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ACID MINE DRAINAGE PROBLEMS IN ENUGU COAL MINES OF ANAMBRA STATE, NIGERIA.

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ABSTRACT

Coal mining in Enugu area began in 1915. Until the advent of Nigerian oil, coal served as the primary source of energy. Interest in the coal industry was reawakened by advances made in Nigeria's steel industry. Five coal seams occur in Mamu Formation. The No. 3 seam maintains a workable thickness in excess of 1.5 m. Overlying the coaliferous formation is the Ajali Sandstone consisting of thick friable, poorly-sorted sandy units of alternating cross-bedded coarse and fine sands with shale/mudstone intercalations. The Ajali Sandstone and the overlying laterite/red earth have high vertical permeability. The formations are intensely-fractured, jointed and faulted. Fracture connectivity between aquifers indicate possible hydrologic continuity across formations. High yielding aquifers exist in Ajali Sandstone and Mamu Formation. The coal mines are bedevilled by mine flooding problems. Large groundwater flows through fractures are continuous. The sources of the water is still uncertain. About 18.1 million litres of acidic water with high iron content is pumped out daily into nearby rivers. Mechanisation of the mines failed woefully because of lack of pre-mechanisation feasibility studies, acid mine drainage problems, corrosion of mine equipments, and slope failures.

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INTRODUCTION

Enugu is the capital city of Anambra State, Nigeria (Fig.1). It is a thriving commercial, coal-mining and industrial centre. In 1909, British geologists discovered the coal deposits and mining began in 1915. The mining has been centred around Enugu. The coal-bearing unit is the Mamu Formation. Five coal seams are known. Only No. 3 seam has been heavily worked (Ugwu, 1984). Though many mines were opened earlier, there are now two active mines in Enugu area: the Onyeama and Okpara Mines. Others such as the Ribadu and Iva Valley Mines have been closed temporarily.

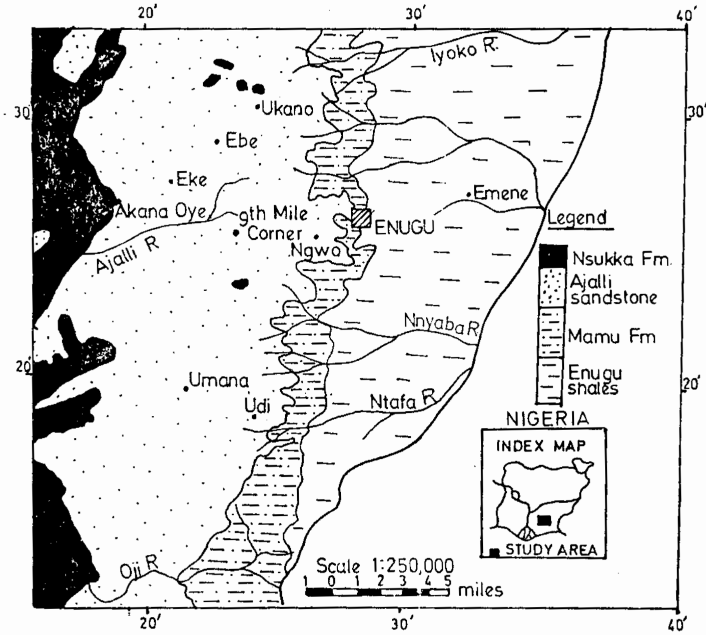

Fig 1 Location of the study area and the general geology

The Nigerian coal deposit has been estimated at 1.5 million tons (Diallah, 1984). Outmoded mining methods have been used so that the required coal outputs for the coal-fired power station at Oji River, the Nkalagu Cement Factory and for exports are not met. Attempts to mechanise mining in the 1970s failed woefully so that the Nigerian Coal Corporation reverted to the old mining methods.

The geologic formations are highly fractured and are aquiferous. The yielding aquifers produce large and continuous groundwater flows that render mining hazardous. The water is acidic and has high iron content. These create dangerous acid mine drainage problems. The sources of the groundwater inflows are not clear.

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The primary objective of this study is to determine the possible source(s) of and evaluate the hydrogeochemistry of the acid mine drainage waters of the Enugu coal mines and proffer suggestions for combating the attendant problems and hazards during mining operations. This would reduce the present wastes of financial and material resources, damages to mining equipments, and sometimes loss of human lives.

