Indicators of wetland acidification and their relevance to environmental impact assessment

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Abstract: Developments in most tropical coastlines are often hampered by acidification, which occurs when sedimentary pyrites are disturbed during construction activities. Acidification causes vegetation die back, fish mortality, heavy metal pollution, corrosion of concrete, steel and other metallic structures. The aim of this study is to develop tools for predicting the likelihood of acidification occurring in advance prior to project implementation. The study found that acidification indicators including land forms, acidophilic bacteria, soil and water properties, mangrove vegetation, and hydrology and sedimentation pattern are useful tools for predicting acidification. The study concludes by providing keys for the identification of problem soils and recommended the mainstreaming of acidification related issues into the overall EIA process.

Keywords: acidification; acidithiobacillus sp.; acid sulphate soils/sediments; dredging; indicators; mangrove; oil exploration; Niger Delta; environment.

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1 Introduction

Environmental impact assessment (EIA) is a well-recognised tool for the prediction, evaluation and mitigation of impacts associated with development activities. In the Niger Delta and indeed many parts of the world, impact assessment studies appear not to have adequately addressed biodiversity issues relating to developments in coastal wetland areas particularly for sensitive ecosystems like mangroves. Acidification, causing biodiversity loss and general habitat damage, often accompanies development and has made developments in these areas unsustainable (Figure 1).

Figure 1 Vegetation damage caused by acidification from a newly dredged oil well access canal (see online version for colours)

Note: The orange coloured discharges from the backswamp indicate acidification.

Generally, mangrove wetlands are spawning grounds for coastal and marine fisheries and provide feeding and nesting habitats for migratory species. Mangrove ecosystems are therefore of relevance to the five biodiversity-related conventions [the Convention on Biological Diversity (CBD), the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), the Convention on the Conservation of Migratory Species of Wild Animals (CMS), the Convention on Wetlands (Ramsar), and the World Heritage Convention (WHC)].

Being the most extensive and complex low land forest/aquatic ecosystem in West Africa, the biodiversity of the Niger Delta wetland ecosystem is of both regional and international importance. The region is rich in aquatic resources such as shellfish and finfish as well as freshwater and mangrove swamps, which make the Niger Delta one of the most fragile, productive and vulnerable ecosystems of the tropical African coastlines.

The delta also contains abundant oil and gas resources, which account for more than 90% of Nigeria's earnings. Exploitation of the rich natural resources has brought the wetland ecosystem under pressure (Moffat and Linden, 1995; World Bank, 1995). For instance as a result of oil exploration activities, there has been quite a lot of dredging going on to make the estuaries/creeks more navigable to drilling rigs, vessels and barges that convey equipments and materials to project locations, construction sites (flow station, gas plants, compressor stations, etc.) and pipeline installation sites. Because of lack of better methods of managing the accompanying dredged spoils from dredging activities, they are generally heaped/dumped by the banks of these water bodies and abandoned, thus forming spoil banks. The environmental impacts associated with the abandonment of dredged spoils in wetlands include alteration of the topography, soil properties and hydrology (Ohimain et al., 2010), which have been variously linked to increased salt water intrusion (Ashton-Jones, 1998), vegetation damage (Fagbami et al., 1988), declining benthic invertebrates (Ohimain et al., 2005) and zooplankton (Ohimain, 2002), alteration of phytoplankton population (Ohimain and Imoobe, 2003) and coastal retreat (Eedy et al., 1994). Habitat modification has also been reported to exacerbate erosion, flooding and subsidence in the Niger Delta (Ebisemiju, 1985, 1988). The altered topography, hydrology and soil properties caused the introduction of invasive species and alter the biodiversity of the mangrove ecosystem (Ohimain et al., 2010), which may also affect ecosystem functions (Ohimain, 2005). Dredging activities and impacts have had devastating consequences on mangrove swamps causing acidification of the immediate environment (Ohimain, 2001, 2003a, 2003b, 2003c; Ohimain and Imoobe, 2003). Other less intrusive developments such as the establishment of farm or fishponds have also led to acidification (Dublin-Green, 1987; Dublin-Green et al., 2003). The impacts of acidification can be overwhelming on the immediate environment and beyond. It includes vegetation dieback (Figure 1), fish kills, heavy metal pollution, corrosion of pipes, concrete and other steel structures (Ohimain, 2008a, 2008b; Ohimain et al., 2008a, 2008b, 2008c).

Worldwide, coastal mangroves are known to contain reduced iron sulphide mineral called pyrite (FeS_2) These pyrites when undisturbed under vegetation and water cover are innocuous, but their disturbance through dredging or trenching often results in severe acidification and ecosystem damage (Ohimain, 2004, Ohimain et al., 2004). Mangrove soil/sediments that have not been previously disturbed under water and/or vegetation cover are often referred to as potential acid sulphate soils (PASS) or sulphidic soils/sediments, while those that have been disturbed, which have started acidifying are called actual acid sulphate soils/sediments (AASS) or sulphuric soils/sediments. Because of the sensitivity, productivity and high biodiversity of mangrove ecosystems, it is therefore imperative to develop unique tools for impact assessment in these fragile ecosystems. The paper is therefore aimed at presenting indicators that a developer will watch out for in order to predict the likelihood of acidification occurring if a proposed site is disturbed.

2 Indicators of acid sulphate soil

There exist a range of indicators to predict and identify potential and actual ASS. These include landscape, soil/sediment and water quality, drainage and biological indicators.

2.1 Water quality and hydrobiology indicators

Surface waters usually give the first signal of acid sulphate conditions. Naturally, during the dry season, the water table is lowered leading to the exposure and oxidation of pyrite resulting in the generation of acid, which are typically released following the first rainfall events. Drain water pH values as low as 1.5 have been recorded (van Mensvoort and Dent, 1998). Ohimain (2008a) recorded pH in the range of 1.3–2.9 in the Niger Delta, whereas more dramatic pH depressions were recorded in Iron Mountain mining site, California, where pH less than zero and negative pH were recorded (Nordstrom et al., 2000).

