Origin of Acid Mine Drainage in Enugu

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ABSTRACT / Mine flooding is a serious problem in the Enugu Coal Mines and has led to the abandonment of two of the four mines. About 1800 m^3 of water is pumped out daily from the mines into the nearby streams. The source of this enormous volume of water has been established based on the hydrodynamics and hydrology of the area. It is shown that although two prolific aquifers—an unconfined and a confined system—overlie the mines, the mine water is derived principally from the unconfined aquifer. The pathway of flow is, however, provided by the numerous fractures connecting the two aquifers and the mine tunnel.

The major hydrochemical activity resulting in pollution of the mine water occurs within the sumps in the floor of the longwalls. These sumps act as oxidation chambers where groundwater from the fractures is mixed and subsequently reacted with sulfur-rich solutes released by coal mining.

Contrary to general belief, the mine drainage has not seriously degraded the chemistry of receiving streams. The pH, electric conductivity and, thus, the dissolved ions were increased less than 10% of the values in the unaffected region.

Introduction

Coal in Nigeria occurs mostly in the Mamu Formation (Lower Coal Measures) of Upper Cretaceous age. Mining activities began in Enugu in 1915. Four mines—Onyeama, Okpara, Iva Valley, and Hayes—were opened, although at the moment only two are in use. The most pressing technical problem affecting coal mining is the influx of water into the mines (mine drainage). Presently the Coal Corporation pumps out about 18 million liters of water daily from the mines into the nearby streams. The drainage pumps in Onyeama mines alone operate at a lead rate of 19,636 m^3/day and would need emergency services in order to cope with sudden and often unexpected flood of water into the tunnels when major fractures are intercepted. The source of this enormous volume of water is, at the moment, not reliably known. Current speculations may be divided into two broad groups: (1) the mine water comes from those aquiferous horizons of the Mamu Formation that are interlayered with the coal seams; and (2) the mine water comes from the overlying and highly prolific Ajali Sandstone.

These speculations are not corroborated with pertinent data. In addition, whereas the mine water is known to be polluted, neither the details of pollution nor the sources of the pollutants is known with sufficient accuracy. These issues have been dealt with in this study. The major aim is to investigate the effects of mining on the hydrodynamics and hydrochemistry of adjacent water systems (both surface and groundwater). In addition, the contributions of the different aquifer systems to the mine drainage problem are assessed; and the major chemical activities leading to the generation of the chemical constituents (pollutants) are also evaluated.

Method of Investigation

Thirty-six test holes have been drilled by the Geologic Survey of Nigeria (GSN) in the Enugu Coal Mine area. These holes penetrate the entire Ajali Sandstone and the upper portion of the underlying Mamu Formation. Core samples and cuttings recovered from these boreholes are reported by de Swardt and Casey (1961) and form the bulk of the lithologic data used, especially in subsurface correlation analysis. In addition, hydrogeologic information was obtained from over 25 water wells drilled at the Ninth Mile Corner (Fig. 1) by the Anambra State Water Corporation (ASWC), the Nigerian Breweries, the Monarch Breweries, and the Nigerian Bottling Corporation.

Geochemical data of pH, electric conductivity (EC), and dissolved oxygen were obtained directly from the mines by the use of Wissenschaftlich-Technische-Werkstatten (WTW) geochemical kit. The use of this portable equipment permitted numerous measurements to be made and also assured the accuracy of the parameters determined. Other parameters such as major ions were not determined because of lack of facilities. Data on these parameters were obtained from existing literature. However, since the major geochemical effects of mining, which are increased

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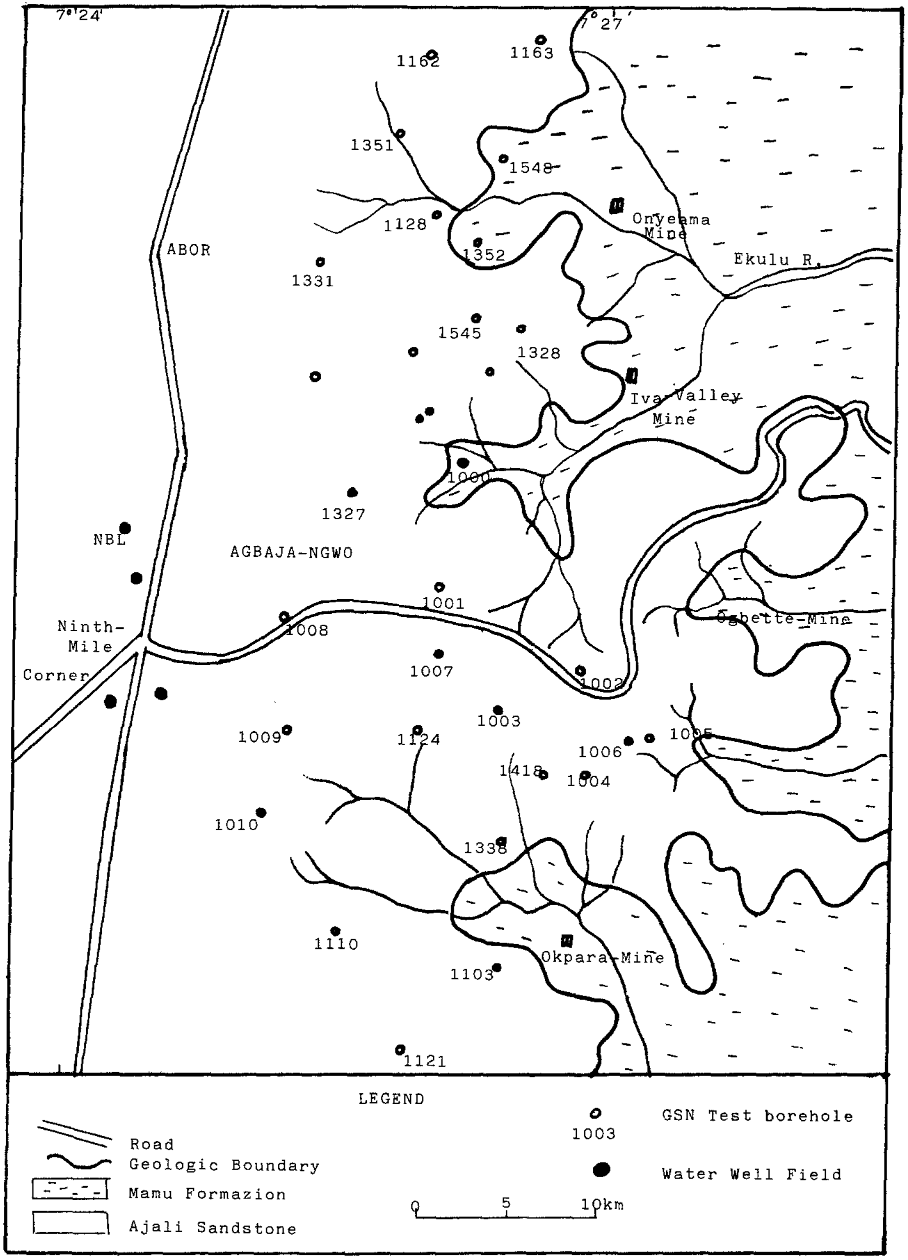

Figure 1. Location and generalized geology of Enugu Coal Mine area.

acidity and dissolved constituents of the mine water, are detectable by pH and EC, the laboratory limitation is not considered a serious defect in the study.

