QUANTITATIVE MODELS TO PREDICT THE RATE AND SEVERITY OF ACID SULPHATE DEVELOPMENT:
A CASE STUDY IN THE GAMBIA

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1 Summary

Using a static model, the amount of acid produced following drainage of sulphidic material can be calculated from the quantity of pyrite sulphur in excess of the soil's neutralizing capacity.
A dynamic model is developed in which the rate of sulphide oxidation is assumed to be controlled by the rate of diffusion of oxygen through water-filled pore space. The rate of acid production is then determined by (1) the excess pyrite S content of the material and (2) its surface to volume ratio - in effect soil structure. Following drainage, unripe soils fissure into coarse prisms of radius less than length. This structure can be modelled approximately by solving equations for the diffusion of oxygen into cylinders.
Both pyrite S and soil structure development occur naturally over a range of values that significantly affects the rate of acid generation. Tables are presented showing the influence of S content and ped size on acid production.
The model is applied to the potential acid sulphate soils of the Gambia. Severe acidity is predicted to develop rapidly if the watertable is lowered. The actual pH values of the soil and river water will depend on the drainage regime and the effectiveness of flushing of acid from the soil to the drainage water.

2 Introduction

Farmers, engineers, planners and investors confront the soil scientist with practical problems of land reclamation. Specific, quantitative answers are required to the following questions:

nature of the problem: 'What problems can be expected?'

extent: 'Where and when will those problems occur?'

magnitude: 'How severe will these problems be; what effects will there be on crop yields, water quality, fisheries and engineering structures?'

alleviation: 'What should be done about it?'

Although the questions and answers are necessarily related to specific development schemes, we must have a theoretical basis for making quantitative predictions. In this paper a physical model of sulphide oxidation is developed to predict the rate of generation of acidity following the drainage of sulphidic material. This model is used to answer some practical questions involved in a major land development project in The Gambia. We accept that the model involves major simplifying assumptions but stating the assumptions serves a useful purpose in identifying those areas where further work is needed and where accurate data are essential.

3 The Gambia Barrage Project

The river Gambia (Figure 1) flows through a region of strongly seasonal climate with an average rainfall of about 1000 mm during a five month wet season and no rain during the seven month dry season. The river is tidal for a distance of more than 200 km upstream and in the dry season, when fresh water flow is much diminished, a tongue of salt water moves upstream almost to the tidal limit. During the wet season fresh water flushes downstream, enabling rice to be grown in the inter-tidal zone when the salt has been washed out from the surface soil.

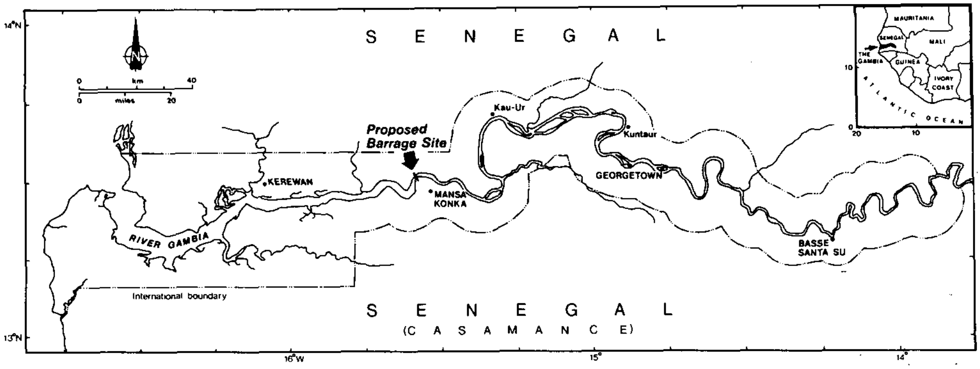


Figure 1. The Gambia: proposed location of barrage

Lower than average fresh water flows, or any increase in the present low level of abstraction of water from the river for irrigation in the dry season, will increase the upstream migration of salt water in the dry season and attenuate the downstream flush of fresh water in the wet season. This will jeopardize some of the existing areas of tidal rice cultivation, estimated to be about 13-19 thousand hectares. A feasibility study has been carried out for a scheme to build a barrage across the tidal river to create, upstream of the barrage, a reservoir of fresh water which would be available for irrigation of a second rice crop in the dry season.

Figure 2 shows the predicted water level of the reservoir assuming average river flow (measured over the period 1970/1971 to 1975/1976) and different levels of water abstraction for irrigation. In the driest of the five years measured, the shortfall of river compared with the average was equivalent to the water use of about 7000 ha irrigated rice.