PHYSIOGRAPHY AND CLIMATE

The study area is bounded by latitudes 6° 24' and 6° 30', and longitudes 7° 26' and 7° 30'. Enugu is bounded in the west by north-south trending escarpment and in the east by Cross River Plains. There are hills, valleys and lowlands. The highs are underlain by Ajalli Sandstone and Mamu Formation while Enugu Shale forms lowlands. Streams, rivers and lakes are scattered over the area. The north-south trending escarpment is steep with hills as elevated as 1000 m above sea level.

Two main seasons exist in Nigeria: the dry season (October to March) and rainy season (March to October). The southward moving Sahara airmass causes dry season. The rainy season follows the northward advance of maritime air from the Atlantic Ocean. The conventional nature of rainfall results in alternating sunny and rainy conditions. Ofomata (1965) stated that annual rainfall (1950-1959) for Enugu was 1,646 mm. The rainfall occurs as violent downpours accompanied by thunderstorms, heavy flooding, soil leaching, extensive outwash, erosion, gullying, and groundwater infiltration.

GEOLOGY AND STRUCTURES

The predominant geologic units (Figs. 1, 2 and 3) are Ajalli Sandstone (Upper Maestrichtian), Mamu Formation (Lower Maestrichtian) and Enugu Shale (Campaniam). The fractured Enugu Shale underlies plains east of the escarpment (Fig.2). It consists of soft mudstone, shale with intercalations of sandstone and sandy shale. The Mamu Formation contains sandstone, shale, mudstone and sandy shale beds. Coal seams in commercial quantities occur (Figs. 3 and 4). The aquiferous sandstones are fine- to medium-grained. The formation is about 395 m thick and is highly jointed and faulted. The Ajalli Sandstone, about 406 m thick,

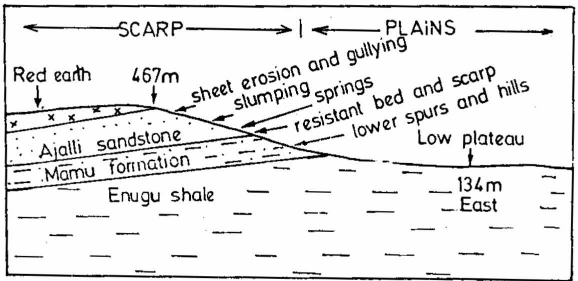

Fig 2 Diagrammatic section across the Enugu escarpment (Modified from Carter 1958)

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consists of thick friable, poorly-sorted sandstone, white in colour but sometimes iron-stained. A marked banding of coarse and fine members occur. Large-scale cross-bedding is characteristic (Reyment, 1965). Intercalations of mudstone and shale occur, and the Ajalli is overlain by laterite/red earth.

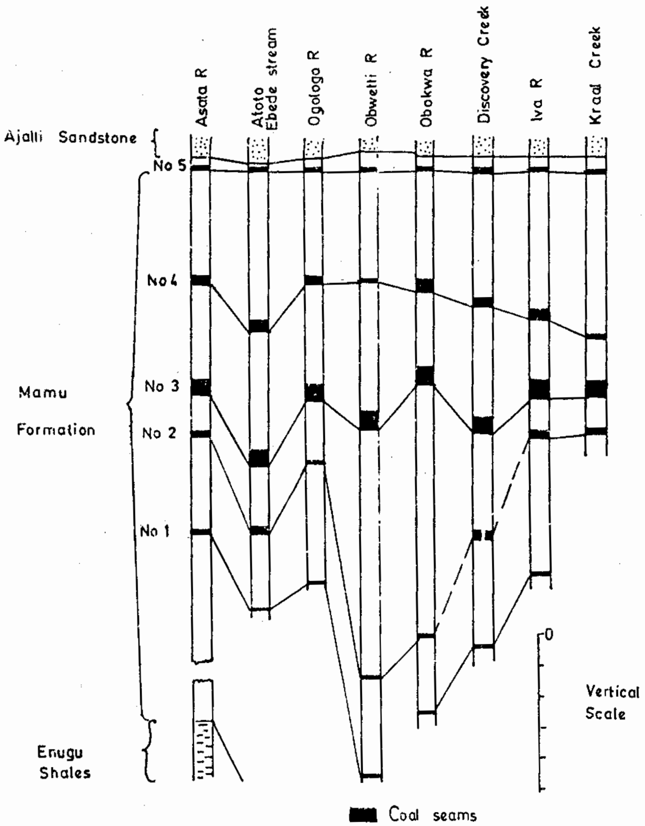

Fig 3 Mamu formation coal sequences in stream/river sections in Enugu (Simpson 1954)