Physiography

The most prominent topographic feature in the mining environment is the Udi plateau. The plateau is a cuesta running north–south with a bold east-facing escarpment and gentle west-dipping slopes (Fig. 1). The surface rises in places to over 300 m above the adjacent plains. On top of this regional terrain are numerous dissected ridges and hills, which give a rugged appearance. Numerous springs and seepages dot the foot of most of the hills and ridges. These springs form the headwaters of the major streams such as the Ekulu and Iva streams at the base of the escarpment. In the vicinity of the mines, many of the springs and seepages are dry, and the streams rise directly from the perennial flood water from the mines.

The ultimate source of water is rainfall, which occurs mainly between April and October. The other months are generally dry except for a few scattered rains. Rainfall is brought by the northward movement

Table 1. Summary of lithologic logs of test boreholes penetrating the coal mine area

Borehole number	Total thickness penetrated (m)		Thickness of sandy horizons (m)		Percentage of sands
	Mamu	Ajali	Mamu	Ajali	Mamu
1000	62	40	61.4	40	99
1001	73.4	112.8	63.8	112.8	86.9
1002	42.7	134.7	33.9	131.0	79.4
1003	36.9	152.4	39.3	149.4	69.1
1004	60.8	149.0	52.0	149.0	85.5
1007	44.8	138.0	37.6	135	83.9
1008	67.4	143.3	62.3	142.5	92.4
1009	30.5	177.4	26.9	177.0	88.4
1010	145.4	170.7	125.9	170.0	86.6
1103	63.4	85.3	49.7	84.5	78.61
1104	53.8	97.5	41.8	97.5	77.6
1110	73.5	173.7	42.1	172.9	57.2
1121	33.2	125.0	19.6	127.5	59.0
1124	52.3	146.3	44.5	145.8	85.1
1127	70.1	91.4	50.6	90.7	72.2
1128	39.6	97.8	12.5	97.5	31.6
1129	32.6	156.0	14.9	156.0	45.7
1162	49.7	198.1	41.5	198.0	83.6
1163	25.0	143.0	16.5	143.0	66.0
1325	48.2	130.0	35.6	130.0	73.6
1327	82.9	103.6	68.3	103.5	82.4
1328	55.8	134	51.5	134.0	92.3
1329	65.8	213	46.9	213.0	71.3
1331	41.1	210.3	29.3	2.0	71.3
1338	99.0	33.5	30.8	33.2	31.1
1351	35	149	30.8	148	88.0

of the moist Equatorial Maritime Air Mass from the Gulf of Guinea with prevailing winds from the southwest. The annual rainfall is about 1800 mm, much of which falls at intensities great enough to generate deep infiltration. The recharge rate is about 30 percent of the annual rainfall at the dip slope underlain by Ajali Sandstone. At the escarpment, recharge is lower because of increasing slope and argillaceous materials. The recharge in this region is about 20% of the annual rainfall (Uma and Egboka 1988).

Geology

The area comprises a thick succession of sedimentary materials belonging to two geologic formations—the Mamu Formation and the Ajali Sandstone—both of which are Upper Cretaceous in age. The younger Ajali Sandstone is composed of thick sequences of poorly consolidated sands of various sizes. The sands are generally whitish, poorly to moderately sorted, and typically cross-stratified. Argillaceous materials are minor and occur as streaks and discontinuous lenses of whitish clayey shale along the main bedding planes. The shale beds generally become more numerous toward the base where there is a gradual transition into the underlying Mamu Formation. In all the lithologic logs examined, sandy horizons comprised more than 75 percent of the formation at each drilled point (Table 1). The Mamu Formation comprises a cyclic sequence of sandstones, shales, sandy shales, carbonaceous shales, and coal seams. Bedding is generally irregular and truncation of bedding due to slumping and contemporaneous erosion is common (de Swardt and Casey 1961). The sandy horizons are generally thick (4–20 m) while the shales are thin (<4 m) but more numerous. Each lithologic horizon usually contains a significant proportion of the other occurring as impersistent bands, lenses, and stringers. Lithologic logs from the upper part of the formation (up to the base of number 3 coal seam) indicate a cumulative sandy content ranging from 31 to 99 percent with an average of 74.5 percent (Table 1). This, contrary to general belief, reveals a dominance of sandy horizons over clays and shales, at least within the upper Mamu Formation.

The two formations are affected by late Cretaceous tectonism leading to the folding, faulting, and fracturing of the rock materials. Figure 2a is a typical

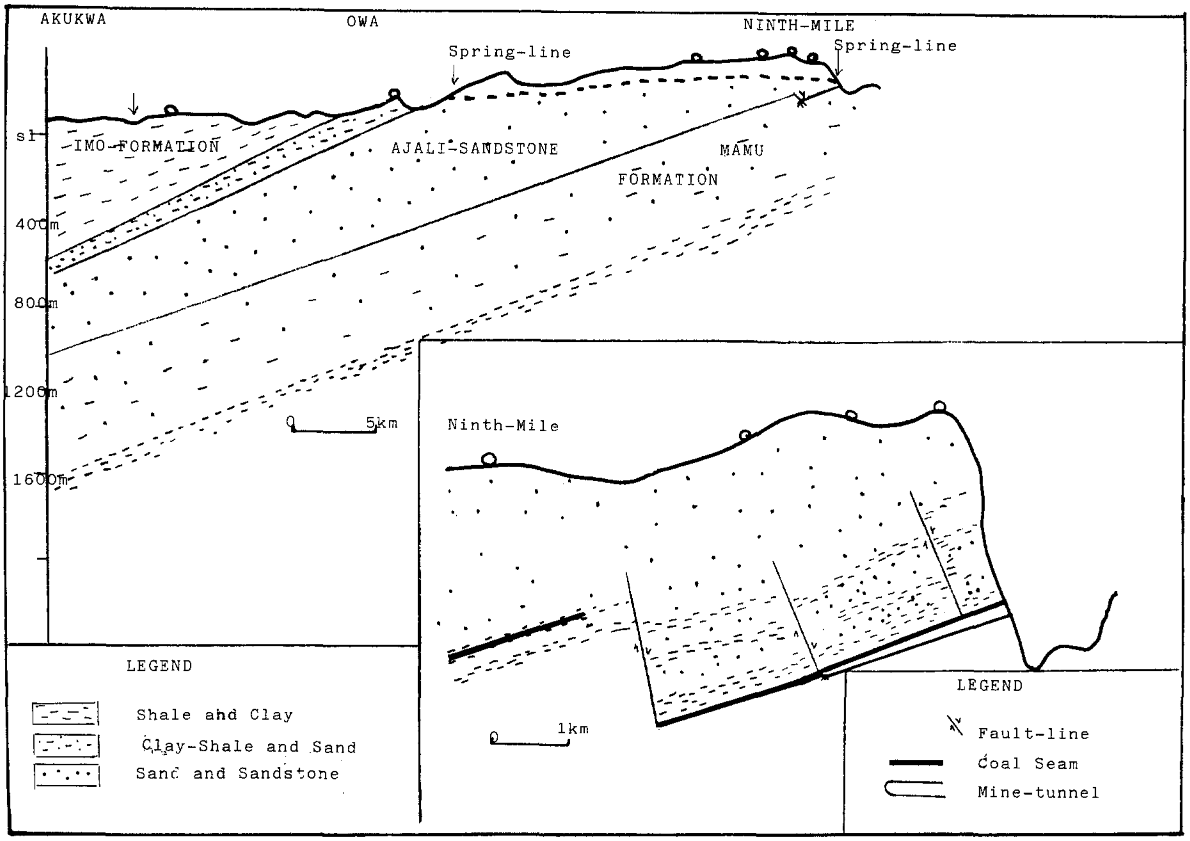

Figure 2. Generalized geologic sections across the area; figure shows regional features and inset the specific features in the mining environment.