Figure 2 Yellowish to reddish ochre and leachates trapped at the mangrove backswamp indicates water acidification (notice background mangrove in early stage of stress)

Field and/or laboratory chemical analysis can be used to indicate coastal acidification. For instance, acid sulphate conditions are indicated by pH value < 4 with > 0.5 mol Fe^{2+} m^{-3} (> 3 mg/l) or > 0.05 mol Al^{3+} m^{-3} (> 0.1 mg/l) (van Mensvoort and Dent, 1998). Analysis of drainage water can give a precise indication of acidification problem; however, acid sulphate pollution in surface waters may be brief and may escape detection by simple random or other probability sampling methods. Moreover, pH alone is not a good indicator of acidification conditions, because pH depends not only on the amount of acid produced from pyrite oxidation but also on acid neutralisation factors such as the buffer capacity of the receiving system and dilution effects. Hence, pH measurements may indicate the net acidity. Notwithstanding, the occurrence of low pH, high aluminium, sulphate and iron content of floodwater often provide the first indicator of acidification (van Mensvoort and Dent, 1998). Figures 1 and 2 show the impacts of acidified flow water (with high sulphate and iron contents) on backswamp mangroves.

The oxidation of sulphides produces waters that are both acid and rich in dissolved iron, aluminium and sulphate. Acidophilic bacteria particularly of the genus Acidithiobacillus present in drainage water forms a gelatinous mass of ochre further oxidise the dissolved iron converting it from Fe^{2+} to Fe^{3+} and the simultaneous oxidation of sulphide to sulphate, which is responsible for the production of ochre and acidity. Yellow to red drain water, scummy or gelatinous ochre deposits (Bloomfield, 1973) and an oily-looking film on water surface indicate very high concentration of dissolved iron being precipitated in more oxidising conditions. This phenomenon is particularly common in disturbed mangrove areas in the Niger Delta. Although, pyrite oxidation is not the only possible source of iron in mangrove ecosystems, other sources include overland run off and the natural geology of the area. The presence of high iron concentrations beyond background levels in a disturbed coastal mangrove estuary suggest that the source of the iron is from pyrite oxidation.

The extreme acidity associated with acid sulphate soil dissolves aluminium from soil/sediment minerals. Water of high aluminium content is one of the main hazards of acid sulphate soil. Aluminium flocculates suspended clay, making drainage water unusually clear often seen after heavy rain fall, which flushes dissolved aluminium out of acid sulphate soil into drains, streams and creeks. However, leaching of aluminium is usually periodic so that the absence of a high aluminium concentration in a sample does not necessarily indicate the absence of acid sulphate soil. Drainage water often assumes a blue green colour, which may be related to their clarity, but also to dissolved iron (Fe^{2+}). These are strong indicators of acidification conditions. More indicating is when waters that are usually muddy becomes crystal-clear or blue green by the flocculation of suspended sediment by dissolved aluminium, which may persist for only a few hours or days, often caused fish kills and red-spot disease in fish (Callinan et al., 1993; Sammut et al., 1995; Woodhead et al., 2000). The occurrence of fish kills and the presence of ulcers in fish indicate acidification conditions. Also, acid sulphate drainage water corrodes concrete and galvanised steel, sluices, culverts, and other engineering structures including oil and gas production facilities, which can also be used as indicators of acidification (Dent, 1986; Yongen et al., 2002).

Typically, the chloride to sulphate ratio in estuaries, coastal and seawater is in the order of 7. Oxidation of sulphide to sulphate in acid sulphate soil narrows this ratio. Therefore, provided that the conductivity of the drainage water is greater than 0.5 mS/cm, a substantial narrowing of the chloride/sulphate ratio indicates a significant addition of sulphate that is most likely to come possibly from the oxidation of pyrite in mangrove soils and sediments. According to van Mensvoort and Dent (1998), any chloride/sulphate ratio in coastal waters below 7.2:1 indicates acidification possibly from pyrite oxidation. Woodhead et al. (2000) summarised the water quality indicators of ASS to include crystal clear water (indicates pH 3–4), yellow brown water indicates dissolved iron presence (iron flocs appears in water at $pH < 4$), blue green water at a pH of 4–5 is caused by aluminium floc, and at pH 5–6 aluminium can change form to produce a milky white appearance. For instance, milky white appearance was observed in a section of a newly dredged canal, where fish kills was noticed in Benin River, Niger Delta (Ohimain, 2003a). The following changes in biophysical parameters may generally indicate that a coastal river is affected by acid leaching from pyritic sediments:

- low water column pH levels (e.g., < 4 in immediate area of impact)
- a dramatic reduction in water column dissolved oxygen concentrations
- excess of sulphate in the water column with chloride/sulphate ratios are often < 3 in acid affected streams
- iron staining in coastal tributaries and increased dissolved aluminium, iron and potentially arsenic concentrations
- extremely clear water where all sediments have settled out due to the flocculating ability of aluminium
- red lesions on fish caused by the ulcer-causing fungus of epizootic ulcerative syndrome (‘red-spot’ disease)
- increased incidence of fish kills and reduction in benthic invertebrates
- the presence of acid tolerant aquatic macrophytes particularly Nymphaea sp [source: http://www.ozcoasts.org.au/indicators/acid_sulfate_soils.jsp (assessed on 15 April 2009].

2.2 Land form indicators

Acid sulphate soils and sediments are most common in tidal swamp and marsh, former tidal areas now built up into deltas and floodplain, and the bed of brackish lake and lagoons (van Mensvoort and Dent, 1998). According to White et al. (1995a, 1995b) ASS of importance mostly occurs n the following land forms:

- coastal lowlands are estuary flood plain Holocene sediments of < 10,000 years old.
- soils of estuarine origin whose surface elevation is < 5 m above mean sea level
- bottom sediments of estuaries and tidal lakes.

Pyrite contents are much higher in sediment that has accreted slowly under lush vegetation than in those that accumulate quickly (van Mensvoort and Dent, 1998; Dent, 1986). In the Niger Delta, pyrite contents are higher on the slowly accreted chikoko mud under the dwarf red mangrove (*Rhizophora mangle*) than under the tall red mangrove (*Rhizophora racemosa*) growing on recently deposited inceptisols (Anderson, 1966). Within any particular wetland, back swamps are more sulphidic than levee and clays more sulphidic that sands. However, pyrite does not accumulate in freshwater swamps or uplands. Though, upland mine spoils containing pyrite behaves exactly as ASS producing acidification upon exposure. Beach ridges in coastal wetlands are commonly sandy and contain shell or coral, which neutralises acids and therefore have low pyrite contents. Tropical coastal landscape forms containing mangroves (Figure 3) are almost and always associated with pyrite deposition and are therefore potential indicators of acidification (van Mensvoort and Dent, 1998; Ohimain et al., 2004).