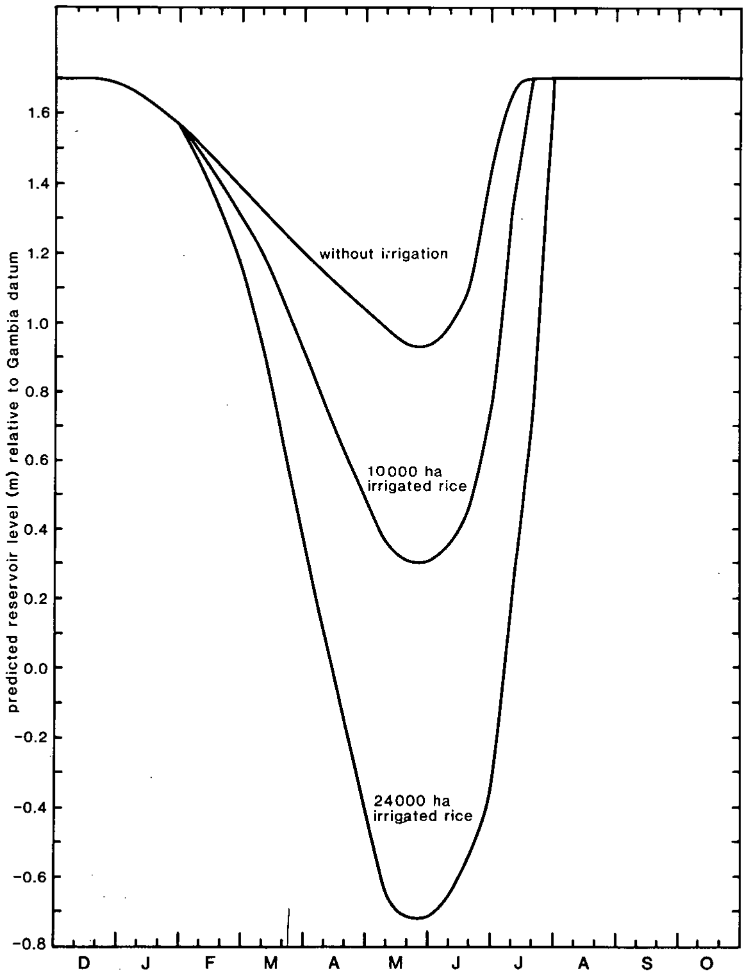


Figure 2. Gambia barrage scheme: predicted water levels in reservoir with water abstraction for different areas of irrigated rice, assuming mean river flow

A reconnaissance soil survey of the area upstream of the proposed barrage (Coode and Partners 1979) indicated extensive areas of unripe, sulphidic soils which would be exposed to the air at low reservoir levels. Subsequent detailed survey (Thomas and Varley, this symposium) demonstrated the presence of 12,900 ha of sulphidic soils upstream of the proposed barrage site.

The elevation of the sulphide datum - the level below which the soil is sulphidic - was established by levelling transects across the intertidal zone, along which stakes coated with red-lead paint were implanted (Figure 3). Hydrogen sulphide generated in the horizon of active sulphate reduction turned the paint black within a week, leaving on the stakes a permanent record of the upper limit of present sulphide accumulation.

The upper limit corresponded closely with the upper boundary of the practically unripe Gr horizon (Dent 1980) identified in the field, and was confirmed by analyses of total S contents (Table 1). Below this level the soils were strongly sulphidic.

Table 1. *Gambia barrage project. Reconnaissance soil survey: soil salinity, sulphur and pH values*

Soil association[1]	Profile Nr.	Horizon[2]	Depth cm	EC_s mS/cm	Total S[3] %	Field pH	pH on exposure[4] 3 (months)	24	Observations on oxidized *samples*
As	03	Gr wγ	1-5	3.0	2.5	7.0	2.8	2.8	
practically			30-50	7.1	5.6	>7.0	2.8/3.0	1.6	heavy jarosite crystalli-
unripe and			80-85	6.1	2.6	7.0	1.5	1.6	sation + some $Al_2(SO_4)_3$
half ripe									
saline gleys	04	Go2 p	0-10	0.6	0.2	5.7/6.5	5.7	6.9	
		Go1 wβ	15-20	1.9	0.3	7.0	5.3	4.2	
		Gr wγ	50-60	9.4	2.4	7.0	1.9	1.2	heavy jarosite
			90-100	7.8	2.0	7.0	1.6	1.6	deposition
	11	Gr p	5-10	2.6	1.3	5.0/5.9	5.3	3.8	
		Gr wγ	40-45	5.4	3.2	5.5/5.9	1.5	1.5	
			90-100	5.2	1.6	6.5	2.0	1.5	
	12	Go1 p	0-10	2.8	0.2	5.3/5.9	5.3	4.6	
		Gr wγ	40-50	9.6	0.9	4.5	3.1	2.7	
			90-100	9.6	3.4	5.9	1.6	1.5	
	16	Gr wγ	10-15	4.2	8.2	5.7/5.9	1.4	1.1	heavy jarosite + gypsum
			40-45	n.d.	3.4	6.5	1.7	1.4	heavy jarosite
			70-80	6.7	6.0	6.9	2.3	1.2	deposition
			100-110	8.4	2.6	6.9	2.5	1.6	
	23	Gr p	10-20	2.2	0.4	6.2	5.0	3.4	gypsum deposition
		Gr wγ	30-40	2.2	2.5	5.9	2.0	1.7	
			90-100	2.2	1.4	5.9	2.1	1.9	
Bs	01b	Go2 wα	30-35	8.6	0.2	5.0/5.7	5.0	4.1	
nearly ripe		Go1 wα	65-70	10.4	0.15	4.7/5.7	4.7	4.2	
saline		J2 wγ	100-110	20.6	n.d.	3.5/4.5	4.5	3.7	
gleys									
	05	Go2 p	0-5	0.7	0.4	5.7/5.7	5.7	5.5	
		Go1 wβ	20-25	0.7	1.2	6.9	3.1	2.6	
		Gr wβ	70-75	12.3	3.6	7.0	2.2	1.1	
	10	Go2 p	0-10	1.7	0.5	6.2	5.7	6.4	
		Go2 wα	15-20	2.0	0.1	4.7/5.0	5.0	4.6	
		Go1 wβ	40-50	2.3	0.6	5.0/5.7	5.1	5.2	heavy iron oxide deposition
		J2 wγ	50-60	4.3	0.6	4.5	4.3	4.3	
		Gr wγ	90-100	4.7	0.6	4.5/6.2	4.3	4.2	
	18a	Go2 p	10-20	0.8	0.2	5.5/5.7	5.5	4.4	
	18c	J2 wβ	30-35	0.7	0.1	4.7/5.7	4.0	3.8	heavy iron oxide deposition
	19	Go2 p	10-15	1.0	0.25	5.3	5.3	3.8	
		Go2 wα	30-35	0.7	0.2	5.3	5.0	3.8	
		Go1 wβ	45-50	1.0	0.1	4.7	4.9	3.7	

Notes are explained on next page.

