls could be imposed over the siting and operation of waste disposal sites, and the lack of pollution is entirely due to chance as no hydrogelolgical studies were carried out. Furthermore, the site closed before the Control of Pollution Act Part I was implemented.

Examination of the plans for the abandoned workings in the area show that the Coleford High Delf was extracted in a succession of gales parallel to the strike. These were originally separated by *in situ* drainage barriers which have now been removed. Only the major barriers diverting free drainage into the Miles Level remains, and any other discharge point would therefore appear unlikely. There are two possible explanations for the absence of pollution at Miles Level. Ponding of water in the workings will permit flow to occur in the Pennant Sandstone overlying the coal, which will be strongly fractured in the vicinity of the barrier due to differential subsidence following abandonment (Aston 1982; Cartwright *et al.* 1983; Neate 1980). Thus substantial amounts of water may be lost to the deep basin by flow over the barrier (Ashley 1930; Miller & Thompson 1974). Work is in progress at present to quantify this effect. Secondly, the Miles Barrier was actually penetrated to the south of Fetter Hill by a single roadway driven from Union Colliery downdip of the barrier. This penetration was accidental, and resulted in the flooding of the colliery with the loss of two horses. The mine manager was dismissed, and the mine was subsequently pumped out and later incorporated into the National Coal Board deep basin mines, the outflow from which discharges at Norchard Drift. It therefore seems possible that this route was taken by the liquid waste tipped at the quarry. This example illustrates the importance of minor roadways which may penetrate barriers and substantially influence the groundwater circulation. Unfortunately, such small exploratory and robber roadways (those entering gales for illegal coal extraction) are not as well documented as this example, and may not be shown on even the most detailed plans.

The nickel and zinc concentrations at Norchard Drift are at present higher than for other mine drainage sites in the Forest of Dean (Table 3), but the

TABLE 2. *Water chemistry data for 1976 from surface streams, springs and groundwater mine drainage discharges near to the Fetter Hill waste disposal site Forest of Dean*

Site	*NGR*	*Distance from waste disposal site (km)*	*pH*	*Cl*	*Fe*	*Cd*	*Cr*	*Cu*	*Ni*	*Zn*
Surface streams and springs										
Ropehouse Ditch	SO61101350	4.8	7.4	20	0.12	<0.01	0.02	<0.01	0.01	0.02
Vallets Wood	SO60901180	1.9	7.4	10	0.37	<0.01	0.02	<0.01	<0.01	0.03
Unnamed 1	SO60801130	1.0	7.1	12	3.7	<0.01	0.01	<0.01	0.01	0.05
Unnamed 2	SO60201030	0.8	7.8	14	0.21	<0.01	0.01	<0.01	0.01	0.01
Mill Hill	SO60800780	1.0	7.2	12	0.14	<0.01	0.01	<0.01	0.01	0.03
Fetter Hill 1	SO60000810	0.1	7.2	21	0.6	<0.01	0.02	<0.01	<0.01	0.04
Fetter Hill 2	SO60000810	0.1	7.7	21	0.24	<0.01	0.01	<0.01	0.01	0.02
Cleave Hill	SO60700830	0.5	7.0	12	0.35	<0.01	0.02	<0.01	0.02	0.06
Groundwater mine discharges										
Old Furnace Level	SO60751155	2.9	7.8	18	0.1	<0.01	0.02	<0.01	<0.01	0.02
Miles Level	SO60710995	2.0	7.1	14	0.07	<0.01	0.02	<0.01	0.01	0.03

All figures expressed as mg/l except pH.

