Acid sulphate soils: a baseline for research and development

To Jim Brockliss, who first showed me how mangrove swamp can be reclaimed, and to Alex Macrae, who showed me that it need not be.

Acid sulphate soils: a baseline for research and development

David Dent

Publication 39

International Institute for Land Reclamation and Improvement/ILRI
P.O. Box 45, 6700 AA Wageningen, The Netherlands 1986.

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ISBN 90 70260 980

Printed in The Netherlands.

Foreword

Acid sulphate soils suffer extreme acidity as a result of oxidation of pyrite. Often they are also unripe; sometimes also saline. Some occur naturally but most have developed as a result of drainage of previously waterlogged coastal alluvium and peat.

Acid sulphate soils pose a range of problems for communities dependent on the reclaimed land – including low crop yields, a restricted range of alternative uses, soil engineering hazards, water pollution, and other environmental risks. These difficulties are not always anticipated, or recognised when they occur, or tackled with up-to-date information. There is a fund of expertise on the causes of, and the solutions to, the problems of these severely acid soils. Drawing together this information will be of benefit to many people, especially in the developing countries of the tropics.

A range of people have to deal with acid sulphate soils:

Farmers face the difficulties at the most basic level. They see symptoms in the crops, and in drainage and floodwaters; they suffer most keenly the consequences of low yields or crop failure; and they must adopt ameliorative or preventative management practices to make a reasonable living.

Agricultural and forestry advisory staff. In most cases these are the people who must diagnose the problems in the field and instruct land users in the techniques for controlling these problems. They need practical guidelines for the identification of acid sulphate soils – guidelines that are appropriate to local conditions.

Civil engineers must cope with a unique combination of corrosion by acidity, salt, and reducing conditions, and with the difficulties of design and construction of earthworks, roads, and drainage systems in unripe materials.

Planning agencies. Economists and planners working on land development projects must be informed about the likelihood of acid sulphate soils occurring in coastal lowlands. They need to know about the agricultural and engineering hazards, and also about the damaging environmental and social impact of the reclamation and development of extensive areas of acid sulphate soils. They need to know what kind of soils information to ask for, and how to use this information in their economic modelling.

Politicians, investors, and international development agencies need to know what problems exist, where they are likely to arise, their possible magnitude, and how they may affect the success of land development. Such decision-makers need to be aware of soil variability – the likelihood of good soils in some places and difficult soils elsewhere, possibly in adjacent areas. They should also be aware of the potential role of specialists in soil survey and land evaluation and the ongoing role of these specialists in the management of the land. They need to know the different costs and likely returns on investment in areas of different soils and different soil patterns, the time scale involved in the development and amelioration of difficult soils, and the benefits of not developing land that has severe soil problems. They need guidance on the development procedure that should be adopted, the decisions that need to be taken at the highest level, and the scientific work that is required to ensure the success of land reclamation and development projects.

Soil specialists need an authoritative and up-to-date technical reference for application in land reclamation and development projects, and as a platform for further research.

It is obvious that there is a need for communication between all these people. Indeed, one of the recommendations of the Symposium on Acid Sulphate Soils held at Bangkok in 1981 was that the available knowledge on acid sulphate soils be published in a brief and easily understandable form. The International Institute for Land Reclamation and Improvement (ILRI) acted upon this recommendation and invited David Dent to write the book. He accepted the challenge and held consultations with many colleagues in ILRI, the Department of Soil Science and Geology of the University of Agriculture in Wageningen, and elsewhere. This book is the result of this joint effort.

Clearly, the need for communication between the wide range of people who have to deal with acid sulphate soils cannot be met by any one publication. To meet the needs of the widest possible range of readers, however, the book is written in discrete sections, each of interest to a particular group. Following a wide-ranging introduction, the book reviews the processes responsible for acid sulphate soils, methods of identification and mapping, agronomic, engineering, and environmental problems, and management experience. Where principles are well established and easily accessible elsewhere a condensed treatment has been possible, as in the case of soil chemistry; where information is scattered or still in embryo, more extended treatment has been needed. The further important aims of the book are to establish a useful, widely-understood terminology and to provide ground rules for management within the framework of alternative management strategies and contrasting physical environments.

David Dent presents a series of recommendations to those who are in a position to influence the course of land development and research. These provide a strategy for land reclamation and conservation that has been developed through consultation and detailed study. These recommendations are placed at the beginning of the book so that readers cannot miss them. Their substance is further developed in the subsequent sections.

I would like to express the satisfaction I feel with the issue of this book. I want to thank everyone involved, and I include not only the author, David Dent, who has done a splendid job, but also the staff of the Department of Soil Science and Geology of the University of Agriculture in Wageningen, who contributed much to this undertaking. It is my fervent hope that this book will truly help towards a better understanding of the problems we are facing when reclaiming coastal lands with potential acid sulphate soils or combatting the problems of acid sulphate soils that have already developed.

Dr. Ir. J.A.H. Hendriks
Director, ILRI

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Acknowledgements

The original ideas for this book were developed in discussions with Ir. H. Dost. Throughout its preparation, Dr. R. Brinkman and Professor L. Pons have been unstinting in their counsel and technical advice. Really they should have written the book and, although I have not always taken their advice, I would like to record my special debt to them.

Many other colleagues have generously given their time and expertise, in contributing material, critically reading sections of the text, and supplying data and photographs: Ir. W. Andriesse, Mr. M. Ashton, Dr. H. de Bakker, Ing. R. O. Bleijert, Dr. C. Bloomfield, Dr. N. van Breemen, Drs. D. Creutzberg, Dr. E. FitzPatrick, Dr. V. Larsen, Ir. M. van Mensvoort, Ir. R. Oosterbaan, Dr. R. Raiswell, and Dr. N. Tovey. Discussions in the field with Mr E. Cox in New Zealand and Professor N. Williams in The Gambia are also acknowledged. Irs. R. Langenhoff and J. Vos critically read and corrected the galley proofs.

The diagrams and maps were prepared for publication by Mr. D. Mew and Mr. B. Davies, with photographic work by Mr. P. Scott and Mr. S. Robinson. Laboratory support has been provided by the New Zealand Soil Bureau, the University of East Anglia, and the Thailand Department of Land Development. The first typescript was produced by Mrs. B. Slade and word processing was by Mrs. J. Willott of Geo Abstracts Ltd., Norwich, U.K.

I should like to thank Professor N.A. de Ridder and the editorial staff of ILRI for their support and expert help throughout this project, especially Mrs. M. Wiersma-Roche, who has rescued the text from clumsiness and inconsistency.

David Dent

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Recommendations for action and targets for research

Continued pressure on land resources will demand further development of marginal and difficult soils including acid sulphate soils. Uniquely, extensive areas of acid sulphate soils have been created directly as a result of attempts at land reclamation – by making polders and draining wetlands – so these problems are of our own making. But all coastal and estuarine alluvial soils are not potential acid sulphate soils, nor are all acid sulphate soils equally bad. Some are indeed very difficult to manage, but as a group they offer a wide range of opportunities for development.

There is a body of scientific knowledge and experience of these soils; further research will surely add to this. There remains a gap between research and its application to management. Recommendations to bridge this gap have been drawn up in consultation with many specialists in this field. Together, these recommendations provide a strategy for land reclamation and improvement.

Recommendations

Policy-makers should seriously consider the benefits of conserving and utilising existing potentially acid wetlands, especially in tidal areas. The mangrove belt serves many functions (including support of offshore fisheries) that are not always appreciated by short-term developers. Freshwater acid sulphate areas are biologically less diverse and less productive. An active policy of developing freshwater acid sulphate areas can include the options of forestry, wetland rice in a monsoon environment, and oil palm or rubber in a permanently wet tropical climate.

If the development option is chosen, there will be local, temporary failures. Delay in achieving acceptable levels of production must also be anticipated. In land settlement schemes, space should be set aside, either to accommodate farmers who have to abandon difficult areas or to be taken up at a later stage when management problems have been solved.

Pilot schemes will be needed to learn essential technical and social lessons on the ground.

No land development should take place without a soil survey and an evaluation of the range of alternative uses. Soil survey can assist land-use planning by identifying and mapping areas that have different requirements or different responses to management. The survey must address the special characteristics of acid sulphate soils that determine performance in both agricultural and non-agricultural uses. These include severe acidity or potential acidity, salinity, drainage, engineering hazards, the severity of these hazards, and the depths at which they occur.

Interpretative maps can be compiled to show land suitability for a range of alternative uses or the severity of specified hazards, and predictions can be made of the effects of alternative systems of management.

Water management is the key to soil management. Development planning must pay particular attention to the nature of wet and dry seasons, and to the availability of water for leaching, irrigation, and the maintenance of groundwater levels. On the basis of present experience, Section 2 outlines ground rules for management within the framework of alternative management strategies. Detailed prescriptions can be made only within specific social contexts and for specific physical environments.

The introduction of new management practices should always be based on the experience gained in local trials, in cooperation with the farmers who work the land. These field experiments must be supported by systematic site characterisation, so that experience and technology can be transferred to comparable areas. Clearly, it would help if a common code of site description, soil classification, and methods of analysis was applied. Proposals for soil classification are made in Section 5 and for survey and analytical methods in Section 7.

Applied research

The emphasis of applied research should be directed to *improvements in low-cost management*, where constraints include the availability of water and fertilizers. Research requirements for rice-based cropping systems include:

- Minimising the oxidation of pyrite and maximising the removal of acidic products by leaching;
- Safely discarding acid surface and drainage water;
- Liming in relatively low doses (a few tonnes per hectare) has sometimes yielded promising responses, but is not always effective. The reasons for these differences should be investigated. Allied to this, studies should be made of the effects of very small applications of lime (0.2 to 0.4 tonnes per hectare) in promoting rapid, healthy soil reduction following flooding.

Studies needed for both rice and dryland crops include:

- The effects on leaching of dryland versus wetland tillage, and cropping systems combining rice with short-duration dryland crops;
- Varietal screening for short-duration, acid-tolerant, salt-tolerant, iron-tolerant cultivars. Fast growth enables the crop to short-cut the period of greatest stress. Comparisons should be made between promising indigenous varieties from different countries;
- Studies on fertilizer application should aim at optimising the use of phosphate. While nitrogen is usually deficient in acid sulphate soils, its application rarely presents specific problems.

Research should be conducted within a framework of baseline survey, followed by the monitoring of crop performance, soil and water composition, and hydrology over at least three consecutive years.

Basic research

Targets for basic research include:

- The physiological mechanisms of tolerance to high aluminium and iron levels in soil solution;
- The main factors determining the rate of reduction following flooding and the rate

of pH-rise to levels beyond those at which toxicity occurs;

- Development of quantitative models to predict the progress and environmental impact of land reclamation. A model of pyrite oxidation is described in Section 3. More comprehensive systems can be built up by fitting together a number of models. These could include models of soil porosity and its development following drainage, the relationships between flooding, or water movement through the soil, and the removal of salts and acidity;
- The effects of changing watertables, or of irrigation or other management techniques, which can now be predicted both spatially and over time by computer simulation. This technique can provide decision-makers with quantitative forecasts of the consequences of alternative policies, but it also places greater demands both on the conceptual and mathematical models available and on the basic survey data;
- The key role of soil survey in development planning, which has already been emphasised. Soil survey must also be supported by an active research programme. Surveyors can adopt one of two strategies: intensive systematic grid survey with massive laboratory support, which is nearly fail-safe but is prohibitively expensive, or rapid free survey, which relies on the surveyor's conceptual model of the relationships between surface features and the soil profile characteristics that determine performance. These field relationships can only be established by local and regional studies of earth surface processes, ecology, environmental chemistry, and soil morphology;
- Modern statistical sampling techniques, which are being developed for rapid estimates of the scales at which acid sulphate soils can be mapped efficiently;
- The severity and reserves of acidity. These cannot be quantitatively determined from morphology and field relationships, but rapid and simple methods are being developed to estimate the amount of acid present and the amount that will be generated upon drainage. These techniques do not require sophisticated laboratory facilities.

1 Fundamental properties of acid sulphate soils

1.1 Significance of the problem

Acid sulphate soils develop as a result of the drainage of parent materials that are rich in pyrite, FeS_2. Pyrite accumulates in waterlogged soils that are both rich in organic matter and flushed by dissolved sulphate, usually from sea water (Plate 1.1). When drainage brings oxygen into these previously waterlogged soils, the pyrite is oxidised to sulphuric acid. Acid sulphate soils develop where the production of acid exceeds the neutralising capacity of the parent material, so that the pH falls to less than 4.

Under these conditions, the range of crops that can be grown is severely restricted and yields are low. Physiological stress on crops in drained acid sulphate soils is attributed principally to aluminium toxicity and associated nutrient deficiencies, especially of phosphate. Acidity can be corrected by liming, but soils that still have reserves of pyrite may require more than 100 tonnes of limestone per ha and this must be incorporated throughout the normal rooting depth of the crop. Unless limestone is available locally, it is impracticable to apply even one tenth of this amount. Flooding,

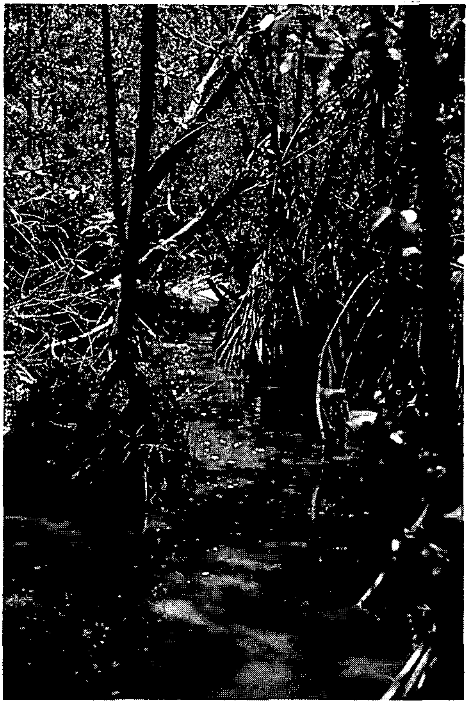


Plate 1.1 *Rhizophora mangle*, Wageningen Creek, Surinam (Leen Pons). Mangrove swamp is the most extensive potential acid sulphate environment, but mangroves also stabilise the coastline and create a diverse and productive ecosystem that supports a great variety of wildlife, including valuable fisheries. Mangrove forest can be managed to yield timber and wood products on a sustained basis.

Plate 1.2 Tidal land bordering the Gulf of Thailand. Most of the useful timber has been cut out. Coastal wetlands offer apparently attractive, easily-reclaimed land, but the acid sulphate hazard cannot be assessed without a soil survey.

for rice cultivation, usually eliminates acidity, but iron toxicity and possibly sulphide or other toxicities, may then occur. In contrast, in old acid sulphate soils where oxidation of pyrite is complete, there may be a significant crop response to quite small applications of lime and fertilizer.

In addition to chemical limitations, there are physical limitations. Root development is restricted, so water reserves in the subsoil are not available to the crop. Soil ripening is arrested, so the soil remains soft and sometimes very slowly permeable, even saline, at shallow depth.

Acid sulphate soils are an almost unique case where the soil problems are so severe that they can dominate most other aspects of land development: from engineering works (including the kind of concrete or steel required, design of roads, embankments, and drainage systems), to agricultural systems (including the choice of crops, disease, lime and fertilizer requirements), to economic and social planning at regional and local level, to the environmental impact of reclamation.

In recent coastal plains and inter-tidal swamps, there are an estimated 12 million ha, mostly in the tropics, in which the topsoil will become severely acid or has already done so as a result of land reclamation. There is probably a much greater area of potentially acid material covered by a shallow layer of non-acid peat or alluvium. Inland, acid sulphate soils have developed naturally as a result of changes in hydrology or relative sea level. The best known example is the Bangkok Plain in Thailand, where acid sulphate soils occupy an estimated 600000 ha. On a world scale, acid sulphate soils are not extensive. But they are important in many regions of critical population pressure, notably in South East Asia and West Africa, where alternative land for subsistence food production and cash crops is not available. The tidal swamps offer apparently attractive and easily reclaimed land, but the distribution and severity of the acid sulphate hazard cannot be assessed without detailed soil survey (Plate 1.2).

The soil problem is deceptively simple – excess acid production leading to toxicity; and the slow rate or, alternatively, high cost of amelioration. However, acid sulphate soils are not uniformly and equally bad; often they occur in intricate patterns in association with non-acid soils. Always there are local variations in the nature and severity of problems, and in their response to alternative management practices.

Better management requires:
- Soil survey to identify and so avoid, or at least anticipate, acid sulphate problems;
- A code of practice for field experimentation and site characterisation, so that experience and experimental data can be transferred to similar areas;
- Quantitative data as a basis for decisions about land development. These may be provided by quantitative models to predict the rate of acid generation and leaching following drainage, the rate of pH rise following flooding, the extent of iron and other toxicity problems, and the rate of amelioration of acid sulphate soils under alternative management;
- Practical guidelines for the reclamation and management of acid sulphate soils, in particular for the identification of the problem in the field, and simple cheap measures to minimise the oxidation of pyrite and combat its consequences;
- Long-term monitoring of alternative management practices and local trials in cooperation with the farmers working the land. These will provide a basis for introducing new practices.

1.2. Identification of acid sulphate soils in the field

The acid test is a soil pH value of less than 4 under aerobic conditions. This is usually associated with yellow mottles or coatings of jarosite and deposition of ochre in the soil or in drainage waters (Plate 1.3, p. 99). In flooded soils, for example in paddy fields, the pH will rise above 4 because of soil reduction, but a sample of an acid sulphate soil allowed to dry will become severely acid again. Sometimes, usually in poorly-drained soils, jarosite cannot be seen even under severely acid conditions.

Acid sulphate conditions occur in sand, peat, and clay, although acid sulphate clays are most extensive. Clay and peat soils that have become acid as a result of recent land drainage typically remain unripe, or under-consolidated. Unripe soils have a very high water content, so they are soft and can be squeezed between the fingers. Drainage eventually brings about soil ripening, which entails an irreversible loss of water, but the process is inhibited by severe acidity because roots are unable to enter the acid layer to extract the excess water. As a result, acid sulphate soils remain poorly-drained and often saline.

Old acid sulphate clays that have ripened naturally typically have a very dark-coloured topsoil, a prominently-mottled subsoil with reddish-brown mottles and nodules of iron oxide, and yellow jarosite mottles at greater depth (Plate 1.4, p. 99).

Although crops may suffer severe physiological stress on acid sulphate soils, specific symptoms are usually absent. In dryland crops, the principal symptom is exaggerated water stress, similar to the effects of salinity. Growth is reduced; leaves die back and scorch. More specifically, the root system is stunted and sometimes conspicuously deformed or 'coralloid'. In rice, the tillers of young transplants may die; 'bronzing' of the leaf tips often occurs and the roots are stained red by heavy iron deposition. Potential acid sulphate soils are not acid but will become acid if they are drained. Typically, they are unripe, saline, and give off a strong smell of hydrogen sulphide when disturbed. Mineral soils are very dark grey and rich in organic matter. They do not contain abundant shell or other carbonates.

For *positive identification*, measure the pH in the field, then take a small sample and treat with hydrogen peroxide or, better, incubate for three months (Section 7.3.2). Measure the pH again. In a potential acid sulphate soil, the pH will fall dramatically – to less than 4 in the incubated sample or to less than 2.5 after peroxide treatment.

Acid or potentially acid layers may be buried by non-acid peat or alluvium. Usually, there is no hazard unless severe acidity develops within one metre of the surface.