geologic section showing the regional features, while Figure 2b shows the specific features in the mine environment. The gentle west-dipping beds, as shown in the figures, are actually the right limb of a north–south trending syncline—the Anambra Basin. The faults are indicated from correlation using index beds. They have also been encountered in the mine tunnels. The fractures are clearly discernible inside the mines and on outcrops of the Mamu Formation, such as those on roadcuts between Ninth Mile Corner and Enugu. Radar imagery studies (Benkhelil 1988) indicate that the fractures continue through the Ajali Sandstone to the surface. They are probably obliterated by deep weathering.

Hydrogeology

Aquifer Systems

Two aquifer systems have been identified in the area (Egboka and Uma 1986). These are unconfined and confined aquifer systems. The unconfined aquifer system is formed by the thick sandy sequences making up the Ajali Sandstone and the sandy beds at the top of Mamu Formation. The depth to the base of the aquifer varies from less than 30 m below the surface at the escarpment to over 150 m beneath Ninth Mile Corner borehole field. The depth to the water table varies from zero at the spring line at the face of the escarpment (Fig. 3) to about 70 m around Ninth Mile. The saturated thickness is also variable and ranges from 30 m to over 100 m, with an average thickness of about 75 m. The variability in these parameters is a reflection of the variable surface topography, faulting, and stratigraphic irregularities.

Borehole yields (at test periods) range from 60 m^3/h to 182 m^3/h with a corresponding stable drawdown of 10–15 m. The transmmissivities, T, evaluated from Logan's (1964) equation range from 120 m^2/d to over 500 m^2, while hydraulic conductivities, K, vary from 1.5 m/d to over 10 m/d. These ranges of values are consistent with T and K values obtained for the Ajali aquifers in southeastern Nigeria (Egboka and Uma 1986).

Confined aquifers occur in the sandy horizons of the Mamu Formation. These sandy horizons are generally thin (<15 m) and contain discontinuous clay–

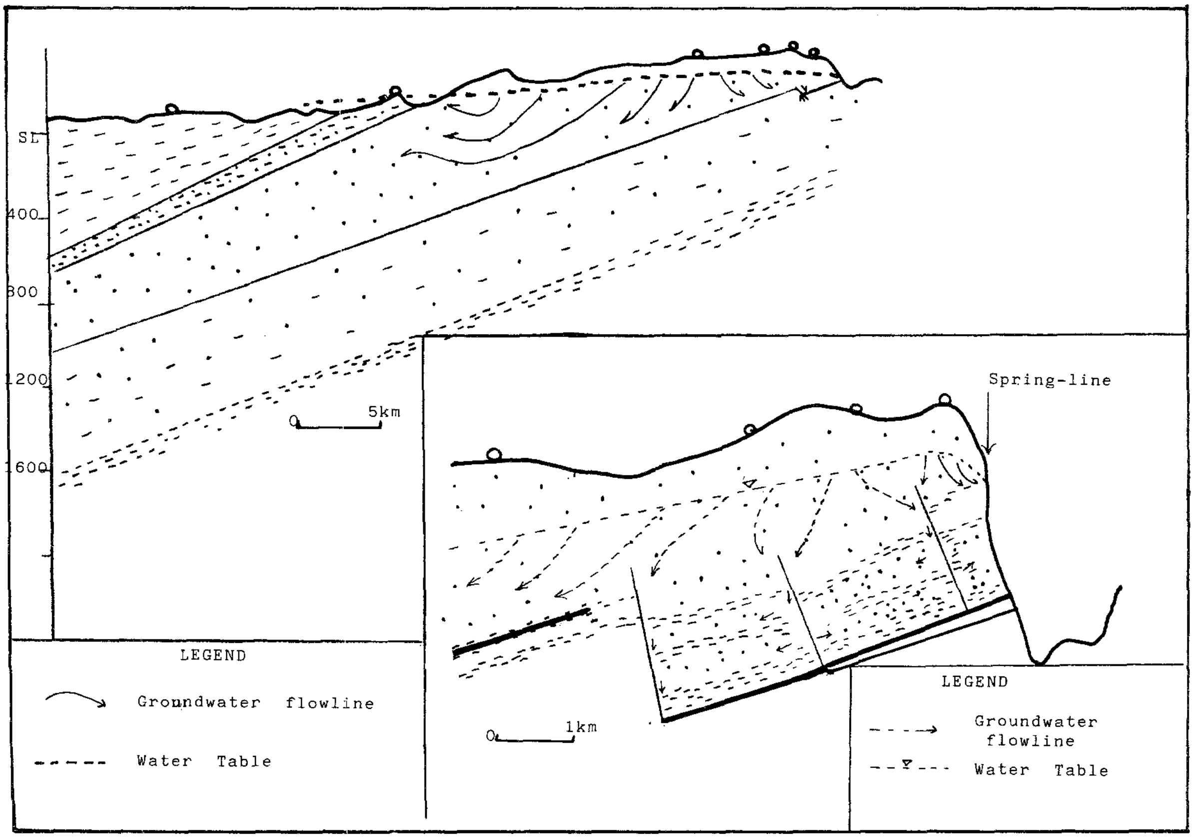

Figure 3. Conceptual models of groundwater flow patterns in the area; figure shows regional trends, whereas inset shows detailed flow in the mining area.

shale lenses and stringers. Stratigraphic logs from the test wells penetrating the formation reveal two to three prominent sandy horizons (>5 m) up to the base of the number 3 coal seam. These aquiferous horizons are separated by thick intercalations of shales, coal seams, and sandstones, which form aquitards. The cumulative thickness of sandy beds (aquifers) encountered in the test holes (up to number 3 coal seam) is displayed in Table 1 and ranges from 12.5 m to about 70 m with an average of 35 m. This average value was taken as the effective thickness of the confined aquifer.

The hydraulic properties of the confined aquifer have not been determined, but similar sandy aquifers have K values ranging from 0.3 to 12 m/d. The corresponding T for an effective thickness of 35 m will vary from 10 to 420 m^2/d. The storativity, S, estimated from Lohman's (1972) equation varies from 3.3E-5 to 2.0E-4. Recharge into the confined aquifer occurs by direct infiltration from rainfall at the escarpment where the sandy units are exposed and by vertical flow from the overlying unconfined aquifer through the connecting fractures.

