Acid mine drainage at a coal mine in the eastern Transvaal, South Africa

S. Geldenhuis · F. G. Bell

Abstract Several mines in the Witbank coalfield in South Africa are affected by acid mine drainage. This has led to a deterioration in the water quality in many surface streams. The Loubert Mine is one such mine. Hence, an initial investigation was carried out to determine the source of acid mine drainage pollution and the associated hydrogeological conditions. The investigation showed that most of the acid mine drainage is emanating from old opencast workings which have been backfilled. Most of the water from the backfilled area drains into control reservoirs. Unfortunately their capacity is limited, which means that water overspills and seeps from them. This water finds its way into a nearby stream, the water of which accordingly has an unacceptably low pH value and high sulphate content. The proposals advanced to control the problem basically involve inhibiting the amount of water infiltrating the backfilled opencast area on the one hand and reducing the amount of water entering the control reservoirs on the other.

Key words Acid mine drainage · Backfilled opencast workings · Hydrogeological analysis · Pollution control

Introduction

Acid mine drainage refers to drainage resulting from the natural oxidation of sulphide minerals found in mine rock or waste; it can be responsible for problems of ground- and surface-water pollution in the area surrounding a mine. As such, acid mine drainage constitutes a notable problem at several mines, either operational or abandoned, in the Witbank coalfield, in the Transvaal, South Africa. Consequently, a number of streams in the north of the coalfield have been affected, leading to deterioration in the quality of the water they contain to levels which are unacceptable. In fact, the pollutant load, at certain localities, is now impacting on receiving surface-water bodies. Concern has led to a number of investigations at some mines in the north of the coalfield with a view to developing a strategy for the control of acid mine drainage at the mines concerned. This paper presents a case history of an initial investigation carried out in an attempt to gain an understanding of the existing surface-water and groundwater systems, and their interaction at Loubert mine where acid mine drainage is responsible for the pollution occurring in a nearby water course.

The Witbank coalfield occurs within the Vryheid Formation of the Ecca Group in the Karoo Sequence, that is, the rocks concerned are of Permian age. The sediments of the Vryheid Formation were deposited in a fluvio-deltaic environment where swamps and marshes existed, in which peat accumulated. However, this environment was unlike that associated with the Coal Measures of the northern hemisphere, these being coals formed in a cold or cool climate. Shales, mudstones, siltstones and sandstones constitute the bulk of the formation, and the coal seams have a relatively high dirt content. For example, the dry-ash content ranges up to 19.5%. In later Karoo times, the Vryheid Formation was intruded by dolerite sills and feeder dykes also are present. Numerous minor faults, many of which are water bearing, interrupt the coal seams. Small fracture zones, which frequently are associated with the upper and lower contacts of sills, also are commonly water bearing.

The most abundant minerals in these coals are clay minerals (primarily kaolinite and illite), together with carbonates (calcite, dolomite, ankerite and siderite), sulphides, quartz and glauconite. Pyrite is the most abundant sulphide mineral, although marcasite does occur. Pyrite also occurs in mudrocks immediately above and below coal seams. Hematite is the principal iron oxide present. Phosphate minerals such as apatite may be present as submicroscopic grains and occasionally occur along with other heavy minerals such as tourmaline, rutile and zircon. Indeed, this type of mineralogy is common to most South African coals (Falcon and Snyman 1986). All these minerals are syngenetic in origin and are

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associated with the coal macerals. In addition, epigenetic carbonates, pyrite and limonite-goethite are present in the cleat in the coal.

History of the mine and background

The Loubert Coal mine is situated some 10 km south-east of Ermelo in the eastern Transvaal in the catchment of the Vaal River. It has operated on various portions of the farm Witbank 262. The original mine was opened in 1928 and worked coal which occurs in the Vryheid Formation. This coal is particularly high in sulphide content, primarily associated with pyrite. Analyses show that the sulphur content varies between 1.01% and 3.26%. Consequently, the coarse discard and slurry associated with the mine contain relatively high levels of sulphide. Hence discharge from the workings and waste has led to concern about the pollution of water in a nearby stream, that is, the Human Spruit.

The original operators of the mine possessed the mineral rights to Portions 22, 23 and 88 of the farm on which the mine is situated (Fig. 1). All three portions were sold in 1988 and Portions 23 and 88 were amalgamated into Portion 89. The new owners obtained a closure certificate for the mining which had been done on Portion 22 but not for Portion 89. In fact, the new owners have never mined on Portions 22 or 89. By the sales agreement between the two companies involved, the new owners accepted liability for any rehabilitation of the ground which they had acquired, stating they owned the surface rights and five-sixths of the mineral rights of Portion 89. In addition they owned the mineral rights on Portion 24, where their present operations are being carried out. The washery with associated slurry dams and spoil heaps are located on Portion 89.