1.3 The natural environment of acid sulphate soils

1.3.1 Accumulation of pyrite

Pyrite accumulates in waterlogged, saline sediments where there is a supply of easily-

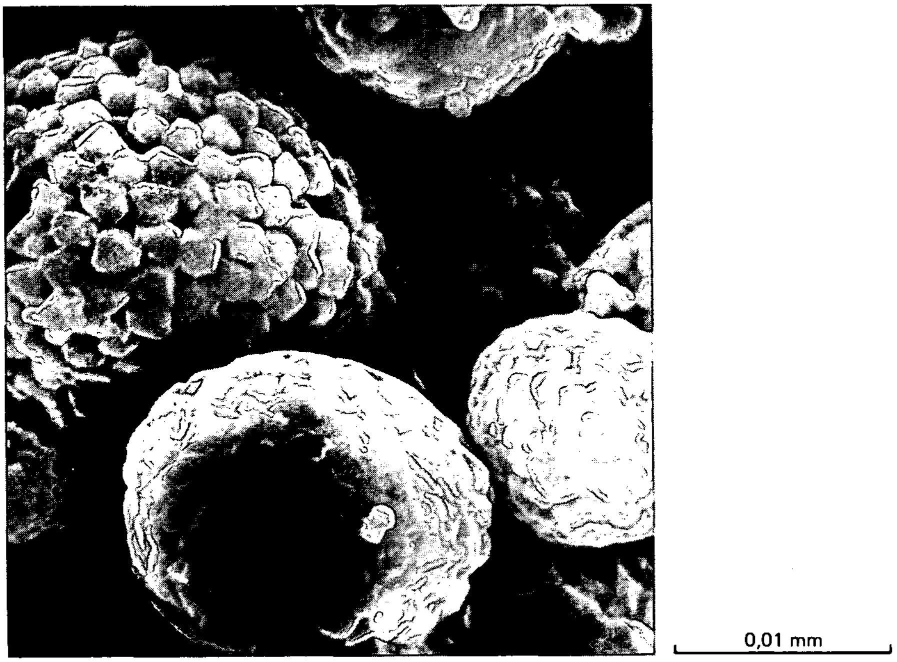


Plate 1.5 Framboidal pyrite. Electron micrograph x 5750 (Keith Tovey). Characteristic spherical nodules of small pyrite crystals

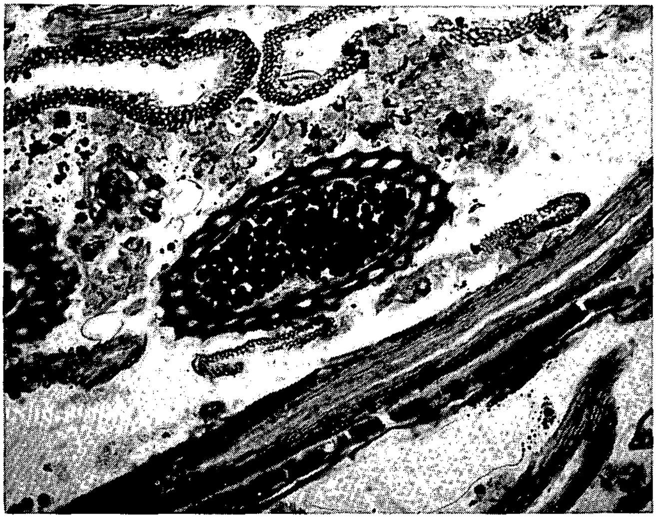


Plate 1.6 Clusters of pyrite crystals associated with decomposing roots in a sulphidic peat soil (E.A. FitzPatrick)

decomposed organic matter. Bacteria, breaking down this organic matter under anaerobic conditions, reduce dissolved sulphate ions to sulphides and iron III oxides to iron II. The main source of sulphate is sea water; most river waters contain little dissolved sulphate. Pyrite is the stable end-product of these reactions (Plates 1.5 and 1.6).

Even under the most favourable natural conditions, the rate of accumulation of pyrite is slow – of the order of 10 kg per cubic metre of sediment per 100 years in mineral soils. This is equivalent to rather more than one per cent dry mass per 100 years.

1.3.2 Neutralising capacity

A soil or sediment containing pyrite only becomes a potential acid sulphate soil when the potential acidity, represented by the pyrite, exceeds the soil's neutralising capacity. The most significant source of neutralising capacity is calcium carbonate. One part by mass of pyrite sulphur is neutralised by three parts of calcium carbonate.

Carbonates may be deposited as clastic material or can accumulate in situ by chemical precipitation or, more commonly, as shell beds. Carbonate contents of shallow-water marine and brackish-water sediments range from negligible in the humid tropics up to 15 per cent or more in the arid and temperate zones. In tropical and sub-tropical environments, the conditions for carbonate accumulation and high pyrite accumulation appear to be mutually exclusive.

1.3.3 Potential acid sulphate environments

Saline and brackish-water tidal swamp and marsh constitute by far the most extensive

Plate 1.7 *Rhizophora racemosa* forest, 30 to 40 m high, The Gambia. This is the usual pioneer species in West Africa, colonising unripe mud within the limits of daily tidal flooding. It is characterised by a tangle of aerial roots and a dense fibrous root mat below the surface.

potential acid sulphate environment (Plate 1.7). The dense vegetation fuels the process of pyrite formation; the tidal cycle brings in sediment, renews the supply of dissolved sulphate, and removes soluble by-products. However, within this landscape there are important differences in potential acidity and other soil characteristics that affect the prospects for land reclamation and development.

Pons et al. (1982) have shown that regional soil patterns are related to changes in relative sea level and the rate of sedimentation, as well as to climate, hydrology, and the chemistry of the floodwaters. Following the last glaciation, the world sea level rose rapidly, reaching about 5 m below the present level about 7000 years ago. Where sedimentation kept pace with the rising sea level, a broad, stable zone of tidal swamp was maintained in which thick layers of sulphidic sediment accumulated.

During the last 7000 years, the sea level has risen more slowly, with fluctuations of 1 to 2 m amplitude (Figure 1.1). Where heavy sedimentation has continued, the coastal swamp has migrated rapidly seawards, leaving behind a band of sediment of much lower pyrite content. In tectonically stable areas, the combination of increasing isolation from tidal influence and a fall in relative sea level has led to the development of extensive acid sulphate soils. In the Chao Phraya Delta, the older sulphidic sediments of the Bangkok Plain are now 1 to 2 m above sea level. They are succeeded, seawards, by a belt, about 100 km wide, of more recent marine alluvium that is mostly not potentially acid. This is shown schematically in Figure 1.2. In contrast, the Irrawady is an example of a river with a very heavy sediment load which has completely buried the older sulphidic clays, so that the soils are potentially acid only at depth and present no hazard. An intermediate situation is represented by the Mekong Delta.

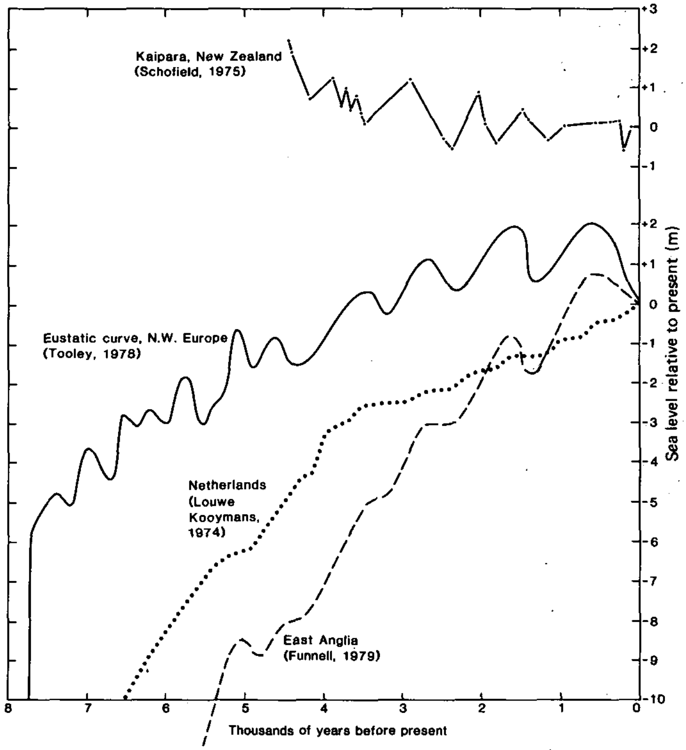


Figure 1.1 Contrasting trends in relative sea level. Kaipara, New Zealand, represents areas of tectonic or isostatic uplift with a stable or falling sea level; East Anglia and The Netherlands have a continuously rising sea level as a result of the eustatic rise in sea level and isostatic sinking of the land; stable coasts have experienced maximum sea levels about 2 m higher than the present.

Here a plain of recent sediments of low pyrite content has succeeded the older sulphidic clays. Broad belts of river alluvium flank the main channels, burying the older sulphidic sediments, so the potential acid sulphate soils are exposed only in the backswamps. In many other low-lying, wet coastal plains, sulphidic alluvium has been buried by the growth of peat.

In detail, soil patterns are more complex. Field relationships between the pyrite content, the depth in the soil profile at which pyrite is concentrated, and the sequential development of tidal landforms are discussed in Section 4.

In certain areas, isostatic or tectonic earth movements have further modified the effects of world sea level changes. A striking example is provided by the exposure of the potentially acid Littorina sediments around the Baltic Sea. These sediments, which originally accumulated on the bottom of a brackish-water sea, are rich in organic matter and contain significant concentrations of reduced iron II monosulphide and pyrite. The isostatic rise of Scandinavia since the last glaciation has carried these sediments above sea level to form acid sulphate soils. In The Netherlands, a rapidly-subsiding area, the sea level has continued to rise. Coastal barriers developed and behind them sulphidic sediments were buried by 4 to 5 m of peat. Acid sulphate soils have been brought to the surface as a result of the drainage of lakes that developed in the peat.

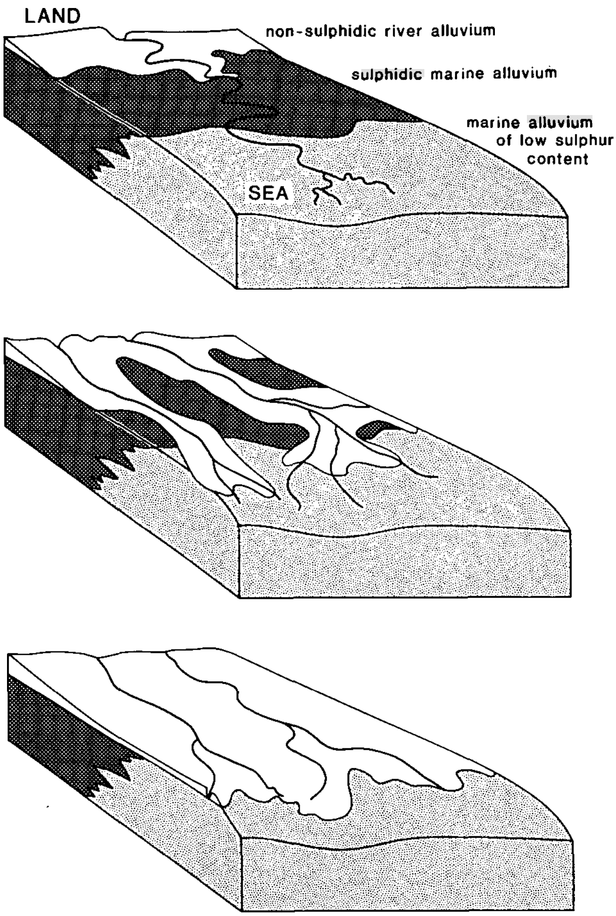


Figure 1.2 The effects of different rates of sedimentation on regional soil patterns: schematic representation of the deltas of:
1 The Chao Phraya, Thailand
2 The Mekong, Vietnam
3 The Irrawady, Burma
(after Pons et al. 1982)

Locally, potential acid sulphate soils have developed inland, in waterlogged sites flushed by sulphate-rich drainage water.

1.3.4 Development of acid sulphate soils following drainage

Potential acid sulphate soils become acid as a result of drainage. Pyrite is stable only under anaerobic conditions. Drainage allows oxygen to enter the soil and pyrite is then oxidised, generating sulphuric acid.

The reaction of pyrite with oxygen is a slow process, but pyrite is rapidly oxidised by iron III in solution. Iron III is thereby reduced to iron II, but iron III is regenerated from iron II by the bacteria *Thiobacillus ferrooxidans*. This catalytic oxidaton of pyrite can take place only at pH less than 4, because iron III is soluble only under these very acid conditions. Possibly another group of sulphur-oxidising bacteria may be involved in the initial acidification of the system.

Overall, the oxidation of pyrite can be represented by the equation:

$$FeS_2 + \frac{15}{4}O_2 + \frac{7}{2}H_2O \rightarrow Fe(OH)_3 + 2\,SO_4^{2-} + 4H^+ \quad (1.1)$$

solid pyrite	dissolved oxygen	colloidal iron III	sulphuric acid

Most of the iron III ultimately crystallises as the reddish brown oxide goethite in mottles, coatings, and nodules within the soil. Some iron II may be lost from the soil in drainage waters, and will precipitate under more oxidising conditions in drains and ditches – which can even be blocked by gelatinous deposits of hydrated iron III oxides.

The severe acidity of acid sulphate soils is responsible for accelerated acid weathering of aluminosilicate minerals and the increased solubility of aluminium. Aluminium is insoluble at pH values above about 4, but is increasingly soluble at lower pH values.

1.3.5 The fate of acidity

If carbonates are present in the soil or added as limestone, acidity is neutralised quickly, mostly to produce gypsum:

$$CaCO_3 + 2\,H^+ + SO_4^{2-} + H_2O \rightarrow CaSO_4.2H_2O + CO_2 \quad (1.2)$$

calcium carbonate	gypsum

Gypsum is sparingly soluble; large crystals only develop in areas with a pronounced dry season.

Some acidity is also neutralised rapidly by exchangeable bases in the soil. The remainder is gradually lost by leaching, or by slow reaction with aluminosilicate minerals.

Acidity is alleviated by flooding. Flooding re-introduces anaerobic conditions and, in the presence of easily-decomposed organic matter, the reduction of iron III oxides, sulphates, and other oxidised species by anaerobic bacteria removes acidity from the system:

$$SO_4^{2-} + 2\,H^+ + 2\,CH_2O \rightarrow H_2S + 2\,H_2O + 2\,CO_2 \quad (1.3)$$

dissolved sulphate	organic matter	hydrogen sulphide

$$Fe(OH)_3 + 2\,H^+ + \frac{1}{4}CH_2O \rightarrow Fe^{2+} + \frac{11}{4}H_2O + \frac{1}{4}CO_2 \quad (1.4)$$

iron III hydroxide	soluble iron II

Reduction in acidity following flooding also alleviates aluminium toxicity. This makes possible the growth of rice, but the crop may still suffer from toxicity by soluble iron and, possibly, hydrogen sulphide or carbon dioxide. Floodwater standing on acid sulphate soils may itself become severely acid and can affect crops growing on neighbouring non-acid soils.

1.4 Agronomic problems

1.4.1 Conditions of plant growth

Acid sulphate soils pose chemical, biological, and physical problems for crops, which have been reviewed by Rorison (1973) and by Bloomfield and Coulter (1973). Chemical problems for dryland crops include:
- Direct effects of severe acidity – primarily the increased solubility and toxicity of aluminium and possibly also iron III, manganese, and hydrogen ions;
- Decreased availability of phosphate, caused by iron and aluminium-phosphate interactions;
- Low base status and nutrient deficiences;
- Salinity.

Under flooded conditions, for example under rice cultivation or fish ponds, acidity is reduced, but new problems include:
- Iron II toxicity;
- Hydrogen sulphide toxicity;
- CO_2 and organic acid toxicity.

Physical problems arise mainly through the inhibition of root development in acid sulphate horizons:
- Crops suffer water stress;
- Soil ripening is arrested. Clay and organic soils remain soft, unable to bear heavy loads, are poorly-structured, and therefore poorly-drained;
- Field drains may be blocked by iron oxide (ochre) deposits.

Unsuitable conditions for most micro-organisms impede the release of nutrients from soil organic matter. Crops under stress are especially susceptible to disease.

1.4.2 Toxicities

Aluminium

At pH values less than 3.5, H^+ and Fe^{3+} ions may inhibit plant growth, but soluble aluminium is likely to be the principal hazard. Aluminium is the principal exchangeable cation in acid sulphate soils; it is also present as colloidal hydroxide or basic sulphate. At pH values less than 4 to 4.5, it is increasingly soluble. Van Breemen (1973; 1976) has shown that Al^{3+} activity is inversely related to pH, increasing roughly 10-fold per unit pH decrease. He reports Al^{3+} concentrations of groundwater from acid sulphate soils in Thailand ranging from 0.015 mol m^{-3} (0.4 ppm) at pH 5.5 to

2.12 mol m^{-3} (54 ppm) at pH 2.8. In oxidation experiments, Al^{3+} concentrations ranged from 0.1 mol m^{-3} (2.7 ppm) at pH 4 to 58 mol m^{-3} (1 500 ppm) at pH 1.8.

Al^{3+} can be toxic in concentrations as low as 0.04 to 0.08 mol m^{-3} (1 to 2 ppm), although there is great variation in tolerance from one species to another and within particular species. Soluble aluminium accumulates in the root tissues, preventing cell division and elongation and, possibly, inhibiting enzymes concerned with synthesis of cell-wall material (Rorison 1973). The result is a stunted and deformed root system. In addition, uptake of phosphate is inhibited because of its absorption by aluminium in the soil and within the roots.

Aluminium toxicity may be avoided by flooding, which raises the soil pH (Figure 1.3), but rice may still suffer from aluminium toxicity on acid sulphate soils if the seeds are broadcast prior to flooding, or if seedlings are transplanted before reduction processes have raised the pH sufficiently to immobilise aluminium.

Iron

Fe^{2+} may be released in toxic concentrations in flooded soils. Ponnamperuma et al. (1973) report values up to 90 mol m^{-3} within two weeks of flooding, but values between 9 and 18 mol m^{-3} are more common. Soluble iron concentrations do not normally remain high, but decrease over a few weeks (Figure 1.4). Some soils yield very little soluble iron, either because of small total iron contents, or small amounts of iron in an easily-reduced form. Old acid sulphate soils, in which most iron is in the form of well-crystallised goethite and haematite, probably fall into the latter category. Young acid sulphate soils with abundant colloidal iron are likely to yield high dissolved iron concentrations following flooding.

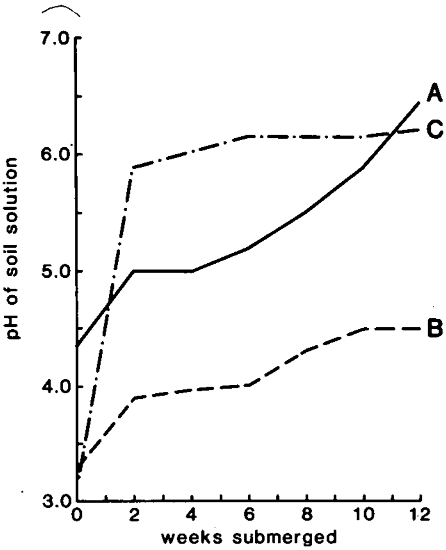
Dissolved iron concentrations in excess of 9 mol m^{-3} are toxic to rice (Nhung and Ponnamperuma 1966), but different varieties show a wide range of tolerance.

Hydrogen sulphide

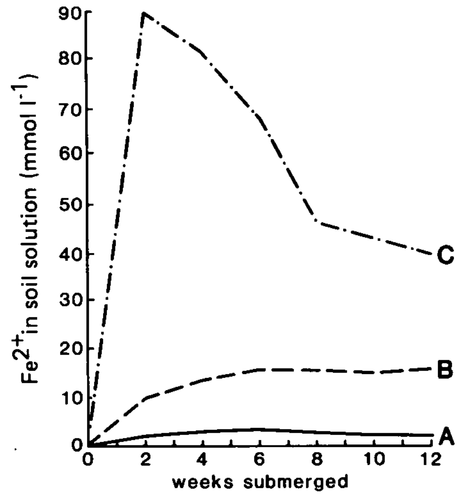
Hydrogen sulphide toxicity may occur as a result of sulphate reduction in flooded soils (Equation 1.3). As in the case of iron II toxicity, rice is the principal crop involved, but H_2S toxicity is possible in dryland crops growing over a sulphidic subsoil or over an acid sulphate subsoil that has been flooded to counteract the effects of extreme acidity.

Very low concentrations of H_2S in solution, in the range of 1 to 2 x 10^{-6} mol m^{-3} impair root functioning. Young rice plants are especially susceptible; older plants appear to be able to counteract H_2S toxicity by creating oxidising conditions around their roots and/or by proliferation of their root system. Plants affected by H_2S are especially susceptible to infection. The conditions of 'akiochi' and 'brusone' are associated with sulphide toxicity.

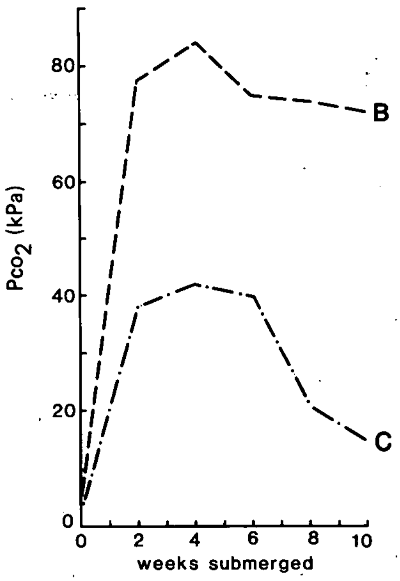
H_2S normally reacts with iron II, yielding FeS and, ultimately, pyrite. Toxicity is associated with soils rich in organic matter and low in iron. The bacteria responsible for sulphate reduction do not operate in acid conditions, so H_2S toxicity only develops after the soil pH has been raised to about 5 by prolonged flooding.