Groundwater Flow Patterns

The pattern of groundwater flow in the area is influenced by a complex of factors including topography, geology (regional dip and structures), as well as groundwater development. A conceptual model of the predevelopment flow pattern is shown in Figures 3a and 3b. In the unconfined aquifer, the water table configuration was a subdued replica of the topography with a mound in the Ninth Mile area corresponding to the crest of the cuesta. Flows were generally eastward toward the spring line on the escarpment and westward along the dip. Flows, as depicted in the model, are supported by the observed spring distribution in the area (Fig. 1). Vertical downward flows into the underlying Mamu aquifers also occurred and were generally through the numerous fractures and stratigraphic discontinuities.

Flow regimens are presently modified by groundwater development including mining. Four major well fields (Fig. 1) are being operated with a total abstraction of about 1000 m^3/h. In addition, about 750 m^3 of water is pumped out daily through the coal

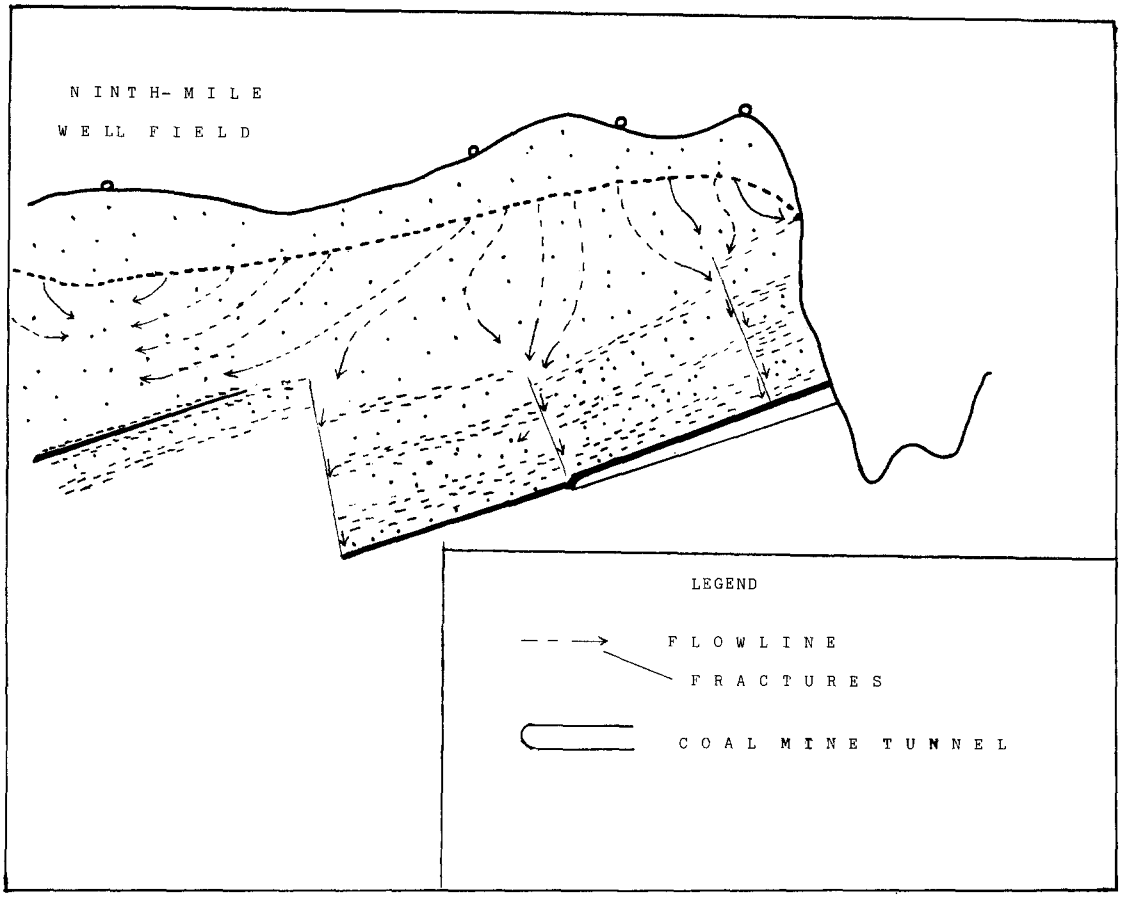

Figure 4. Conceptual model of groundwater flow in the coal mine area after groundwater development began.

mines. A conceptual model of the resulting flow pattern is shown in Figure 4. The model assumes that the fractures act as vertical drains through which groundwater enters into the mines. It further assumes that groundwater flux in the fractures generally from the overlying unconfined aquifer downward into the mines and laterally into the confined aquifers. This is so because the hydraulic head in the unconfined aquifer is always greater than in the confined aquifer. The model is thus consistent with established hydraulic guidelines (Bear 1972, 1980; Toth 1962; Freeze and Witherspoon 1966). A clear implication of this flux pattern is that flow into the mines through the fractures will continue to occur so far as the fractures remain open and new ones are intercepted during subsequent mining operations. Down dip outflow in the unconfined aquifer is intercepted by the Ninth Mile borehole field as shown in the figure. The ultimate result of groundwater development is the shifting of the regional groundwater divide westward (Fig. 3 vs. Fig. 4).

Origin of the Mine Water

Figure 4 indicates that groundwater enters the coal mines mostly through the fractures. This is consistent with field observations and historical records of the miners. It was observed that the roofs and sides of the mines are completely dry except where some fractures are intercepted. Water seeping out from such fractures collects in sumps at the floor of longwalls (active mine tunnels) and are subsequently pumped out of the mine through the main adit channel. Flows were also observed from the floors of some the longwalls but such flows were very minor. Some fractures filled with compact clayey materials (mudrock), similar to the roof materials, were observed to be dry. This also is true for the minor jointing in the coal seams (cleating). The conclusion drawn from the observation is that seepage is confined to the major fractures such as those extending into the Ajali Sandstone.

In order to understand the effect of each of the aquifer systems, two assumptions will be made: (1)

that the mine water is derived entirely from the Ajali aquifer, and (2) that the water is solely from the confined (Mamu) aquifer.

In the first assumption, the total abstraction from the unconfined aquifer (including abstraction in the Ninth Mile well field but excluding spring flows) is 1750 m^3/h or 15.3 × 10^6 m^3/yr. An equivalent volume of recharge from rainfall is needed to balance this enormous volume and ensure long-term equilibrium in water levels. A recharge of 30 percent and annual rainfall of 1800 mm will require an area of 28.4 km^2. This is equivalent to a radius of influence of about 3.0 km centered at the Ninth Mile. This value is reasonable and acceptable considering the underlying calculation.

In the second assumption, the total annual abstraction from the Mamu aquifers is 750 m^3/h or 6.6 × 10^6 m^3/yr. A recharge of 20 percent for the same annual rainfall will require a recharge area of 18.25 km^2. This implies a recharge length of about 36.5 km since the average width of the sandy horizons of the Mamu Formation exposed at the escarpment is about 0.5 km. Such a recharge length (of 36.5 km) is unreasonable considering the hydraulics of the area. Moreover, it assumes negligible connectivity between the two aquifer systems, which is not plausible.

An alternate method in the second assumption is to further assume that the entire confined aquifer is being dewatered. In this case the total volume of water released from storage within the mining environment of average area of 30 sq km (assuming $S = 1.0 \times 10^{-4}$ and effective thickness of 35 m) is 1.05×10^5 m^3. This is about 2 percent of one year's discharge from the mines.