Table 1 (continued)

Soil association[1]	Profile Nr.	Horizon[2]	Depth cm	EC_s mS/cm	Total S[3] %	Field pH	pH on exposure[4] 3 (months)	24	Observations on oxidized samples
Cs	08	Ah	1-6	0.3	0.6	5.4	5.3	4.9	
ripe saline		Bg cs	20-25	0.7	0.03	5.7	5.7	6.3	
gleys		Bg	40-50	1.7	0.2	6.0	5.7	7.7	shell present
		Go2 wα	60-80	1.1	0.3	6.5/7.0	6.2	7.0	shell present
	09	Ahg	10-20	1.3	0.2	5.4	5.5	4.4	
		Bg	50-60	2.3	0.1	5.3	5.5	5.0	
		Go2	90-100	8.1	0.6	5.0	5.0	4.7	
	20	Bg	15-20	0.4	n.d.	5.3	5.2	4.4	
		Bg2	45-50	5.2	0.1	4.7/5.0	5.0	4.7	
B	25	Go2 wα	10-20	n.d.	0.6	5.7	5.0	4.0	
nearly ripe		Go1 wβ	50-55	2.4	0.1	4.7/5.0	5.0	4.0	
gley		Gr wγ	90-100	0.5	0.3	5.5/5.7	4.8	3.9	
C	24	Apg	0-10	2.2	0.05	5.9/6.0	5.5	4.2	
ripe gley		Bg	30-40	1.3	0.12	4.7/5.5	5.0	4.2	
		Bg2	55-60	1.3	0.02	5.0/5.5	5.3	4.8	
D		Ah	0-5	0.2	0.03	5.9	5.0	n.d.	
imperfectly		Ag	20-25	0.6	0.05	5.0/5.7	4.9	n.d.	
drained, ripe		2Bg cs	65-70	0.2	0.01	6.5	4.3	n.d.	
alluvial gley		3Bg cs	100-110	0.3	0.25	6.0	4.6	n.d.	

[1] Soil associations and profiles from 1:100,000 reconnaissance survey, Coode & Partners 1978

[2] Horizon nomenclature follows Dent 1980:

Gr	not ripe, permanently reduced, sulphidic
Go1	not ripe, partly oxidising, usually sulphidic
Go2	not ripe, mottled, not sulphidic
J2	not ripe, jarosite pore fillings and cutans, severely acid
A	ripe topsoil
B	ripe, mottled and structure development

Additional subscripts:

p	cultivated topsoil
h	uncultivated topsoil rich in organic matter
g	gley morphology in ripe soils
cs	gypsum deposition
wα	nearly ripe
wβ	half ripe
wγ	practically unripe

[3] Total S determined by X-ray fluorescence

[4] pH on exposure: 500 g samples were stored at field moisture content at 25°C in thin-walled polythene bags and pH measured using a glass electrode pH meter after 3 and 24 months

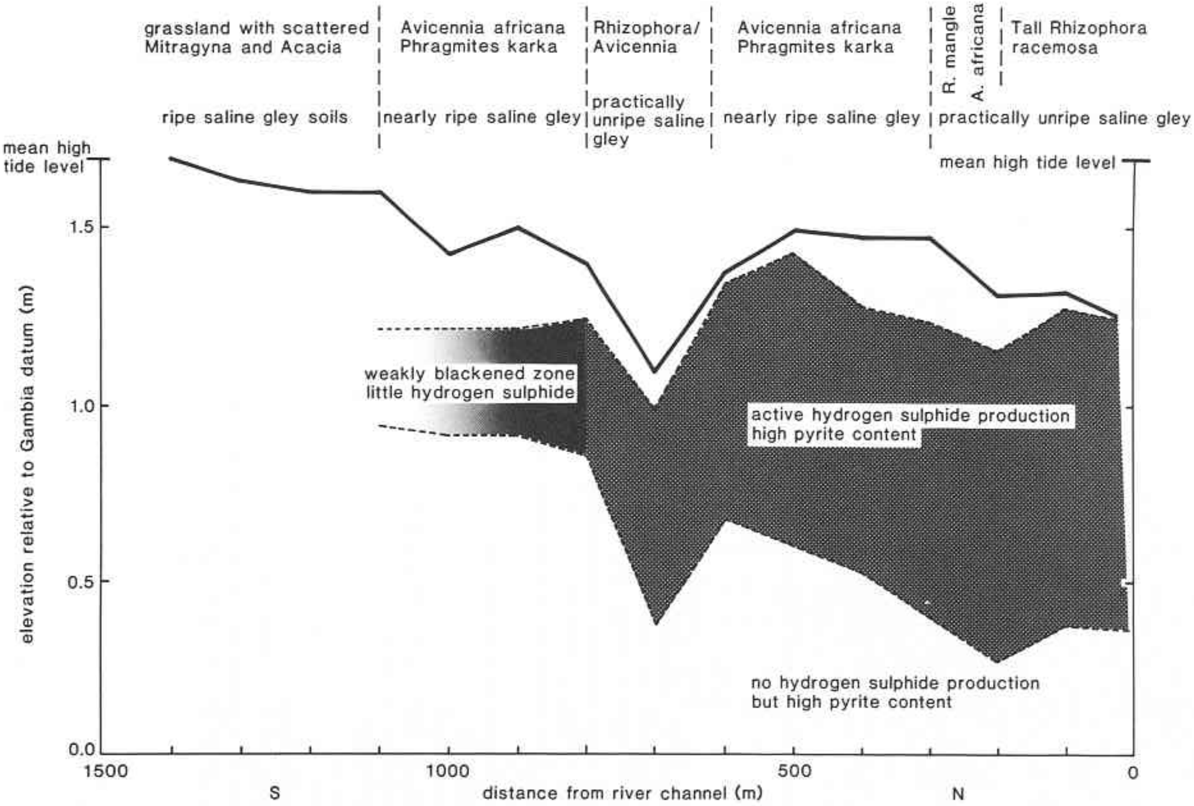


Figure 3. Levelled transect at Sankwia 5 km northeast of Mansa Konko, The Gambia: vegetation, soils and level of sulphide datum

The mean elevation of the sulphide datum in the proposed reservoir area (Figure 3) is +1.3 m above Gambia datum and mean high tide level is +1.7 m. Under a conventional barrage operation, abstraction of water for irrigation of 24,000 ha irrigated rice would lower the water level in the reservoir more than two meters below the sulphide datum in a year of average river flow. Under these conditions acidification of the sulphidic material is inevitable. Figure 4 shows the ultimate pH value, plotted against total sulphur content, of samples collected during the reconnaissance survey which were allowed to oxidise slowly at their field moisture content in thin-walled polythene bags.