In terms of liability, the State is responsible for the costs of rehabilitation involved in pollution control at any mine which ceased operations prior to the Water Act of 1956. This applies to the underground workings occurring in Portions 22 and 89, which were abandoned in 1943. The proportion of the costs for which the State will be responsible will ultimately be determined by the relative contribution of the underground workings to the pollution problem. The present owners will be responsible for the remainder of the costs.

The underground workings of the initial owner (i.e. on Portions 22 and 89) are situated on a topographic high which drains towards the Human Spruit in the south (Fig. 2). In addition, opencast operations were carried out, mostly to the south of the water divide in the area. All opencast workings were carried out after 1978.

Water draining from the workings to the south collects in three pollution control reservoirs (in South Africa a reservoir is referred to as a dam), which are situated just above a small sandstone escarpment along the south-

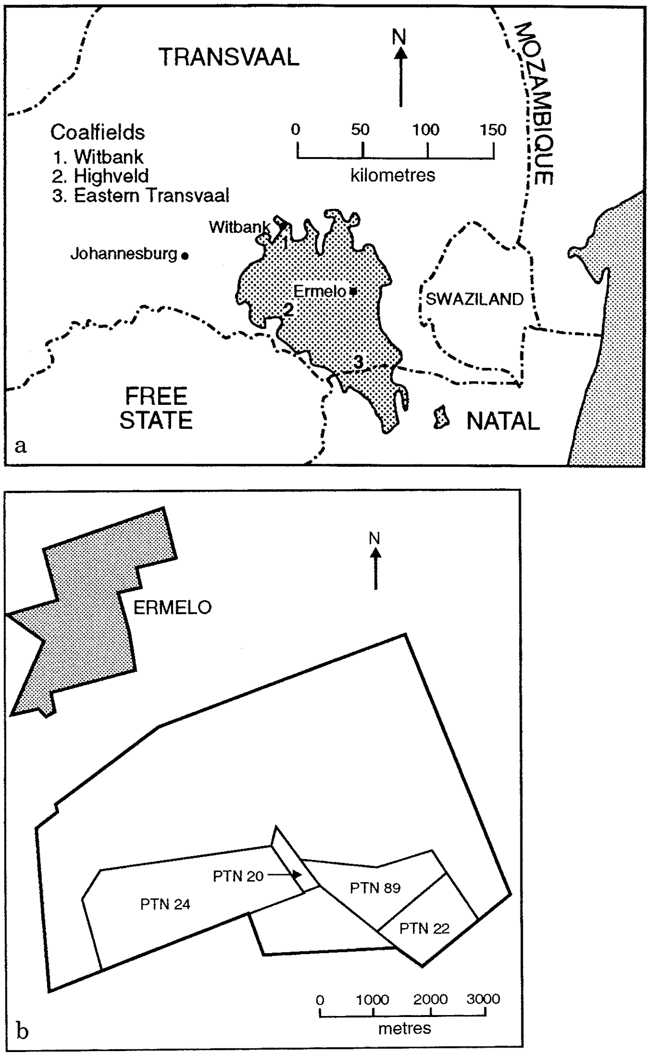


Fig. 1
Location of Loubert Mine: **a** Location of Witbank Coalfield. **b** Location of the mine

western boundary of Portion 89. The reservoir to the west (dam 1) is used as a return water reservoir for the washery plant. The relative contributions from various sources to these collection reservoirs are shown in Fig. 3. The catchment areas of the collection reservoirs and surface-water flow directions are shown in Fig. 4a, while the subsurface flow paths and catchment divides are indicated in Fig. 4b. Spillage and seepage from these reservoirs flow into the Human Spruit, and have a significant effect on the soils around and the water quality in the stream. The surface- and groundwater systems on the site are interconnected, with surface-water percolating to the groundwater table and groundwater issuing at the surface where the water table intersects sloping ground.

A limited amount of opencast mining was done to the north of the divide which does not drain into the Human Spruit. The area has been restored. There also was a very small section of underground mining in this area, but it was not connected with the other underground workings.