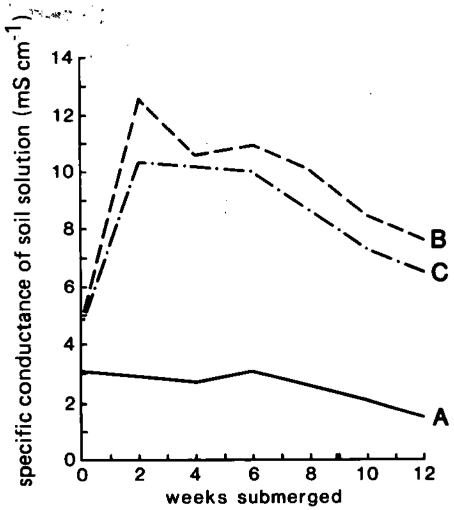
1.3 pH



1.4 Water-soluble iron



1.5 CO_2 concentration



1.6 Salinity

Soil A Ongharak Series, Thailand: a ripe acid sulphate clay
Soil B Long-My Series, Vietnam: a half ripe saline acid sulphate clay
Soil C A half ripe saline acid sulphate clay, Sariaya, Philippines

12 kg sample submerged and soil solution sampled fortnightly.
(after Ponnamperuma et al. 1973)

Figures 1.3 to 1.6 Response to flooding of contrasting acid sulphate soils

Carbon dioxide and organic acids

CO_2 is produced mainly by the decomposition of organic matter. It accumulates in flooded soils, and in acid soils that are rich in organic matter and iron. Partial pressures of CO_2 in solution may rise to 80 kPa within two weeks of flooding, but then decline rapidly as a result of escape and reduction to methane. In soils low in iron, pCO_2 rises to about 50 kPa within two weeks of flooding, then declines slowly to about 30 kPa (Figure 1.5).

Carbon dioxide concentrations greater than 15 kPa retard root development, leading to wilting and reduced nutrient uptake.

Organic acids are also produced by anaerobic breakdown of organic matter. Normally their existence in the soil is emphemeral, but under severely acid conditions their breakdown is inhibited and they can persist in a toxic, undissociated state (Tanaka and Navasero 1967).

1.4.3 Salinity

Tidal and recently-reclaimed sulphidic soils have large concentrations of soluble salts as a result of prolonged flooding by sea water. Soluble sulphates are also produced by the oxidation of pyrite. (In Figure 1.6, the initial increase in salinity might be caused by oxidation of pyrite.) Where the soil is permeable, these salts are readily leached by rainfall and flooding by fresh water. Persistent salinity is related to poor drainage, which may result from several factors:

- Inadequate main drainage;
- Inefficient operation of floodgates;
- Seepage through sandy material adjacent to the sea wall;
- Unripe subsoil.

Where severe acidity inhibits soil ripening, clay subsoils can remain very slowly permeable. Soluble salts are not leached and may accumulate in the rooting zone, especially in the dry season.

Salinity levels in acid sulphate soils are inevitably very variable. The highest levels occur in young acid sulphate soils in regions with a pronounced dry season, such as Senegambia, where EC_e values in excess of 80 mS cm^{-1} occur in the upper 30 cm (Vieillefon 1977; Marius 1982) and surface salt crusts form during the dry season. In contrast, in the humid climate of Northland, New Zealand, salinity in the upper 30 cm is usually reduced to less than 5 mS cm^{-1} within 15 years of drainage; and maximum values in the upper metre range between 10 and 30 mS cm^{-1} after 15 years of drainage and between 2 and 15 mS cm^{-1} after 45 years. The highest values coincide with poor drainage and an unripe subsoil. In old acid sulphate soils in Thailand (van Breemen 1976), soluble salts occur at greater depth and absolute salinity levels are yet lower. EC_e values in the upper 30 cm are less than 5 and usually less than 1 mS cm^{-1}, and maximum values in the upper 1 m range from 1 to 7 mS cm^{-1}.

The osmotic effect of high concentrations of soluble salts inhibits the uptake of water and nutrients. In addition, toxicity by specific ions, notably Na^+ and Cl^-, is common. Tolerance of salinity varies widely between different crops (Ayers and Westcot 1976). Yields of most crops are affected by EC_e ranging from 1.5 to 7 mS cm^{-1}, and maximum tolerable levels range from 10 to 20 mS cm^{-1}.

1.4.4 Nutrient deficiencies

Nutrient deficiences are likely to affect crop production on acid sulphate soils when other limiting factors, such as overwhelming toxicity and salinity, have been overcome. They are to be expected especially in two situations: in old, leached acid sulphate soils and in severely acid organic soils.

Phosphate availability is usually restricted, and added phosphates are strongly absorbed by acid sulphate soils. This may be attributed to the high content of active aluminium and iron, which form very insoluble phosphates at low pH. Nevertheless, very good responses to added phosphate have been reported for rice (Section 2.6.3). Under reducing conditions, some of the iron and, possibly, aluminium phosphate becomes available, but their release by flooding will gradually be reduced by ageing and crystallisation.

Acid sulphate soils that have undergone a long period of leaching will be depleted of bases and weatherable minerals. Their exchange complex will be saturated with aluminium. Deficiences of calcium, magnesium, potassium, manganese, zinc, copper, and molybdenum have been reported (Bloomfield and Coulter 1973), but there are no specific deficiences related to acid sulphate conditions and in many cases acid sulphate soils are no more base-deficient than many other leached tropical soils.

Unfavourable conditions for micro-organisms restrict the release of nutrients from the decomposition of organic matter. Nitrate and phosphate are the nutrients chiefly concerned. The symbiotic fixation of nitrogen by *Rhizobia* associated with legumes will also be restricted by the effects of low pH and low phosphate availability. Mycorrhiza, which contribute substantially to the uptake of phosphate in phosphate-poor soils, may be effected by extreme acidity.

1.4.5 Arrested soil ripening

Freshly-deposited muds that are rich in clay and organic matter have water contents of as much as 80 per cent by volume. Their water content is reduced by consolidation and, more importantly, by the extraction of water by the roots of marsh and swamp vegetation. Even under continuously waterlogged conditions, water content may be reduced to between 60 and 75 per cent. As continued deposition of mud raises the soil surface above low tide level, the water content of the surface horizons is reduced to between 55 and 65 per cent by drainage at low tide, by direct evaporation from the surface, and by the increasingly vigorous root system of the natural vegetation (Pons and Zonneveld 1965).

Extraction of water from the soil brings about irreversible shrinkage and the development of structural fissures. The process is known as *soil ripening* (Section 3.5), and is associated with an increase in permeability as a result of fissuring. In non-sulphidic alluvial soils, artifical drainage accelerates soil ripening. Where acid sulphate conditions develop, roots cannot penetrate the acid horizon, or any underlying layers, and ripening is arrested.

Horizons with dense root systems of reed, mangrove, or *Nypa* palm are naturally very permeable and drain rapidly but, without the development of a vigorous living root system, the underlying horizons remain very slowly permeable. Permeability in the undrained soil is due almost entirely to burrows and channels left by decayed plant roots. These tend to collapse or fill following drainage, so unless vigorous soil life constantly produces new pores, the permeability of the soil is reduced. Even where good surface drainage is provided, unripe soils remain poorly drained and sometimes saline. They are soft and intractable, limiting mechanisation and posing engineering problems for earth structures and foundations.

1.5 Engineering problems

Engineering problems posed by acid sulphate soils include:
- Corrosion of metal and concrete;
- Low bearing strength and uneven subsidence of unripe soils;
- Blockage of land drains by ochre.

1.5.1 Corrosion

Mild steel, galvanised steel, and most aluminium alloys are corroded by the acidity and dissolved salts in acid sulphate soils and drainage waters. Steel is also attacked under severely reducing conditions. This can cause serious problems for pipelines, pylons, piles, and other structures.

In addition to direct acid attack, concrete is corroded by soluble sulphate. $Ca(OH)_2$ in the concrete is transformed to gypsum $CaSO_4.2H_2O$, involving an increase in volume. The gypsum further reacts with tricalcium aluminate $3CaO.Al_2O_3$ in the concrete, forming etteringite $3CaO.Al_2O_3.CaSO_4.32H_2O$, which results in a large increase in volume and a reduction in strength of the concrete.

Corrosion can be limited at extra cost by using sulphate-resisting cement, thicker concrete, sacrificial electrodes, stainless steel, or hardwood, where appropriate, and by coating exposed structures with bituminous composition; but the combination of extreme salinity and acidity should be avoided if possible.

1.5.2 Unripe soils

Low bearing capacity and uneven subsidence in unripe soils pose problems for the foundations of buildings and roads. For large structures, piles must be sunk to underlying layers of sufficient bearing capacity.

Earth structures suffer from slow consolidation and from shrinking and fissuring as drying takes place. A particular problem with acid sulphate soils is that earthworks are not readily colonised by vegetation, so they are exposed to erosion by wind, rain, and wave action.

1.5.3 Blockage of drains by ochre

Poor drainage is always a problem in unripe soils, and underdrainage using clay tiles or perforated plastic pipe may be considered when the topsoil is sufficiently ripe to support machinery. However, where the soil contains pyrite, drainage leads to the precipitation of very large quantities of colloidal iron III oxides, or ochre, in and around the drains.

$$Fe^{2+} + \tfrac{1}{4}O_2 + H^+ \xrightarrow{\textit{Thiobacillus ferrooxidans}} Fe^{3+} + \tfrac{1}{2}H_2O \qquad (1.5)$$

$$Fe^{3+} + 3\,H_2O \xrightarrow{\textit{hydrolysis at pH} > 3} \underset{\text{ochre}}{Fe(OH)_3} + 3\,H^+ \qquad (1.6)$$

Underdrainage systems can be completely blocked within one year or a very few years of installation (Trafford et al. 1973), so open ditches, supplemented where appropriate by mole drains, should be used.

Basic design criteria for earthworks, roads, and drains are given in Section 2.8.

1.6 Environmental problems

1.6.1 Environmental impact

The physical, chemical, and living systems of any area have evolved through reactions with one another. They are all inter-dependent and any change in one facet of the environment inevitably brings about adjustment in others. The environmental impact of a land development encompasses all changes in the total environment resulting from that development. These changes may not be planned; often they are indirect and unintentional; sometimes they occur at a distance from the original development.

For example, the reclamation of 10000 ha of mangrove swamp and salt marsh for rice cultivation inevitably results in the loss of those 10000 ha of natural habitat. It also has implications for the sediment balance and water chemistry of the whole estuary or delta, and for all aquatic life dependent on the contribution of that area to the ecology of the shallow waters of the region – including insects, molluscs, crustacea, fish, and wildfowl. Commercial offshore fisheries may be seriously affected. If acid sulphate conditions develop, then acid saline effluent from the reclaimed land may disturb, or wipe out, whole aquatic communities at some distance from the reclamation, and for many years to come.

Obviously, the environmental impact of the reclamation on the region will be greater if those 10000 ha make up most of the local mangrove and salt marsh community of the region, than if they represent only a small proportion. Likewise, a single massive development will have a more severe impact than piecemeal or phased development.

The side effects of land reclamation have received less scientific study than engineering and agronomic problems. Now they are receiving increasing attention in countries that have relatively little wetland that is capable of more intensive use and which, at the same time, can afford the luxury of balancing considerations of wildlife and public amenity against the needs of land for agricultural or industrial development. In these circumstances, it is possible to assign substantial economic benefits to not developing land or to low-intensity management, especially where drainage is likely to lead to the development of acid sulphate soils (Turner et al. 1983).

The environmental impact of draining potentially acid sulphate soils may be considered under the following headings:
- Loss of wetland habitat;
- Loss of amenity;
- Changes in sedimentation and erosion;
- Changes in water chemistry;
- Disease.

1.6.2 Loss of habitat

Wetlands are increasingly under pressure from development and, in developed countries, are now relatively rare. The ecological impact of land drainage is by no means confined to the drained area. There are implications throughout the web of life that is dependent on mangrove and salt marsh. These are primary producers of organic food, and provide sheltered, shallow-water feeding and breeding grounds for insects, shellfish, crustacea, fish, and wildfowl. It is necessary to scrutinise proposals for reclamation to ensure that an adequate area of natural marsh or mangrove is left to serve as a base for the local food chain.

1.6.3 Loss of amenity

The amenity and recreation value of wetlands is increasingly recognised. Mangrove swamp, salt marsh, and marshland pastures have an aesthetic, landscape value; a scientific value for the study of ecology of natural and little-managed habitats; and recreational value for fishing, shooting, boating, and as empty space which, in industrialised societies, is increasingly hard to find.

1.6.4 Sedimentation and erosion

Swamp and marsh vegetation stabilise mud banks and act as sediment traps for silt and clay that would otherwise remain in suspension in shallow tidal waters. Reclamation affects the pattern of tidal currents and will inevitably lead to a changed pattern of erosion and sedimentation.

1.6.5 Pollution

Where acid sulphate soils develop, dramatic changes in water chemistry take place, and these are exported from the reclaimed area with the drainage waters. Pollution problems have been extensively studied in relation to the acid drainage waters of mines and mine spoil containing pyrite. Mine spoil remains almost sterile and unsightly, and drainage waters may affect entire catchments (for example Temple and Koehler 1954; Pedersen et al. 1978).

Acid floodwaters generated over large areas of acid sulphate soils may adversely affect crops growing on adjacent, better soils (Section 2.3.3). Flushes of severe acidity from acid sulphate soils have been implicated in the death of aquatic plants, shellfish, crustacea, and fish in both tidal and inland waters in many parts of the world (for example Dunn 1965; Gosling and Baker 1980; Marius 1982). Direct toxicity by dissolved acid and aluminium will be greatest in fresh and brackish waters that are weakly buffered.

The acidity may arise from any combination of direct reclamation of sulphidic soils, lowering the watertable in adjacent areas, and unusually dry seasons affecting the regional watertable. Obviously, the regional impact of acid drainage or flood waters will be greater from large developments than from small-scale reclamation. Dent and Raiswell (1982) have developed a quantitative model of pyrite oxidation which can be used to predict the effects of acid production from the drainage of large areas of sulphidic soils (Section 3.6).

Colloidal iron III hydroxide is unsightly. It settles on aquatic vegetation, reducing the intensity of light reaching the leaves, and is occasionally produced in such quantities as to clog drains and waterways, both directly and through its rapid colonisation by reeds.

In industrialised estuaries, the sediments may contain a high proportion of man-made detritus – cinders, fly ash, urban and industrial wastes containing heavy metals. We are ignorant of the toxic effects of some of these materials or the difference in solubility that might arise from a significant lowering of the pH of the environment.

1.6.6 Disease

New disease hazards are not specifically connected with the development of acid sulphate soils, but are associated with any land settlement scheme that transforms the ecology of an area. The replacement of saline or brackish water tidal swamp by a densely-settled farmland with a permanent network of freshwater irrigation or drainage ditches opens new possibilities of bilharzia, typhoid, cholera, and waterborne parasites. Malaria is endemic in most tropical and subtropical wetlands, but although some species of mosquito are eliminated by the change to freshwater, other malaria-carrying species take their place.

1.7 Economic and social implications

Wise planning of land reclamation must take into account the great variety of soil conditions that may be encountered. Acid sulphate soils are by no means a uniform group: they encompass all degrees of acidity, salinity, and physical problems from slight to insuperable. Very often, they occur in complex patterns with non-acid soils, and the details of their distribution and severity can be mapped only by detailed survey. Severe acid sulphate conditions restrict the choice of crops; yields will be low and in some areas crops will fail totally for many years. In some areas, amelioration is physically or economically impracticable. Elsewhere, the difficulties may be avoided by flooding or by high watertable management for rice, oil palm, or grassland; or dryland crops may be grown following amelioration by leaching and liming, although several years of special management may be required before good yields are obtained. In all cases, costs will be higher and returns lower than for most non-acid soils and the likelihood of local, even if temporary, failures must be acknowledged.

Brinkman (1982) has drawn a broad distinction between the development possibilities and problems of the salt water and freshwater zones. Mangroves, swamp forest, and salt marsh are an integral part of a diverse and very productive ecosystem, which includes commercial fisheries. The tidal forest can yield timber, fuel, cellulose, and other products. In West Africa and South East Asia, in estuaries with wet-season freshwater floods that flush the salt from the surface soil, the natural vegetation is cleared for tidal rice. Traditional methods of cultivation yield up to 2 tonnes ha^{-1}, although the usual figure is nearer 0.7 tonnes ha^{-1}.

Alternative uses of the land include rice cultivation with a controlled water regime, brackish-water fish ponds, and salt pans. However, any alteration of the tidal regime requires engineering and chemical inputs, and drainage of the soils rich in pyrite will always generate acidity, which must leach into neighbouring tidal waters.

Economic evaluation of development must assign realistic values to the natural production or potential of the land and must take into account the delay in returns on investment, especially from agricultural enterprises from which only low yields can be expected for many years. The environmental impact of large reclamations of acid sulphate soils in the tidal zone is likely to be disastrous, through loss of habitat and pollution. Conversion of unsuccessful fields to fish ponds is feasible, but requires further engineering, and therefore more capital, and unrestricted access to tidewater for every operator.

In the freshwater zone, the options are fewer and the problems somewhat different. Extensive areas of acid sulphate soils occur and the development of these areas will require a new physical infrastructure of roads, drainage and irrigation canals, housing and services, and a new social organisation. In contrast to the salt-water zone, there is little or no tidal effect to assist drainage and the removal of acid effluent.

Commonly, there are broad strips along the rivers that do not have acid sulphate problems. Also, there may be large areas that are responsive to quite small applications of lime and fertilizer. This is especially true of ripe acid sulphate soils that have leached and weathered naturally and no longer have reserves of pyrite in the rooting zone.

The economic viability of land development depends not only on the attributes of land, but on the relative costs of inputs – drainage, irrigation, lime, fertilizer, crop protection, seed, and other production costs – and, on the other hand, on prices and subsidies. Land reclamation or improvement may be profitable by any economic yardstick.

For example, on the ripe acid sulphate soils of Thailand, lime applications of between 10 and 15 tonnes $CaCO_3$ equivalent ha^{-1} have raised average farmers' yields (1975-1979) from 1.5 to 2.7 tonnes ha^{-1} for transplanted rice and from 1.1 to 2.1 tonnes ha^{-1} for broadcast rice. On these soils, one application of lime will last about 5 years.

The benefit:cost ratio of the project as a whole is greater than 2.

However, the response to lime and fertilizer depends a great deal on the initial fertility of the soil. In the case of the more severely acid Thai soils, Charoenchamratcheep et al. (1982) report up to 3-fold returns on the cost of lime application of 5 to 10 tonnes $CaCO_3$ equivalent ha^{-1} and up to 5-fold returns on the optimum combination of the lime with N and P fertilizer in the first year of application.

Under the price and subsidy structure of the European Economic Community, farmers in the east of England now find it profitable to improve the drainage of clay soils with unripe, potentially acid subsoils and to convert them from grassland to wheat growing. Providing the acid layer is deeper than 60 cm, yields of 4 to 6 tonnes ha^{-1} may be obtained without special management. On acid peat soils, where a greater range of crops may be grown once acidity is overcome, applications of as much as 100 tonnes lime ha^{-1} can be justified in financial terms (Dent and Turner 1981).

In many other cases, where there is no local source of cheap lime or where the price obtainable for the product is low, reclamation or improvement of acid sulphate soils cannot be financially justified, even where labour costs are low.

The need to create a viable social organisation is common to all land settlement schemes. Planners involved in the development of land with acid sulphate soils must face up to the near certainty of local agricultural failures. All experience is against large 'one shot' development schemes where all the land is cleared, drained, and peopled, with some degree of government assistance or direction. Few of the farmers will have any experience of the soil problems they will face and will not have the technical expertise or capital required to overcome them.

Drawing an analogy with examples of spontaneous colonisation of acid sulphate soils in South East Asia, Brinkman (1982) suggests that new planned settlement schemes should have a wide mesh – including physical space that can be filled gradually, allowing for experimentation and small-scale mistakes, and also allowing for temporary abandonment of areas that prove especially difficult for the early colonists. In the early stages of development, only a few of the meshes of the plan are filled in. These must include roads, main drainage and irrigation canals, and essential services.

The success of land development is also very dependent on the calibre of the pioneering settlers, who need to be selected for their farming, management, and innovative ability. They should also have a personal stake in the success of the new venture and, if possible, come from a common locality so that they bring with them social contacts that will help them to build a new community. As more settlers gradually arrive, they will find older as well as recently-established settlers in the new area, with a range of practical experience on how to use the land.

It is obvious that soil survey in advance of a new development can help to avoid some of the economic and social problems. It can identify the most suitable soils for the first stages of settlement; guide the layout of embankments, roads, and canals; and anticipate some of the physical difficulties that will arise. The potential of the soil team – surveyor, agronomist and laboratory support – is not limited to this. Once development is under way, ongoing work is needed to monitor the response of crops, soil, and environment to the reclamation methods and management applied; to identify the causes of trouble as it arises; and to develop, in cooperation with the farmers, improved management applicable to each individual parcel of land.

2 Management

2.1 Alternative management strategies

If a potential acid sulphate soil is drained, it will become severely acid and large quantities of sulphuric acid and iron will be released into the drainage system. The nearer the surface the acidity, the more acute its effects on crop yield; the more intense the acidity, the longer its effects will last. But feasible management strategies for acid sulphate soils are determined only partly by the severity of the acidity hazard and other soil conditions. Equally, they are determined by climate (especially the nature of the wet and dry seasons), by hydrology (including flooding, availability of irrigation water, and access to tidewater), and by the economic opportunities available to the people who depend upon the land. In any particular case, the best option is determined by the demand for the land and its products, and the availability of technology, finance, and material inputs.