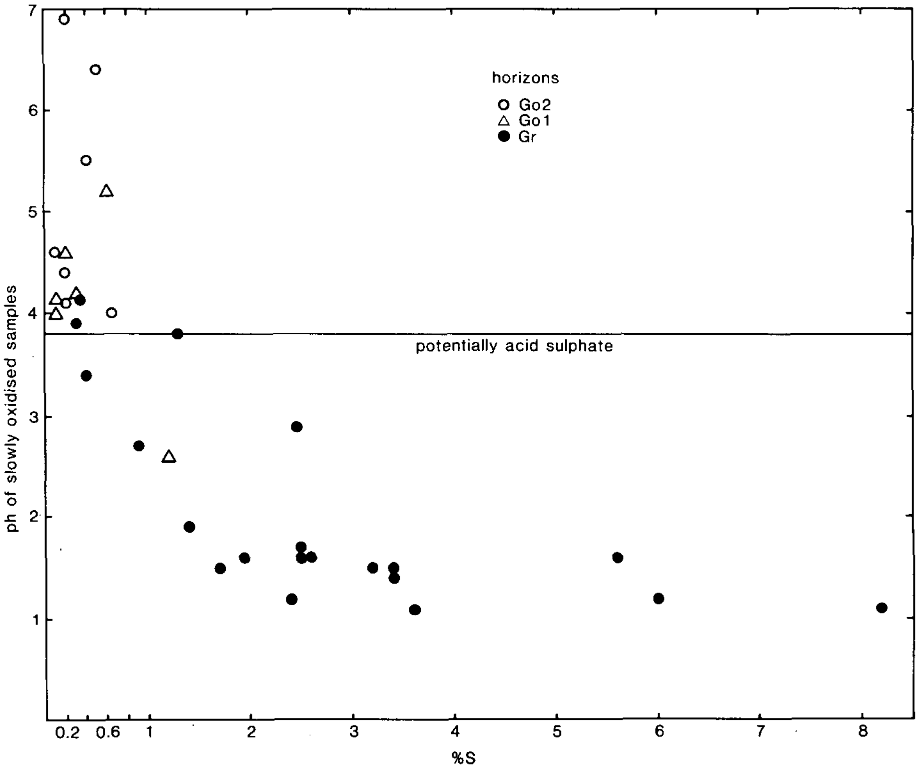


Figure 4. Total sulphur content, and pH values of samples after 2 years oxidation under moist conditions

4 Prediction of the rate and severity of acid sulphate development

Oxidation of wet mud in polythene bags serves to identify the acid sulphate problem, but is inadequate to forecast the rate of acid generation and the fate of the acid under a range of possible drainage conditions in the field. We have tried to estimate the rate of acid production using a simplified model of oxidation by diffusion of oxygen into the sulphidic material.

4.1 A static model

The amount of acid generated depends on the initial concentrations and the fate of the iron sulphides. Four possible cases have been identified:

1) All iron oxidized and remaining in solution as Fe^{3+}

$$FeS_2 + \frac{15}{4} O_2 + \frac{1}{2} H_2O \rightarrow Fe^{3+} + 2SO_4{}^{2-} + H^+ \qquad (1)$$

2) Iron released as Fe^{2+}

$$FeS_2 + \frac{7}{2} O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4{}^{2-} + 2H^+ \qquad (2)$$

3) All iron oxidized and hydrolyzed to iron III hydroxide

$$FeS_2 + \frac{15}{4} O_2 + \frac{7}{2} H_2O \rightarrow \underset{\substack{\text{iron III}\\ \text{hydroxide}}}{Fe(OH)_3} + 2SO_4{}^{2-} + 4H^+ \qquad (3)$$

4) Formation of jarosite

$$FeS_2 + \frac{15}{4} O_2 + \frac{5}{2} H_2O + \frac{1}{3} K^+ \rightarrow \frac{1}{3} \underset{\text{jarosite}}{KFe_3 (SO_4)_2 (OH)_6} +$$

$$\frac{4}{3} SO_4{}^{2} + 3H^+ \qquad (4)$$

The conspicuous deposition of hydrated iron oxide and jarosite in young acid sulphate soils suggests that the net result of pyrite oxidation in sulphidic materials is represented by equations (3) and (4).

Van Breemen (1976) argues that in acid ($pH < 4.4$) oxidized environments ($Eh > 400$ mV) jarosite is more stable than amorphous ferric oxide; and field observations confirm that the more severe the acidity, the more dominant is jarosite deposition over iron oxide deposition. Acid generation according to equation (4) is pursued below. In terms of acid production per mole of pyrite this equation predicts three moles of H^+. Although jarosite is ultimately hydrolized to goethite, releasing a further mole of H^+, this reaction goes to completion over many years rather than months under field conditions.

The Gambian sulphidic Gr horizons analyzed have a mean sulphur content of 3.5 per cent, equivalent to 6.54 per cent by mass of pyrite. Assuming an apparent density of 0.63 g cm^3 (Dent 1980 and a small number of determinations in samples from The Gambia), the amount of pyrite per cubic meter of sulphidic material is 3.44×10^2 moles. By equation (4) oxidation of this pyrite will liberate 10.31×10^2 moles H^+.