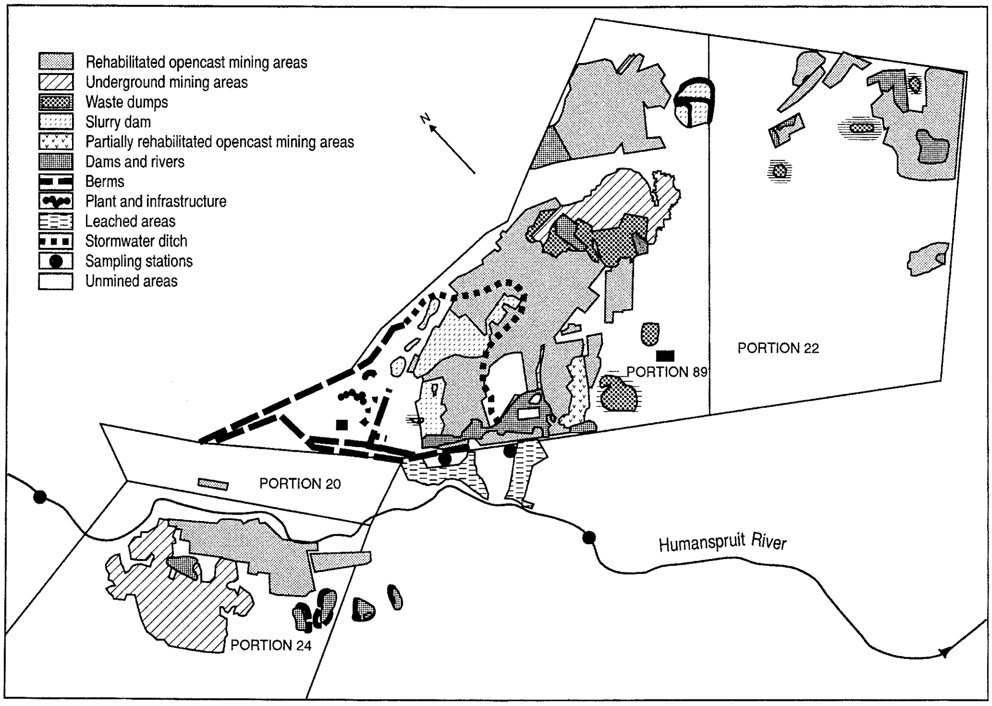


Fig. 2
General surface plan of the mine

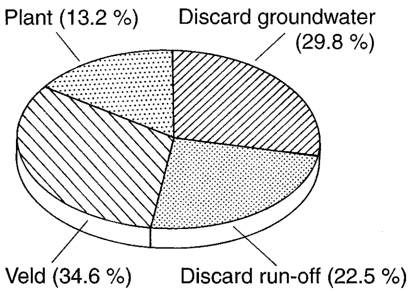


Fig. 3
Proportion of various inflows into collection reservoirs.

The restoration in this area seems to be satisfactory and pollution problems are not immediately apparent.

As remarked, part of the pollution problem on the southern slope of Portion 89, to the immediate south-east of the mine, emanates from the old workings. The lower (C_l) seam was mined in the underground workings, while the upper (C_u) seam was opencasted over the old workings. Both the seams were opencasted away from the underground workings. The pillar between the underground and opencast workings is about 15 m thick, and the opencasting did not break into the underground workings. Seepage through the C_l seam in the highwall was not significant, but acid seepage into the footwall of the opencast workings and in the adjacent valley was a problem during the opencast operation.

An investigation was therefore undertaken to attempt to determine the origin and extent of the pollution, that is, the acid mine drainage problem. The results of the investigation would then allow proposals to be developed for controlling the problem.

Hydrogeological investigation

The desk study that preceded the investigation involved the examination of topographic maps, mine drawings, some limited previous water quality analyses and copies of relevant correspondence, all relating to the mined area. It showed that the information on the surface and underground activities of the mine was not well understood.

A surface-water hydrological analysis was undertaken and concentrated on the area comprising the plant and the restored opencast workings to the north of the Human Spruit. This area, of approximately 187 ha, was identified as a major source of pollution to the Human Spruit from both groundwater and surface-water flows.

The objective of the hydrological analysis was to determine an understanding of the existing surface- and groundwater systems and their interaction. Consequently, a simple empirical water balance model was developed to simulate the current mine water system and to quantify the effluent entering the Human Spruit, taking into account both surface run-off and seepage. Spillage from two of the reservoirs (dams 1 and 2) situated in the south of the site was identified as a major source of polluted water discharging into the Human Spruit. Figure 5 shows that most spillage occurs during the summer months, which is to be expected, since this is the season when rain falls, with none falling during the dry winter months. The hydrological analysis therefore concentrated on the development of a model to simulate the variation in the monthly spillage from these reservoirs. The model based on monthly water balance took into account the climatic conditions, topography, mine infrastructure, surface-water run-off and groundwater seepage flow direction. Empirical methods were used to determine the run-