Water management is the key to soil management. Root development is always restricted in acid sulphate soils, so that a dry season of more than a few weeks severely limits agricultural opportunities, unless water is available for irrigation or to maintain a high watertable artificially. Because flooding alleviates acidity, rice is always likely to be the principal crop grown on acid sulphate soils in warm regions. In temperate areas, grassland under high watertable management occupies a similar niche.

Prospective developers face a series of choices:

- To develop or not to develop;
- If the development option is chosen – to adopt a minimum disturbance strategy or to attempt total reclamation;
- Several minimum disturbance strategies are available:
  - Flooded rice cultivation relies on the reduction of acidity by flooding. A number of management systems have evolved, examples of which will be described in the following pages;
  - Shallow fish ponds are an alternative use where there is unrestricted access to tidewater;
  - Some dryland crops, including oil palm, coconut, and grassland, can be grown with a constant high watertable, which minimises the oxidation of pyrite;
  - Where the water regime can be controlled, good responses to modest dressings of lime and fertilizers and to selected or improved crop varieties are sometimes achieved. However, the choice of crops and the timing of operations remain severely limited.
- Total reclamation can be slow and expensive. It is likely to be an economic proposition only where the initial acidity is moderate or has already been reduced by a long period of weathering and leaching, where there is excess rainfall or adequate water to leach the residual salts and acidity, where lime and fertilizers are readily available, and where there is a strong demand for land.

2.2 Avoidance of development

If alternative land is available for development, the simplest and cheapest policy is to leave acid sulphate soils well alone. This is the only course of action that does not preclude other alternatives in the future. Especially in the case of tidal land, the value of mangroves, salt marsh, and mud flats to commercial fisheries and wildlife should be recognised. Direct economic benefits can accrue from the exploitation of natural products (for example mangrove forestry; FAO 1982) and from recreation.

2.3 Flooded rice cultivation

2.3.1 Tidal rice

In the estuaries of many tropical rivers, fresh water is backed-up by the tide during the rainy season. Where there is a minimum of 100 days of fresh tidewater flooding, clearance of mangroves and reedswamp for rice cultivation has been successful, even where potentially acid soil is present within 20 cm of the surface (Plates 2.1 and 2.2). The secret of success is that the natural hydrology remains undisturbed. Twice-daily flooding by fresh water in the wet season and by salt water in the dry season prevents oxidation of the pyrite.

Many attempts to extend rice cultivation into areas of permanent salinity by exclud-

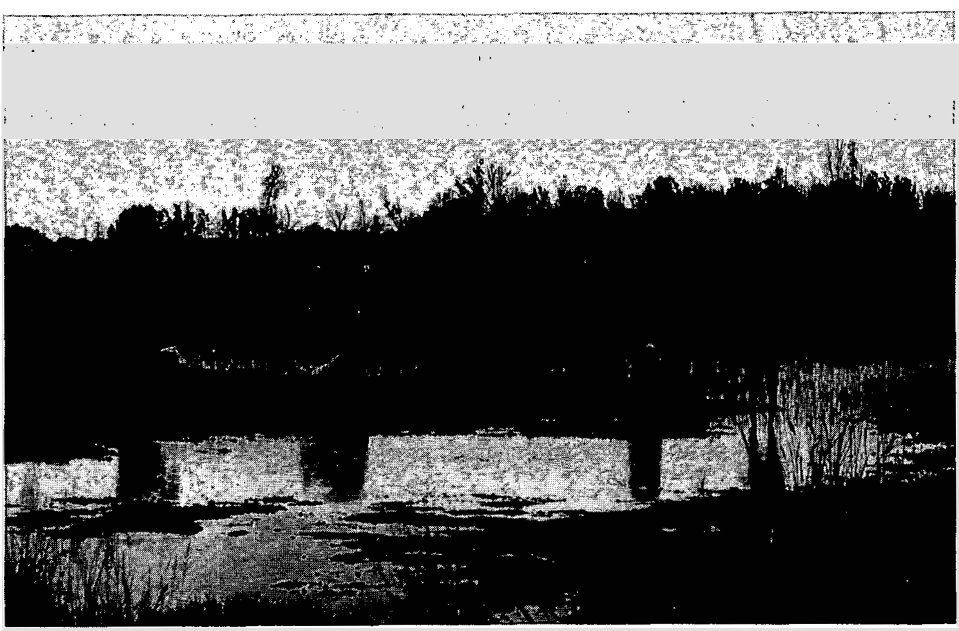


Plate 2.1 Tidal rice cultivation following clearance of mangroves, The Gambia. At this site, 140 km upstream, the salinity of the river water is less than 5 mS cm^{-1} from mid-August to late January in an average year. However, river flow varies a lot from year to year. Rice is planted in September and harvested in December-January. Average yields are about 0.7 tonnes ha^{-1}, but some farmers achieve about 2 tonnes ha^{-1} in good years.

Plate 2.2 Large rice seedlings, suitable for transplanting into tidal land with an uncontrolled water level and risk of salinity and toxicity, The Gambia.

ing tidal flooding have failed because this leads to drying of the soil and oxidation of the pyrite. Table 2.1 shows the effects of excluding tidewater in the dry season at Rokupr Rice Research Station in Sierra Leone. From 1935 to 1943, the farm was tidal; from 1944 to 1947, tidal influence was excluded by perimeter bunds and yields fell dramatically; after 1948, tidal flooding was restored and yields recovered equally dramatically.

Table 2.1 Yields of rice, tonnes ha^{-1}, West Africa Rice Research Station, Rokupr (from Bloomfield and Coulter 1973)

Block No.	Average under tidal regime 1935-1943	Tidal flooding excluded				Tidal flooding restored				
		1944	'45	'46	'47	'48	'49	'50	'51	'52
22	1.9	0.9	0.0	0.0	0.0	0.8	2.0	1.7	2.6	3.3
23	2.3	1.2	0.2	0.0	0.0	1.3	2.7	2.4	2.6	3.0
24	2.6	2.0	0.7	0.2	0.2	1.1	3.0	3.0	2.7	–
25	2.0	1.7	0.1	0.1	0.2	2.0	3.3	2.7	2.9	3.5
26	2.6	0.8	0.2	0.0	0.0	1.0	2.1	3.2	1.9	3.9
27	3.2	1.1	0.6	0.0	0.0	0.9	2.3	2.6	2.5	3.4

2.3.2 Seasonally-flooded rice

Acid sulphate soils that are seasonally flooded by deep water, for example the Bangkok Plain, have traditionally been broadcast with floating rice. This grows as a dryland crop before flooding. Yields are low, partly because of aluminium toxicity before reducing conditions are established.

The introduction of high-yielding, short-duration varieties offers the opportunity of transplanting seedlings into flooded soils as the floodwaters recede, thereby avoiding the period of low pH and aluminium and iron toxicity. Xuan et al. (1982) report yields of 4.6 to 6 tonnes grain ha^{-1} on acid sulphate soils in the Mekong Delta where the crop is transplanted after the period of deep flooding. Phosphate fertilizer is applied and supplementary irrigation from freshwater canals is needed if drought occurs before ripening.

2.3.3 Reclamation by intensive shallow drainage

Extensive areas of acid sulphate soils have developed in the backswamps of the Mekong Delta, where bunds have been built to exclude saline water. Rice is grown successfully on raised beds drained by an intensive network of broad, shallow ditches. For reclamation, fields are laid out in strips 9 m by 36 m. Between each strip, a ditch about 1 m wide and 0.3 to 0.6 m deep is dug by spade, the slices of soil being spread evenly over the intervening strips to make raised beds. Each shallow ditch opens at one end to a main drainage canal (Plates 2.3 and 2.4).

During the dry season, oxidation and acidification occur. Leaching commences with the first heavy rains, in April. Drainage water is allowed to collect in the ditches until it reaches the surface of the raised beds; then, with the next rains, the accumulated acid water is allowed to drain to the river at low tide. This leaching cycle is repeated two or three times until the whole region is flooded by the river.

The raised beds are weeded and tilled at the beginning of the rainy season. Rice

Plate 2.3 Reclamation of acid sulphate soils by intensive shallow drainage, Mekong Delta, Vietnam.

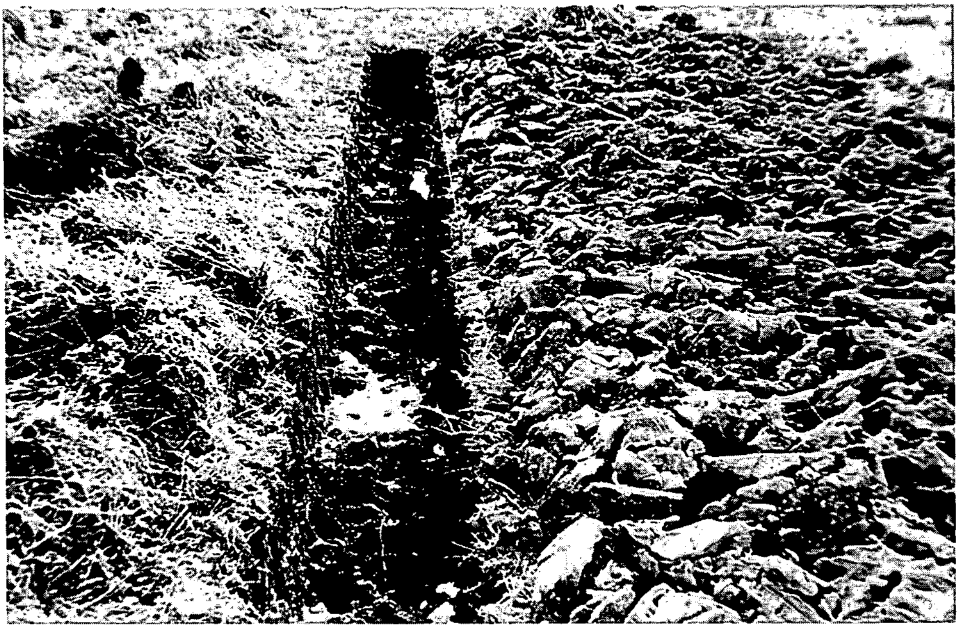


Plate 2.4 Topsoil from the broad shallow ditches is spread evenly between the ditches to build a raised bed about 9 m wide, Mekong Delta, Vietnam.

is sown on nursery beds in early June; then 45 to 60 day-old seedlings, 0.6 to 1 m tall, are transplanted into the flooded beds. Local yields on undrained acid sulphate soils are only 0.2 to 0.5 tonnes ha^{-1}, but under this system of shallow drainage and leaching, yields of about 4 tonnes ha^{-1} are obtained.

Xuan et al. (1982) report that the acid sulphate horizon in these polders occurs at a depth of 30 to 60 cm, in which case it is likely that little sulphidic or severely acid soil is spread over the raised beds. Much of the free acid accumulated during the dry season will be leached via the drainage network; then soil reduction under flooded conditions will raise the pH, reducing the level of soluble aluminium, prior to transplanting. The use of saline- and acid-tolerant varieties and the transplanting of large seedlings will also counteract toxicity.

Of course, the leached acid has to go somewhere, and the reclamation of large areas of acid sulphate soils has led to increased acidity of the floodwaters, affecting crops in adjacent areas.

2.4 Rain-fed rice cultivation

Rice is grown successfully on acid and potentially acid clay and muck in the humid tropics where a constant high watertable can be maintained. In Brunei, Williams (personal communication) has found that resistance to acidity is greatly enhanced in large-sized seedlings of any variety; most yield reduction is attributed to death of tillers in the first three weeks after transplanting.

Acidity problems are greatly increased where it is not possible to maintain a constant high watertable because of a pronounced dry season. However, rice farming is carried out during the rainy season by a variety of local indigenous systems. The reasons for their success and their limitations have not been established, but two common features seem to be avoidance of deep drainage and minimal disturbance of the sulphidic subsoil.

The following example of rice cultivation on ridges has features in common with several traditional farming methods on acid sulphate soils.

2.4.1 Rainwater polders, Guinea Bissau

Guinea Bissau experiences a five-month dry season and a rainfall of between 1 000 and 2 000 mm in the wet season. The tidal creeks do not carry sufficient fresh water for tidal rice cultivation but polders are made in the tidal zone with earth bunds, 1.5 to 2 m high, to exclude salt water. Within these polders, small bunds about 30 cm high divide the land into irregular parcels, according to the microtopography, and pond up rainwater in the wet season (Plate 2.5). Local varieties of upland rice are transplanted into ridges and yield between 0.5 and 1.5 tonnes grain ha^{-1} (Oosterbaan 1982).

In the dry season, the soil becomes very saline and, in some cases, severely acid. In the wet season, there is leaching of soluble salts and acid. Surplus water drains via the old creeks within the polder and escapes through culverts that can be blocked

Plate 2.5 Rainwater polders, Guinea Bissau. Dikes along the main creeks keep out the salt water. The crop is supplied entirely by rainwater, which is retained within the polder by low bunds that divide the land into irregular parcels, according to the slope. Within each parcel, the topsoil is ridged by hand cultivation and rice seedlings are transplanted into the ridges in August for harvest in November. Yields are limited by salinity and severe acidity (Roland Oosterbaan).

to prevent the re-entry of salt water.

Cultivation on ridges of topsoil is a common practice on acid sulphate soils and is widely used for rice in West Africa. In this case the ridge and furrow system will:

- Promote leaching of soluble salts and acid from the ridges in the rainy season;
- Promote drainage of surplus water;
- Increase the effective rooting depth where the ridges are constructed entirely of non-acid topsoil.

This system is labour-intensive and relies on surface drainage for removing salts and acid. Yields are low and vary according to rainfall. Environmental impact is minimised by the piecemeal nature of development and the preservation of most of the tidal creeks and fringing mangroves.

2.5 Controlled high watertable management for perennial crops

Rice is the only major crop that can take advantage of the reduction of acidity that follows the flooding of acid sulphate soils. However, the production of acid can be limited by keeping the sulphidic subsoil waterlogged. If an acid or potentially acid layer is present within 60 cm of the surface, crop options are effectively limited to grassland in temperate regions and to oil palm, rubber, and coconut in the humid tropics. Maintenance of a constant high watertable is obviously difficult if there is a pronounced dry season; then the operator may be faced with the alternatives of allowing the watertable to fall, which leads to oxidation of pyrite in the subsoil, or allowing brackish water into the drainage system to maintain the water level.

2.5.1 Oil palm

Acid sulphate conditions impair root development in oil palms, causing severe water stress and nutrient deficiencies, but spectacular responses to a controlled high watertable have been obtained, especially where severe acidity occurs close to the surface. Figure 2.1 compares the yields obtained on acid and non-acid soils in Selangor, Malaysia, from oil palms planted in 1952. Yields on acid sulphate soils declined after the drains were deepened from 0.9 m to 1.2 m. The recovery of yields following the raising of the watertable to 0.6 m is remarkable, although yields remained below those on non-acid soils. However, Toh and Poon (1982) report that yields of oil palm established more recently on acid sulphate soils, with high watertable management from first plantings, have been similar to those on normal soils.

Toh and Poon recommend field drains at 50 m intervals leading to collector drains at right angles every 400 m, leading in turn to main drains parallel to the field drains at 800 m intervals. Typical dimensions are given below, although these should be modified according to the volume of water to be discharged and the hydraulic conductivity of the soil.

Type of drain	Width (m) Top	Bottom	Depth (m)
Field	1.0	0.45	0.75
Collector	2.0	0.6	1.5
Main	3.3	1.2	1.8-2.4

To maintain a watertable at about 0.6 m, the main drains can be blocked by weirs of used fertilizer bags packed with soil, or by wooden sluices. The most convenient points to block the drains are at culverts where the concrete or masonry face of the culvert reduces seepage around the sluice.

Even with the sluices in place, the watertable will fall during dry periods and the accumulated acid must be flushed out during wet periods by opening the sluices before the water level is allowed to build up again to the required level (Plate 2.6, p. 100).

2.5.2 Grassland

A minimum disturbance strategy has also been successful in establishing productive grassland on acid sulphate soils in north western Europe and New Zealand, providing that there is a minimum thickness of 20 cm of topsoil at a pH greater than 4.5. The first priorities are drainage and protection from flooding. Surface water must be removed as quickly as possible. The watertable must be held at a sufficient depth below the surface to permit the leaching of soluble salts, to maintain an aerated rooting zone for the crop, and to promote a firm, ripe topsoil that will support grazing and mechanised operations. These objectives may conflict with the need to keep the subsoil waterlogged.

Drainage for grassland management is usually achieved by a system of broad, deep open drains, including the former tidal creeks. Surface water drainage from basins and backswamps is achieved by an ad hoc network of shallow, ploughed or spade-dug ditches, cutting through the natural levees. The watertable is maintained in the drains by sluices. Outflow to the tidal river may be by floodgates, opening at low tide, or by pumping.

Where sulphidic material lies close to the surface, a compromise has to be adopted whereby the watertable is maintained at the minimum depth consistent with farming operations and any acidity generated above the watertable is dealt with by occasional moderate applications of ground limestone (about 5 tonnes ha^{-1}), incorporated into the surface by a spring tine or shallow chisel plough.

Where extreme acidity can be avoided, grassland responds well to modest applications of phosphate fertilizer. Then acid-tolerant strains of trefoil (*Lotus pedunculatus*) and clover (*Trifolium repens*) can be established (Plate 2.7). Useful grasses tolerant of moderately acid, slightly saline conditions include ryegrass (*Lolium perenne*), Harding grass (*Phalaris tuberosa*), Bermuda grass (*Cynodon dactylon*), and wheat grass (*Agropyron elongatum*).

There are several difficulties inherent in high watertable management:
- The watertable must be strictly controlled to minimise the oxidation of pyrite. This

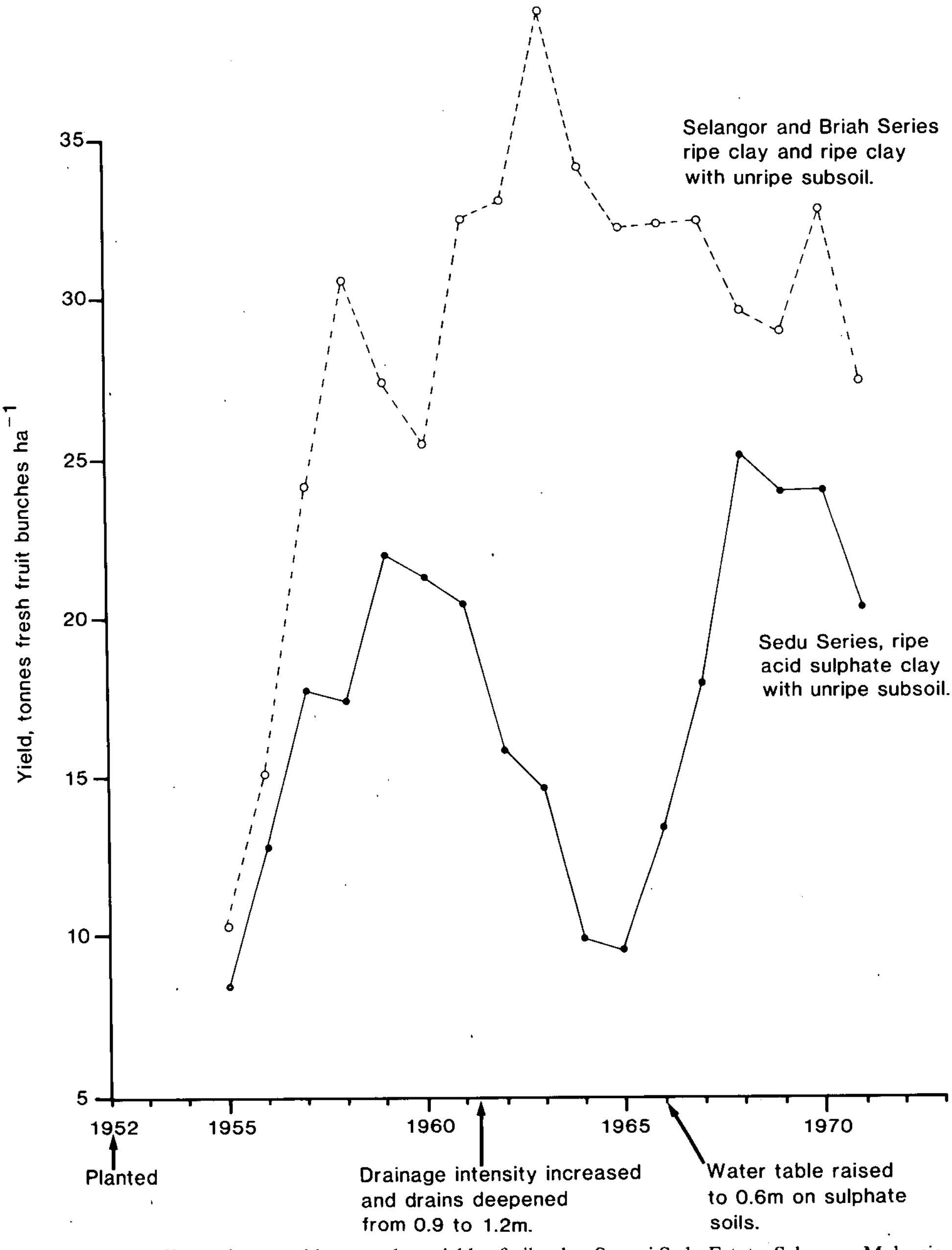


Figure 2.1 The effects of watertable control on yields of oil palm, Sungei Sedu Estate, Selangor, Malaysia. The data are recalculated from Poon (1974) and represent estate management blocks in which significant areas of non-acid soils are included with the acid Sedu Series.

may involve sluices to maintain the watertable at different levels in different parts of a polder, according to the depths at which sulphidic or acid sulphate layers occur. Manual operation of the floodgates is necessary in dry periods to back up drainage water to prevent the watertable dropping. During a prolonged drought, the water-

Plate 2.7 Successful high watertable management of former mangrove swamp, Hokianga, New Zealand, after 40 years of drainage. A single moderate application of lime after 25 years of drainage and subsequent aerial topdressing of superphosphate and normal liming encourage grass and, especially, legumes. The watertable is maintained at a depth of about 0.6 m by floodgate drainage at low tide.

table will drop anyway and acidification will occur unless water can be led back into the ditches:

- Where the groundwater is saline, there is an upward movement of soluble salts into the rooting zone during dry weather;
- Where sulphidic material occurs close to the surface, the watertable cannot be lowered sufficiently to allow leaching of salts or ripening to produce a firm topsoil without exposing the sulphidic layer. This problem usually occurs in the lowest parts of the landscape, which present trafficability, drainage, and engineering difficulties associated with the unripe subsoil. Some acidification in these areas may have to be accepted and combatted by liming.