Figure 3 Mangrove landscapes are indicators of ASS (see online version for colours)

2.3 Sedimentation pattern, drainage and hydrology indicators

According to Dent (1986), sulphidic soil develop most extensively where clayey sediment accretes slowly in saline and brackish water with copious amount of organic matter supplied by swamp vegetation particularly mangroves (Figure 3). The longer the duration of saline or brackish swamp conditions, the greater the input of organic matter, the greater accumulation of pyrite. This explains why the older chikoko muds colonised by *R. mangle* have higher pyrite content than the recently deposited inceptisols colonised by *R. racemosa*. Shelter from strong current and wave action is conducive to the accumulation of mud and its colonisation by vegetation. Favourable conditions occur in deltas, sheltered estuaries, coastlines protected by barrier islands and bars, and even open shores where wave energy is dissipated across a broad, gently sloping coastal shelf. Differences in the micro-topography, which influence drainage and hydrology, also affect acidification potential (Ohimain et al., 2010). The lowest parts of the inter-tidal zone are flooded most of the time, so these soils are permanently reduced, they are therefore PASS. In the higher parts of the tidal landscape, the upper horizons of the soil are predominantly exposed and become oxidised, and are therefore predominantly AASS. The tidal range and the effectiveness of drainage, determine the thickness of oxidised, non-sulphidic material that will accrete above the permanently reduced, sulphidic subtraction. Several hundreds of years seem to be needed for pyrite to accumulate in excess of the neutralising capacity of the soil (van Mensvoort and Dent, 1998). Therefore, potentially acid soils are likely to develop only in relatively stable system. Ecosystems subject to alternate erosion and deposition will not accumulate high concentration of pyrite, which explains why inceptisols under tall mangrove covers often have low pyrite content. Pons et al. (1982) attribute the apparent removal of dissolved sulphide and bicarbonate and the increased accumulation of pyrite, to more effective tidal flushing. Flushing is enhanced by the network of tidal creeks, and by greater soil permeability associated with a higher content of organic matter. Tidal flushing promote pyrite formation, by removing bicarbonates, supplying the limited amount of dissolved oxygen necessary to form pyrite from reduced sulphide, and accelerating the rate limiting processes that are otherwise dependant on diffusion (Macdonald et al., 2002).

The rate of sedimentation and the age and stability of the landscape determine the time available for the accumulation of pyrite. Where the rate of sedimentation is slow and condition for pyrite accumulation have persisted over a long period, very high-reduced sulphur contents may occur. On the other hand little pyrite is formed in a rapidly aggrading landscape where there is much shorter period of favourable conditions for pyrite accumulation (van Mensvoort and Dent, 1998; Macdonald et al., 2002). This phenomenon is quite striking in the Niger Delta (Figure 3) where low pyrites accumulates in a rapidly accreting sediments dominated by the tall red mangrove, *Rhizophora racemosa*, whereas, high pyrite concentrations are found in the slowly accreting sediments dominated by *Rhizophora mangle* (short red mangrove). If the natural hydrology of the wetland remains undisturbed, sulphidic materials remain reduced and therefore no acid is formed, except during droughts or prolonged dry season when the water table is lowered, resulting in oxidation and acidification. However, on the other hand, when the land is drained or excavated, acidification begins. In summary therefore, drainage, sedimentation pattern, hydrology and land use pattern can act as indicators of ASS.

2.4 Vegetation indicators

Generally, acid leaching reduces the diversity of aquatic life, although species of reed (*Phragmites* species) and water lily (*Nymphaea* spp) have been known to exhibit remarkably resistant and may come to dominate these habitats (Woodhead et al., 2000). These plants can therefore be used to indicate acidification. But vegetation plays more than successional role in indicating acidification. According to Dent (1986), vegetation controls the process of pyrite formation by supplying readily decomposed organic matter. The characteristic vegetation of inter tidal swamps in the tropics is mangrove. Mangroves extend lower into the tidal zone and sometimes below sea level in brackish water. In a particular locality, the different swamps and marsh species indicate current differences in micro-topography, hydrology and salinity (Dent, 1986, Ohimain et al., 2010). Individual species or plant associations appear not to exert specific effect on pyrite accumulation. However, different species occupy particular niche or landscape position that is related to climate, tidal exposure, depth of flooding, drainage and salinity (Mitsch and Gosselink, 2001; Kathiresan and Bingham, 2001). Notwithstanding, the pioneer ASS studies carried out in the Niger Delta, showed strong correlation between landscape position, mangrove vegetation type and pyrite accumulation (Anderson, 1966). The concentrations of total sulphur in different mangrove landscapes including a rapidly accreting soft mud dominated by *Rhozophora racemosa* (tall red mangrove), slowly accreting mangrove backswamp peat (chikoko) dominated by *Rhizophra mangle* (short red mangrove), saline sands supporting a variety of mangrove (*Avicennia Africana* and *Leguncularia*) and freshwater-mangrove transition zone had percentage of total sulphur in the range of 0.135–1.80%, 1.30–8.80%, 0.11–4.10 and 0.06–6.30% respectively (Anderson, 1966). According to van Mensvoort and Dent (1998), mangrove vegetation in its variety indicates tidal water but with different species indicating different stages of sedimentation and, by association, differences in soil texture, ripeness and pyrite concentration. Because of the striking relationship between mangrove vegetation, coastal sedimentation pattern and pyrite formation, vegetation can be used as an indicator of

ASS. However, vegetation indicators must be used with caution, because vegetation responds to the present conditions of flooding, salinity and sedimentation, whereas soils have accumulated over hundreds or thousands of years, during which the conditions may have changed significantly (Diemont et al., 1993; Macdonald et al., 2002). Vegetation is therefore a sensitive indicator of present site condition. It defines more localised site conditions than surface waters and broad landforms. Generally, very high pyrite content is known to occur in peat soils that have been subjected to long periods of brackish water inundation (Dent, 1986) such as the chikoko mud under short red mangrove. While intact mangrove species indicate the presence of PASS, the presences of scalds (bare and burnt patches) indicate AASS (Woodhead et al., 2000).