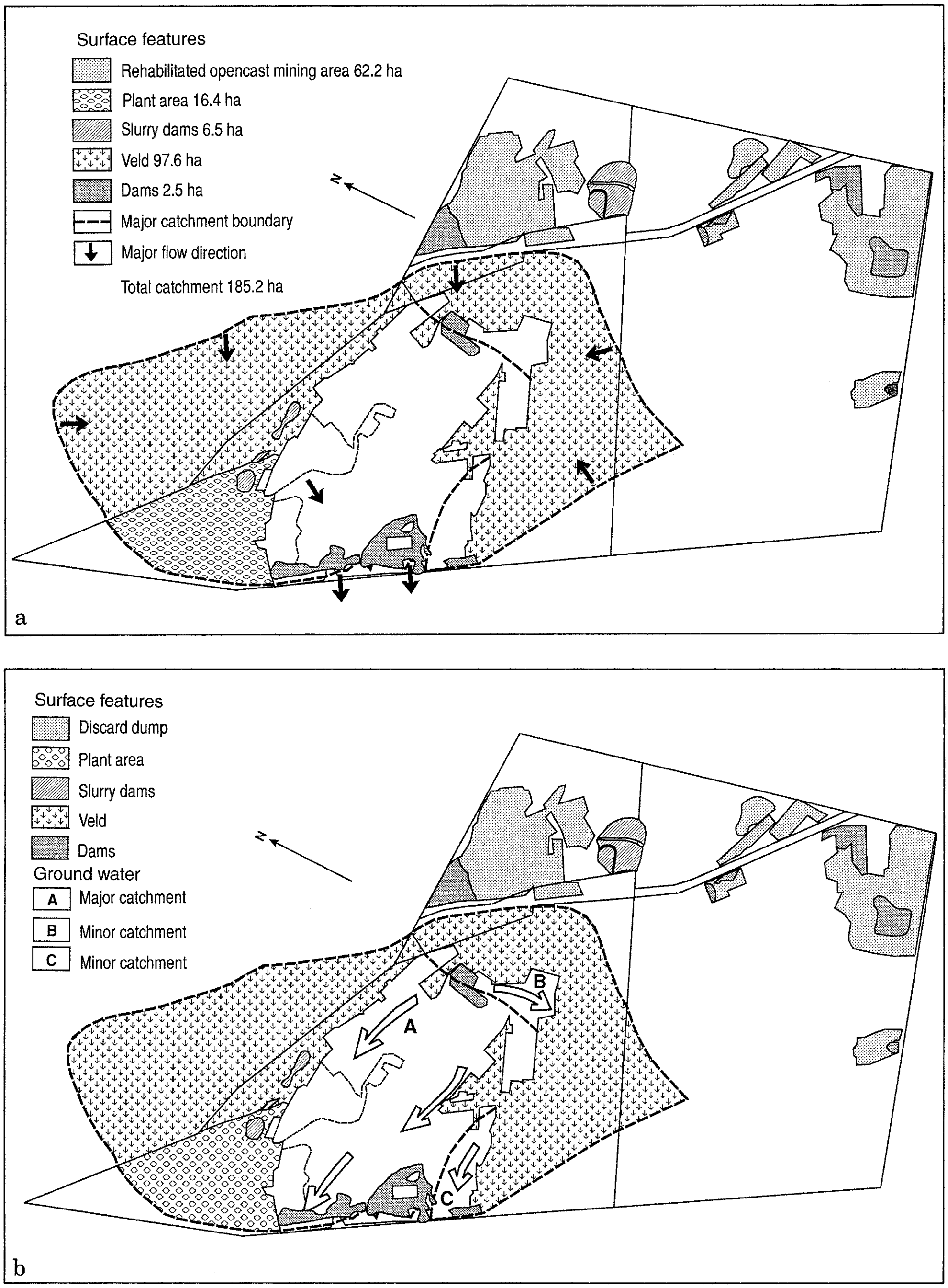


Fig. 4
a Surface features and catchment boundaries showing direction of overland flow. **b** Subsurface flow direction

off, infiltration, seepage and evaporation from the catchments and mine infrastructure. A schematic cross-section through the mine site is shown in Fig. 6, illustrating the inputs and outputs used in modelling.

The results of the hydrological analysis showed that collection reservoirs 1 and 2 did not have enough storage capacity to act as storm-water or polluted-water retention structures. Hence, the volumes of water flowing into these collection reservoirs would have to be reduced. The biggest contribution to the system is run-off from the veld, so that its control would make a significant difference to the inflows into the collection reservoirs. Nonetheless, the quality of the veld water run-off is suitable for discharge into the Human Spruit. The next largest contributor to the system is water from the restored opencast workings. This water is polluted, and so measures will have to be taken to attempt to reduce its volume. A reduction of water from the restored area, in turn, would reduce the spillage from the collection reservoirs into which it flows. In order to minimize spillage from the collection reservoirs, they should be kept at a low top water level. This would involve by-passing the run-off from the veld, minimizing infiltration of rainfall into the restored areas by, for example, placing compacted clay covers over them and using water from the collection reservoirs for plant operation.