All these difficulties are exacerbated in tropical and sub-tropical regions with high rates of evaporation and long periods of drought, where a greater thickness of non-acid topsoil is required to maintain a crop.

2.6 Total reclamation

If the maintenance of flooding or a high watertable is impractical or undesirable, the task of ameliorating acid sulphate conditions must be faced. In some soils, sufficient shell is present to neutralise all or most of the acidity. In temperate regions, shell beds commonly occur close to the surface in tidal mud flats, and transported shell may be associated with levee and beach deposits. In some of the inland polders of The Netherlands, sulphidic muds were underlain by marl at shallow depth, so that the acidity problem was solved by deep ploughing to bring up the marly subsoil.

In the absence of naturally-occurring calcium carbonate, total reclamation of acid sulphate soils involves drainage, leaching of acid and soluble salts, and the incorporation of lime and fertilizer to remedy the residual acidity and nutrient deficiencies.

To estimate the limestone requirement of a potential acid sulphate soil, we must take account of the oxidisable sulphur content (usually determined as a percentage of the dry mass), its vertical distribution, the apparent density of the soil, and the required rooting depth. The acidity generated from 1 kg of oxidisable sulphur can be neutralised by 3.1 kg of pure $CaCO_3$. The gross limestone requirements can be estimated from Table 2.2 which shows: 1) the limestone requirements to neutralise the potential acidity of a 10 cm thick layer of soil; and 2) the approximate neutralising capacity of the soil, assuming that there is no shell. To estimate the limestone requirement, subtract 2) from 1).

2.6.1 Drainage and leaching

It is clear that the application of sufficient limestone to neutralise all the potential acidity of a sulphidic soil will usually be impracticable and hugely expensive. A more practical solution may be to encourage the oxidation of pyrite and the leaching of acid by a period of drainage, then to counteract the residual acidity. The prime considerations will be the time required for complete oxidation of the pyrite in the rooting zone and the environmental impact of the acid drainage water. Systematic data on the rate of oxidation of pyrite under field conditions are scarce. Dent and Raiswell (1982) have modelled the rate of oxidation in undisturbed, drained soils (Section 3.6) on the basis of the rate of diffusion of dissolved oxygen into the system and the initial content of pyrite. For example, an initial oxidisable sulphur content of 3.5 per cent

Table 2.2 Lime requirements for complete neutralisation, in relation to total oxidisable sulphur content

	Lime requirement of a layer 10 cm thick (tonnes $CaCO_3$ ha^{-1})						Effective neutralising capacity of a 10 cm layer containing no $CaCO_3$ (tonnes $CaCO_3$ equivalent ha^{-1})*	
Apparent density of the soil ($g\ cm^{-3}$)	Percentage oxidisable sulphur 0.5	1	1.5	2	3	4	Clayey soils	Sandy soils
0.6	9	19	28	37	56	74	11	2
0.7	11	22	33	44	65	87	13	2
0.8	12	25	37	50	74	99	14	2
0.9	14	28	42	56	84	112	16	3
1.0	16	31	47	62			19	3
1.1	17	34	51	68			20	3
1.2	19	37	56	74			22	4

* A neutralising capacity of 18 milli equivalents per 100 g is assumed for clayey soils, and 3 milli equivalents per 100 g for sandy soils. These are estimates based on tidal soils in Northland, New Zealand. Between half and two thirds of this cation exchange capacity is available to neutralise acidity. Clay soils derived from strongly-weathered rocks in tropical regions probably have lower neutralising capacities.

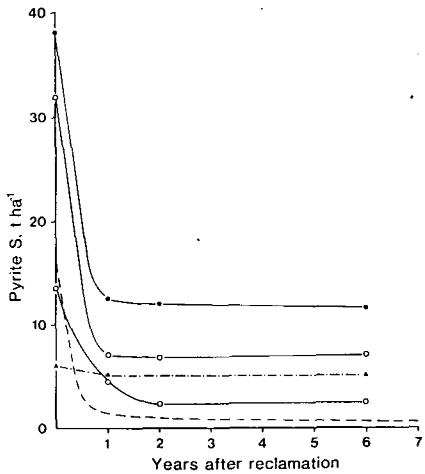


Figure 2.2 Rate of oxidation in field experiments on deep soil mixing, Stauning, Denmark.

will be reduced to about half over 50 years. This is in line with a crude estimate of the rate of removal of sulphides from polders in Hokianga, New Zealand, where leaching for 40 years to a depth of about 50 cm below the sulphide datum, with an average winter rainfall surplus of 450 mm, has reduced the average lime requirement from 172 tonnes ha^{-1} to 80 tonnes ha^{-1}.

A more rapid rate of oxidation and leaching is reported by Larsen and Andersen (1977) from field experiments on deep soil mixing in Denmark. Figure 2.2 shows that with effective drainage and soil mixing to a depth of 70 cm, more than half the pyrite was oxidised in the first year following treatment. Figure 2.3 shows that the leaching of soluble sulphates following drainage is a slower process than oxidation but, under these conditions, was complete after seven years.

2.6.2 Salt water leaching

Even after prolonged drainage and leaching, we are left with a soil that is severely acid and aluminium-saturated. Sea water will counteract soil acidity and displace part of the exchangeable aluminium from the acid sulphate soil. Where salt water is easily

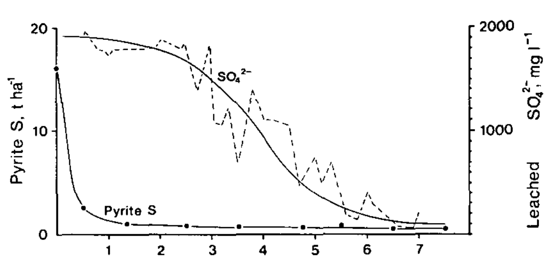


Figure 2.3 Rate of removal of pyrite and sulphates from the upper 70 cm of the soil profile, Stauning, Denmark (after Larsen 1978).

applied and can be leached subsequently by fresh water, this technique is of potential value in accelerating the rate of reclamation and reducing the lime requirement. Successful field experiments on leaching with salt water have been reported for sugar cane in Guyana (Evans and Cate 1962) and for rice in Sierra Leone (Hart et al. 1963). Structural stability is often a problem in soils with high exchangeable sodium, but critical values depend very much on clay mineralogy. There are increasingly severe structural problems in illite clays when the exchangeable sodium percentage rises to 10 to 15; in smectite clays an exchangeable sodium percentage of 10 to 15 is optimum. Where aluminium is the dominant cation, the critical limit is nearer 40 per cent sodium, so the high exchangeable sodium percentage brought about by saltwater leaching may not be a problem in acid sulphate soils.

2.6.3 Crop response to lime and fertilizer

Complete soil mixing to the depth of the desired rooting zone will rarely be practicable or economic. Likewise, the compounding of flood protection and drainage costs over many years before a crop can be obtained makes reclamation by leaching financially unattractive. However, there are large areas of acid sulphate soils, such as those of the Bangkok Plain in Thailand, where natural weathering and leaching over a long period has removed reserves of pyrite to depths of 1 m or more. In such cases, the lime requirement is very much lower (in the range of 5 to 20 tonnes ha^{-1}) and an attractive crop response can be achieved by moderate applications of lime and fertilizer.

Responsive soils are those that *do not have* reserves of pyrite or jarosite close to the surface, or high values of exchangeable aluminium. On such soils, moderate applications of lime will significantly reduce soluble aluminium levels and enable crops to respond to conventional fertilizer applications without necessarily raising the pH much above 4.5. Methods of determining the lime requirement are described in Section 7.3.12.

Rice

Rice is particularly well adapted to acid sulphate soils because it grows under flooded conditions that depress aluminium toxicity and increase the availability of phosphate. Rice yields comparable to those of non-acid soils can be obtained by a combination of two or more of the following practices with NPK fertilizers:
- Keeping the soil submerged as long as possible before transplanting;
- Liming;
- Applying manganese dioxide;
- Growing insect- and disease-resistant varieties that are tolerant of acid sulphate conditions.

On ripe acid sulphate clays in Thailand, Maneewon et al. (1982) and Charoenchamratcheep et al. (1982) have reported significant responses to optimum combinations of lime and ammonium phosphate or rock phosphate, in terms of both yield and financial benefit. Figure 2.4 demonstrates that:

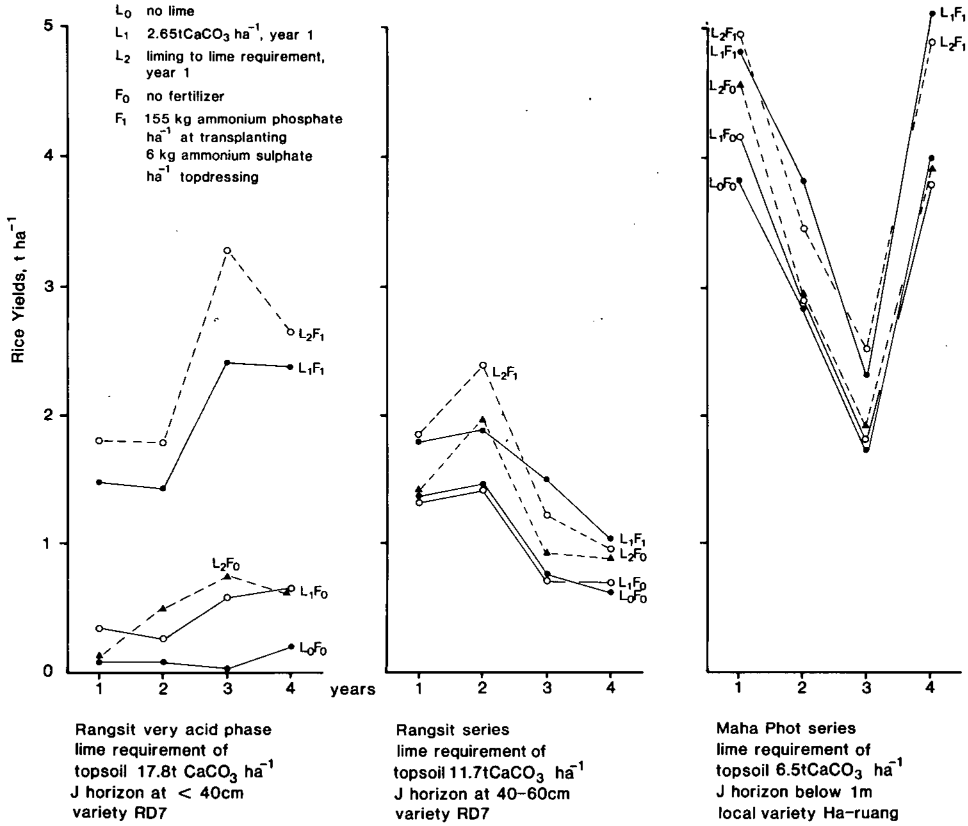


Figure 2.4 Response of rice yields to lime and fertilizer on acid sulphate soils in Thailand (data from Maneewon et al. 1982).

- Application of lime alone is not very effective;
- There is an excellent response to nitrogen and phosphate in combination with lime applications much lower than the full lime requirement.

Wherever rice is grown on an acid sulphate soil following the inevitable acidification during the dry season, the aim of management is to promote rapid healthy soil reduction as soon as possible after flooding. Brinkman (1982) has suggested that very small annual applications of lime (for example 100 or 200 kg ha^{-1}) could promote soil reduction by a localised improvement in conditions for bacterial action. From such nuclei, reduction and consequent decrease of acidity could proceed relatively quickly throughout the soil mass, reducing the risk of aluminium toxicity and probably also iron toxicity. Wen and Ponnamperuma (1966) and Ponnamperuma and Solivas (1982) have advocated the application of manganese dioxide at a rate of 100 kg ha^{-1} to depress iron toxicity.

Williams (1980), working on raw unripe acid sulphate soils in Brunei where there is no dry season, has obtained spectacular yield responses to lime applications of up to 4 tonnes ha^{-1}, well below the soils' full lime requirement (Figure 2.5). In his trials, tillering was directly related to soil pH, not to H_2S concentration (Table 2.3).

There remains scope for selection of cultivars that are tolerant of acid sulphate con-

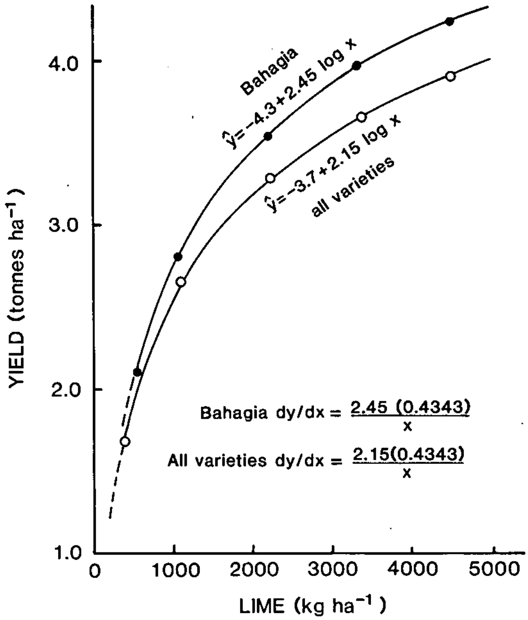


Figure 2.5 Yield response to lime, raw acid sulphate soil in Brunei (from Williams 1980).

Table 2.3 Tillering of rice variety Bahagia at 30 days in field plots in relation to the pH and H_2S concentration of the flooded soil (from Williams 1980)

Tillers (average of 10 plants)	pH	H_2S (average percentage blackening of 5 red lead probes)
4	4.0	39
9	4.3	25
9	4.4	44
14	4.5	27
15	4.7	31
10	4.8	20
15	5.1	29

ditions. Ponnamperuma (1982) reports that in twelve replicated trials with 55 rice varieties on four sites with unripe acid sulphate soils in the Philippines, tolerant varieties averaged yields of 4.8 tonnes ha^{-1} compared with 2.2 tonnes ha^{-1} for sensitive ones. Only NPK fertilizer was applied, without lime or managanese dioxide.

Dryland Crops

The trigger effect of small applications of lime does not apply to dryland crops. If the soil cannot be flooded, total reclamation requires satisfaction of the lime requirement and incorporation of this lime throughout the rooting zone of the crop. Field experiments in Denmark (Larsen and Andersen 1977) have shown that much higher

Table 2.4 Yield response to lime application, Stauning, Denmark (from Larsen and Andersen 1977)

Lime applied, tonnes $CaCO_3$ ha^{-1}		pH		Yield, tonnes ha^{-1}			
Topsoil	Subsoil	Topsoil	Subsoil	Barley	Oats	Grass	Sugar beet
0	0	3.8	3.4	13	19	34	53
60	0	7.1	3.7	24	58	43	62
15	45	6.6	5.7	34	53	89	116

yields can be obtained by liming both topsoil and subsoil compared with liming the topsoil only. Root crops and grass, in particular, benefit from the deeper rooting zone, probably because of their long growing season and consequent water requirements during late season drought (Table 2.4).

Lime applied to the surface mostly stays there. Incorporating it deeper than normal plough depth is both difficult and expensive. In the first place, suitable implements are not generally available; in the second place, the energy costs of deep cultivations are very high. In the English Fenland, Smith et al. (1971) report successful operations with a single blade subsoil raiser/mixer and a double digging plough in which forward bodies remove topsoil and rear bodies work deeper. Anderson and Hendrick (1983) describe a soil chisel/ slitter that can inject lime suspension along a narrow slit in the subsoil. This requires less energy than soil mixing and may significantly increase root penetration of the subsoil in some acid sulphate soils.

Other ameliorants of proven value in reducing soil acidity include oil palm bunch ash, oil palm sludge, filter mud (spent lime) from sugar refineries, and basic slag from the steel industry. Any of these can be valuable where there is a local supply.

Phosphate and nitrogen will always be in short supply on acid sulphate soils. Phosphate is strongly retained by aluminium and also by iron at low pH. The availability of nitrogen is restricted by the slow mineralisation of organic matter and by unfavourable conditions for symbiotic nitrogen fixation by legumes, especially phosphate deficiency, although tropical legumes appear to be more tolerant of acidity than temperate species. Accurate placement of phosphate fertilizer will be beneficial on acid sulphate soils, and usually ground rock phosphate will be as effective as more expensive soluble phosphate fertilizers.

Copper deficiency is the most frequently reported minor nutrient deficiency on acid peat and muck.

Tree crops

Tree crops that offer prospects of development on acid sulphate soils include oil palm and rubber, which can be grown with a controlled high watertable. Possibly, coconut and cocoa may be grown on ripe acid sulphate or aluminium-saturated clays which no longer have reserves of pyrite near the surface. Alternatively, mounds of leached soil may be built up gradually around the trees as they grow and increase their water and nutrient demands. In Thailand, *Casuarina junghuiana* is grown as a forestry species on severely-acid ripe soils. The trees are planted on parallel ridges of topsoil, the intervening furrows providing drainage and a degree of water storage. *Melaleuca leucoden-*

dron, which grows naturally on acid sulphate soils in South East Asia, is sown as a timber crop on seasonally flooded acid soils in Vietnam (Plate 2.8). The investigation of other species may well be worthwhile.

Plate 2.8 *Melaleuca* woodland growing on a severely acid clay, flooded in the wet season, Mekong Delta, Vietnam (Leen Pons).

Tropical crops

Tropical crops that are tolerant of severe acidity and low levels of phosphorus and nitrogen include pineapple (*Ananas comosus*), which is successful on both mineral and peat soils and prefers pH values less than 4.3, and cassava (*Manihot esculenta*), which can yield 85 per cent of its maximum yield at pH 4 and 80 per cent Al^{3+} saturation (Abruma-Rodriguez 1982), although it requires a friable soil and is perhaps best suited to acid peat and muck. Sugar cane (*Saccharum* spp.) is grown successfully at moderate levels of acidity (Evans and Cate 1962).

Temperate crops

Besides grass, temperate crops that can be grown where severe acidity occurs at a depth greater than 60 cm include wheat (*Triticum*), oats (*Avena*), rye (*Secale*), and potato (*Solanum tuberosum*). In all cases, there is scope for varietal selection for tolerance to high aluminium and low phosphate.

2.6.4 Irrigation

Water stress is the most common symptom shown by dryland crops growing on acid sulphate soils. In most cases, there is a significant yield response to supplementary irrigation, but the financial benefits of irrigation are likely to be less on acid sulphate soils than on normal soils.

2.6.5 Drainage problems

Problems specific to acid sulphate soils are the calculation of drain spacing and the blockage of pipe drains by ochre. Calculations of drain spacing are based on measurements or estimates of saturated hydraulic conductivity, using the Hooghoudt formula for homogeneous soils, or the Ernst formula for two-layered soils (ILRI Publ. 16, Vol 2, van Beers 1979). The degree of uncertainty in determining hydraulic conductivity is considerable at the best of times. In unripe clays, permeability is due to burrows and coarse root channels that can be destroyed during reclamation and are not renewed once severe acidity develops. On the other hand, unripe soils shrink as they ripen, opening a system of inter-connected fissures that increase permeability. Obviously, the situation to avoid is the disturbance of existing porosity and the development of severe acidity that arrests ripening.

Open ditch drains should be used until most of the pyrite above the watertable has been oxidised. Subsurface pipe drains will otherwise be clogged by ochre deposits (Bloomfield 1972; Trafford et al. 1973). No amount of fibre wrapping or backfilling will cope with the heavy iron deposition associated with a pyrite-rich soil. In some situations, it may be practicable to maintain the water level in open main drains *above* the level of pipe drain outlets, except when maximum discharge is required.

Simple, self-jetting drains are used in the Yangtse Delta Polder (Figure 2.6). Alternating crops of wheat and rice are grown in the dry and wet seasons respectively. For rice, the drain is plugged and the ditch level is high to maintain a high water level in the polder. Prior to the rice being harvested, the water level in the main drain is lowered and the plug removed. The drainage system is then flushed by the hydraulic head of the water within the polder.