2.5 Soil/sediment/spoil indicators

Upon examination, the colour of soil, sediment or dredged material (spoil) can be used to indicate acidification. PASS are typically dark grey or dark greenish grey in colour, but are strongly reduced soil. According to van Mensvoort and Dent (1998), dark grey or dark greenish grey hydrogen sulphide stinking, unripe mud that contains abundant rotted organic matter and which blackens on exposure to the air is always strongly indicate PASS. Dull grey colours are characteristic of waterlogged soil, which are typically PASS. A dark greenish grey colour indicates a condition in which pyrites are formed particularly if there are enough supply of sulphate from seawater. Black mottling usually indicates the presence of iron monosulphide (FeS) (Bush and Sullivan, 2002). Conditions for sulphide accumulation do not indicate the amount of sulphide present or the likelihood of acid neutralising minerals. An unstable soil colour, particularly blackening within a few seconds or minutes if exposed to the air, indicates a very high content of oxidisable sulphide (van Mensvoort and Dent, 1998).

PASS develops to AASS when disturbed. Dredged sediment/spoils will quickly develop acidity if it contains pyrites (Ohimain et al., 2004). Upon disturbance, the soil matrix of PASS which is initially grey begins to change colour to pink, yellow and orange. Usually there are yellow mottles and coating of jarosite, very pale in colour, almost cream, when fresh but ageing to yellow and often associated with crusty ochre (Figure 4). In extreme cases, lemon yellow and white crystals of acid iron sulphate may precipitate on drying surface. These features develop within a few weeks in spoil dumps on the surface, and indicate a raw acid sulphate soil in which active acid generation is taking place. Field pH is typically in the order of 3.0 or less (van Mensvoort and Dent, 1998). These features are striking indicators of AASS. Although, in rare cases, organic rich soil that remain wet do not develop yellow mottle, they become severely acid possibly because of formation of iron organic complexes that preempt precipitation of jarosite (van Mensvoort and Tri, 1988; Andriesse, 1993). Redoximorphic features of soils and spoils also indicate the level of acidification. For instance, the straw yellow mottles of jarosite or in the most extreme cases, lemon yellow iron sulphate are indicative (Figure 4). Oxidation of pyrite also releases iron, some of which are deposited in the soil and sediments as crusts, coating and mottles or ochre usually where the acid solution is neutralised. The deposited mottles are ultimately transformed to other Fe-S minerals mostly orange red goethite and dark red hematite (Ivarson et al., 1982). Jarosites are transformed to iron oxide. These minerals only develop under severe acidity that is associated with oxidation of sulphides, hence their presence is indicative of acidification conditions (van Mensvoort and Dent, 1998).

Figure 4 Mottled soil following disturbance (oil field site preparation) indicates ASS (see online version for colours)

2.6 Microbial indicators

It has been variously reported that the process of pyrite formation under anaerobic conditions is mediated by microbial sulphate reduction processes in coastal environments where the sea constantly supply sulphate and iron from over land runoff under anaerobic conditions provides suitable conditions for increased sulphate reduction process (Berner, 1970; Howarth, 1979, Pons et al., 1982; Goldhaber and Kaplan, 1982; van Breemen, 1976, 1982, 1988). Therefore, under saline/brackish wetlands conditions in the presences of sulphate reducing bacteria (SRB) indicates pyrite formation potential and hence acidification upon drainage. Intact mangrove soils are known to contain high populations of SRB along with products of sulphate reduction processes including pyrite, hydrogen sulphide (source of the observed foul odour in mangrove swamps) and metals sulphides (van Breemen, 1988; Pons et al., 1982; Goldhaber and Kaplan, 1982; Ivarson et al., 1982; Ohimain, 2001). While microbial sulphide reduction process indicates PASS, microbial oxidation process cause the oxidation of pyrite leading to the formation of sulphate acidity indicates AASS conditions. It has been variously documented that sulphide oxidising bacteria of the genus *Acidithiobacillus* (formally called *Thiobacillus*) is responsible for catalysing the oxidation of exposed pyritic sediment, leading to AASS situations (Colmer and Hinkle, 1947; Singer and Stumm, 1970; Arkestyn, 1980; Ivarson et al., 1982; Ross et al., 1982; van Mensvoort and Dent, 1998; Bosecker, 1994;

Ritsema et al., 2000; Schipers et al., 2000). Therefore, the presence of SRB in sheltered coastal wetlands indicates PASS, while *Acidithiobacillus* sp. indicates AASS conditions.

2.7 Field indicators of acid sulphate soils

There are clear field indicators of the presence PASS, AASS and their redox products. One or combination of the following criteria can be used to indicate ASS (White et al., 1995a, 1995b). Note that many of these indicators have been previously discussed, the emphasis here is to highlight field conditions that can quickly be used by a developer for indicating the presence of problem ASS.

- acidic drainages from surface or ground water with pH less than 4
- sediment or soil which, when saturated has pH less than 4 usually with clear or milky green drain water coming from, or within the site (see Table 1)
- extensive iron stains on drain surfaces or stream banks, or iron stained drain water and orange red, ochre deposits in and around drain or stream (Figure 1)
- pale yellow surface encrustations on exposed soil or spoil heaps (Figure 4)
- augured soil or excavated pits hole inspection indicating any pale yellow (jarosite) or orange red iron oxide deposits in fissures and old root channels or iron oxide mottling
- excessive corrosion or etching of concrete and/or steel structures exposed to ground and drainage waters or soil, rapid corrosion of fresh steel
- a sulphurous smell after rains following a dry spell or when the soil is disturbed.

If a site has one or more of these features then AASS are indicated. The above indicators are due to the oxidation of iron sulphides in sulphidic sediments, which produce AASS. In PASS, the sulphides are unoxidised and may not have these indicators. PASS are mostly located beneath AASS, except for sulphidic bottom sediments in estuaries and tidal swamps, where potential acid sulphate material exist on their own), or disturbed areas where all material may be AASS (Figure 4). However, PASS is characterised by the following features (Dent, 1986; van Mensvoort and Dent, 1998; Macdonald et al., 2002):

- they are found below the water table
- they have close to neutral pH
- may be blue grey to dark greenish-grey unripe soft mud
- mid to dark grey silty sands or sands
- dark grey to black bottom sediments of estuaries or tidal swamps
- may smell of rotten egg gas (H_2S)

If these indicators are present, then it is highly likely that sulphidic sediments are present, which can be confirmed by further chemical analysis. Table 1 summarised both the field and laboratory properties of ASS.