The beds have a regional dip of 1^{o} to 2^{o}N. They are heavily fractured, jointed and faulted. The coal seams exhibit broad undulations. Their axes run west-south-west (Simpson, 1954). Major faults include Iva, Obwetti, Onyeama, Creek and Juju. These have criss-crossing minor faults, slips and grabens. The disturbed conditions of lithologic units, weathered nature of fault zones, uncertainty of direction and throw of major faults, and huge groundwater flows render coal mining hazardous.

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HYDROGEOLOGY

Surface Water Hydrology

The area is drained by many streams and rivers (Fig.1) that include Ekulu, Iva Valley, Asata and Ogbete. The rivers originated as springs (Fig. 2) from the Ajalli aquifers and flow across Mamu Formation. The rivers have indented the escarpment resulting in gully erosion at head-waters. During the rainy season, scarp regions become highly-saturated, and water table rises. Conditions favourable to mass movement of material on slopes are created thereby causing emergence of springs that erode valley walls and expand existing gullies. The surface water originating from the Ajalli aquifers receives more water discharging from Mamu aquifers. The acid mine drainage waters from various mines are pumped continuously into rivers, thereby, polluting them. The Ekulu River is used as part of urban water supply for Enugu. Some of the rivers are fracture-controlled at their source areas and along their flow directions.

Groundwater Hydrology

The sedimentary and tectonic processes created a complex system of geologic and hydrologic depositional environment. Presently, incomplete information on aquifer parameters and boundaries exist. There are no monitoring programmes. The sources of groundwater flows are not defined, the movements of the piezometric surfaces are unknown, and no detailed hydrogeochemical records. These information are required for solutions of planning and mining problems.

The lithologic logs (Fig. 4) are for boreholes drilled in the Onyeama mine area. Boreholes BH16 and BH15 at higher elevations have sandy layers. They form water table aquifers in Ajalli Sandstone. The Mamu pressure aquifers occur deeper. Boreholes BH27 and BH30 are in valley areas where the Ajalli Sandstone has been lost to erosion showing only Mamu aquifers. Figure 1 shows the Ajalli Sandstone as the source area for emerging springs, streams and rivers and recharge zone for confined and unconfined aquifers. Table 1 shows the aquifer parameters in Ajalli Sandstone and Mamu Formation (Egboka, 1984). The values indicate aquifers of high yield and good performance. These contribute to extensive groundwater mine flooding problems. Pore water pressure causes heaving and subsequent collapse of mine walls and tunnels. Thus, the seemingly uncontrollable flooding has been a great danger to coal production.

Groundwater flows into the mines through fractures. Over the catchment area, a groundwater flow of up to 90,000 $m^3\ dy^{-1}$ was estimated by Offodile (1980). This flow is equivalent to $4.2 \times 10^7\ m^3\ yr^{-1}$. About $1.36 \times 10^4\ m^3\ dy^{-1}$ of groundwater from the Onyeama mine are pumped into Ekulu River. This volume is equivalent to about $4.96 \times 10^6\ m^3\ yr^{-1}$. Egboka (1984) got a value of $2.1 \times 10^6\ m^3\ yr^{-1}$ for a Mamu aquifer. These closely-related values are strong indicators of good yielding aquifers that have discharge areas into mines, rivers, and flood plains. The drainage pumps in Onyeama mine operated at a lead rate of 19,636 $m^3\ dy^{-1}$ and would need emergency services in order to cope with sudden and often unexpected in-rush of water into the tunnels when major fractures are intercepted (Offodile, 1980).