To estimate the net production of acid, a measure of the neutralizing capacity of the soil is required. Calcium carbonate in the form of shell was rarely observed in the field. In the absence of carbonates the only acid-consuming reactions at low pH values are ion exchange and the incongruent dissolution of silicates.

All sulphidic soils examined were of clay texture, clay content ranging from 56-80 per cent, but there are no data on clay mineralogy or cation exchange properties. The principal sources of sediment are likely to be highly weathered detrital sediments of Tertiary age dominated by quartz and kaolinite (Dunsmore et al. 1976). Determinations of cation exchange capacity of comparable ripe, non-sulphidic soils (Jackhally and Kudang Series) range from 8-20 m.e. per 100 g for samples low in organic matter up to 30-35 m.e. per 100 g for samples with 5-6 per cent carbon, that is 15 and 30 m.e. per 100 g clay (Land Resources Division, unpublished). This suggests a clay fraction of mixed composition, predominantly kaolinite but with some illite or smectite.

Cation exchange is a source of instant neutralization. If we adopt a medium value of 20 m.e. per 100 g cation exchange capacity, excess acid production will be 9.05×10^2 moles H^+ per cubic meter. This free acid released by oxidation of pyrite may remain in situ to react slowly with the residual silicates or may be leached from the system.

Under artificial oxidizing conditions where all the acid remains in situ, buffering reactions maintain the pH values above 1.0 (Table 1) but the extent of neutralization in the field will depend on the rate of acid generation and the effectiveness of leaching.

4.2 A dynamic model

4.2.1 The rate of oxidation of pyrite

The sulphidic material is initially close to neutrality but it acidifies rapidly on exposure to oxidizing conditions.
The lower pH brings Fe^{3+} into solution and promotes a rapid catalytic oxidation of pyrite

$$FeS_2 + 14\ Fe^{3+} + 8H_2O \rightarrow 15\ Fe^{2+} + 2SO_4{}^{2-} + 16H^+ \qquad (5)$$

Fe^{3+} is returned to the system by bacterial oxidation of Fe^{2+} by *Thiobacillus ferrooxidans*

$$Fe^{2+} + \tfrac{1}{4}\ O_2 + H^+ \rightarrow Fe^{3+} + \tfrac{1}{2}\ H_2O \qquad (6)$$

The rate of reaction will be controlled by the surface area of the pyrite and the rate of transfer of oxidants (O_2 and Fe^{3+}) into the system. In the case of recently deposited sulphidic materials such as the Gambian alluvium in which the particle size of the pyrite is small, the rate limiting factor is likely to be the diffusion of oxygen into the system.

4.2.2 Simplifying assumptions

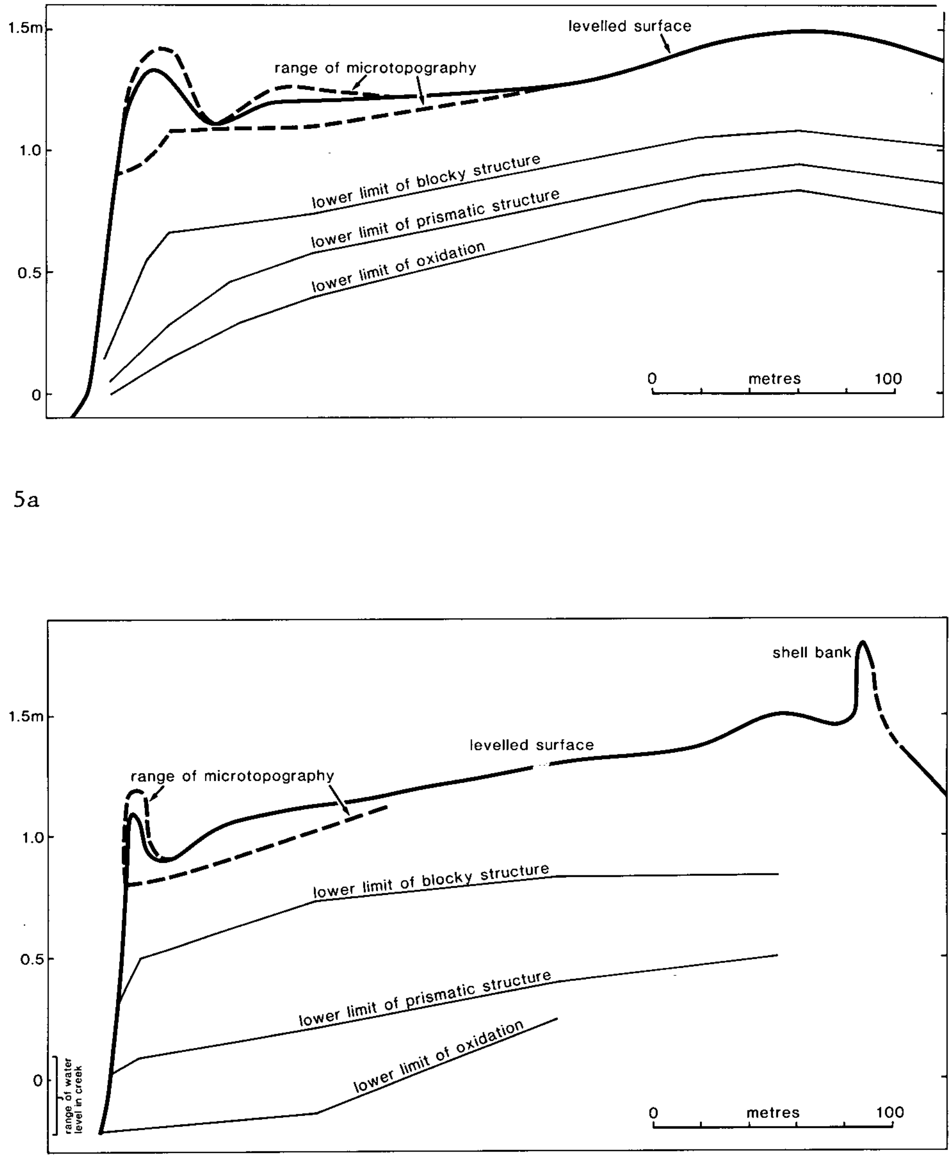
1) *The rate of oxidation of pyrite is controlled by the rate of O_2 transport through water filled pores,* i.e. rate of reaction is faster than the rate of diffusion.
2) *Oxidation of organic matter consumes negligible oxygen compared with oxidation of pyrite.*
3) *No blockage of pores by precipitates.*

4) *No hindrance of O_2 diffusion* by collision and interaction with soil particles (i.e. sediment tortuosity factor = 1, tortuosity is likely to be small for non-charged, molecular species).