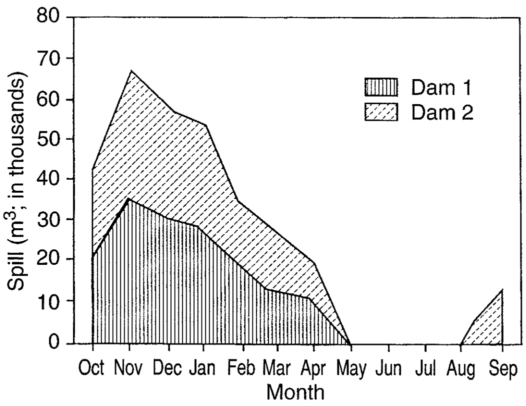


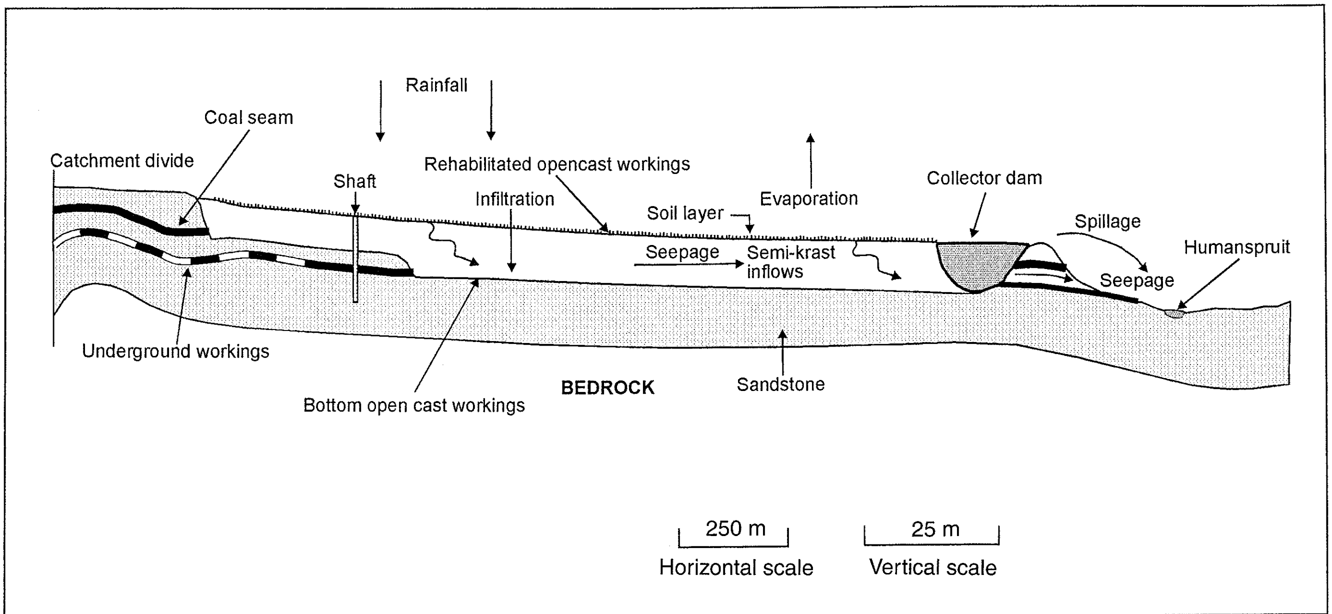
Fig. 5
Spillage from reservoirs (dams) 1 and 2

Where polluted groundwater is near the surface, an electromagnetic (EM) survey often proves an effective means of delineating plumes. In other words, conductivity profiling can usually detect the width of a plume if it is more than 20% of the depth. In such cases the conductivity of the polluted groundwater should be appreciably higher than that of the surrounding groundwater. Hence an electromagnetic survey was undertaken to map the likely positions of near-surface groundwater pollution plumes and seepage pathways in the backfilled opencast mine areas to the east of the plant. The objective of the mapping was to provide additional information on the possible nature, depths and directions of polluted near-surface flow in the backfill and to provide possible target sites for location of monitoring boreholes. The EM data were used to help define the hydrogeological model for acid mine drainage, with the results being incorporated into a rehabilitation plan. The EM survey allowed the identification of the boundaries of the opencast and underground mining areas, as well as identifying the major polluted groundwater flow directions (Fig. 7). It also helped confirm that the old mining plans were essentially correct.

Because of the very coarse character of the backfill in the backfilled opencast areas, voids are present in the backfill, giving rise to what has been referred to locally as a "semi-karst" condition. Where these voids are interconnected, they form open flow channels where the flow is very rapid. The major flow during times when the system is recharged by rainfall or stormwater run-off then occurs through these conduits. Polluted water tends to seep out of the backfill slowly and degrades the quality of the water present in the conduits. Therefore the quality of water exiting in springs and seepage points shows an improvement during high infiltration periods but the quality deteriorates when flows decrease. This has an impact on the options available for rehabilitation of such systems.