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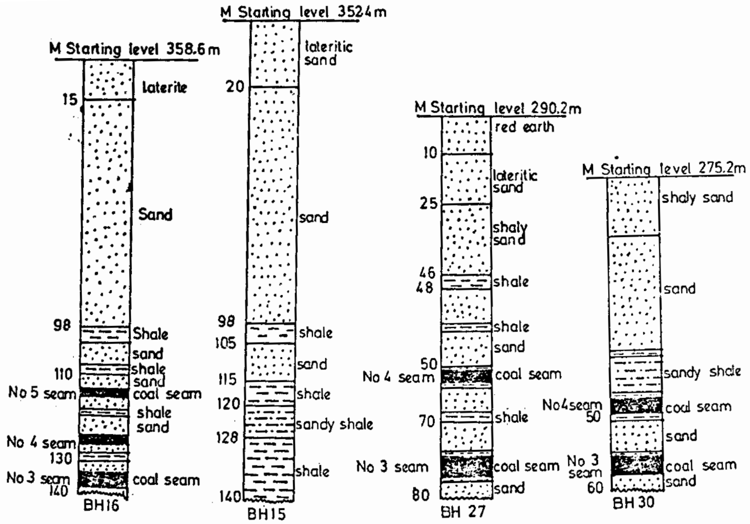

Fig. 4 LITHOLOGIC LOG OF BOREHOLES

Table 1. Aquifer parameters within Ajali Sandstone and Mamu Formation (Egboka, 1984).

Aquifer	Ajali Sands	Nkpologu Sands	Mamu Sands(1)	Mamu Sands(2)
Formation	Ajali Ss	Ajali Ss	Mamu Fm	Mamu Fm
Hydraulic conductivity (cm s^{-1})	9.2×10^{-3}	2.1×10^{0}	9.2×10^{-3}	2.6×10^{-2}
Specific discharge (m^3 m^{-2} yr^{-1})	17.5	3,936.0	14.5	40.4
Groundwater velocity (m^3 yr^{-1})	49.9	1,900,000	48.4	134.6
Total discharge (m^3 hr^{-1})	109.7	29,223.7	12.4	23.1
Transmissivity (m^2 yr^{-1})	3.2×10^{5}	8.5×10^{7}	4.4×10^{4}	8.1×10^{4}

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Hydrogeochemistry

Table 2, 3 and 4 show hydrogeochemical parameters for Ninth Mile Corner Borehole Complex, Surface Water bodies, and Enugu coal mine groundwaters respectively. Except for slight acidity, the Ninth Mile Corner borehole water tapping Ajalli Sandstone aquifers (Table 2) is of good quality. The surface water bodies (Table 3) except for the high iron content are of similar quality. It must be noted that these surface waters originated from the Ajalli aquifers and have travelled for a short distance. The high iron could be from eroded sediments and nearby coal mines. The mine water (Table 3) is of poor quality.

The pH shows the mine water to be acidic. The total iron concentration is high and so are sulphate and silica. Despite the possibility of atmospheric contamination during water sampling, dissolved oxygen values (D.O.) are low. The hydrogeochemistry of Iva Valley mine waters generally shows higher values than other mines. This could mean: a possible different source for Iva Water; a different geochemistry for Iva Valley strata and coal; or their geochemical evolutions differ. The geochemistry of Onyeama mine water after a heavy rain differs from values measured during no rain (Table 4). This indicates a fast hydrologic connectivity between rain water and mine aquifers.

DISCUSSION

The aquifer parameters from Ajalli and Mamu aquifers have shown high water yielding formations. The present understanding is that the acid mine drainage has its source in overlying Ajalli aquifers, entering the mines through fractures. Presently, water supplies to Enugu comes from the conjunctive use of Ninth Mile Corner boreholes and Ekulu River. The Anambra State Water Corporation is worried about the potential pollution threats from the acid/iron rich mine waters. The Corporation is also considering the possible use of treated mine water for domestic and industrial uses (Egboka, 1985).