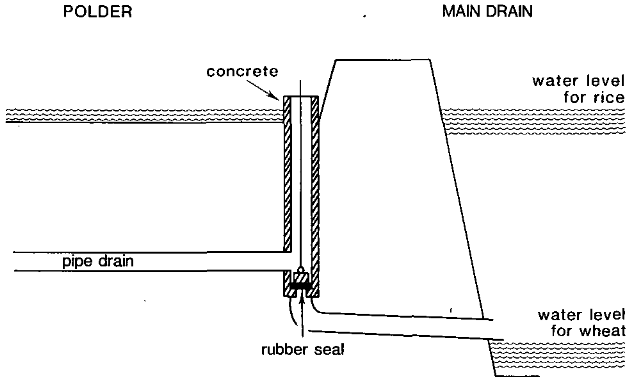


Figure 2.6 Self-jetting drains used in the Yangtse Delta Polder (personal communication, colleagues of the Institute of Soil Science, Chinese Academy of Sciences, Nanjing).

2.7 Non-agricultural uses

Any agricultural use of acid sulphate soils will yield lower returns or will require greater inputs than for equivalent non-acid alluvial soils. Diversification of land use is therefore of particular importance to communities dependent upon acid sulphate soils.

2.7.1 Urban and industrial development

Any urban and industrial development on acid sulphate soils faces the engineering problems of unripe soils, corrosion of structural materials and pipelines, and flooding hazards (Section 2.8). However, the higher cost of developments on acid sulphate soils may sometimes be justified by enabling more fertile soils to be reserved for agricultural production.

Freshwater reservoirs to supply urban developments or irrigation can be constructed relatively easily by the embankment of extensive, low-lying areas. Problems associated with acid sulphate soils will include instability of banks due to shrinkage of unripe mud and poor colonisation by vegetation. Potentially more serious and more difficult to rectify is the transfer of acid and soluble iron from the bed of the reservoir to the stored water following any period of drying-up.

2.7.2 Salt pans

Salt pans can be a very profitable use of tidal land where there is a long dry season and saline tidewater is available.

2.7.3 Fish ponds

Fish ponds are widely developed in South East Asia, particularly for milkfish (*Chanos chanos*) and prawns (*Microbrachium* or *Penaeus monodon*). Milkfish are cultivated in shallow ponds, with about 0.3 m water depth; prawns require a depth of about 1 m and are less tolerant of water quality. Both require unrestricted access to tidewater.

Ponds are constructed by excavating a layer of soil and building this into an enclosing dike. The bottom of the pond slopes gently to a shallow central channel, leading to a sluice gate which connects the pond to a tidal river and enables the pond to be filled and drained during the tidal cycle.

Before each fish crop, the pond bottom is drained to destroy predators, parasites, and disease carriers; the pond bottom is then fertilized and the pond is filled. Algae begin to grow, and fry or fingerlings are introduced to graze the algae. After 3 to 5 months, depending on the food supply and the growth of the fish, the pond is harvested. Yields range from about 150 kg milkfish ha^{-1} to about 2 tonnes ha^{-1}. High yields require good quality stock, good water quality, nitrogen and phosphate top-dressing and, for prawns, supplementary feeding of fish and slaughter waste.

On acid sulphate soils, drying of the pond bottom produces severe acidity. Following flooding, the pond soil is once again reduced. Some acid is consumed by reduction of iron III oxides to iron II but acid, aluminium salts, and soluble iron diffuse into the pond water. Within a few days, the iron II is oxidised, generating more acidity and producing colloidal iron III hydroxide, which remains suspended in the pond water for several days. Under these conditions, the growth of algae and fish is very poor. Further losses of stock can be caused by heavy rains, which bring a sudden influx of acid and soluble aluminium from the banks. Fish crops remain poor for up to ten years after the construction or deepening of ponds in acid sulphate soils. Application of phosphate fertilizer is ineffective and the lime requirements for neutralisation are prohibitive.

By thinking positively about the dry season, Brinkman and Singh (1982) have developed a method of rapid reclamation:

- In the early part of the dry season, the pond is dried thoroughly and harrowed;
- The pond is filled with brackish tidewater. The pH of this water is measured immediately, and every few hours thereafter. Probably it will drop from that of seawater (7 to 9) to below 4. At the first opportunity after the pH of the pond water has stabilised, the pond is drained. (This drainage water should be returned to the sea, not to another pond!) The pond is refilled; then drained again as soon as the water reaches a constant pH. This cycle is repeated as long as the constant pH remains below 5. When the pH remains above 5, the pond bottom is drained, dried thoroughly and cultivated, and then refilled as before. This time the pH probably will not drop as low as in the first cycle of filling and draining. As many as three drying cycles may be required until the stable pH of the water brought into the dry pond remains above 5.

Plate 2.9 Brackish water fishponds in acid sulphate soils near Iloilo City, Panay Islands, Philippines (Robert Brinkman).

- At the same time as the pond is being reclaimed, acid must be removed from the surrounding dikes. This is achieved by carefully levelling the dike tops and building small bunds along each side to produce shallow basins. Brackish water is brought up to these basins to keep them flooded. When the pond bottom is ready for drying, the dikes should also be allowed to dry. Finally, the bunds are removed, and the top and side leading to the pond are broadcast with 5 to 10 kg ground limestone for each 10 m of bank.
- Finally, the pond is drained, and 0.5 tonnes ground limestone ha^{-1} is broadcast over the bottom, together with normal fertilization, for example 2 tonnes ha^{-1} chicken manure. Following flooding and stocking, nitrogen (urea) is added as topdressing: 8 kg N ha^{-1} every 2 to 3 weeks; phosphate is added every couple of days in small doses to avoid immobilisation, or a weekly portion of about 5 kg P_2O_5 ha^{-1} is placed in jute bags, just submerged, to dissolve slowly.
- To prevent fish kills by seepage of acid from the dikes, the pH of water along the dikes should be checked during rains. If the pH drops below 5, ground limestone should be broadcast into the water (about 1 kg every 10 m). The pH should be checked again over several days and liming repeated if necessary.

With this procedure, brackish water fish ponds in acid sulphate soils have been reclaimed in a single dry season, and yields of milkfish obtained that are comparable to those of well-managed ponds in non-acid soils (Plates 2.9 and 2.10).

Plate 2.10 Milkfish (*Chanos chanos*), about four months old, from brackish water fish ponds. Those on the left are from an acid sulphate pond; those on the right are from a former acid sulphate pond now completely reclaimed (V. P. Singh).

2.8 Engineering

This section highlights the geotechnical problems associated with acid sulphate soils and the kinds of soil investigation needed for land reclamation works. Some engineering hazards are common to all unripe materials; others are peculiar to acid sulphate soils.

2.8.1 Corrosion of structural materials

Cement is attacked by dissolved sulphate; steel is subject to slow dissolution by strong reductants; both steel and cement are rapidly attacked by acid (Plate 2.11). Each of these conditions may occur in acid sulphate areas. Several approaches are possible to extend the life of steel and concrete structures in these circumstances:

Plate 2.11 Steel sluice gate replaced after about seven years because of corrosion in acid sulphate drainage water. Only the stainless steel axle of the roller (top left centre) is unaffected (Robert Brinkman).

Avoidance
The distribution of aggressive soils must be mapped. It may then be possible to site structures in safe locations where acid sulphate conditions will not occur. Avoidance will be the cheapest solution whenever it is feasible.

Tolerance
Materials that resist acid sulphate conditions, such as stainless steel, sulphate-resistant

cement, acid-resistant masonry or hardwood, can be used. Generally this will be a very high-cost solution. Stainless steel would be considered only for key parts of costly structures. Specifications for tolerant materials must take account of the degree of acidity and salinity expected. In acid sulphate soil, pH values may locally be as low as 2 for long periods. Dissolved sulphate contents in acid sulphate soils range from 10^3 to 2 x 10^4 g m^{-3}, compared with 3 to 4 g m^{-3} in average river waters and 3 x 10^3 g m^{-3} in seawater. Minimising the area of contact with aggressive solutions is often practicable. Porous concrete must be avoided. The sand and gravel aggregate must not contain salts. Smooth, pre-cast piles are preferable to piles poured in place.

Sacrifice

A thickness of sacrificial concrete may be included in the design of structures; steel reinforcement must be covered with at least 50 mm of concrete. Further protection may be achieved by mixing lime with the soil layer surrounding the metal or concrete. This requires an excess of lime over the potential acidity of the soil (for example 5 per cent by mass, in a layer about 1 m thick around the structure). The lime barrier may not protect indefinitely where there is lateral movement of acid groundwater.
Metals can be cathodically protected from acid attack by sacrificial electrodes.

Insulation

Susceptible materials can be coated with plastic or bituminous composition. Defects in the insulation may cause local dissolution or failure.

Inhibition

Acids and sulphates can be reduced to solid sulphides by maintaining water-saturation in the surrounding soil. If reduction will not start spontaneously, it can be promoted by mixing in some decomposable organic matter. In some cases, iron oxide may be needed as well. The hazard of dissolution remains until the pH has become near neutral; sulphate attack of cement will persist until the soluble sulphates are reduced. If waterlogged conditions are not maintained, the hazards will recur.

2.8.2 Earthworks

Siting of dikes

The siting of dikes, or stopbanks, is crucial to the success of land reclamation. They are a major initial cost and also need ongoing maintenance. The decision on the area to be reclaimed should take account of the soil pattern, in particular the potential value of the land involved and any soil characteristics that present engineering problems.
In tidal areas, soil with enough nearly ripe, sulphide-free topsoil to make reclamation worthwhile occurs in three situations:
- Areas of active sedimentation;
- Low-lying marine or estuarine terraces, which require protection from very high tides and storm waves;
- Stumps of former terraces planed-off by wave action.

Wherever the overall effect of waves and tides is to cause erosion, any earth dike will be removed or undermined unless special measures are taken. **Sites of active erosion** usually have a narrow, steeply-sloping inter-tidal zone backed by a low cliff. Where mangroves are present, they are stunted and have exposed lateral roots. Erosion is a particular hazard at sites subject to tidal scour, or exposed to strong winds with a long fetch over deep water where big waves can build up. **Sites of net deposition** can be identified by a broad, very gently-sloping tidal zone with a thick accumulation of soft mud, usually colonised by vigorous mangrove or salt marsh vegetation. Even where there is net deposition of sediment, erosion may take place during storms and the dike must be able to withstand this, although in the longer term sediment will accumulate at the seaward side of the dike and wave attack will gradually diminish.

A new dike will itself modify the effects of waves, tides, and currents. For major works, expert advice should be sought on the risks of damage to new and existing embankments. Where an extensive area is to be reclaimed, it may be advantageous to reclaim piece by piece, beginning with the most sheltered section which will serve as a trial of the design and construction employed and which will often accelerate the deposition of mud in adjacent areas.

Materials available for dike construction

Local materials will be used as far as possible to minimise transport costs (Plate 2.12). Locally available materials have very different mechanical properties (Table 2.5).

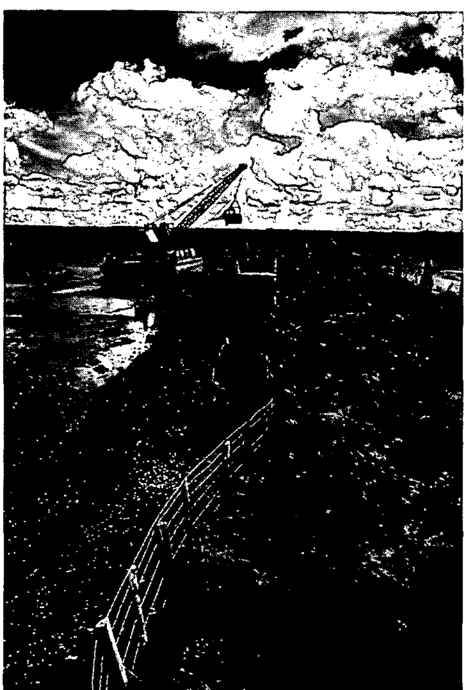


Plate 2.12 Construction of a dike across a broad tidal creek, Kaipara Harbour, New Zealand. A small dragline can operate from pontoons at low tide.

Table 2.5 Physical properties of saturated soil materials

Material	Bearing strength (kPa)	Cohesive strength (remoulded shear strength, kPa)	Permeability	Apparent density ($g\ cm^{-3}$)
Sand	Normally high (>200 kPa) except when underconsolidated and subject to an upward flow of water	Little or none, depending on clay content	High	1.2-1.6
	Provides stable foundation but may first require consolidation	No resistance to slumping under internal water pressure	Drains rapidly	
		No resistance to wave action	Allows seepage	
Practically unripe and half ripe mud	Very low (<20 kPa)	Low (<6kPa)	Very low	0.6-0.8
	Does not provide stable foundations	Flows and slumps; weak resistance to wave action	Does not drain; does not permit significant seepage	
Nearly ripe mud	Variable (20-80 kPa) but increases with drainage	High (7-20 kPa)	Moderate to low if undisturbed	0.1-1.0
	If thick, provides stable foundation for small structures	Resistant to slumping and wave action	Very low if reworked	
			Does not permit significant seepage	
Ripe clay	Moderate (>80 kPa) increases with drainage	High (>20 kPa)	Low if reworked	1.0-1.4
	Provides stable foundations for small structures	Resistant to slumping and wave action	Does not drain or permit significant seepage	

Notes on Bearing Capacity:

For wet mud and clays, bearing capacity $= \frac{5.7s}{F_s}$

where s = shear strength of underlying material (kPa) and
F_s = factor of safety (at least 1.5)
i.e. bearing capacity = 3.8 s

For sand, bearing capacity $= 3.8s + 0.33\gamma BN_j$

where γ = unit weight of soil,
B = mean width of loaded area,
N_j = factor depending on frictional properties of the soil

Frictional angle	N_j
15°	1
20°	2.5
25°	6
30°	30
35°	40

Nearly-ripe mud is the most suitable material available in the tidal zone. It is most conveniently gathered by scraping a thin layer of mud from the surface, beyond the berm of the bank. Material from the main collector drain, probably of variable composition, may also have to be used as fill. Unripe material should be excavated in one bite and placed in its new site with minimum disturbance, otherwise it suffers a loss of structure and will flow. Do not dig deeply for borrow material; the deeper material is less ripe and more sulphidic, or sandy. Ripe clay brought from inland has a higher bulk density and causes greater consolidation of the substrata, although a bank constructed of ripe material will itself suffer less consolidation in the long term. Sand is quite unsuitable unless it is retained by fabric membrane (for example Terram; ICI 1978). Banks built principally from sand will be washed away almost immediately.

Design

The greater the tidal range, the higher the dike must be and the greater the problems of foundations, settlement, and the build-up of water pressure within the dike. Dike height (H) may be calculated as follows (Figure 2.7):

$$H = c\{h + f_h(s_{max} + w_{max})\}$$

where c = allowance for consolidation and settlement. This value depends on the materials used and the nature of the substratum. The dike should be built at least 20 per cent oversize to allow for this, giving c a value of 1.2;

h = the difference between the highest spring tide level and the base of the dike. The high water mark can be found approximately by observations of high tide levels over several tidal cycles, in conjunction with tide tables. The level of the base of the dike may be found by levelling from the high water mark, or by direct measurement of the depth of water at the site of the proposed dike at high tide on a calm day;

s_{max} = the increase in tide level due to storm surges;

w_{max} = the increase above tide level due to normal waves;
(s_{max} and w_{max} can be found only by local observations, but general guidelines may be provided by the official Marine Division.)

f_h = the margin of safety. The greatest damage to dikes is caused by overtopping. The margin of safety, by which ($s_{max} + w_{max}$) must be multiplied to allow for uncertainties, depends on the accuracy of the information available. It should be at least 1.5

SLOPE: The maximum stable slope of the dike is determined by the cohesion (shear strength) and unit weight (γ) of the building material; the height of the dike; and the nature of the sub-stratum, especially the thickness of mud over any underlying more stable or granular material, which will usually be sand.

The maximum slope may be calculated from the stability chart (Figure 2.8). In general, the greater the height of the dike, the lower the angle of slope must be. Likewise the greater the thickness of unripe mud over underlying stable material, the lower the angle of slope permitted.

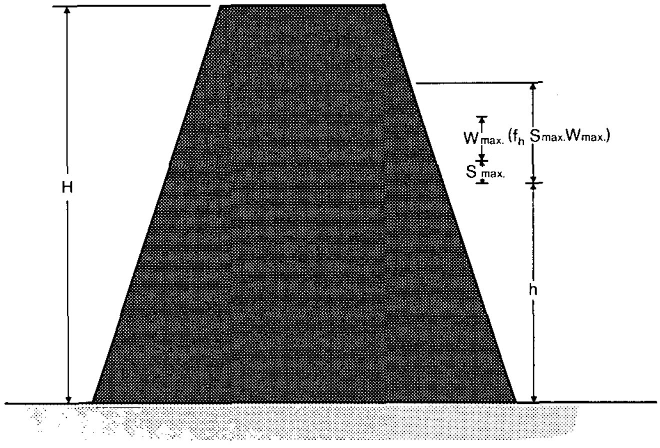


Figure 2.7 Calculation of dike height.

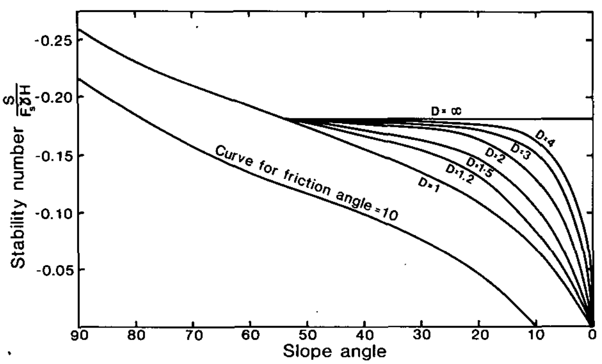


Figure 2.8 Stability curves for wet mud.

D = ratio of height of dike H to height over stable substratum DH. Evaluate the stability number and read off on the appropriate stability curve to find the slope angle. Where D is large and the stability number is less than 0.18, an embankment cannot be made with the material.

If the soil has significant amounts of sand, steeper slope angles are possible, but more sophisticated tests are required to determine the angle of friction of the material. These tests will be performed by a consultant in soil mechanics.

Figure 2.8 Includes a stability curve for material with an angle of friction of 10°. If, for example, stability number is 0.15, then material with an angle of friction of 10° can have a slope of 67°, compared with the slope of 37° possible with muds of little frictional resistance.

For data on other friction angles, see for example, Figure 8.8 in Capper and Cassie (1975).

Worked example:

Shear strength (s)	10 kPa
Factor of safety (F_s) for stability	1.5
Height of dike (H)	3 m
Unit weight (γ)	16 kNm^{-3}

i) Evaluate the expression $\frac{s}{\gamma H F_s} = \frac{10}{16 \times 3 \times 1.5} = 0.14$, which is the stability number;

ii) Find the depth to any underlying stable layer;
iii) Read off on Figure 2.8 to determine the slope angle.

These calculations assume that there is no frictional strength in the mud used for the construction of the dike. This is close to the real situation in the critical period during and immediately after construction. In all situations, the stability of the dike will increase with time due to consolidation, which increases the cohesive strength of muddy materials and increases the frictional strength of sandy materials. Also, colonising vegetation will reinforce the face of the dike.

Note that the height to which a dike may be built is limited by the bearing capacity of the underlying soil. If underlying unripe mud prevents the building of a dike of the height required, then the mud must be dredged out till firm underlying material is reached (see Table 2.5).

WIDTH: The sloping surface of the watertable within the dike, from high-tide level to the watertable within the polder, should intersect the base of the dike – not the internal face – otherwise failure may occur due to the internal water pressure. For an homogeneous clay dike, the hydraulic gradient should never exceed 1 in 7 (Figure 2.9 a).

Problems associated with unripe materials are:

- Consolidation of the dike and substratum. The dike should be built 20 per cent oversize to allow for consolidation and settlement. The strength of the dike will increase as it consolidates, but consolidation of unripe material is very slow. The seaward face should be of the ripest material available. Internal sand drains can be incorporated to improve the speed of consolidation (Figure 2.9 b), but there is then an added risk of dike failure (if the clay face is not completely impermeable) due to seepage and washout of the sand. This danger can be avoided by enclosing the sand drains in fabric membrane, which will also filter fine particles that would otherwise clog the drain. Thin horizontal layers of sand are effective in de-watering the unripe clay, providing that they can seep drainage water to a free face or a vertical drain;
- Erosion. Reinforcement against wave action may be provided at critical sites by mattresses of brushwood pinned to the seaward face of the dike or by a barrier of angular rubble. Fabric membrane may be used here to prevent the removal of earth particles by water action, but it must be supported by resting on the slope and must be tucked into the dike. It does not rot but should be protected from sunlight either by a cover of rubble or bitumen. High dikes can be built up in layers with membrane tucked between each consecutive layer.