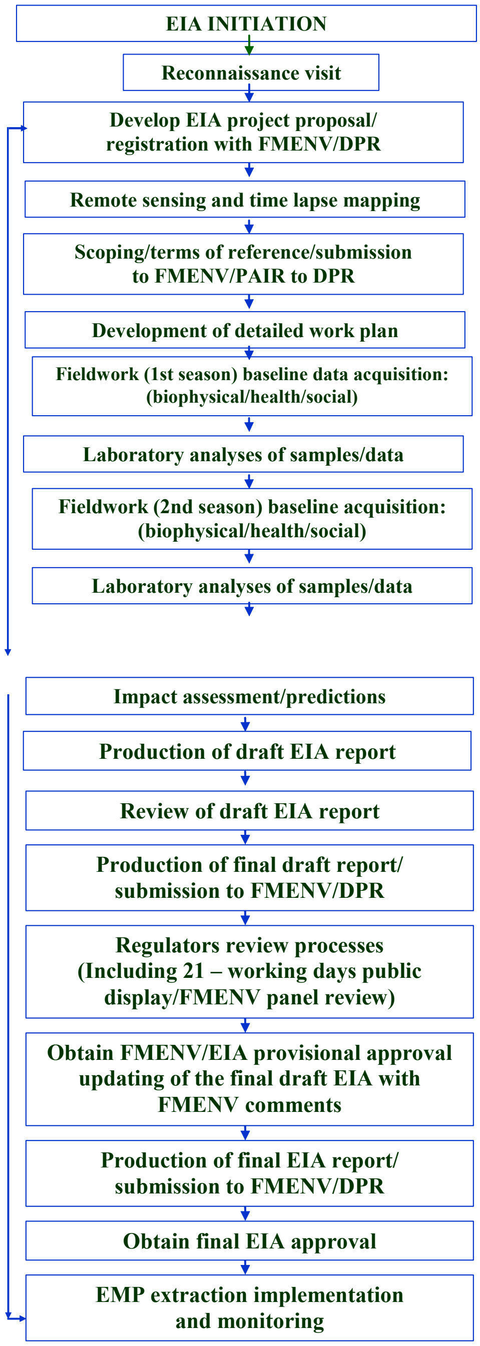
Table 1 Field and laboratory indicators of acidification

Characteristics	*Indicating parameters*	*AASS indicators*	*PASS indicators*
Water quality	pH	Field pH < 3	Field pH that reduced by 0.5 units or more after peroxide oxidation
	Colour	Yellow or orange brown discharges	-
	Fe	> 3 mg/l (when pH < 4)	
	Al	> 0.1 mg/l (when pH < 4)	
	Cl/SO_4 ratio	< 7	-
Microbiology	Presence of indicating microbes	Sulphur and iron oxidising bacteria	Sulphate reducing bacteria
Vegetation	Indicating species	Former mangrove that have been cleared	Mangrove plants such as *Rhizophora, Avicennia germinans, Laguncularia, nipa fruiticans*
Odour	H_2S	-	Sulphide smell
Soil	Colour	Yellow	Black or (Hue 10 YR; chroma 1 and hues 2.5 Y, 5 Y, N and 5 GY)
	Minerals	Pyrite, jarosite, goethite, hematite	Jarosite
	Mottles	Present	absent

3 Relevance of acidification indicators to EIA studies

EIA studies are typically carried out in most countries prior to major development activities in order to predict in advance the potential impacts of the project activities on the environment. Typically, in most tropical countries, a two season field baseline data gathering of biophysical and other parameters is carried out to account for the seasonal variation of the physic-chemical environment (Figure 5). However, simple or even systematic random sampling procedures sometimes fail to identify the presence of potential or actually acid sulphate soils. So the developer is unable to predict in advance the possible impact of their development activities on the formation of acidification. Acid sulphate soils are distributed globally with a large presence in Asia and Africa (Table 2). Because of the global nature of the problem, there is the need to develop tools for the identification of potentially problem soils.

Figure 5 The Nigerian EIA process (see online version for colours)



Notes: FMENV = Federal Ministry of Environment, Abuja.
DPR = Department of Petroleum Resources, Lagos.

Table 2 Regional distribution of acid sulphate soils

Region	*Area (million ha)*
Africa	3.7
Near and middle East	-
Asia	6.7
Australia	-
Latin America	2.1
North America	0.1
Europe	-
World total	12.6

Source: Andriesse and Mensvoort (2006)

Because of the potentially devastating effects of acidification, it is recommended that acidification related-issues should be taken on board early in the EIA process starting from EIA screening. For instance, during reconnaissance field visits and remote sensing studies, conscious efforts should be made to identify wetlands in the study area, which might be at risk. There are standard methods for identification of wetlands ranging from the primary indicator method to the conventional three-indicator method, where wetlands are identified by the presence of hydric soils, hydrophytic vegetation and wetland hydrology (Environmental Laboratory, 1987; Mitsch and Gosselink, 2001). Since not all wetland develop into acids upon disturbance, attention should be focused on mangroves, salt marshes and other coastal landscape, which are potentially ASS. Mangroves or salt marsh that might develop acidity problems on disturbance should be identified during EIA scoping, and acidification issues added to terms of reference (TOR) and work plans. During field data gathering soil, spoil and sediment samples including profile samples should be collected and tested for both PASS and ASS. Field indicators are very useful in the identification and characterisation of acid sulphate soils. Field pH, peroxide oxidation pH, moist incubation pH can variously be carried out to confirm the potential acidification problems (Ohimain, 2008a, 2008b). During sampling in a mangrove area, if field test did not reveal the presence of PASS or AASS from samples collected using simple, systematic or other probability sampling methods, consider the use of purposive or other non-probability sampling methods.

If it is confirmed that a proposed project site contains pyrites that could be oxidised upon disturbance during site construction activities causing acidification, alternative project sites should be selected especially if the proposed development involve certain activities such as dredging, site clearing, trenching, piling, etc. See Table 3 for a list of selected activities that could trigger acidification. If the proposed development involves one or more of these activities, it will require mitigation measures including the implementation of acid sulphate soil management plans (ASSMP). Also, where alternate suitable site for the proposed development cannot be secured, strategies for the minimisation and mitigation of the potential impacts of acidification should be put in place and implemented. Mitigation measures specific for the management of acidification can be found in Ohimain (2002, 2004).