If we assume that the rate-limiting process is diffusion of oxygen through water-filled pores, then the rate of oxidation at any point will be related to the distance from the air-water interface. Practically unripe soils under mangrove vegetation are typically very permeable, because of a large proportion of coarse bio-pores, and auger holes bored to 1 m fill with water within a few minutes. However, unless ripening and consequent deep fissuring of the soil mass takes place, lateral drainage over longer distances may be very restricted. The sulphuric horizons of young acid sulphate soils of clay texture commonly fissure into prismatic peds of the order of 20-30 cm cross section. As ripening proceeds these peds fissure into smaller cubic blocks. However, in the absence of artificial drainage the depth of fissuring is reduced at increasing distances from natural creeks (Figure 5).

We are making the further assumption that:

5) *The soil fissures into prismatic peds*, of radius << length, and further that the diffusion of oxygen into these peds can be approximately equated to the rate of diffusion of oxygen into cylinders of equivalent radius.



5a

5b

Figure 5. Levelled traverses of polders in Northland, New Zealand showing the lower limits of structure formation and oxidation relative to the water level in draining creeks

a) Waireia Creek after 7 years drainage

b) Omanaia River after 15 years drainage

4.2.3 *Calculation of rate of oxidation*

At time t = 0 the water in pores opening to the surface of the ped becomes saturated with oxygen and the soil is oxidized from the surface inwards. The model assumes instantaneous reaction, so the effect of diffusion plus reaction is analogous to diffusion alone, but with a correspondingly reduced diffusion coefficient - in effect slower diffusion (Crank 1975). If the true diffusion coefficient of dissolved oxygen is D, then the appropriate reduced value for the case of diffusion plus reaction is given by $\frac{D}{R+1}$, where R is defined as below.

Concentration of oxidizable material, expressed as the number of moles of O_2 required for its oxidation	= R ×	Concentration of O_2 in water, expressed in moles

Under reaction conditions of 30°C and $5^{o}/oo$ salinity, the solubility of oxygen is 4.58×10^{-4} moles per litre.

Volume of a cylinder with radius 10 cm and length 200 cm = 6.28×10^4 cm^3
= 62.8 litres.

Mass of this cylinder = $6.28 \times 10^4 \times 0.63$ (apparent density).

Mass of pyrite = $6.28 \times 10^4 \times 0.63 \times \frac{6.54}{100}$
= 2.59×10^3 g
= *21.6 moles pyrite*

This pyrite consumes $21.6 \times \frac{15}{4}$ moles O_2 = *80.9 moles* O_2.

The cylinder has 77 per cent water filled pore space, so there are 48.4 litres of water. Thus the pyrite consumes $\frac{80.9}{48.4} = 1.67$ moles O_2 per litre of water.

We can now evaluate R:

$$1.67 = R \times 4.58 \times 10^{-4}$$
$$R = 3.64 \times 10^3$$

At 30°C the diffusion coefficient D, for O_2 in water = 2.62×10^{-5} cm^2 s^{-1} (Lerman 1979, p. 76), thus D corrected from diffusion plus reaction

$$= \frac{2.62 \times 10^{-5}}{3.64 \times 10^{3}}$$

$$= 7.2 \times 10^{-9}\ cm^2\ s^{-1}$$

Crank (1975) gives the solution for diffusion (non-steady state) into a cylinder as:

$$\frac{Mt}{M_\infty} = 1 - \Sigma_{n=1}^{\infty} \frac{4}{a^2\ \alpha_n^2} \exp\ (-D\alpha_n^2 t)$$

where

Mt = quantity of diffusing substance which has entered the cylinder in time t

M_∞ = corresponding quantity after infinite time, i.e. complete oxidation

a = radius of cylinder

D = diffusion coefficient

t = time

α_n = the root of Jo $(a\alpha_n) = 0$

Jo is the Bessel Function of order zero. Values of α_n are given in tables (Aramowitz and Steyum 1965). The diffusion equation must first be transformed so that each α_n is accompanied by a, i.e. $(a\alpha_n)$ because the tables give values of Jo for $(a\alpha_n)$.

$$\frac{Mt}{M_\infty} = 1 - \Sigma_{n=1}^{\infty} \frac{4}{(a^2\alpha_n^2)} \exp\ \{ -D \frac{(a^2\alpha_n^2)t}{a^2} \}$$

n	1	2	3	4	5	6
$a\alpha_n$	2.4048	5.5201	8.6537	11.7915	14.9309	18.071
$a^2\alpha_n^2$	5.783	30.47	74.87	139.0	222.9	326.6

We are going to sum a series of diminishing terms to infinity. Except for very large values of a, this series converges rapidly. t is in seconds so replace by T in years

$$t = T \times 3.15 \times 10^7$$

Note that $\frac{Mt}{M_\infty}$ corresponds to the fraction of the cylinder oxidized.