  Rapid establishment of vegetation on the dike will protect it against waves and rain. Where the dike is built of potentially acid mud, a surface layer of non-acid soil or the application of lime and phosphate will assist the establishment of a plant cover. Colonisation of mangrove or salt-marsh vegetation seawards of the dike provides significant protection against erosion and will encourage further sedimentation, reducing wave action and, in some situations, eventually making more land available for reclamation;
- Crossing and filling of creeks. This is the most difficult operation because, as the width of the creek is narrowed, the tidal scour is increased. In some cases, the sub-

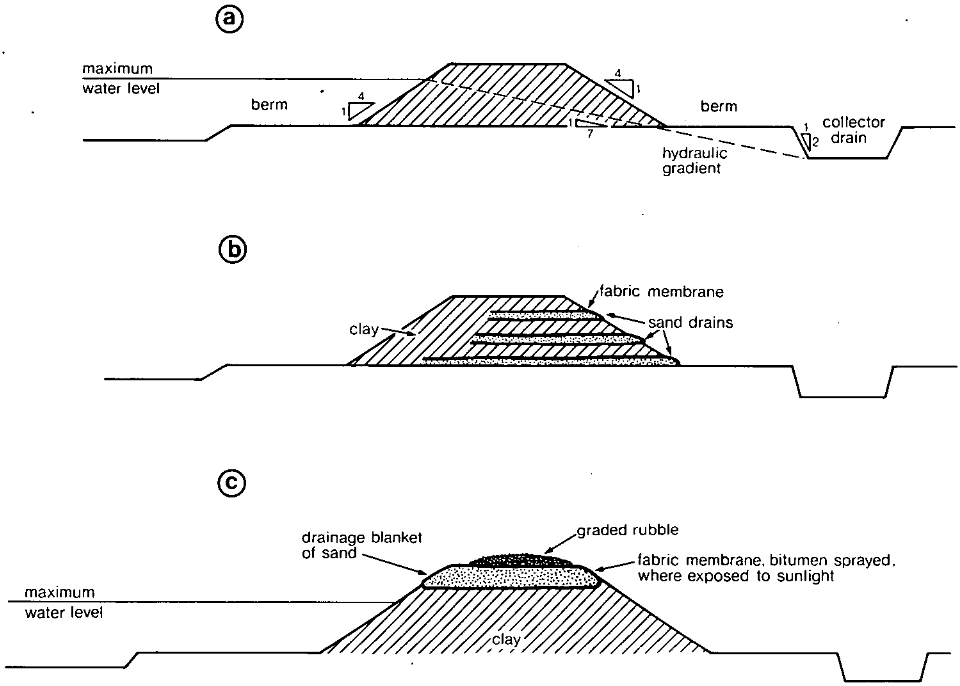


Figure 2.9 Schematic design sections for earth dikes:
(a) Slopes and maximum level of the watertable within the dike at high tide
(b) Dike construction showing fabric-wrapped sand drains to accelerate consolidation
(c) Dike carrying all-weather access road.

stratum is thick, practically unripe mud, which provides poor support for the dike. Where a dike must be built across very soft material, the best procedure is to build it slowly, increasing the loading stage-by-stage to avoid the risk of failure of the substratum. Earth dikes can be reinforced in difficult places by driving piles down to a firmer substratum and fixing hurdles of brushwood between the piles to give support until the material has consolidated.

2.8.3 Access roads

Access and drainage must be planned together. Culverts are required to carry drains beneath roads. Roads and access points to fields should avoid the lowest, least-ripened parts of the reclaimed area since the mechanical strength of the soil in these areas is always low. Wet soils suffer badly from puddling, and vehicular traffic over them quickly produces a quagmire.

Main access roads must be all-weather roads. These require a base of hardcore, and drains along either side. Where roads are laid over unripe or peaty soils, the pumping effect of traffic causes the hardcore to sink into the underlying soft material. This can be prevented by laying mattresses of logs or brushwood or a fabric membrane below the hardcore (Figure 2.10). A layer of sand encased in fabric membrane may also be used to provide a firm subgrade for roads across soft areas (Figure 2.9 c).

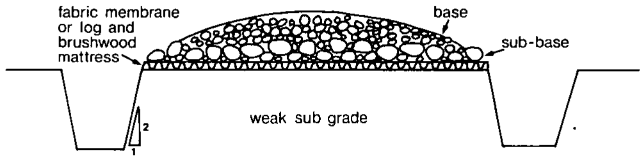


Figure 2.10 Schematic design for an all-weather road over unripe material.

Even where the expense of a rubble road is not justified, drainage along either side of the track is still essential since the mechanical strength of clayey materials is dramatically reduced under wet conditions.

2.8.4 Drainage

The *main drainage system* should be able to maintain the watertable in the polder at a sufficient depth below the surface to permit the leaching of salts and enough ripening of the topsoil to support agricultural operations. It must be capable of removing excess rainfall from the polder and drainage water from the upland catchment, preferably within a single tidal cycle.

In most cases, effective drainage will be achieved with the least amount of earthmoving if existing creeks are used as main drains. The creek bottoms are the lowest points of the landscape and the natural relief is graded towards them. This natural drainage may require extension and in some places deepening, especially in the backswamp areas where the creeks can be extended to form a ring around the polder. A main drain along the foot of the neighbouring upland will intercept runoff and any springs along the footslope; a further collector drain along the inland margin of the dike may be necessary to carry water from minor creeks and secondary drains to a small number of outlets through the dike, and also to intercept any saline seepage under the bank.

Where there is only a very slight fall from the backswamp to the drain outlet, deepening and straightening the natural channels will improve the rate of flow.

The aims of *field drainage* are to facilitate leaching of salts and to create an aerated rooting zone for dryland crops and a topsoil firm enough to support stock or farm machinery. In sandy soils the watertable quickly adjusts to the new level. In clays where ripening has begun before reclamation, drainage and leaching can begin as soon as the water level in the main drains is lowered. Dryland plants colonize quickly and the extraction of water from the soil by their roots accelerates ripening and the development of soil structure. A system of deep, interconnected fissures is developed, which carries surplus water rapidly to the drains. Unripe clays drain very slowly. To establish internal soil drainage, it may be worthwhile to establish a dense cover of vegetation that is tolerant of waterlogging and salinity (for example reeds).

Apart from the margins of the creeks, the slopes of the reclaimed area will be very slight and, in the early stages of reclamation, shallow ditches at about 20 m intervals will help carry drainage water quickly to the main drains. Although the creek channels are the lowest parts of the landscape, they are usually bordered by natural levees, which are higher than the adjacent flats and basins, and a careful assessment is required to adjust the secondary drainage system to the natural topography. Following drainage, the land will settle unevenly as a result of soil ripening. The backswamps and unripe flats will settle more than the levees, so that the lowest parts of the polder sink relatively most. This will exacerbate the difficulty of providing adequate drainage for the whole area. For large drainage schemes, a detailed topographic survey should be undertaken and an assessment made of the expected land subsidence due to drainage.

Optimum drain size and spacings can be calculated from data on the amount of water to be discharged, the rate of discharge required, the depth of drainage required, and the saturated hydraulic conductivity (or permeability) of the soil (see for example van Beers 1979; Ilaco 1981). Unripe acid sulphate soils and potential acid sulphate soils pose two particular problems to conventional drainage design:

- Firstly, if the development of severe acidity is to be avoided, the watertable must not be allowed to fall below the sulphide datum – the level at which potentially acid material occurs. Broad, shallow ditches may have to be used instead of deeper, narrower ones and, where a large-section ditch is required, the water level in the ditch must be maintained above the sulphide datum by sluices;
- Secondly, the saturated hydraulic conductivity of unripe mud changes during soil ripening.

Subsurface pipe drains are not recommended in the early stages of land reclamation because they are likely to be blocked by deposition of ochre and disturbed by uneven subsidence.

3 Chemical and physical processes in acid sulphate soils

3.1 Potential acidity

The essential chemical processes of acid sulphate soils are, firstly, the formation of pyrite in a waterlogged environment, and subsequently, the oxidation of this pyrite following natural or artificial drainage. The involvement of bacteria in the process of oxidation was first elucidated by Colmer and Hinkle (1947), and the topic has been reviewed most recently by van Breemen (1976), Goldhaber and Kaplan (1982), and Nordstrom (1982).

3.1.1 Formation of pyrite

The formation of pyrite involves:
- Reduction of sulphate ions to sulphides by sulphate-reducing bacteria decomposing organic matter;
- Partial oxidation of sulphides to elemental sulphur or polysulphide ions;
- Formation of iron monosulphide (FeS) by combination of dissolved sulphides with iron. The iron originates mostly as iron III oxides and silicates in the sediment, but is reduced to iron II by bacterial action;
- Formation of pyrite by combination of iron monosulphide and elemental sulphur (Rickard 1973). Alternatively pyrite may precipitate directly from dissolved iron II and polysulphide ions (Roberts et al. 1969; Goldhaber and Kaplan 1974).

Whatever the mechanism, the formation of pyrite with iron III oxide as a source of iron may be represented by the following overall equation:

$$Fe_2O_{3(s)} + 4SO_{4\,(aq)}^{2-} + 8CH_2O + \tfrac{1}{2}O_{2(aq)} \rightarrow 2FeS_{2(s)} + 8HCO^-_{3(aq)} + 4H_2O \quad (3.1)$$

iron III oxide from the sediment	sulphate ions from seawater	organic matter	dissolved oxygen

The essential conditions for pyrite formation are as follows:

An anaerobic environment
Sulphate reduction takes place only under severely reducing conditions, which are provided by waterlogged sediments that are rich in organic matter (Section 4). Decomposition of this organic matter by anaerobic bacteria produces a reducing environment. Intermittent or localised oxidation also appears to be necessary to generate elemental sulphur or polysulphide ions from sulphides (Pons et al. 1982).

A source of dissolved sulphate
Usually this source will be sea water or brackish tidal water, but pyrite is occasionally

associated with sulphate-rich groundwaters (Chenery 1954; Thompson 1972; Poelman 1973).

Organic matter
Oxidation of organic matter provides the energy requirements of sulphate-reducing bacteria. Sulphate ions serve as the electron sink for their respiration and are thereby reduced to sulphide:

$$SO_4^{2-} + 2CH_2O \rightarrow H_2S + 2HCO_3^- \qquad (3.2)$$

The amount of sulphide produced is directly related to the amount of organic matter metabolised. Several authors have noted a close correspondence between the organic matter and pyrite contents of sediments (Harmsen 1954; Berner 1970) and suggest that the supply of organic matter commonly limits the amount of pyrite produced (van Beers 1962; Rickard 1973).

A source of iron
Most soils and sediments contain abundant iron oxides and hydroxides. In an anaerobic environment, they are reduced to Fe^{2+}, which is appreciably soluble within the normal pH range and may also be mobilised by soluble organic products.

Time
Little is known about the rate of pyrite formation in the natural environment. Solid-solid reaction between FeS and S appears to be slow, taking months or years to produce measurable amounts of pyrite, whereas direct precipitation from dissolved Fe^{2+} and polysulphide may, under favourable conditions, yield pyrite within days (Goldhaber and Kaplan 1974; Howarth 1979). On the basis of radiocarbon dating of accreting sediment under mangrove vegetation in northern New Zealand, a rate of accumulation of 6 kg S m^{-3} of sediment per 100 years is estimated (Section 4.2.1). This is equivalent to 2×10^{-3} mol dm^{-1} yr^{-1} and may be compared with the range of 7×10^{-8} to 5×10^{-1} mol dm^{-3} yr^{-1} presented for recent marine sediments by Goldhaber and Kaplan (1982). Potential acidity can only develop if at least part of the alkalinity formed during sulphate reduction (represented as HCO_3^- in Equation 3.1) is removed from the system. In addition to diffusion, flushing by tidal action is likely to be particularly effective in removing HCO_3^-, renewing SO_4^{2-}, and supplying the limited amount of dissolved oxygen that appears to be necessary for pyrite formation.

3.1.2 Acid-neutralising capacity

A soil containing pyrite is only a potential acid sulphate soil if the potential acidity represented by the pyrite is greater than the acid-neutralising capacity of the soil. The neutralising capacity of the soil is provided by:
- Carbonates;
- Exchangeable bases;
- Easily-weatherable silicates.

Calcium carbonate stands out in both its rate of reaction and neutralising capacity at pH values close to neutrality. Its neutralising capacity is 20 moles acid kg^{-1}. If one mole of pyrite is equivalent to four moles H^+ (Equation 3.9) the acidity from the oxidation of 1 per cent by mass of pyrite sulphur is balanced by 3 per cent of $CaCO_3$ (Equation 3.12).

After dissolution of any carbonates present, further acid displaces exchangeable bases. In marine clays with a large proportion of smectite, as much as 0.5 per cent by mass of pyrite S may be neutralised. Clays that are predominantly kandite and soils of low clay content have very much lower neutralising capacities.

At pH values below about 4, there is a significant dissolution of silicate clays (van Breemen 1973; 1976). The rate of reaction is relatively slow and in most cases appears unlikely to prevent the development of acid sulphate conditions, although the severity of acidity is certainly reduced.

Occurrence and distribution of carbonates

Wherever there is a waterlogged soil or sediment with a pyrite S content greater than about 0.5 per cent, the amount and distribution of carbonates determines whether or not an acid sulphate soil can develop. Carbonate contents range from negligible, in most shallow-water marine and brackish-water sediments of the humid tropics, to 15 per cent or more in some comparable sediments of the temperate and arid zones.

Carbonates occur in marine sediments as biogenic (especially shell and coral), precipitated, and clastic material. Clastic carbonates are localised, depending directly on the source of sediment. Chemical precipitation of carbonates is insignificant in shallow-water sediments where there is dense vegetation. Precipitation is favoured by a pH in the alkaline range, but in sulphur-accumulating environments a weakly acid reaction is maintained, possibly by CO_2 from root respiration and the decay of organic matter, and H_2S from sulphate reduction. Kooistra (1978) suggests that sulphide oxidation at low tide may also generate acidity. Under these conditions, carbonates are dissolved. Thick oyster shells are severely corroded when buried by sulphidic mud, and thin-walled shells, which may be common on the surface, are conspicuously rare in sulphidic sediments. Dissolution of carbonates in tidal sediments is also reported by van der Sluijs (1970) and Salomons (1974).

Shellfish have specific niches in the inter-tidal environment. Most are filter feeders in clear, well-oxygenated waters and they are most abundant on bare inter-tidal flats. Oysters, which grow on the stilt roots, pneumatophores, and trunks of mangroves, are a notable exception. Very muddy waters where sediment is accreting rapidly are not favourable to filter feeders although large concentrations of detrital shell may occur as beach deposits.

In tropical and sub-tropical marine and brackish-water sediments, the conditions for in situ carbonate accumulation and high pyrite accumulation appear to be mutually exclusive. However, high carbonate and high pyrite contents can occur in the same sediment: for example when a shell-rich mud is colonised by mangrove vegetation and is subsequently enriched in pyrite.

3.2 Oxidation

Pyrite is stable only under reducing conditions. Drainage brings about oxidising conditions, initiating the oxidation of pyrite and the generation of acidity. Drainage may occur naturally, as a result of a fall in relative sea level or reduced frequency of tidal flooding, or by some combination of deliberate exclusion of tidal action and lowering of the watertable. Oxidation of sulphidic material may also occur locally as a result of the mining of sulphidic ores and coal, and in cuttings through sulphidic sediments.

3.2.1 Oxidation of pyrite

Oxidation of pyrite in acid sulphate soils takes place in several stages, involving both chemical and microbiological processes. Initially, dissolved oxygen reacts slowly with pyrite, yielding iron II, and sulphate or elemental sulphur:

$$FeS_2 + \frac{1}{2}O_2 + 2H^+ \rightarrow Fe^{2+} + 2S + H_2O \qquad (3.3)$$

Further oxidation of sulphur by oxygen is very slow, but may be catalysed by autotrophic bacteria at pH values close to neutrality:

$$S + \frac{3}{2}O_2 + H_2O \rightarrow SO_4^{2-} + 2H^+ \qquad (3.4)$$

Initial acidification may also be brought about by chemical oxidation of amorphous iron monosulphide, although only very small amounts of FeS are present, even in intensely black horizons:

$$2FeS + \frac{9}{2}O_2 + (n+2)H_2O \rightarrow Fe_2O_3 . n\,H_2O + 2SO_4^{2-} + 4H^+ \qquad (3.5)$$

Once the pH of the oxidising system is brought below 4, Fe^{3+} becomes appreciably soluble and brings about rapid oxidation of pyrite:

$$FeS_2 + 2Fe^{3+} \rightarrow 3Fe^{2+} + 2S \qquad (3.6)$$

The half time of this reaction is of the order 20-1000 minutes (Stumm and Morgan 1970). Reaction of iron III with sulphur is also very rapid and the overall oxidation of pyrite by iron III may be represented as:

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad (3.7)$$

In the presence of oxygen, the iron II produced by these reactions is oxidised to iron III. At pH values lower than 3.5, chemical oxidation is a slow process with a half time of the order of 1000 days (Singer and Stumm 1970). However, autotrophic bacteria, which seem to be ubiquitous in sulphidic and acid sulphate soils, overcome the kinetic barriers that exist in purely chemical systems. At low pH, *Thiobacillus ferrooxidans* oxidises reduced sulphur species and also iron II, thereby returning iron III to the system (Arkesteyn 1980):

$$Fe^{2+} + \frac{1}{4}O_2 + H^+ \xrightarrow{Thiobacillus\ ferrooxidans} Fe^{3+} + \frac{1}{2}H_2O \qquad (3.8)$$

The rapid catalytic oxidation of pyrite by Fe^{3+} ions is limited by pH, because Fe^{3+} is appreciably soluble only at pH values less than 4, and because *Thiobacillus ferrooxidans* does not grow at a higher pH. In calcareous soils, the oxidation of pyrite is probably slow. Iron III oxides and pyrite may be in intimate contact, but the rate of oxidation will be constrained by the insolubility of iron III.

The different stages of oxidation do not necessarily occur at exactly the same point. Field and micromorphological examination of acid sulphate soils shows distinct separation of pyrite and its oxidation products: jarosite, iron oxides, and gypsum. In horizons where there is a reserve of pyrite to be oxidised, this is confined to the cores of peds, whereas jarosite and iron oxides and gypsum are closely associated with pores and ped faces (Plates 3.1 and 3.2, p. 110). Van Breemen (1976) suggests that oxygen reacts with dissolved iron II before it can reach the pyrite and that iron III is the immediate oxidant, as depicted in Figure 3.1.

Under a climate with pronounced wet and dry seasons, oxidation of pyrite may continue after flooding, using the oxidative capacity that was stored as iron III oxide during the dry season. Even so, the supply of oxygen appears to be the rate-limiting factor in the oxidation of pyrite under acid conditions in the field. Excavated pyritic material is oxidised very much faster, and suffers a much lower pH than the same

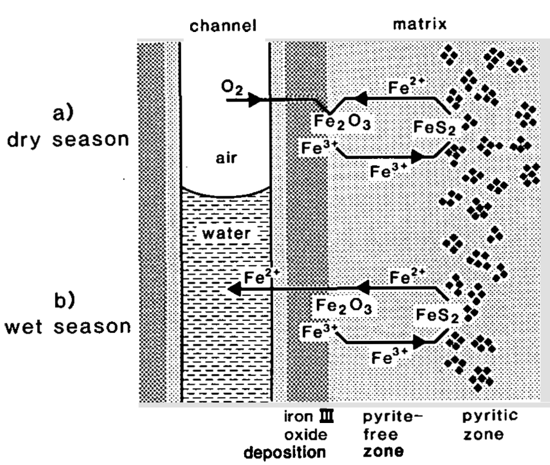


Figure 3.1 Model of pyrite oxidation in an acid sulphate soil (after van Breemen 1976):

a) During the dry season, oxygen diffuses into the soil from pores and fissures. Fe^{2+} ions in solution are oxidised to Fe^{3+} ions or oxides. At low pH, some Fe^{3+} remains in solution, diffuses to the pyrite surface where it is reduced to Fe^{2+}, liberating acidity. Fe^{2+} diffuses back towards the oxidation front where it is oxidised, liberating more acidity.

b) Some oxidation of pyrite can continue under acid, waterlogged conditions, using the reserve of iron III oxides. In this case, Fe^{2+} ions migrate out of the soil into drainage or floodwaters before being oxidised.

material in situ. So long as there is a reserve of pyrite to be oxidised, deepening of drainage or an unusually dry season invariably leads to increased production of acidity. Conversely, acid production is stopped by raising the watertable.

3.2.2 Oxidation products of pyrite

Most of the acidity generated by the oxidation of pyrite by iron III (Equation 3.7) is spent in the subsequent oxidation of iron II back to iron III (Equation 3.8). The net result, with iron III hydroxide as an end product may be expressed as:

$$FeS_2 + \frac{15}{4} O_2 + \frac{7}{2} H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \qquad (3.9)$$

This releases 4 moles of acidity per mole of pyrite oxidised.