Table 3 Activities requiring dredging and canalisation in the Niger Delta

Sector	*Activity*	*Tasks*
Oil industry	Drilling	Dredging of navigation route to permit rig movement and barges for transportation of equipment and materials
		Dredging of drilling site (location assess preparation)
	Pipelines (including flow line and bulk lines)	Pipeline transportation, installation and maintenance
	Production facility Installation	Transportation of oil and gas infrastructure, modules, flowstation components, production trains etc
		Sand winning and filling for infrastructure installation (site preparation)
	Production support logistics	Transportation of supplies such as food, fuel, lube oil etc to the flowstation, gas plants or other production facilities
	Maintenance	Sweeping is required to maintain navigability of the canals
	Camp/accommodation	Construction of site camps, accommodation, messing and recreational facilities
Government	Navigation canals	Construction of canals linking coastal communities
	Port development	Deepening of ports and harbours
	Reclamation	Sand filling and reclamation/ expansion of communities
Others	Sand winning	In several communities, both artisanal and large scale commercial sand mining are common
	Environmental dredging	Removal of contaminated materials from the riverbed. Also, the removal of water hyacinth and the accompanying silt build up to ease navigation.
	Agriculture	Site clearing, heaping and sand filling for cropping
	Fisheries	Construction and operation of fish and shrimp ponds
	infrastructure	Construction of roads, houses and other super structure

One of the most efficient strategies for the management of acidification is prevention. Preventive measures are very important because once acidification starts it is very difficult to control. The proper handling of sediments/soils/spoils containing pyrite is the best preventive method. Proper handling techniques are based on the premise that environmental factors, which control the growth of acidithiobacilli, also influence acidification (Ohimain et al., 2004). Such factors include water, air and the presence of pyrite. Hence, proper handling to prevent or control acidification is focused on techniques that selectively eliminate one of this factors, e.g., by preventing either air or water from reaching the materials, neutralise acidity or inhibit acidithiobacilli and other acid forming bacteria (Ohimain, 2002). There are practical ways of selective handling of materials containing pyrite. For instance, if the materials are drained and placed in confined disposal facilities away from water inundation, the materials will not result in acidification even though air and acidithiobacilli are present. On the other hand, if the materials are buried or disposed at the seabed, though water and acidithiobacillus are present but because of the anaerobic nature of the seabed acidification will not ensue. Though lime and biocides application are known to inhibit acidithiobacilli and can therefore prevent acidification only if they are applied early, but once acidification has commenced both liming and biocide are of little importance, because ferric iron (Fe^{3+}), which is one of the by-product of microbial pyrite oxidation, will continue to oxidise more pyrite even when acidithiobacilli are inhibited by the biocides and lime.

4 Conclusions

Acid sulphate soils abound in many coastal areas of the world. Incidentally, most development activities occur in these areas including oil and gas exploration, agriculture and aquaculture, marine and other economic activities and infrastructural developments. Most of the world's mega cities are also located in coastal areas. Because of acidification and the attendant environmental impacts that often follow developments in many tropical coastlines especially those dominated by mangroves and salt marshes makes such development unsustainable. Acidification, which ensues when sedimentary pyrites are disturbed during construction activities, causes vegetation die back, fish mortality, heavy metal pollution, corrosion of concrete, steel and other metallic structures. This study present indicators that can be used to identify problem acid sulphate soil ahead of development activities, which includes land forms, acidophilic bacteria, soil and water properties, mangrove and salt marsh vegetation, hydrology and sedimentation pattern. The study recommends the mainstreaming of acidification related issues into the overall EIA process and development plans.

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References

Anderson, B. (1966) *Report on The Soils of The Niger Delta Special Area*, Niger Delta Development Board, Port-Harcourt, Nigeria.

Andriesse, W. (1993) 'Acid sulfate soils diagnosing the illness', in Dent, D. and Van Mensvoort, M.E.F (Eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulfate Soil*, pp.11–30, ILRI Publications 53, International Institute for Land Declaration and Improvement, Wageningen, The Netherlands.

Andriesse, W. and van Mensvoort, M.E.F. (2006) 'Acid sulfate soils: distribution and extent', *Encyclopedia of Soil Science*, 2nd ed., Taylor and Francis/CRC, Boca Raton, Florida, DOI: 10.1081/E-ESS-120006641.

Arkestyn, G.J.M.W. (1980) *Contribution of Microorganisms to the Oxidation of Pyrite*, PhD thesis Wageningen University, The Netherlands.

Ashton-Jones, N. (1998) *The Human Ecosystems of the Niger Delta: An ERA Handbook*, Environmental Rights Action, Benin City.

Berner, R.A. (1970) 'Sedimentary pyrite formation', *American Journal of Science*, Vol. 15, No. 1, pp.81–103

Bloomfield, C. (1973) 'Acidification and Ochre formation in Pyritic soils: in dost acid sulphate soils', *Proceedings of the International Symposium on Acid Sulphate Soils*, 13–20 August 1992, Wageningen, p.40, Vol. 2, International Institute for Land Reclamation and improvement, Wageningen, 51, The Netherlands.

Bosecker, K. (1994) 'Microbial leaching', in Prave, P., Faust, U., Sitting, W. and Sukatsch, D.A. (Eds.): *Fundamentals of Biotechnology*, pp.660–683, VCH, Germany.

Bush, R.T. and Sullivan, L.A. (2002) 'Iron monosulfides at the oxidation front of a coastal acid sulfate soil', in Lin, C., Melville, M.D. and Sullivan, L.A. (Eds.): *Acid Sulfate Soils in Australia and China*, pp.131–141, Science Press, Beijing, China.

Callinan, R.B. Fraser, G.C. and Melville, M.D. (1993) 'Seasonally recurrent fish mortalities and ulcerative disease outbreak associated with acid sulphate soils in Australian estuaries', in Dent, D.L. and van Mensvoort, M.E.F. (Eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soil*, March 1992, pp.403–410, Ho Chi Minh City, Vietnam, International Institute for land Reclamation and Improvement (ILRL), Wageningen, The Netherlands.

Colmer, A.R. and Hinkle, M.E. (1947) 'The role of microorganisms in acid mine drainage: a preliminary report', *Science*, Vol. 19, pp.253–256.

Dent, D. (1986) 'Acid sulphate soils: a baseline for research and development', *International Institute for Land Reclamation and Improvement*, Wageningen.

Diemont, W.H., Pons, L.J. and Dent, D.L. (1993) 'Standard profile in acid sulfate soil', in Dent, D. and Van Mensvoort, M.E.F (Eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulfate Soil*, pp.51–59, ILRI Publications 53, International Institute for Land Declaration and Improvement, Wageningen, The Netherlands.