TABLE 3. *Nickel and zinc concentrations in mine drainage waters from the Forest of Dean. Figures are averages for the years 1983/1984 Expressed as μg/l*

Sample site	*Ni*			*Zn*			*Ni/Zn*
	n	x	S.D.	n	x	S.D.	
Norchard Drift	48	100.6	27.4	48	44.8	20.8	2.2
Old Furnace Level	43	30.0	1.5	43	34.4	17.4	0.9
Miles Level	43	31.4	5.6	43	27.9	14.2	1.1
Independent Level	43	31.0	4.4	41	17.9	10.6	1.7
Cannop Level	41	35.7	3.5	7	21.0	14.6	1.7
Parkend Mine Drainage	7	<30.0	—	5	22.0	8.4	1.4
Speculation Level	5	<30.0	—	2	<10.0	—	3.0
Old Bobs Mine Drainage	2	<30.0	—	2	<10.0	—	3.0
Woorgreens Level	2	<30.0	—	1	20.0	—	1.5
	1						

concentrations have mirrored those of iron and declined exponentailly with time (Fig. 4). The ratio of nickel to zinc are also within the range observed at other sites in the Forest of Dean (Table 3), and does not suggest significant contributions from the Fetter Hill leachate. It must, therefore, be concluded that the large dilution and residence time of water in the deep basin have prevented significant transmission of the pollutants, whose mobilization has also been restricted by the high pH of the mine waters (pH 6.5–7.2) and of the disposed sludge (pH 10.5–12.5).

Although in this instance disposal of wastes into flooded mine workings presented a low risk of pollution, relatively rapid transmission through such workings can also occur, as indicated by the tracer test discussed above. The average velocity indicated by time to peak concentration was 4.6×10^2 m/day. This compares with values of between 1.6×10^2 and 1.3×10^2 m/d determined in South Wales Coal Measures by Parsons & Hunter (1972). Artificial tracing experiments thus not only provide an indicator of probable groundwater residence times, but may also indicate the potential pollutant pathway.

At a second disposal site, Howlers Hill Quarries, the situation is geologically similar to that at Fetter Hill, except that the Ridge Anticline interupts the easterly dip of the beds, causing local flow to the north along the Coleford High Delf workings. The quarry is, however, very close to the Old Furance Level, which discharges directly into the Cannop Brook. Although there is some ponding behind a collapsed section of the level, travel times are very short (groundwater velocities determined by tracer tests are typically about 0.02 m/s—Aldous & Smart in preparation), and attenuation of any pollution is unlikely. Domestic refuse is the major component of the waste disposed at this site, but there is a high proportion of inert compared with prutescible material. Furthermore, prior to tipping, the site was prepared by the construction of a thick infill of sandstone rock waste on the quarry floor. The quarry walls were also partially lined with polythene to retard groundwater inflow. After 7 years there has been no measurable contamination of the Old Furnace Level waters.

This successful outcome of waste disposal at Howlers Hill can be attributed to the careful site preparation and management, and the high porportion of inert waste. However, the site also has several favourable hydrogeological characteristics. The unsaturated zone above the level of the Coleford High Delf workings which partially underlie the site is about 60 m thick, permitting some improvement of leachate quality during percolation despite the flow being predominantly in fractures. The Coleford High Delf Seam and associated seat earth is in fact absent under part of the site where the Horse Washout occurs (Buddle 1842). Percolating leachate may therefore continue vertically downward through the Pennant Sandstone and into the deep basin, rather than being deflected downdip into the Coleford High Delf workings, and along the coal barrier into the Old Furnace Level in the manner described previously. Furthermore, because of the westerly dip associated with the Ridge Anticline which underlies Howlers Hill, any leachate intercepted on the Coleford High Delf Seam will be diverted towards the Horse, and may thus again not enter the Old Furnace Level. Finally, the dilution of any leachate entering the Old Furnace Level will be large; estimates based on the relative catchment areas suggest dilution values in excess of 800 times.