Generally, since it is known that the fractures cut across both Mamu and Ajali Formations and that the hydraulic heads in the confined aquifer are less than in overlying unconfined aquifer, it will be reasonable to expect fluxes to be downward through the fractures into the mines and into the confined aquifers. The flow to the confined aquifer will cease only when the head in the two aquifers is the same. Such a situation should result in large drawdowns in the pumping well fields and even drying out of some of the Ninth Mile boreholes. No such drying out has been reported; rather, it is known that the water levels in the well fields have reached a quasiequilibrium with pumping.

The conclusion that can be drawn from the foregoing is that, although high-yielding aquifer systems occur in both the Ajali and Mamu Formations, the hydraulic relationship between the two systems indicates that the dominant flow in the connecting fractures and thus into the coal mines is from the unconfined aquifer in Ajali Sandstone. Flows from the Mamu aquifers are generally through the few minor fractures terminating within the formation or by upward seepage through the mine floor. Observations within the mine tunnels during the field study show that such flows are minor relative to the flux through the major fractures. For instance, the flow from the minor fractures were insignificant seepages, occurring as linear wet surfaces tracing the exposed fractures, whereas those from the major fractures occurred as springs at the walls of the tunnels. The discharge of the springs, estimated crudely using plastic containers, ranged to more than 0.5 l/sec/m of the exposed fracture.

Table 2. Summary of hydrochemistry of Enugu coal mine waters[a]

Constituent	Range (mg/l) Max	Min	Average conc.	No. of samples
Ca^{2+}	24.05	1.6	6.04	32
Mg^{2+}	158.08	6.08	31.94	32
$Na^+ + K^+$	20.88	3.52	7.13	30
SO_4^{2-}	420	14.8	136.39	32
SO_3^{2-}	0.6	2.2	1.38	19
Cl	17.37	1.99	4.86	32
$HCO_3^- + CO_3^{2-}$	80.5	3.4	31.25	32
Free CO_2	230	4.0	51.68	30
Free O_2[b]	8.0	1.5	4.0	50
Total Fe	25.76	8.4	8.94	32
TDS[b]	715	8.5	195.15	80

[a] Data sources: Egboka and Uma (1985), Okagbue and Onuoha (1986), and Ezeanyim (1988).

[b] Analyzed in this study.

Hydrogeochemistry

The hydrogeochemistry of waters from the coal mines and environs have been investigated by several authors including Egboka and Uma (1985), Okagbue and Onuoha (1986), and Ezeanyim (1988). Table 2 summarizes the available information while Figure 5 is a graphical display of the data on a ternary (Piper 1944) diagram. Magnesium and iron are the major cations. Mg^{2+} varies from 6.08 to 158.08 mg/l with an average of 31.94 mg/l in 32 samples, while iron varies from 0.4 to 25.76 mg/l with an average of 8.94 mg/l for the same number of samples. The other cations—sodium, potassium, calcium—are generally less than 10 mg/l. The major anion in most samples is sulfate (SO_4^{2-}). It ranged from 14.8 to 420 mg/l with an average of 136.39 mg/l and constitutes 44 percent to over 95 percent of the total ionic content (equivalent per

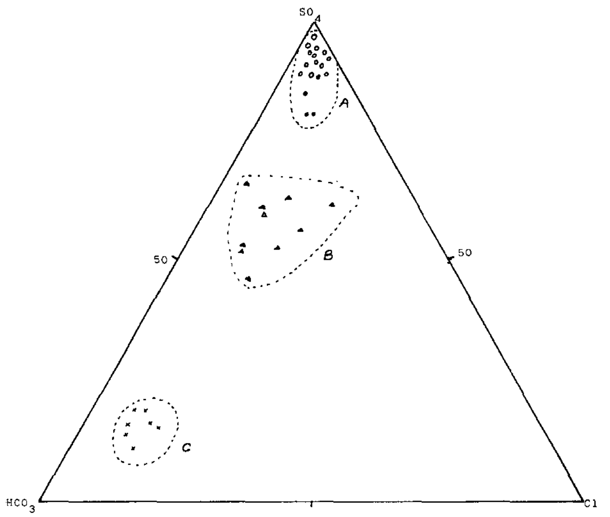

Figure 5. Graphical display of the data on a ternary diagram.

million [epm]). However, in a few of the samples, especially those from environments not directly influenced by mining activity, bicarbonate ion is dominant.

There is a characteristic ionic imbalance when the epm concentration of cations is listed against those of anions. The imbalance, which is in favor of anions, is ascribed to the presence of hydrogen sulfide and free sulfur (S_2^0) in the system. The oxidation of these materials to sulfate and sulfuric acid (as explained later) is not accompanied by a corresponding solution of cations; hence the ionic imbalance.

Figure 5 reveals the presence of three hydrochemical groups. In the first group, SO_4^{2-} constitutes more than 80 percent of the total anionic content (in epm). This group is associated with high anion content (>5.0 epm), high imbalance in the cation–anion fractions, and pH values less than or equal to 3.5. In the second group, SO_4^{2-} is still dominant but constitutes between 47 and 78 percent of the total anions. This group is characterized by medium anion content (3–5 epm) and moderate pH ranging from 4.0 to 5.6. The third group is characterized by low anion content (<2.0 epm) and relatively high pH (5.5–6.5).

There is also a distinct relationship between electric conductivity (EC) and total dissolved solids (TDS) and between EC and sulfate ions. These relationships are shown graphically in Figures 6a and 6b. From the graphs, the empirical relationship between the parameters may be expressed mathematically as;

$$\text{TDS} = 0.5\ \text{EC}$$

$$SO_4^{2-} = 0.42\ \text{EC}$$

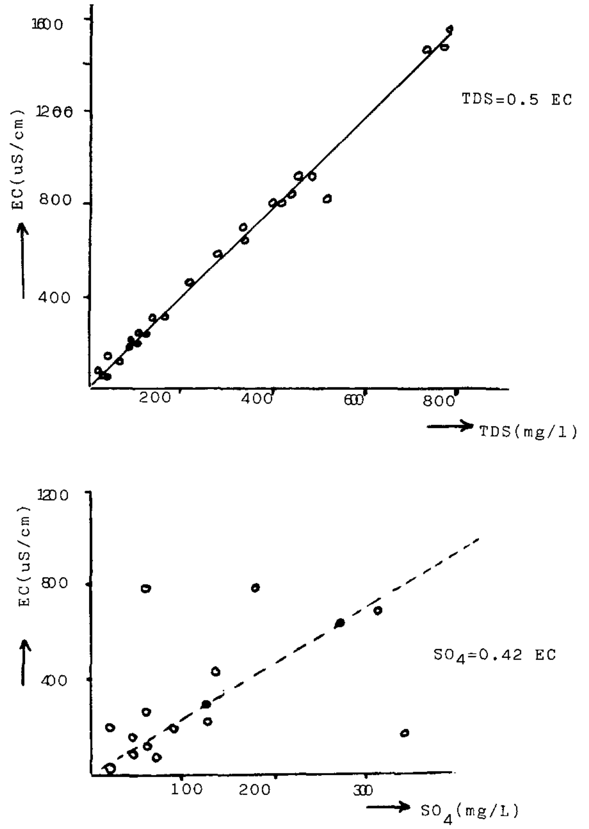

Figure 6. Graphical relationship between (a) electric conductivity and total dissolved solids and (b) electric conductivity and sulfate ions.