Four sample sites were chosen to monitor water quality. These were on the Human Spruit upstream of Loubert mine, on the Human Spruit downstream of Loubert mine, at the overflow from the central reservoir (dam 2), and at the overflow from the mine return water reservoir (i.e. dam 1 in Fig. 7). A flow measuring weir was installed at the downstream sampling point, but was unfortunately washed away almost immediately after completion. The weir was rebuilt, but little flow data was available at the completion of this particular investigation. From the few results of flow obtained, it appeared that this generally was just less than a litre per second, though flows of 3 and 5 l s^{-1} were recorded in November 1991. A summary of the water quality data from the four sites is given in

Fig. 6
Schematic section through backfilled opencast area showing water inputs and outputs



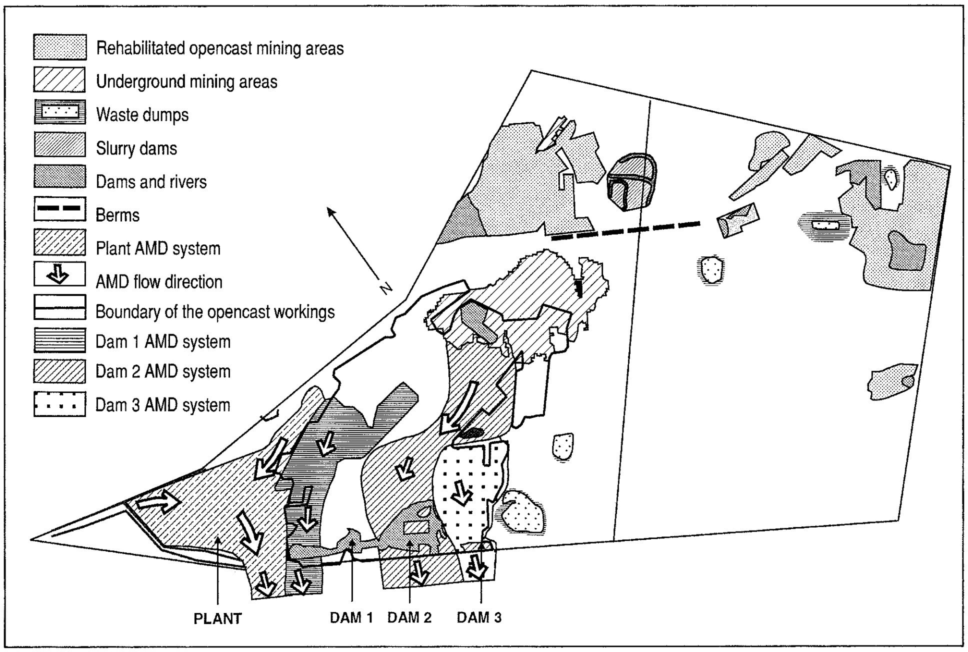


Fig. 7
Acid mine drainage systems

Tables 1–4. South Africa recognizes three guideline limits for water quality for domestic use, namely, a maximum limit for no risk, a maximum limit for insignificant risk (i.e. the lowest quality water acceptable by health authorities) and a maximum limit of low risk whereby water is of undesirable quality (Anonymous 1993). These limits were previously described as recommended, maximum permissible and crisis limits respectively (Kempster and Smith, 1985). In the case of sulphate content these limits are 200, 600 and 1 200 mg l^{-1}. For conductivity and pH value they are respectively 70, 300 and 400 mS m^{-1} and 6–9, 5.5–9.5 and 4–11. Lastly, they are 1, 5 and 10 mg l^{-1}, respectively, for zinc, although zinc was not a significant pollution parameter in this instance.

The results in Tables 1–4 were obtained primarily from November 1991 through to February 1992, that is, during the summer rain season. The Human Spruit upstream of the mine was unaffected, the pH values, electrical conductivity and sulphate content of the water being acceptable in terms of quality for domestic use. However, the water in the Human Spruit downstream of the mine is generally above the maximum limit of low risk in terms of pH and sulphate content. In fact, such water is likely to present a severe danger to health due to the toxic effects associated with dissolved metal ions. The poorest-quality water was associated with the central control reservoir (dam 2), which is supplied by water draining from the backfilled opencast area to the immediate north. All the pH value results are well beyond the maximum limit of low risk, as are the great majority of those for electrical conductivity and sulphate content. In the latter case, over 75% of the results showed the water having a sulphate content of 3 000 mg l^{-1} and over. This water is overspilling into the Human Spruit. The water in the return water reservoir (dam 1) is similar to that found in the sampling point on the Human Spruit downstream of the mine. The conductivity ranges from 350 to 570 mS m^{-1} in the central reservoir (dam 2; TDS approximately 3 500 to 5 700 mg l^{-1}) and from 230 to 370 mS m^{-1} in the plant return reservoir (dam 1; TDS approximately 2 300 to 3 700 mg l^{-1}). With annual spillage from these two reservoirs being in the region of 300 000 m3, this converts to a load of approximately 1 200 Mg y^{-1}. These figures do not include the potential contribution to the system by inflow from the underground workings. Although it was not clear from the work done during the investigation what the relative con-