Rates of oxidation for different sizes of cylinder

For a cylinder 30 cm diameter, a = 15 cm.

$$\frac{Mt}{M} = 1 - (0.692.e^{-0.0058T} + 0.131.e^{-0.031T} + 0.053.e^{-0.074T} +$$

$$0.029.e^{-0.14T} + \ldots)$$

For T = 1 year $\frac{Mt}{M_\infty} = 1 - \sim 0.912 = 0.08$

For T = 5 years $\frac{Mt}{M_\infty} = 0.146$

For T = 50 years $\frac{Mt}{M_\infty} = 0.46$

For decrease in a, the rate of oxidation increases significantly. A summary of calculated values of degrees of oxidation as a function of time and diameter of cylinder is presented in Table 2 and Figure 6.

Table 2. Rate of oxidation for different cylinder sizes, 3.5% S

Time (years)	5	10	20	30	50
Fraction oxidized					
30 cm diameter	0.15	0.22	0.30	0.36	0.46
20 cm	0.23	0.32	0.42	0.52	0.64
15 cm	0.30	0.41	0.55	0.65	0.78
10 cm	0.43	0.58	0.76	0.86	0.95

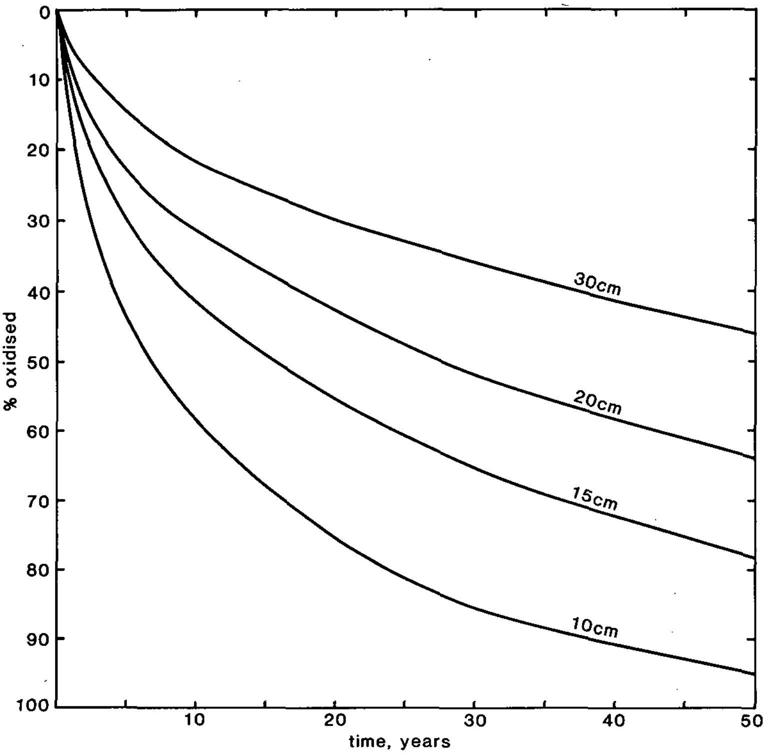


Figure 6. Rates of oxidation of pyrite for cylinders of different diameters, at a sulphur content of 3.5%

Rates of oxidation for different pyrite contents

The above calculations refer to sulphidic material of 3.5 per cent total S = 6.54% pyrite.

Similar calculations have been performed for 2% S (3.75% pyrite) and 5% S (9.38% pyrite), for cylinders of diameter 15 cm and 30 cm. New values for R must be evaluated for different pyrite contents.

Data for the fraction of material oxidized as a function of time for different pyrite contents are presented in Table 3, and plotted in Figure 7.

Table 3. Rate of oxidation (fraction oxidized) for different S contents and cylinder diameters

Time (years)	5	10	20	30	50
Cylinder diameter 15 cm					
2.0% S	0.39	0.52	0.69	0.79	0.91
3.5% S	0.30	0.41	0.55	0.65	0.78
5% S	0.25	0.35	0.47	0.56	0.69
Cylinder diameter 30 cm					
2% S	0.20	0.28	0.39	0.46	0.57
3.5% S	0.15	0.22	0.30	0.36	0.46
5% S	0.13	0.18	0.25	0.31	0.39

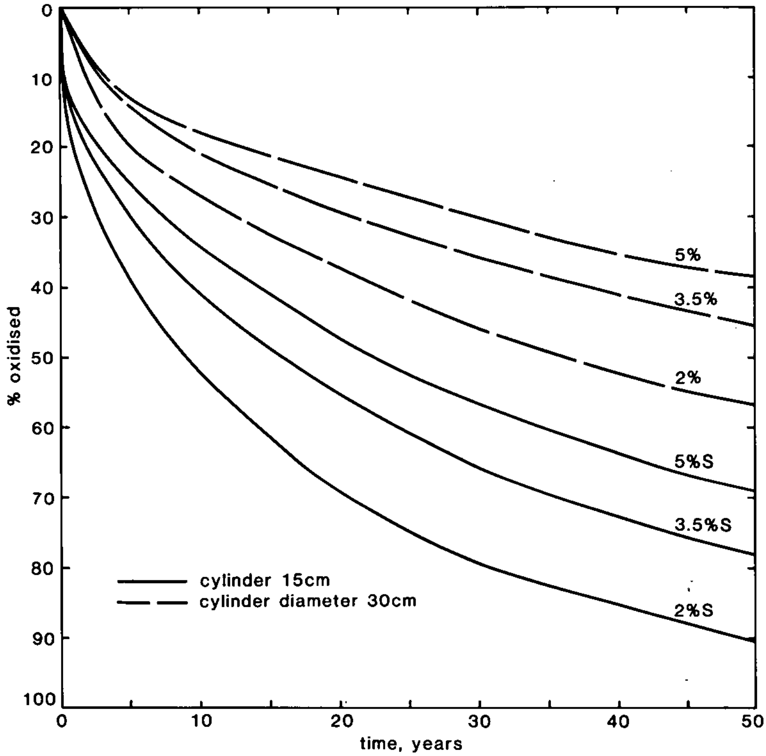


Figure 7. Rates of oxidation of pyrite for materials of different sulphur contents, in cylinders diameter 15 cm and 30 cm

5 Application of the dynamic model to The Gambia

5.1 Rate of acid generation

From the predicted water levels of the reservoir behind the proposed barrage (Figure 2) it can be seen that even without abstraction of water for irrigation the watertable will fall below the sulphide datum for three months of the year. Severe acidity will develop in the upper layer of the whole area of sulphidic soils during the first year of barrage operation. The greater the abstraction of water, the greater the depth of drainage and hence the greater the acidification.