Dublin-Green, C.O. (1987) *Investigations of Acid Sulphate Soils of the Brackish Water Experimental Fish Farm, Rivers State*, UNDP/FAO Report Number ARAC/87/WP/9.

Dublin-Green, C.O., Ayinla, A.O. and Ogori, T.K (2003) 'Management of fishpond built on acid sulphate soils in Buguma Creek, Niger Delta, Nigeria', *J. Appl. Sc. Environ. Mgt*., Vol. 7, No. 2, pp.39–43.

Ebisemiju, F.S. (1985) 'Some observations on coastal processes and shoreline retreat in the Western Niger Delta, Nigeria', *Malaysian J. Tropical Geogr.*, Vol. 12, No. 12, pp.20–30.

Ebisemiju, F.S. (1988) 'Human impacts on marine processes in the western Niger Delta', in Sada, P.O. and Odemerho, F.O. (Eds.): *Environmental Issues and Management in Nigerian Development*, pp.239–251, Woye and Sons Press Ltd., Ilorin, Nigeria.

Eedy, W., Rodgers, B., Saunders, K.E. and Akindunni, F. (1994) 'Applications of satellite remote sensing to coastal recession analysis in Nigeria', Paper presented at the *Coastal Zone Management '94 Conference*, Halifax, Canada.

Environmental Laboratory (1987) *Corps of Engineers Wetland Delineation Manual*, Technical Report 7-87-1, USACE, Vicksburg.

Fagbami, A.A., Udo, E.J. and Odu, C.T.I. (1988) 'Vegetation damage in an oilfield in the Niger Delta of Nigeria', *J. Tropical Ecol.*, Vol. 4, pp.61–75.

Goldhaber, M.B. and Kaplan, I.R. (1982) 'Control and consequences of sulphate reduction in recent marine sediments', in Kittrick, J.A., Fanning, D.S and Hossner, L.R. (Eds.): *Acid Sulphate Weathering SSSA*, pp.19–36, Special Publication No 10, Soil Science Society of America, Madison, Wisconsin.

Howarth, R.W. (1979) 'Pyrite: its rapid formation in a salt marsh and its importance to ecosystem metabolism', *Science*, Vol. 203, pp.49–51.

Ivarson, K.C., Ross, G.J. and Miles, N.M. (1982) 'Microbiology transformation of iron and sulphur and their applications to acid sulphate soil and tidal marshes', in Kittrick, J.A., Fanning, D.S. and Hossner, L.R. (Eds.): *Acid Sulphate Weathering*, pp.1–18, SSSA Special Publication No. 10, Soil Science Society of America, Madison, Wisconsin, pp.57–76.

Kathiresan, K. and Bingham, B.L. (2001) 'Biology of mangrove ecosystems', *Adv. Mar. Biol.*, Vol. 40, pp.81–251.

Macdonald, B.C.T., Smith, J., Melville, M.D. and White, I. (2002) 'Acidd sulfate soil research in Australia', in Lin, C., Melville, M.D. and Sullivan, L.A. (Eds.): *Acid Sulfate Soils in Australia and China*, pp.1–14, Science Press, Beijing, China.

Mitsch, W.J. and Gosselink, J.G. (2001) *Wetlands*, Van Nordstram, New York.

Moffat, D. and Linden, O. (1995) 'Perception and reality: assessing sustainable development in the Niger River Delta', *Ambio*, Vol. 24, pp.527–538.

Nordstrom, D.K., Alpers, C.N., Ptacek, C.J. and. Blowes, D.W. (2000) 'Negative pH and extremely acidic mine waters from Iron Mountain, California', *Environ. Sci. Technol.*, Vol. 34, No. 2, pp.254–258.

Ohimain, E.I., Imoobe, T.O.T. and Benka-Coker, M.O. (2002) 'Impacts of dredging on zooplankton communities of Warri River, Niger Delta', *Afr. J. Environ. Pollut. Health*, Vol. 1, pp.37–45.

Ohimain, E.I. (2001) *Bioremediation of Heavy Metal Contaminated Dredged Spoil from a Mangrove Ecosystem in the Niger Delta*, 341 pages, PhD thesis, School of Postgraduate Studies, University of Benin, Nigeria.

Ohimain, E.I. (2002) 'Sustaining stakeholders' values through proper handling and restoration of abandoned waste dredge spoils in the Niger delta', Paper presented at the *Department of Petroleum Resources' Health, Safety and Environment (HSE) Conference*, 9–11 December 2002, Abuja, Nigeria, available at http://www.nigeriaoilandgas-hse.org/conf2002/script_42.asp (accessed on 15 April 2009).

Ohimain, E.I. (2003a) 'Environmental impacts of oil mining activities in the Niger Delta mangrove ecosystem', *Proceedings of the International Mine Water Association (IMWA) 2003 Congress*, Johannesburg, South Africa.

Ohimain, E.I. (2003b) 'Available options for the bioremediation and restoration of abandoned pyritic dredge spoils causing the death of fringing mangroves in the Niger Delta', Paper presented at the *International Biohydrometallurgy Symposium (IBS 2003)*, 14–19 September 2003, Athens, Greece.

Ohimain, E.I. (2003c) 'Preservation of Niger Delta wetland resources through proper handling and rehabilitation of abandoned waste sulfidic dredge spoils', in Uzochukwu, G., Schimmel, K., Reddy, G.B., Chang, S.H. and Kabadi, V. (Eds.): *Environmental Science and Technology*, pp.3–12, Battelle Press, Columbus.

Ohimain, E.I. (2004) 'Environmental impacts of dredging in the Niger Delta; options for sediment relocation that will mitigate acidification and enhance natural mangrove restoration', *Terra et Aqua*, Vol. 97, pp.9–19.

Ohimain, E.I. (2005) 'Alien plant invasion of spoil banks in a mangrove ecosystem in the Niger Delta', Paper presented at the *26th Society for Wetland Scientist Conference*, June 2005, Charleston, NC.

Ohimain, E.I. (2008a) 'Application of moist incubation pH measurements for indicating wetlands acidification', *Intl. J. Biotech. Biochem.*, Vol. 4, No. 3, pp.275–282.

Ohimain, E.I. (2008b) 'Assessment of the impacts of dredging and drainage on the mangrove soils from selected rivers in The Niger Delta, Nigeria', *Intl. J. Nat. Appl. Sci.*, Vol. 4, No. 3, pp.299–304.