Table 2. Ninth Mile Corner Borehole Complex

Geochemical parameters	Borehole 1	Borehole 3	Borehole 6	Borehole 7	Borehole 10	Borehole 11	Borehole 12
pH	5.3	5.5	5.2	5.6	5.41	5.2	5.1
Turbidity	0.28	0.9	0.22	0.3	0.90	0.27	0.28
Colour (Hazen units)	5	5	5	5	5	5	5
Electrical conductivity mhos cm^{-1}	18.6	20.0	23.0	27.5	20.0	28.0	27.0
Total hardness mg l^{-1}	7.0	8.0	8.0	8.0	8.0	9.5	6.5
Ca-hardness "	2.0	3.8	3.5	5.0	6.0	6.5	3.0
Mg-hardness "	5.0	4.2	4.5	3.0	2.0	3.0	3.5
Silica as SiO_2 "	17.0	16.0	13.0	16.0	12.0	16.0	16.0
Nitrate "	-	1.0	-	0.6	20.0	2.4	1.2
Total Iron "	0.3	0.28	0.2	0.75	0.46	0.32	0.15
Chloride as Cl "	2.10	3.55	3.4	3.5	2.84	7.09	5.67
Chloride as NaCl "	3.46	5.86	-	-	-	-	-
Total alkalinity "	4.5	-	10.0	40.0	24.0	7.5	5.2
Total dissolved solids mg l^{-1}	11.5	12.0	14.0	17.0	-	17.0	-
Total solids "	36.0	23.0	4.2	63.0	42.0	33.0	37.0
Free Carbon dioxide "	81.66	-	93.21	80.26	93.28	114.5	105.6
Dissolved oxygen "	24.0	-	5.30	6.10	5.80	5.4	-
Temperature °C	-	-	28.6	28.5	29.0	28.5	28.7

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Table 3. Hydrogeochemical data of Surface water bodies

Geochemical parameters	Ekulu River (Rainy Season)	Ekulu River (Dry Season)	Iva Valley River (Rainy Season)	Iva Valley River (Dry Season)	Spring Water Enugu	Treated Ekulu River Water
pH	6.50	6.64	6.30	6.61	6.50	6.50
Turbidity	25.20	4.00	216.93	47.30	10.80	4.30
Colour (Hazen Units)	250	60	50	130.	30.	10.
Electrical conductivity mhos cm^{-1}	48.00	75.00	72.00	73.00	2.30	65.00
Total hardness mg l^{-1}	14.00	23.00	27.00	17.00	8.00	24.00
Ca-hardness "	7.00	9.90	7.50	6.00	3.00	12.30
Mg-hardness "	7.00	13.10	20.10	11.00	5.00	11.70
Silica as SiO_2 "	11.00	40.00	10.00	30.00	8.00	16.00
Nitrate "	-	0.50	0.90	0.07	nil	0.30
Total iron "	1.34	0.48	0.25	13.60	1.90	0.32
Sulphate "	8.50	28.86	23.60	-	15.86	22.40
Manganese "	-	-	1.58	-	-	0.35
Chloride as Cl^- "	3.50	6.38	2.13	3.10	4.30	9.20
Chloride as NaCl "	5.75	-	3.51	-	-	16.00
Total alkalinity "	9.40	46.00	9.00	1.80	31.00	11.00
Total dissolved solids mg l^{-1}	29.50	45.20	45.00	53.00	-	40.00
Total solids "	279.00	67.00	169.00	-	46.00	77.00
Temperature °C	26.00	29.00	-	-	28.00	-

Table 4. Hydrogeochemical data of Enugu Coal mine groundwater

Geochemical parameters	Onyeama mine	Onyeama mine (after heavy rain)	Ribadu mine	Iva Valley mine
pH	3.70	4.10	4.05	2.55
Turbidity	26.30	106.10	-	-
Colour (Hazen units)	5	230	15	5
Electrical conductivity mhos cm^{-1}	78.00	130.00	-	-
Total hardness mg l^{-1}	30.00	48.00	12.0	80.0
Ca-hardness "	5.00	12.00	-	-
Mg-hardness "	7.00	36.00	-	-
Silica as SiO_2 "	20.00	30.00	25.00	60.00
Nitrate "	0.17	0.01	-	
Total iron "	5.61	1.49	6.74	56.04
Sulphate "	39.30	43.00	-	427.65
Chloride as Cl^- "	4.00	2.20	10.20	20.00
Chloride as NaCl "	3.46	3.63	-	
Total alkalinity "	-	-	-	-
Total dissolved solids mg l^{-1}	45.75	-	-	-
Total solids "	98.00	260.00	-	-
Dissolved oxygen "	6.00	-	4.00	4.00
Consumed oxygen "	1.00	-	3.50	12.70
Acidity cc	0.60	-	0.35	15.00
Potassium mg l^{-1}	1.38	-	3.00	9.88
Sodium "	6.38	-	8.20	3.50
Manganese "	1.46	2.60	-	-