If we assume fissuring of the sulphidic material into peds of 20 cm diameter, a total S content of 3.5% and a horizontal watertable, the net acid generation will be 35.4 moles H^+ per square meter at the T = 1 year rate. This will decrease to 6.6 moles $H^+ m^{-2}$ where T = 10 years, i.e. after about 40 years of drainage to this depth. These values refer to a year of average river flow. Drawdown of the watertable and hence acid generation will be substantially greater in years of low river flow. These are probably low estimates of the rate of acid generation because no allowance has been made for entry of oxygen into the system through coarse pores, or for continued fissuring as the soil mass slowly ripens.

5.2 Fate of the acid

In the Gambian situation a large proportion of the annual increment of acid will be flushed from the soil into the reservoir at the beginning of the wet season. We have no information about the effectiveness of leaching or the buffering effect of dissolution of the silicate clays, but if the whole increment is leached there will be an annual input to the reservoir of 29×10^7 (area of sulphidic soils) $\times 35.4 = 10^{10}$ moles H^+ at the T = 1 year rate, decreasing to 2×10^9 moles H^+ at the T = 10 years rate.

Figure 8 depicts the pH values of the reservoir in mid July, assuming abstraction of water for 24,000 ha rice, oxidation at the T + 10 years rate, total washout of acid, and homogeneous mixing with the reservoir water along 1 km sections. For washout of only 10 per cent of the acid the pH values will be one unit higher. Once the reservoir has been replenished the acidity will be progressively diluted as more fresh water floods downstream and carries the acid beyond the reservoir.

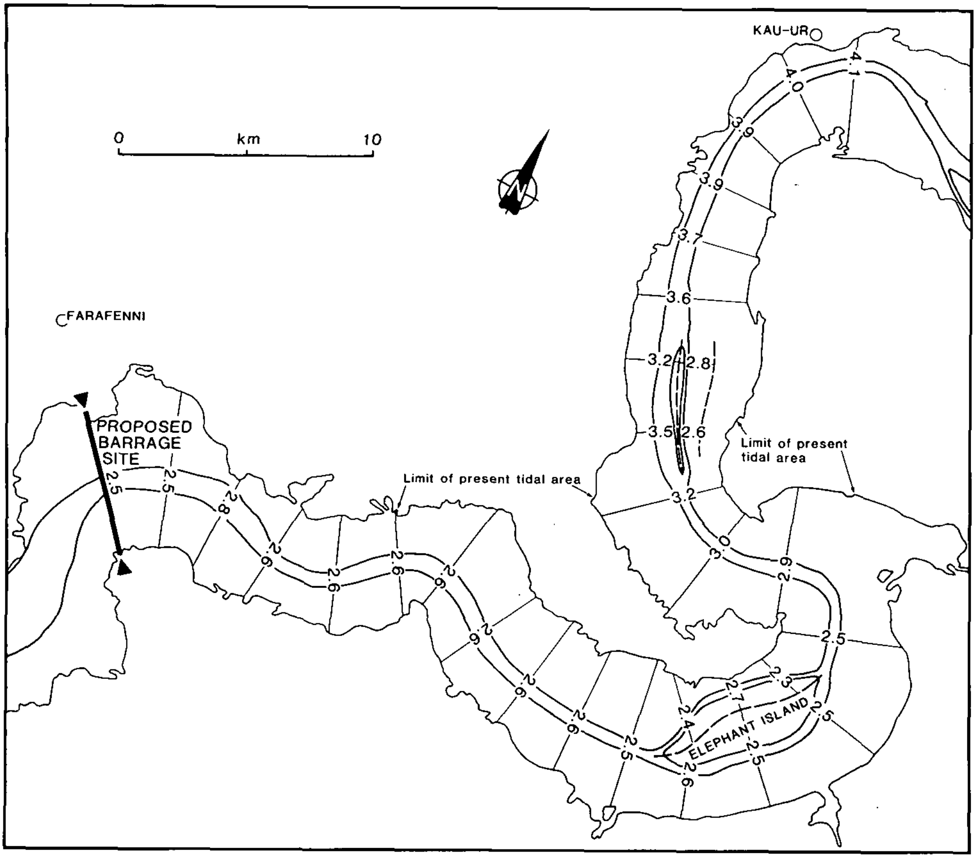


Figure 8. Predicted pH values of the River Gambia upstream of the proposed barrage in mid-July, assuming abstraction of water for 24,000 ha irrigated rice, oxidation at rate T = 10 years for 20 cm peds, and complete washout of acid into the reservoir

More sophisticated calculations could be performed but are hardly justified in view of the many untested assumptions already used. The above is sufficient to indicate the order of magnitude of the problem.

- In the area of sulphide soils upstream of the barrage the development of acidity and changed hydrology will combine to kill the present vegetation and aquatic life.

- Loss of vegetation cover is likely to lead to bank erosion and siltation of the reservoir.
- There are engineering considerations involving the effects of the acidity and high dissolved sulphate content of the reservoir water on steel and concrete structures.
- The ecological effects of the annual flush of acid will extend far downstream of the reservoir and will recur annually for many years.

If the model is correct within an order of magnitude, two alternative design options for the barrage must be considered.

1) Locate the barrage upstream of the most extensive areas of sulphidic soils.
2) A more sophisticated system of water management involving the maintenance of the water level in the reservoir above the sulphide datum. This may be done by the controlled introduction of dense saline water through the barrage into the bottom of the river channel to compensate for the loss of fresh water by abstraction and irrigation (Coode and Partners 1978).

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