Table 1
Analysis of water from Human Spruit upstream of mine

date	rain (mm)	pH	EC (mS m^{-1})	SO_4 (mg l^{-1})	Zn (mg l^{-1})
13/3/91		7.28	33	25	
25/6/91		8.28	52	95	
13/11/91		5.88	39	146	0.10
22/11/91		7.78	40	18	0.01
26/11/91		6.58	35	55	0.11
4/12/91	38.88	8.88	24	36	0.04
5/12/91	4.38				
9/12/91	3.58				
10/12/91	30.00				
11/11/91	22.88				
12/12/91	9.88	6.58	27	46	0.01
17/12/91	10.88				
19/12/91		6.68	35	39	0.02
3/1/92		5.78	42	17	0.03
6/1/92	35.00				
13/1/92	12.00				
16/1/92	22.00	7.68	42	162	0.02
21/1/92	2.00				
25/1/92	6.00				
28/1/92	2.50				

Table 2
Analysis of water from Human Spruit downstream of the reservoir

date	rain (mm)	pH	EC (mS m^{-1})	SO_4 (mg l^{-1})	Zn (mg l^{-1})
23/3/88		3.40	150	900	
7/2/91		3.50	39	70	
13/3/91		4.30	65	275	
25/6/91		3.20	176	968	0.59
13/11/91		2.38	398	9582	1.05
13/11/91		2.00	216	1200	0.68
20/11/91		2.58	288		
22/11/91		2.48	233	1269	0.66
26/11/91		2.18	400	2859	0.74
4/12/91	30.88	3.98	48	154	0.06
5/12/91	4.58				
9/12/91	3.58				
10/12/91	38.00				
11/12/91	22.00				
12/12/91	9.80	3.68	72	374	0.11
17/12/91	18.00				
19/12/91		2.00	237	1952	0.97
3/1/92		2.00	437	3232	1.92
6/1/92	35.00				
7/1/92		2.06	482	2879	0.68
13/1/92	12.00				
16/1/92	22.00	2.00	112	553	0.24
21/1/92	2.08				
25/1/92	6.00				
28/1/92	2.58				

Table 3
Analysis of overflow from central reservoir (dam 2)

date	rain (mm)	pH	EC (mS m^{-1})	SO_4 (mg l^{-1})	Zn (mg l^{-1})
23/3/90		2.68	397	3000	
7/2/91		3.38	75	300	
13/2/91		2.50	462	275	
25/6/91		2.78	520	4600	4.68
4/9/91		2.00	567	5002	3.87
13/11/91		2.00	464	4850	3.18
20/11/91		2.10	468		
22/11/91		2.00	498	4413	4.00
26/11/91		2.00	584	4299	4.47
4/12/91	38.00	2.00	372	4336	3.33
5/12/91	4.58				
9/12/91	3.58				
10/12/91	30.66				
11/12/91	22.00				
12/12/91	9.00	2.38	452	4387	2.77
17/12/91	10.00				
19/12/91		2.00	416	4671	3.81
3/1/92		2.18	362	4373	3.38
6/1/92	35.00				
7/1/92		2.00	368	4509	3.49
13/1/92	12.00				
16/1/92	22.00	2.00	493	4428	3.44
21/1/92	2.00				
25/1/92	6.00				
28/1/92	2.50				

Table 4
Analysis of overflow from mine return water reservoir (dam 1)

date	rain (mm)	pH	EC (mS m^{-1})	SO_4 (mg l^{-1})	Zn (mg l^{-1})
4/9/91		2.38	327	2196	0.35
13/11/91		2.28	263	1537	0.61
22/11/91		2.38	288	1006	0.66
26/11/91		2.28	283	1758	0.74
4/12/91	30.00	2.18	268	1978	0.55
5/12/91	4.58				
9/12/91	3.58				
10/12/91	30.88				
11/12/91	22.00				
12/12/91	9.00	2.58	257	1786	0.45
17/12/91	10.00				
19/12/91		2.10	228	1948	0.42
3/1/92		2.20	344	1999	0.62
6/1/92	35.00				
7/1/92		2.10	371	2183	0.68
13/1/92	17.00				
16/1/92	22.00	2.20	363	2363	0.72
21/1/92	2.00				
15/1/92	6.08				
28/1/92	2.58				

tributions of the opencast and underground systems were, some preliminary calculations suggest that the underground workings could contribute a maximum of approximately 20% of the polluted water entering the Human Spruit. Hence the results confirm that much of the site is strongly acid generating and the quality of this water is unacceptable. The two surface-water bodies in Portion 22 (Fig. 7) were also sampled and the results were acceptable, confirming that pollution from this area did not pose a threat.

When the rainfall over the period of the study is examined in conjunction with the other data it can be seen that it has no effect on the quality of the upstream water in the Human Spruit. This sampling point was upstream of all the coal workings. On the other hand, rainfall had a significant effect on the downstream water samples, especially on the conductivity and dissolved salts, while the pH is not as significantly improved during rainfall events. In other words, an inverse relationship exists between the amount of rain which falls and conductivity. Rainfall has a negligible effect on the quality of the water spilling from the central reservoir. This indicates that the rinsing effect of the flow through the backfilled opencast areas is not effective in promoting good quality run-off during moderate rainfall events. In the same way, rainfall has a minimal effect on the water spilling from the plant return water reservoir (dam 1).