The present investigations seem to show that the acid mine drainage groundwater comes from two sources. The Ajalli aquifers are suggested to contribute about 30% while Mamu ones yield about 70% of acid mine drainage. Figures 1 and 2 show that waters from Ajalli aquifers discharge and flow across Mamu Formation. The water in Mamu aquifers is

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under pressure, although their piezometric surfaces have not been established. The surfaces may lie within the Ajalli Sandstone or below. Figures 3 and 4 show that Mamu aquifers are deep-seated. The Mining activities are concentrated in deep No. 3 coal seam. The mines hardly intersect the Ajalli aquifers, hence whatever its water contributions may not exceed 30%. How this mixing occurs is not yet known although Table 4 suggests hydrologic connectivity between the surface flows and Onyeama mine flows.

One of the main constituents of forming coal is water, particularly during the peatification stage, water being present in very large amounts (Allardice and Evans, 1978). As coalification proceeds, the water is squeezed out to form groundwater. Other water sources include clay dewatering (Powers, 1967), dehydration of gypsum (Heard and Rubey, 1966), conversion of anhydrite to native sulphur (Manhein, 1970), and coalification of coal beds (Law et al., 1983). Coal-derived water may contribute to development of abnormally high pressures in coal-bearing sequences (Powers, 1967; Burst, 1969; Magara, 1975; and Law et al., 1983). All these are applicable to the acid mine drainage of Mamu Formation coal deposits. Much of the pressure water (70%) bedevilling mining is contributed by Mamu aquifers. The hydrogeochemistry of both waters differ markedly such that even the contribution from good quality Ajalli water (younger) does not seem to dilute the poor quality Mamu water (older). The implication is that dewatering schemes should be concentrated in the Mamu aquifers.

Acid mine drainage occurs during oxidation of iron sulphide (FeS_2) to form sulphuric acid. In Mamu Formation, pyrite and marcasite occur. The following reactions may be in progress:

$$FeS_2 + 7/2\ O_2 + H_2O \longrightarrow FeSO_4 + 2H^+ + SO_4^{2-} \qquad (1)$$

$$FeSO_4 + 2H_2O \longrightarrow Fe(OH)_2 + SO_4^{2-} + 2H^+ \qquad (2)$$

$$Fe(OH)_2 + H_2O \longleftrightarrow Fe(OH)_3 + H^+ \qquad (3)$$

Dissolved oxygen, water and pyrite react to yield iron hydroxide, sulphate and hydrogen. Continued supply of dissolved oxygen through fractures and during mining to groundwater enhances oxidation of pyrite and continuous inputs of H^+ and SO_4^{2-}, thereby raising the acidity. This is the main cause of acid mine drainage problem that has been environmentally-damaging in many mining regions (Moran et al., 1978). The precipitated ferric iron gives familiar red colour to groundwater and also forms red scums.

In addition to iron compounds and sulphuric acid produced, other compounds result from secondary reactions. They include reactions between ferrous sulphate, sulphuric acid and compounds in clays, shales and sandstones associated with the coal beds. Large influx of water and air together with exposure of acid-producing materials provide necessary conditions for reactions to occur. Mined, tunnelled, back-filled areas and abandoned mines provide for easier movement of water and air; and overflow or thorough-flow through these becomes major contributor of acid water. Cessation of mining activity as prevalent in Enugu area aggravates the problem since water is no longer pumped out or drained regularly and exposure time for acid-producing reactions is increased.

The acid mine drainage problems in Enugu mines has caused great damages to

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both human and material resources. An attempt to mechanise the mines that cost millions of naira by a foreign company without prefeasibility studies resulted in loses of equipments and falls in coal output (Table 5). Acidic mine waters and hydrogen sulphide gas are deleterious to the health of miners. Acidic water is continuously pumped into surface waters to pollute water supplies, vegetation, aquatic flora and fauna. Leachates from gangue waste dumps are also polluting. All these problems would be clearer for solution if more detailed hydrogeologic, hydrogeochemical and isotope hydrologic studies can be done. At the moment, funds are severely limiting.

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