These case studies indicate that safe disposal of waste within Coal Measures strata is possible, particularly when groundwater discharge is to the deep confined basin. However, the prediction of the effects of waste disposal in the unconfined coalfield is difficult. Even though an adequate knowledge of mine workings may be gained from plans, and the general principles governing their hydrogeological behaviour are known. Many effectively non-predictable factors are also critical. These include the effects of ponding, the nature of the remaining mined voids, uncharted workings and uncertainty about the hydrological integrity of coal barriers. Thus, the uncertainties involved are such that containment philosophies for waste disposal in such hydrogeological environments are necessary to avoid the possibility of ground and surface water pollution.

Conclusions

In 1972, 13% of the total groundwater abstraction in England and Wales was from Coal Measures aquifers, of which 42% was from abandoned coal mines. Most of this water was of poor quality and only 3.5% of the total abstraction was used, the remainder being disposed to surface watercourses (Rae 1978). There is now a widespread appreciation of the potential environmental effects of these acid and ferruginous discharges. This study has demonstrated that careful planning of drainage routes prior to colliery abandonment is necessary to minimize water quality problems associated with these discharges.

Small scale mining continues in many coalfields after abandonment of the major mines. Until recently the possible hydrological and environmental effects of this activity have not been seriously considered, but these can be significant, because much of the unmined coal remaining forms barriers to free drainage. The reduction and diversion of flow in free drainage levels can therefore occur as a result of continued extraction. Further post-abandonment hydrological changes may also be caused by deterioration in structures designed to retard infiltration into mine workings, and the resulting flow diversion may cause pollution of previously clean groundwater discharges.

In many Coal Measures areas, there is a need to protect surface waters from the effects of new open-cast workings, and from waste disposal into mine and surface workings. Experience suggests that deep disposal may prove relatively safe where long residence times, and large dilutions occur, but the problem is more severe for free drainage which generally has a more rapid transmission. Moreover, it is relatively difficult to predict the probable effects of waste disposal on particular groundwater discharges.

In Britian there is a statutory obligation to survey the extent of mine workings. These plans form an essential though imperfect basis for the interpretation of the hydrological function of the workings. However, many mine plans are incomplete and sometimes erroneous. Because interpretation of the flow routes in mine voids depends largely on the nature of any coal barriers remaining, a single unrecorded roadway may substantially alter the flow conditions underground. Furthermore, little is known about the nature of abandoned mine voids. Our observations suggest that those responsible for substantial water transmission may remain relatively open, but further work is needed on this topic, particularly for inaccessible deep workings. Other difficulties relate to blockage and ponding of the roadways and drainage lines, which can substantially divert flow, but for which the location, extent and response cannot be predicted.

With the current contraction of the coalmining industry in Britain, hydrogeologial problems related to abandoned mines are likely to increase. Our work suggests that interpretations based upon mine plan data and a general understanding of the behaviour of such aquifers are unlikely to be adequate, and more detailed studies involving water tracing and borehole investigation of head conditions and the nature of mined voids will necessary, if any adequate prediction of environmental impacts is to be made.

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References

ADDIS, M., SIMMONS, I. G. & SMART, P. L. 1984. The environmental impact of an opencast operation in the Forest of Dean, England. *Journal of Environmental Management*, **19**, 79–95.

AHMAD, M. U. 1974. Coal mining and its effect on water quality. *Proceedings of the American Water Resources Association*, **18**, 138–48.

ASHLEY, G. H. 1930. Barrier pillar legislation in Pennsylvania. *Transactions of the American Institute of Mining Engineers* (*Coal Division*), **69**, 76–97.

ASTON, T. R. C. 1982, *Hydrologeological aspects of rock mechanics and mining subsidence around longwall mining extractions*. Ph.D thesis, University of Nottingham.

BUDDLE, J. 1842, On the great fault called the Horse in the Forest of Dean Coalfield. *Transactions of the Geological Society*, **6** (2nd Series), 215–20.

CAIRNEY, T. & FROST, R. C. 1975. A case study of mine water quality deterioration, Mainsforth Colliery, County Durham. *Journal of Hydrology*, **25**, 275–93.