It was concluded that the site is acid generating except for the restored area to the south east of the mine area (Portion 22). In addition, water emanating from the partially restored opencast and underground mining areas (the latter are still being worked) of Portion 24 does not pose a threat to the Human Spruit at present, as the pollutant load in this water appears to be minimal. This area was therefore not investigated in any detail. At present the major load of pollutants is generated by the restored opencast mining area where most of the opencast, and indeed underground mining was carried out by the previous mine owner (Portion 89).

Pollution control options for acid mine drainage

Accurate prediction of acid mine drainage is required in order to determine how to bring it under control. Control can be attempted in three ways, namely, control of the acid-generation process, control of acid migration, and collection and treatment of acid mine drainage (Connelly and others 1995). Source control of acid mine drainage involves measures to prevent or inhibit acid generation. Such control methods involve the removal or isolation of sulphide material, or the exclusion of water or air. The latter is much more practical and can be achieved by covering over acid-generating material.

Migration control is considered when acid generation cannot be inhibited. Since water is the transport medium, control relies on the prevention of surface-water entry to the source of acid mine drainage by diversion of surface-water away from the source or by prevention of infiltration of precipitation into the source by the placement of cover materials. Release control is based on measures to collect and treat acid mine drainage. In some cases, especially at working mines, this is the only practical option available.

It would not be economical to attempt to remove the sulphide-bearing material from the site. In addition, exclusion of oxygen by the use of a water cover is not practical, taking the nature of the topography and low rainfall into account. Exclusion by the use of an oxygen-impermeable liner for the whole site or the worst parts of the site is feasible, but would be very expensive and subject to practical limitations in terms of making such a cover permanently effective. In the same way, the exclusion of water from the system would be costly and difficult. Accordingly, it was recommended that acid-generation control should not be considered. Hence attempts would have to be made to minimize the movement of the acid mine drainage once it has formed. Measures to do this are essentially based on controlling the water inflow into the system and in so doing constraining the transport medium. The options included:

1. Diversion of clean surface run-off from the veld. The storm-water drainage system installed at the mine could be upgraded relatively easily. An important aspect of the upgrade would be to reduce the amount of water entering the two reservoirs (dams 1 and 2), as it does at present.
2. The mine should use the water from all three reservoirs for plant operation. At present only the water from one reservoir (dam 1) is used. This also would help to reduce the volume of water in the reservoirs and thereby reduce or eliminate spillage and seepage.
3. Inflow points to the backfill in opencasted areas should be sealed. Storm-water channels should be lined. Sealing could be carried out with a number of materials. There is a possibility that locally available pulverized fly-ash (PFA) could be used for this purpose because of its alkalinity and the fact that it is somewhat cementitious.
4. Ponding of water on the backfilled opencast areas should be eliminated. This water becomes acid and infiltrates into the groundwater system, leading to an increased pollution load and better transport of the acid mine drainage. The amount of earthworks required to level the area would be relatively small.
5. Run-off from the restored areas should be promoted if the quality of the run-off is acceptable. It should be diverted around the mined area.
6. Impermeable clay liners should be placed on part of the restored areas if the previous measures do not give an acceptable reduction in pollution load.
7. Attempts should be made to cut off or isolate those parts of the groundwater system associated with the underground workings if the load reduction is still not acceptable. However, a cut-off trench formed of soil-bentonite could prove expensive.

Collection and treatment of remaining seepage and spillage load may be considered as part of an interim measure, or less preferably as a long-term option. In the latter case attention would have to be given to financial guarantees to sustain the treatment after closure of the mining operation. Whichever methods are eventually chosen, they will have to be implemented in a phased manner. Regular monitoring also will have to be undertaken to determine the effectiveness of the measures adopted.

Conclusions

Acid mine drainage is associated with coal mines, and is due to the oxidation of sulphide minerals in mine rock or waste which are exposed to air and water. It can lead both to ground- and surface-water pollution with elevated levels of sulphate in the water. Acid mine drainage constitutes an environmental problem at the Loubert mine, in the eastern Transvaal. Polluted water arising from mining is affecting the Human Spruit and the generation of acid mine drainage is associated primarily with the restored opencast areas found on Portion 89 of the mine. The partially restored opencast workings and underground workings on Portion 24 do not at present pose a significant pollution threat to this stream. Since the generation of acid mine drainage at this mine cannot be prevented, any remedial measures will have to involve an attempt to control the movement of acid mine drainage by minimization of water flow through the backfill in the offending opencasted areas. This will involve the placement of compacted clay covers over the opencast area. Any seepage from underground workings could be interrupted by a cut-off trench filled with a soil-bentonite mixture. Collection and treatment would prove very expensive.

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