These equations, which are similar to those obtained from most groundwater environments (Lloyd and Heathcote 1985; Freeze and Cherry 1979), indicate that the TDS and SO_4^{2-} of the mine waters could be approximately obtained by measuring their ECs. These results lead to further field work as discussed in subsequent sections.

The pH similarly shows a relationship with the EC. Figure 7a is a graphical display of pH vs EC on arithmetic paper while Figure 7b is a semilog plot of the same data. These figures indicate that the pH has a logarithmic relationship with the electrical conductivity (EC). The implication is that the sources/causes of acidity and electric conductivity in the waters are related. The pH does not, however, show similar relation with SO_4^{2-} (Fig. 7c), and this was taken to imply that SO_4^{2-} is not the only source of acidity in the waters. This is compatible with field observations (as stated later) that the source water is already acidic before it comes into contact with solutes generated from mining.

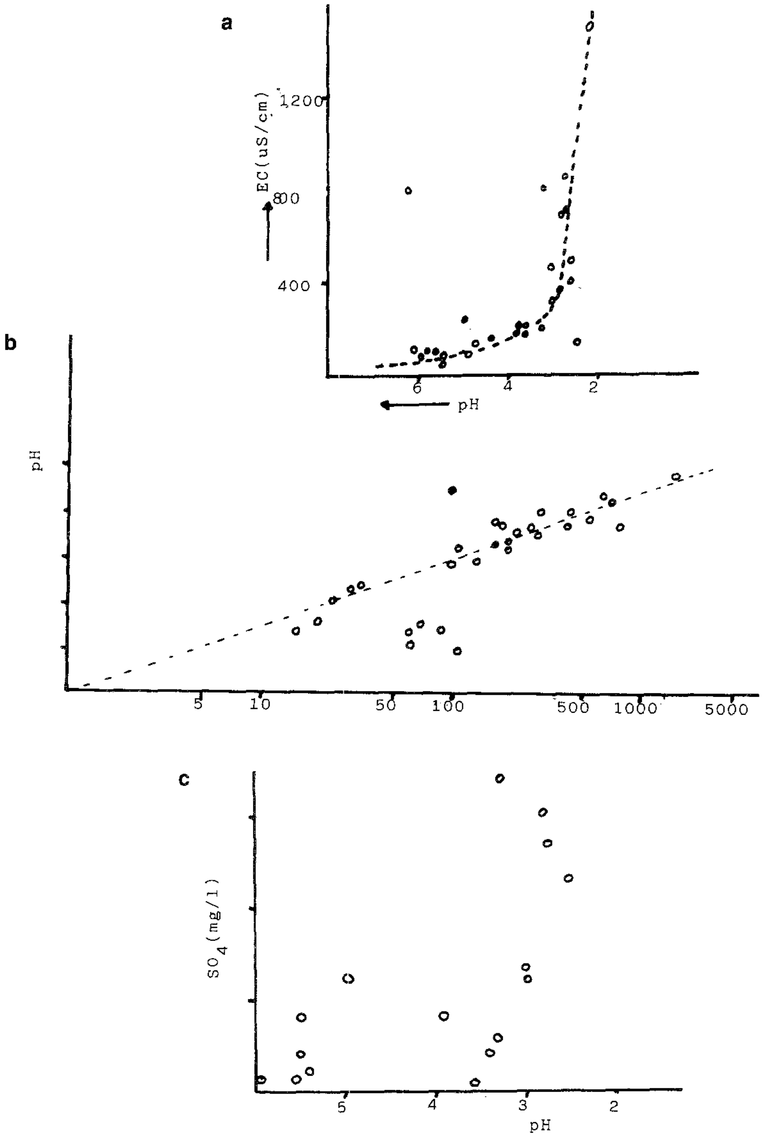

Figure 7. Graphical relationship between (a) pH and electric conductivity (arithmetic scale), (b) pH and electric conductivity (semi-log scale), and (c) between pH and sulfate ions.

Origin of Mine Water Pollution

A more detailed investigation was carried out to find the sources of the various groups of water in the mines and thus gain insight into the nature of hydrochemical activities in the mines. The investigation consisted of in-situ measurement of pH, EC, dissolved oxygen, and temperatures at several locations within the Onyeama mine using the WTW field chemical kit. The relationships between these hydrochemical parameters and the TDS and SO_4^{2-} of the mine waters have already been evaluated in preceding sections. Altogether 64 samples from seepage faces along fractures, longwall floors, subadit and main adit channels, and springs/streams issuing out from abandoned longwalls were analyzed. The data obtained are summarized in Table 3.

The EC of the samples ranged from 15 to 204 μS/cm with an average of 69.9 μS/cm for fracture water, 60–850 μS/cm with an average of 168.4 μS/cm for mixed water at longwall sumps; 71.5–108.6 μS/cm with an average of 80.3 μS/cm for streams in the abandoned longwalls; and 60.1–173.0 with an average of 74 μS/cm for the mixed water in adits. These values indicate large variability of the parameters within each section of the mine. The chemical activity within each section thus varies. However, there is a consistently high value of EC in the water at longwall sumps and generally lower values in the other sections. The electric conductivity of the mine waters has already

Table 3. Some in-situ properties of Onyeama mine water

Parameter	No. of measurements	Range		
		Min	Max	Mean
a. *Seepage water in fractures*				
pH	26	4.5	6.0	5.65
EC (μS/cm)	26	15.0	204	69.6
Dissolved O_2 (mg/l)	26	0.5	4.6	2.5
Temp (°C)	26	25.7	30.4	28.1
b. *Mixed water in longwall sumps*				
pH	15	2.8	5.7	4.9
EC (μS/cm)	15	60	850	168.4
Dissolved O_2 (mg/l)	15	2.5	5.6	4.7
Temp (°C)	15	27.6	29.3	28.7
c. *Stream from abandoned longwalls*				
pH	8	5.49	5.9	5.84
EC (μS/cm)	8	71.5	108.6	80.3
Dissolved O_2 (mg/l)	8	2.2	4.5	3.1
Temp (°C)	8	27.9	29.0	28.5
d. *Mixed water in Main Adit Channel*				
pH	10	3.9	5.69	5.2
EC (μS/cm)	10	60.1	173.0	74.0
Dissolved O_2 (mg/l)	10	3.3	6.0	5.6
Temp (°C)	10	28.4	29.6	28.7
e.[a] *Water issuing from the Mines in Adits 1 & 2*				
pH	5	4.9	5.62	5.39
EC (μS/cm)	5	45.2	52.7	48.92
Dissolved O_2 (mg/l)	5	7.4	8.0	7.68
Temp (°C)	5	28.3	28.6	28.5

[a] e represents the average contribution of the Onyeama mine water to environmental pollution in the area.

been shown to relate directly to the TDS and SO_4^{2-} content of the waters. The measured values thus indicate high TDS and SO_4^{2-} in the longwall sumps and relatively lower values in the other section of the mine.

The pH values also gave a definite variation pattern. In the fracture waters, the pH ranged from 4.5 to 6.0 with an average of 5.65, while the value in the longwall sump waters ranged from 2.8 to 5.7 with an average of 4.9. In the mixed water at the main adit, the pH varied from 3.9 to 5.7 with an average of 5.2. Streams from abandoned longwalls were generally similar in pH as the water seeping down along fracture faces.