CARTER, M. G. 1979. Restoration of a toxic waste quarry. Journal of *Environmental Management*, **9**, 123–9.

CARTWRIGHT, K., HUNT, C. S., BROWER, R. D., & NELSON, W. J. 1983. Pore water pressures in roof of an underground coal mine in Illinois. *Groundwater*, **21**, 311–16.

EMRICH, G. H. & MERRITT, G. L. 1969. Effects of mine drainage on groundwater. *Groundwater*, **7**, 27–32.

FORREST, J. C. 1920. The underground barriers of the Cannock Chase Coalfield. *Transactions of the Institute of Mining Engineers*, **59**, 115–31.

HACKBATH, D. A. 1979. The effects of surface mining of coal on water quality near Grande Cache, Alberta. *Canadian Journal of Earth Sciences*, **16**, 1242–53.

HART, C. E. 1953. *The Free Miners of the Forest of Dean and Hundred of St Brivals*. British Publishing Company, Gloucester.

HENTON, M. P. 1974. Hydrogeological problems associated with waste disposal into abandoned coal workings. *Water Services*, October 1974, 349–52.

—— 1983. *Origin and disposal of ferruginous mine waters*. Presented at the Hydrological Group Meeting of the Geological Society of London, 7 June 1983, Aston University.

MATHER, J. D., GRAY, D. A. & JENKINS, D. G. 1969. The use of tracers to investigate the relationship between mining subsidence and groundwater occurrence at Aberfan, South Wales. *Journal of Hydrology*, **9**, 136–54.

MILLER, J. T. & THOMPSON, D. R. 1974. Seepage and mine barrier width. *5th Symposium Coal Mine Drainage Research, Louisville*, 103–27.

NEATE, C. J. 1980. *Effects of mining subsidence on the permeability of coal measures rocks*. Ph.D thesis, University of Nottingham 1980.

PARSONS, A. S. & HUNTER, M. D. 1972. Investigation into the movement of groundwater from Bryn Pit above Ebbw Vale, Monmouthshire. *Journal of the Institute of Water Pollution Control*, **71**, 568–72.

PORGES, R., LOWELL, A. & BALLINGER, D. 1966. Re-assessing an old problem—Acid mine drainage. *Proceedings of the Americal Society of Civil Engineers. Journal of the Sanitary Engineering Division*, **92**, 69–83.

RAE, G. 1978 *Mine drainage from coalfields in England and Wales. A summary of its distribution and relationship to water resources*. Central Water Planning Unit Technical Note 24.

REHM, B. W., GROENEWOLD, G. H. & MORIN, K. A. 1980. Hydraulic properties of coal and related materials, Northern Great Plains. *Groundwater*, **18**, 551–61.

SCHUBERT, J. P. 1980. Fracture flow of groundwater in coal-bearing strata. *Symposium on Surface Mining Hydrology, Sedimentology and Reclamation*. University of Kentucky, Lexington, 61–73.

SIEGEL, S. 1956. *Nonparametric Statistics for the Behavioural Sciences*. McGraw Hill, New York.

Appendix

Glossary of terms used in the paper

Adit	Entrance to or roadway within mine (Synonymous with level).
Coal barrier	An area of coal left intact between two adjacent mines, which prevents the ingress of water from one mine to another.
Cross measure	Direction perpendicular to the strike of the coal seam; normally an adit, level or roadway which cuts through the sequence of rocks between the surface and coal seam.
Free drainage	Water whose movement is induced by gravity; normally associated with gentle upward angle of level adit or roadway.
Gale	The area of coal mined from adit, level or colliery.
Level	Horizontal or near horizontal roadway within mine (Synonymous with adit).
Long Measure	Direction parallel to the strike of the coal seam. Normally a level, adit or roadway which follows the strike, at an upward angle to induce free drainage.
Robber roadway	Roadway, level or adit which has removed coal from or connected two mines through a coal barrier.