Ohimain, E.I. and Imoobe, T.O.T. (2003) 'Algal bloom in a newly dredged canal in Warri, Niger Delta', *The Nigerian J. Sci. Res.*, Vol. 4, No. 1, pp.14–21.

Ohimain, E.I., Andriesse, W. and van Mensvoort, M.E.F. (2004) 'Environmental impacts of abandoned dredged soils and sediments: available options for their handling', *Restoration and Rehabilitation. J. Soils and Sediments*, Vol. 4, No. 1, pp.59–65.

Ohimain, E.I., Bamidele, J.F. and Omisore, O.O. (2010) 'The impacts of micro-topographic changes on mangroves of the Benin River, Niger Delta', *Environmental Research Journal*, Vol. 4, No. 1, pp.167–172.

Ohimain, E.I., Benka-Coker, M.O. and Imoobe, T.O.T. (2005) 'The impacts of dredging on macrobenthic invertebrates in a tributary of the Warri River, Niger Delta', *Afr. J. Aquatic Sci.*, Vol. 30, No. 1, pp.49–53.

Ohimain, E.I., Jonathan, G. and Abah, S.O. (2008a) 'Variations in heavy metal concentrations following the dredging of an oil well access canal in the Niger Delta', *Adv. Biol. Res.*, Vol. 2, Nos. 5–6, pp.97–103.

Ohimain, E.I., Imoobe, T.O.T. and Bawo, D.D.S. (2008b) 'Changes in water physico-chemistry following the dredging of an oil well access canal in the Niger Delta', *W. J. Agric. Sci.*, Vol. 4, No. 6, pp.752–758.

Ohimain, E.I., Agedah, E.C. and Briyai, F.O. (2008c) 'Thioleaching of heavy metal contaminated sediments using Matin's medium', *Intl. J. Biotech. Biochem.*, Vol. 4, No. 3, pp.263–273.

Pons, L.J., Van Breemen, N. and Driessen, P.M. (1982) 'Physiography of coastal sediments and development of potential soil acidity', in Kittrick, J.A., Fanning, D.S and Hossner, L.R. (Eds.): *Acid Sulfate Weathering*, pp.1–18, SSSA Special Publication No. 10, Madison Wisconsin.

Ritsema, C.J., Van Mensvoort, M.E.F., Dent, D.L., Tan, Y., Van den Bosch, H. and Van Wijk, A.L.M. (2000) 'Acid sulphate soil', in Summer, M.E (Ed.): *Handbook of Soil Science*, pp.121–154, CRC Press, LLC Boca Raton, Florida.

Ross, G.J., Iverson, K.C. and Miles, N.M. (1982) 'Microbial formation of basic ferric sulphates in laboratory systems and in soil', in Kittrick, J.A., Fanning, D.S. and Hossner, L.R. (Eds.): *Acid Sulphate Weathering*, SSSA Special Publication No 10, pp.77–94, Soil Science Society of America, Madison, Wisconsin.

Sammut, J., Melville, M.D., Callinan, R.B. and Fraser, G.C. (1995) 'Estuarine acidification: impacts on aquatic biota of draining acid sulphate soils', *Australian Geog. Stud.*, Vol. 33, pp.89–100.

Schipers, A., Joszsa, P., Sand, W., Kovacs, Z. M. and Jelea, M. (2000) 'Microbiological pyrite oxidation in a mine tailing heap and its relevance to the death of vegetation', *Geomicrobiol. J.*, Vol. 17, pp.151–162.

Singer, P.C. and Stumm, W. (1970) 'Acid mine drainage: the rate-determining step', *Science*, Vol. 167, pp.1121–1123.

van Breemen, N. (1976) *Genesis and Solution Chemistry of Acid Sulphate Soils in Thailand*, Report 848, Centre for Agricultural Publishing and Documentation, Wageningen.

van Breemen, N. (1982) 'Genesis, morphology and classification of acid sulphate soil in coastal plains', in Kittrick, J.A., Fanning, D.S and Hossner, L.R. (Eds.): *Acid Sulphate Weathering*, pp.95–108, SSSA Special Publication No 10, Soil Science Society of America, Madison, Wisconsin.

van Breemen, N. (1988) 'Redox processes of iron and sulphur involved in the formation of acid sulfate soil', in Stgucki, J.W., Goodman, B.A and Schwertmen, U. (Eds.): *Iron in Soil Clay Minerals*, pp.825–841, D. Reidel Publishing Company, Dordrecht, The Netherlands.

van Mensvoort, M.E.F. and Dent, D.L. (1998) 'Acid sulphate soil', in Lal, R., Blum, W.H., Valentine, C. and Stewart, B.A. (Eds.): *Method for Assessment of Soil Degradation*, pp.301–335, CRC Press, LLC, Boca Raton, Florida.

van Mensvoort, M.E.F. and Tri, Q. (1988) 'Morphology and genesis of actual acid sulphate soils without jarosite in the Ha Tien plains, Mokong Delta, Vietnam', in Dost, H. (Ed.): *Selected Papers of the Dakar Symposium on Acid Sulphate Soils*, pp.11–15, ILRA Publication 44, Wageningen, The Netherlands.

White, I., Melville, M.D., Lin, C., Van O Ploo, P., Sammut, J. and Wilson, B.P. (1995a) 'Identification and management of acid sulfate soils', in Hazelton, P.A. and Koppi, A.J. (Eds.): *Soil Technologies – Applied Soil Science*, pp.463–497, Australia Society of Soil Science, Sydney, Australia.

White, I., Melville, M.D., Lin, C., Sammut, J., Van Oploo, P. and Wilson, B.P. (1995b) 'Fixing problems caused by acid sulfate estuarine soils', in Copleland, C.C. (Ed.): *Ecosystem Management*, The Legacy of Science, Halstead Press Sydney.

Woodhead, A., Jenkins, A. and Wood, M. (2000) *Acid Sulphate Soils: Keys to Success*, ASSMAC and NSW Agriculture, Australia.

World Bank (1995) *Defining an Environmental Development strategy for the Niger Delta*, Vol. 1, West Central Africa Department, Washington DC.

Yongen, L., Hongfu, W. and Jihong, Z. (2002) 'Corrosion of cement products and metal materials by acid sulfate soils', in Lin, C., Melville, M.D. and Sullivan, L.A. (Ed.): *Acid Sulfate Soils in Australia and China*, pp.230–232, Science Press, Beijing, China.