The dissolved oxygen was found to be generally lower for water issuing directly as spring/seepage in the fractures (0.5–4.6 mg/l) than for water in the sumps and adit channels (2.5–6 mg/l). This is expected since the springs/seepages represent groundwater effluent that has little contact with ventilated air in the tunnels. The dissolved oxygen in the sumps and adits is due to tunnel ventilation. The dissolved oxygen in streams from abandoned longwalls is low (2.2–4.5), probably because the abandoned tunnels are not ventilated. The dissolved oxygen content of the mine waters was thus used as an additional indication of water source. The temperature of the waters was generally uniform (25.5–30.5°C), although the springs and seepages were often cooler (25.5–28.5°C) than the other sources.

A significant finding is that the EC and thus the TDS and SO_4^{2-} of the waters are highest in the longwall sumps, while the values in the other sections, especially the source water from the fractures, are low. Similarly, acidity (indicated by pH) is high in the longwall sumps and low elsewhere. However, the actual concentrations of these parameters within the longwalls vary from sump to sump. At five of the 15 measurement points (in the longwall sumps) the pH was less than 3.0 and EC more than 500 μS/cm, while in the rest, the pH was between 3.0 and 5.7 and EC between 60 and 170 μS/cm. The implications of this are further examined in the subsequent sections.

Hydrochemical History of Mine Water

The chemical activity in the various sections of the mine may be evaluated by tracing the chemical history of the mine waters. It has already been shown that mine water originates from groundwater fluxes down some of the fractures cutting through the mines. At the entrance point of the groundwater into the mine tunnel, pH and EC measurements indicate that the water is chemically pure, although with a pH of about 5.6. The acidity at this point is similar to that of groundwater obtained from the unconfined aquifer in the Ninth Mile well fields, which has been explained to be due to solution of carbon dioxide (Egboka and Uma 1985).

As the water flows into the sumps in the longwalls, it comes into contact and consequently reacts with solutes weathered out during mining. Existing data indicate that the solutes are mostly sulfur compounds associated with the coal seam. The sulfur compounds generally occur as the mineral pyrite (FeS_2), which is commonly associated with the coal seam and the underclay beds and sometimes as free sulfur (S_2^0). The reaction of interest, which is the oxidation of sulfur-rich minerals, sulfates, and sulfuric acid, is accelerated by the presence of H_2CO_3, already present in the groundwater, and dissolved oxygen derived from mine ventilation. This is represented by the following reaction equations:

$$2FeS_2 + 7O_2 + 2H_2O = 2FeSO_4 + 2H_2SO_4 \quad (1)$$

$$1/2S_2^0 + 2O_2 + 2H_2CO_3 = H_2SO_4 + 2HCO_3^- \quad (2)$$

$$Fe_2(SO_4)_3 + 6H_2O = 2Fe(OH)_3 + 3H_2SO_4 \quad (3)$$

The reactions result in increased dissolved ions and thus the electric conductivity of the sump waters. In addition, the pH is reduced by the H_2SO_4 generated. The reaction rate and the chemistry of the final sump water appear to depend on the amount of solute present. In some longwalls, where solute concentration in the coal seam is low, the pH of the resulting solution is relatively high and conductivities are moderate (60–170 μS/cm), whereas in areas of abundant solute concentration, the pH of the resulting solution is low (<3.0) and conductivities may range to more than 800 μS/cm. Water resulting from the latter plot as group 1 in the ternary diagram in Fig. 5. The varied concentration of solutes explains the variable concentration of the geochemical parameters in the longwall sumps.

Some of the reactions do not go to completion, probably due to insufficient contact/reaction time, as indicated by the presence of dissolved sulfides in the waters (Table 2). As mine water is pumped from the longwall sumps into the main adit channel and subsequently out of the mines, more chemical reaction probably takes place. However, the EC of the mine water is lowest at the exit of the mine (Table 3), while the pH is relatively high. This is due to dilution resulting from mixing of water from different parts of the mine (e.g., active and abandoned longwalls, etc).

Table 3a–d show the general chemistry of the water from the various sources within the mines, while Table 3e represents the average effect of several sources as measured at the main outlet (exit point of the adit). Table 3e thus represents the result of mixing water from sources a–d. The values, however, do not reflect the volumetric effect of each source since no flow measurement was made. This notwithstanding, the values in Table 3e are acceptable approximations of those in Table 3a–d.

The adit water is fed to nearby streams. As this final water that leaves the mine (tunnel) is not badly degraded, its effect on the gross chemistry of the receiving streams should be minimal. Measurements taken downstream (discussed in the next section) confirm this. In fact, the pH and electric conductivity of the streams to about 2 km downgradient is generally higher than 6.0 and lower than 50 μS/cm, respectively.

Pollution Potentials of Mine Waters

Three main streams, the Ekulu, Ogui and Agbani, receive mine-related drainage in the Enugu area. Only one—the Ekulu river—was investigated, partly because of its accessibility. In addition, the other two receive effluents from urban refuse dumps at several points, and it would be difficult to isolate the singular effect of mine-related activity. The Ekulu river receives effluent from the Onyeama mines. The three tunnels located in this area are the most actively worked and contribute about 75 percent of the current coal production in the Enugu area.

Sampling started at about 400 m upstream of the first mine-related dump and continued to about 2 km downstream of the last visible mine spoil dump. The parameters of pH, EC, and dissolved oxygen were again monitored at several points along the stream course, including immediately after the effluent of any mappable seepage from the mine spoil dumps and in-situ coal seams. It has already been shown that the pH and the EC are reliable indices of mine drainage in the area. In addition, five samples, one each from upstream and about 3 km downstream and three in between were collected and analyzed for their total iron content. Although this was not enough for detailed studies, it gave useful insight on the impact of mining on the stream.

Figure 8 is a plot of the pH, EC, and total iron versus the length of flow. Points where mine drains and seepage effluents from the spoils enter the stream are shown as arrows. The values of the parameters for

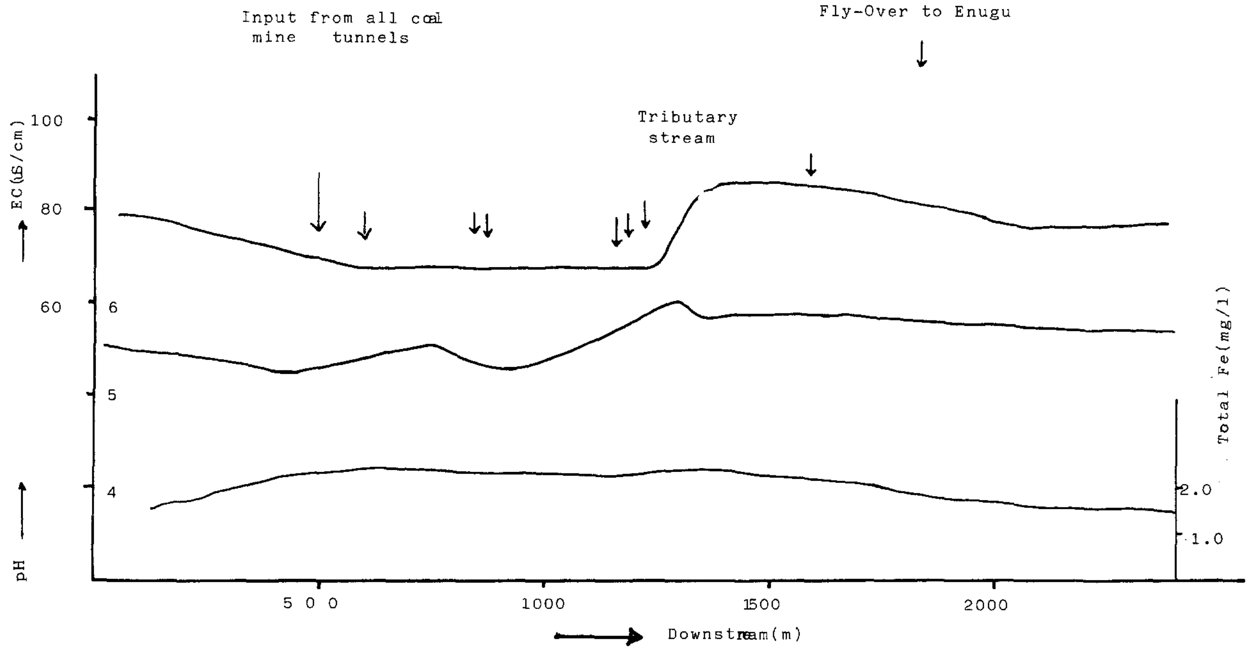

Figure 8. Variation of hydrochemical parameters downstream of the Ekulu River (in the vicinity of mining).

the various mine effluents at the point of entering the stream are listed in Table 3. The figure shows essentially the same trend for both pH and conductivity. This is expected since the two parameters have the same source. The pH showed more rapid fluctuation but within a range of 5.25–6.0. There is a noticeable drop in pH (increase in acidity) at the point of effluent of the coal mine drains and up to the last effluent seepage from the mine spoils, which are dumped some few tens of meters away from the immediate valley of the stream. The stream quickly recovers after the last mine spoil dump (at about 800 m from the mine tunnels). The recovery is indicated by the increase in pH to about 5.75 and is possibly related to the mixing and subsequent dilution from a tributary stream. As shown in Table 4 this tributary stream has a pH of 6.1 and EC of about 52 µS/cm. The two streams are not gauged, but casual evaluation shows the tributary to be about 60 percent of the main stream.

The electric conductivity curve is similar to that of pH but showed a sharper rise after the mixing of the two water sources. The rise in the conductivity at this region is rather surprising since the two streams have approximately the same value prior to the mixing. A possible explanation is chemical reactions leading to the dissolution of some suspended particles in the stream. The striking fact is that both pH and EC do not appreciably differ before and after input from the mine drainage and related activity.

It would appear (Table 4) that effluents from the several spoils dumped along the stream course and from the exposed coal seams have even more impact than those directly from the mine. Seepages from the spoils have pH values ranging from 3.0 to 4.5 and ECs of 140–905 µS/cm. This is high when compared to the corresponding values from the mines. However, although the seepages are numerous (about 22 seepages were encountered during the field survey), individual flows are less than 1.0 l/min and the combined discharge from all the seepages is less than 0.1 percent of the Ekulu river (which has flow of more than 1.0 m^3/sec in the region of the study). This probably explains why the bulk chemistry of the river was not significantly affected by the seepages. In the peak of the rainy season, when the seepages are more intensive, their impact may be more relevant. However, the concentration of the parameters may be lower and bulk flow of the Ekulu river will also increase in this period. The fractional effect of the mine spoil seepages may remain insignificant. Monitoring is still continuing and the true situation will soon be apparent.

Iron Pollution

Only five samples were analyzed for total iron concentration, and this is hardly enough for accurate projections. The result of the analysis is also plotted in Figure 8. The total iron content of the part of the stream unaffected by mining (upstream of the mines) is about 1.8 mg/l. This increased to about 2.3 mg/l in

Table 4. Some hydrochemical parameters of the Ekulu stream in the vicinity of the coal mine area

Sample	Type	pH	EC (μS/cm)	O_2 (mg/l)	Discharge (l/min)
1	Adit 1	5.4	46.8	7.7	2500
2	Adit 2	5.6	55.0	7.6	2500
3	Adit 3	4.0	103	3.6	2500
4	Seepage from mine spoil	5.5	92	7.1	0.5
5	Seepage from mine spoil	3.3	771	—	0.7
6	Seepage from mine spoil	3.0	905	—	0.2
7	Seepage from mine spoil	4.5	140	—	0.7
8	Seepage from mine spoil	4.7	104	3.8	1.2
9	Seepage from mine spoil	5.8	125	—	0.2
10	Seepage from coal seam	5.3	98	5.3	0.2
11	Seepage from coal seam	3.9	295	6.0	0.1
12	Seepage from coal seam	3.9	255	4.2	2.5
13	Seepage from coal seam	5.3	70.2	4.2	1.5
14	Seepage from coal seam	5.7	71.0	—	0.8
15	Tributary stream	6.5	76.0	7.5	—
16	Tributary stream	6.0	122	8.2	—
17	Main tributary	6.1	51.7	7.2	—

the region where mine drainage and seepage from related activities enter the river. At about 1.0 km downstream of the last mine effluent, the stream recovers and iron content decreased to about 1.5 mg/l. Despite the sparse data, it is clear that the stream was already polluted with respect to the dissolved iron content, and the effect of mining (which is a subdued increase by about 0.5 mg/l) quickly disappears some 2 km downstream of the mine.

Concluding Remarks

The Enugu coal mine environment contains two aquifer systems—an unconfined aquifer in the Ajali Sandstone and a confined aquifer system in the Mamu Formation. These aquifers are prolific and are connected by a system of fractures. Field observations show that the mine water originates from groundwater down-fluxing through the fractures into the mine tunnels. Hydrodynamic considerations indicate that the fracture water is generally from the unconfined aquifer. However, minor flows occur from the confined aquifer mostly by upward flow through the tunnel floor.

The water is polluted after it has entered into the mines. The major hydrochemical activity is oxidation and occurs within the sumps in the longwalls. The sumps act as oxidation chambers where groundwater from the fractures react sulfur-rich solutes released from mining. The rate of reaction varies and so does the chemistry of the resulting water. In favorable situations, the pH of the water may be lower than 3.0 and electric conductivity higher than 800 μS/cm, while in unfavorable situations little reaction takes place and the mine water has a chemical quality similar to the groundwater in the aquifers.

Generally, the water from the several sections of the mine is mixed before reaching the exit at the mine entrance. This results in dilution and improvement of water quality. The final water that leaves the mines is not seriously degraded except for high iron content (about 8.9 mg/l) and acidity (pH 5.4). Measurements downstream show that the mine water has only a minor impact on the chemical quality of the receiving streams.

Groundwater influx into the mines cannot be prevented, considering the hydraulics of the area. However, the problem it poses to mining may be reduced by accurate mapping and advanced prediction of the location of the fractures. This would help the miners prepare for the high groundwater influx that would result when a fracture is intercepted.

The environmental effect of the mine water may be reduced and eventually eliminated by treating and recycling it for use. Treatment of the mine water may not be costly, since it only involves aeration to remove the dissolved iron and addition of lime to improve the pH.

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