Iron Oxides

Where the pH of the soil remains above 4, iron III oxides and hydroxides precipitate directly by oxidation of dissolved iron II. Where active oxidation of pyrite is taking place, colloidal iron III oxides commonly appear in drainage water (see Plate 2.6). Goethite is the most commonly identified iron oxide. Sometimes it may be slowly transformed to haematite (see Plates 4.14 and 4.15):

$$\underset{\text{goethite}}{2FeO.OH} \rightarrow \underset{\text{haematite}}{Fe_2O_3} + H_2O \qquad (3.10)$$

Haematite has not been reported from young acid sulphate soils produced by artificial drainage, though it is common in old acid sulphate soils such as those of the Bangkok Plain.

Jarosite

Characteristic pale yellow deposits of jarosite $KFe_3(SO_4)_2(OH)_6$ precipitate as pore fillings and coatings on ped faces under strongly oxidising, severely acid conditions: Eh greater than 400 mV, pH less than 3.7. Jarosite may occur in a range of solid solutions with natrojarosite and hydronium jarosite, where Na and H_3O replace K, but the potassium form predominates. Its formation from pyrite may be represented as:

$$FeS_2 + \frac{15}{4} O_2 + \frac{5}{2} H_2O + \frac{1}{3} K^+ \rightarrow \frac{1}{3} KFe_3(SO_4)_2(OH)_6 + \frac{4}{3} SO_4^{2-} + 3H^+ \qquad (3.11)$$

At higher pH values, jarosite is metastable with respect to goethite and ultimately it is hydrolysed to the iron oxide:

$$KFe_3(SO_4)_2(OH)_6 \rightarrow 3FeO.OH + K^+ + 3H^+ + 2SO_4^{2-} \quad (3.12)$$

In the field, brown rims are visible around the yellow jarosite deposits within 10-20 years of drainage, and in old acid sulphate soils the horizon of jarosite mottling, adjacent to the still-reduced pyritic substratum, is succeeded by an horizon with conspicuous mottles, nodules, pipes, and coatings of iron oxide (see Plate 1.4). Microscopic examination of thin sections (see Plates 4.10 to 4.15) and X-ray diffraction reveal that the yellow mottles characteristic of acid sulphate soils contain predominantly jarosite, but also invariably goethite. Brown and red mottles in acid sulphate soils are predominantly goethite, sometimes associated with jarosite and sometimes with haematite (van Breemen 1976).

Sulphates

Most of the iron mobilised by oxidation of pyrite remains in the soil profile, but only a small fraction of the sulphate is retained, as jarosite or gypsum. Most soluble sulphur is lost to drainage although some diffuses downwards to the reduced substratum and is reduced once again to sulphide.

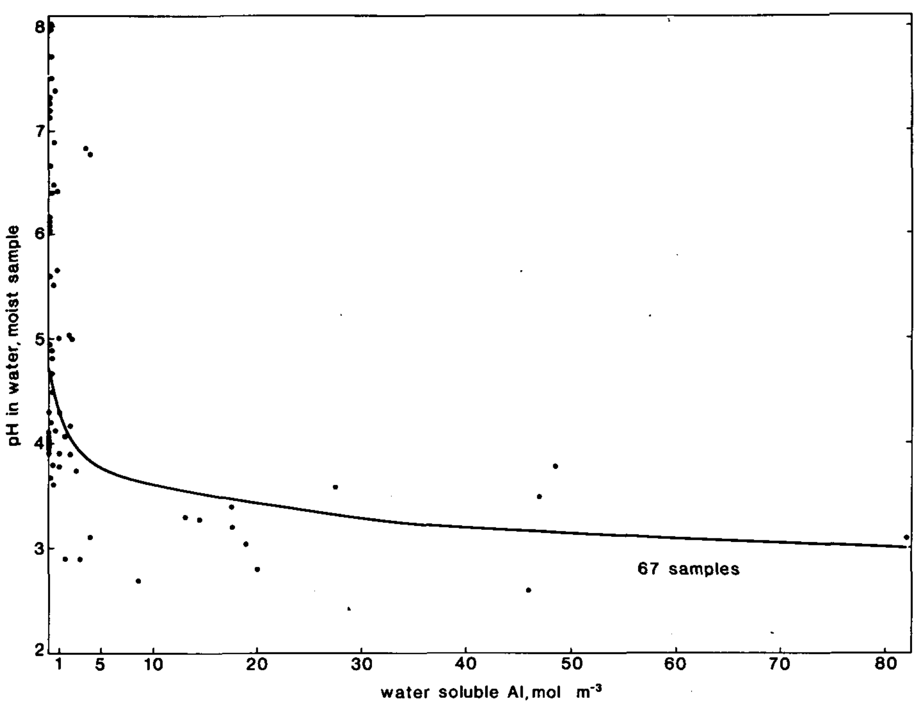


Figure 3.2 Relationships between pH and the soluble aluminium content of moist samples from Northland, New Zealand.

Gypsum is formed in acid sulphate soils by the neutralisation of acidity by calcium carbonate:

$$CaCO_3 + 2H^+ + SO_4^{2-} + H_2O \rightarrow CaSO_4.2H_2O + CO_2 \qquad (3.13)$$

Gypsum appears as as powdery efflorescence on ped faces and ditch sides. Large crystals are commonly present in acid sulphate soils that experience a pronounced dry season.

Acid hydrolysis of silicates and Al^{3+} activity

The severely acid environment of an acid sulphate soil enhances the weathering of silicate minerals. In the field, pH values of acid sulphate horizons are usually in the

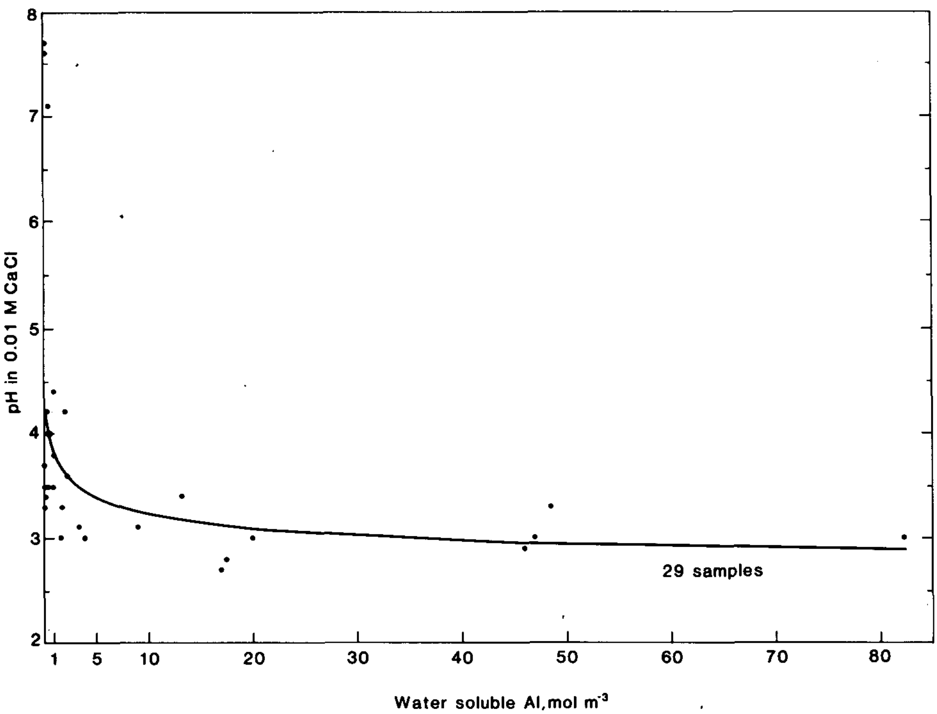


Figure 3.3 Relationships between pH in 0.01M $CaCl_2$ solution and the soluble aluminium content of dried samples from Northland, New Zealand (from Metson et al. 1977).

range 3.2 to 3.8 (Bloomfield et al. 1968; van Breemen 1976; Dent 1980). Even moist incubation of sulphidic material in polythene bags, which allows no leaching of acid, rarely produces pH values less than 1.5, typically accounting for less than 10 per cent of the acidity generated by oxidation of pyrite (Dent and Raiswell 1982). Buffering under these severely acid conditions is attributed to acid hydrolysis of aluminosilicate clays.

High contents of dissolved silica and Al^{3+} are a striking characteristic of soil and groundwater. Dissolved Al^{3+} activity appears to be directly related to pH (Figures 3.2 and 3.3); as pH rises, aluminium is precipitated as hydroxide or basic sulphate (van Breemen 1973; 1976).

3.3 Reduction processes in acid sulphate soils

Decomposition of organic matter generates electrons. Under aerobic conditions, the principal electron sink is oxygen. In most soils, flooding is followed within a few hours or days by exhaustion of dissolved oxygen by aerobic micro-organisms. In a flooded soil, decomposition of organic matter is continued by anaerobic bacteria which reduce nitrate, manganese oxides, and ultimately iron III oxides and sulphate.

Reduction is accompanied by increasing concentrations of CO_2, HCO_3^-, Fe^{2+}, and also exchangeable cations such as Ca^{2+} displaced by iron. Significantly, reduction decreases acidity by consuming hydrogen ions, for example:

$$Fe(OH)_3 + 2H^+ + \frac{1}{4}CH_2O \rightarrow Fe^{2+} + \frac{11}{4}H_2O + \frac{1}{4}CO_2 \tag{3.14}$$

The response to flooding of acid sulphate soils is very variable (see Figures 1.3 to 1.6), but compared with normal soils the speed of reduction is hampered by the extreme acidity, low nutrient status, low content of easily-decomposed organic matter, or some combination of these conditions unfavourable to anaerobic bacteria. Prolonged flooding eventually reduces acidity, but sometimes the pH remains below 5, perhaps partly because of strong buffering at low pH.

A rise of pH following flooding reduces Al^{3+} activity. This permits the growth of rice, but in some acid sulphate soils flooding leads to toxic concentrations of dissolved iron (Equation 3.14), hydrogen sulphide (Equation 3.2), or carbon dioxide. Very high levels of dissolved iron are associated with young acid sulphate soils that contain abundant, easily-reduced iron oxides. Where pyritic subsoil is present at shallow depth, reduction of iron III by pyrite may also contribute to high levels of dissolved iron II in the flooded soil. Toxicity by hydrogen sulphide is not specific to acid sulphate soils. The contributory conditions are a high content of easily-decomposed organic matter and abundant soluble sulphate.

Floodwater standing on acid sulphate soil commonly becomes severely acid. Moormann and van Breemen (1978) report floodwater pH values as low as 3.5, associated with dissolved Al^{3+} values of 0.3 – 2.6 moles m^{-3}, on the Plain of Reeds in Vietnam. Where there is a pronounced dry season, acidity generated by oxidation of pyrite at some depth in the soil migrates towards the surface and may produce efflorescences of acid salts: for example hydrated $NaAl(SO_4)_2$, $MgAl_2(SO_4)_4$, $FeSO_4$, $Al_2(SO_4)_3$. Dissolution of these salts by the flooding liberates acidity. Subsequently, soil reduction produces Fe^{2+} balanced by sulphate anions. The iron is oxidised at the soil-water interface, liberating acidity into the floodwater:

$$Fe^{2+} + \frac{1}{4}O_2 + \frac{5}{2}H_2O \rightarrow Fe(OH)_3 + 2H^+ \tag{3.15}$$

3.4 Leaching

Soils that are periodically flooded by tidewater contain soluble salts in concentrations ranging from substantially greater than sea water in dry climates (EC_e greater than 100 mS cm^{-1})to substantially less. Reclamation involves flooding by freshwater or leaching by rainfall to remove excess salts. Thereafter the watertable must be maintained well below the rooting depth of the crop to prevent capillary rise of salts into the rooting zone.

In most newly-reclaimed soils, leaching is promoted by the development of fissures during soil ripening and by a network of coarse pores, inherited from the tidal soil. Persistent salinity is usually related to poor drainage. Poor drainage can be caused by a high watertable in the polder, seepage through embankments, or slow permeability. Slow permeability may be related to unripe material with few coarse pores, the arrest of physical ripening and structural development by severe acidity, the blockage of field drains by ochre deposits, or to the collapse of soil structure.

An unstable soil structure can be produced by the leaching of soluble salts from soils with a high exchangeable sodium percentage. This is unlikely to be a problem in soils that are initially rich in pyrite. Either the acidity generated by oxidation of pyrite is neutralised by calcium carbonate, releasing soluble calcium that replaces exchangeable sodium and promotes a stable soil structure; or severe acidity liberates soluble aluminium that likewise displaces sodium and promotes structural stability.

Free acid may be leached from an acid sulphate soil like any other soluble constituent. However, acidity represented by adsorbed iron and aluminium is not leached by fresh water. Brackish tidewater can replace this adsorbed acidity by ion exchange, which may be represented as:

$$\text{clay-Al}_{(s)} + Mg^{2+}_{(aq)} + Na^{+}_{(aq)} \rightarrow \text{clay-Mg,Na}_{(s)} + Al^{3+}_{(aq)} \qquad (3.16)$$

At the high pH of the leaching water, the aluminium will immediately precipitate as hydroxide or basic sulphate, releasing soluble acid that can be leached from the system:

$$Al^{3+}_{(aq)} + 3H_2O \rightarrow Al(OH)_{3(s)} + 3H^{+}_{(aq)} \qquad (3.17)$$

3.5 Soil Ripening

The concept of soil ripening embraces all the physical, chemical, and biological processes by which a freshly-deposited mud is transformed to a dryland soil (Smits et al. 1962; Pons and Zonneveld 1965).

Physical ripening essentially involves an irreversible loss of water. Clayey and organic-rich sediments deposited in water have a very open structure and, consequently, a very high water-filled pore space. Plate 3.3 shows the high pore space and also the small areas of contact between individual particles or aggregates. This structure is easily deformed and the material has little frictional or cohesive strength. Although the total pore space is high, there are no coarse pores, so hydraulic conductivity is low except through old root channels and burrows.

During accretion of sediment in a tidal environment, water is lost as a result of

Plate 3.3 Microstructure of unripe clay x 9 000 (electronmicrograph by Keith Tovey).

consolidation, by evaporation from the surface, drainage at low tide, and, most importantly, through extraction of water by plant roots. Evaporation and transpiration are critical to soil ripening because a large force is necessary to remove water from the small pores in the sediment. Drainage by gravity alone does not achieve this.

Removal of water leads to the partial collapse of the initial, very open micro-structure; to shrinkage and consequent fissuring of the soil; and to an increase in the area of close contact between individual particles and aggregates. This in turn increases the cohesive strength of the material. Ripening is a one-way process. Once the open micro-structure of the unripe soil has collapsed, it can only be re-created by erosion, dispersion, and redeposition of the sediment, or by puddling, as in the topsoil of a rice paddy.

The degree of ripening can be assessed in the field by squeezing the soil in the hand:

Totally unripe mud is fluid; it flows between the fingers. In predominantly mineral sediments, the water content is more than 80 per cent by mass;

Practically unripe mud is very soft, sticks fast to everything, and can be squeezed through the fingers by very gentle pressure. Its water content is between 70 and 80 per cent. A man will sink in to his thighs unless supported by vegetation;

Half ripe mud is fairly soft, sticky, and can be squeezed through the fingers. Its water content is between 65 and 75 per cent and its mechanical strength when disturbed is low. A man will sink ankle to knee deep unless supported by vegetation;

Nearly ripe material is fairly firm; it tends to stick to the hands, and can be kneaded but not squeezed through the fingers. Its water content is between 55 and 65 per cent. If it is not churned up, it will support the weight of stock and ordinary wheeled vehicles;

Ripe material is firm, not particularly sticky, and cannot be squeezed through the fingers.

Sandy materials are considered to be physically ripe.
The stage of ripening is defined more precisely by the **n-value** (Pons and Zonneveld 1965). This is the quantity of water in grams absorbed by one gram of clay in the soil, derived from the equation:

$$n = \frac{A - 0.2R}{L + bH}$$

where:
A = the percentage of water in the soil in field condition, calculated on dry soil basis;
R = the non-collodial part of the soil (percentage sand + silt);
L = percentage clay;
H = percentage organic matter (percentage carbon x 1.74);
b = the ratio of the water absorption capacity of organic matter to clay (3 for well-humified organic matter, 4 or more for partly-decomposed organic matter).

The basic field characteristic of ripening is consistence. The n-value is a useful analytical tool which works well in soils of uniform mineralogy dominated by illite, as in The Netherlands. It has not been tested in soils dominated by either kandite or smectite clays. A more universal measure of the stage of ripening is shear strength, which can be measured quickly in the field with a hand shear vane (see Section 7.3.6). However, roots and shells can interfere with the vane, and the method is not appropriate for sandy soils because of their frictional strength.

Table 3.1 defines ripening stages according to both n-value (after Pons and Zonneveld 1965) and shear strength. The shear strength values quoted here are from field measurements in New Zealand and may not be universally applicable.

Table 3.1 Quantitative definitions of stages of ripening

	n-value	Shear strength, kPa	
		Initial	Remoulded
Totally unripe	>2.0	5	0
Practically unripe	1.4–2.0	4–15	1–3
Half ripe	1.0–1.4	16–30	4–6
Nearly ripe	0.7–1.0	30–50	7–20
Ripe	<0.7	>50	>20

The rate of physical ripening is determined by the rate of removal of water from the soil matrix. This is governed by the balance between input by rainfall, flooding, and seepage; and losses from evaporation, transpiration, and drainage under gravity. Internal soil drainage is governed by the thickness and hydraulic conductivity of the unripe material, and the presence of interlayered and underlying sandy materials. Because

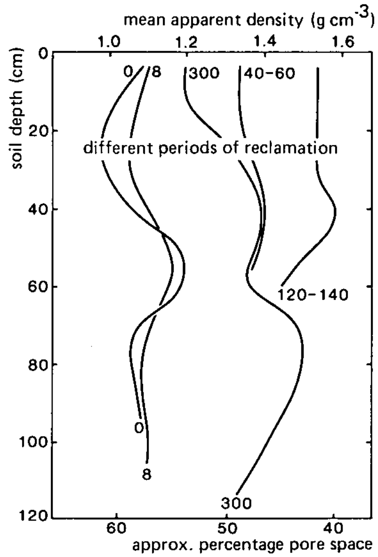


Figure 3.4 Soil ripening: apparent density of calcareous clay soils after different periods of reclamation, The Wash, England. The low values in the topsoil of the 300-year-old polder are due to the crumb structure built up under long-established pasture.

the rate of movement of water through both unripe soil and dry soil is very slow, ripening of the subsoil depends, above all, on plant roots penetrating the subsoil, which increases the energy gradient between the unripe soil and the evaporating force of the atmosphere. Rijniersce (1982) has developed a mathematical model of physical soil ripening for the IJsselmeerpolders which could be adapted to predict the rate of ripening in other areas. Even with intensive drainage and favourable chemical conditions in the rooting zone, physical ripening of a thick clay layer requires several decades. In The Wash polders of East Anglia, Dent et al. (1976) found that physical ripening was complete to 60 cm within 40 years (Figures 3.4 and 3.5). Obviously, the greater the deficit of rainfall compared with potential evaporation, the more quickly ripening can proceed.

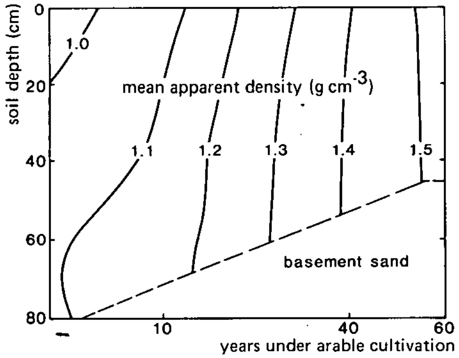


Figure 3.5 Cubic trend surface analysis of apparent density plotted against depth and period of reclamation, The Wash, England. The soils sampled are under continuous arable cultivation. Soil texture varies from silty clay to clay loam, 35 ± 8 per cent clay (from Dent et al. 1976).

Acid sulphate conditions arrest physical ripening because they prevent roots ramifying in the acid layer. Physical, chemical, and biological ripening are not always in phase. A waterlogged, sulphidic sediment may become physically ripe as a result of slow, geological consolidation. Under arid conditions, a drained acid sulphate soil can develop a physically ripe surface crust that is severely acid and still retain reserves of pyrite. Usually however, the different facets of ripening proceed together. Once reserves of pyrite are exhausted and free acid is leached, soluble aluminium levels are reduced and roots colonise the former acid sulphate horizon, bringing about physical ripening. This in turn promotes drainage, and a more varied and productive living community.

3.6 Modelling the rate of acid production

An outstanding characteristic of acid sulphate soils is their rapid rate of change. Sulphidic soil may become severely acid within a few days or weeks of exposure to the air. In the field, where impeded drainage usually limits the rate of oxidation, acidity and mobile iron may become apparent within a few months of the initiation of land drainage. On the positive side, free acid may be spent within a few years if intensive drainage and leaching can be maintained.

If we want to predict the engineering or environmental hazards of acidity, or the extent to which the lime requirement can be reduced by oxidation and leaching, or the time scale of the acidity problem, we need to know the total potential acidity, its distribution, and the rates of acid production and leaching under specified field conditions.

3.6.1 A static model

The amount of acid generated depends on the amount of oxidisable sulphides and the course of the reaction. Eh/pH conditions in acid sulphate soils overlap the stability fields of iron II, iron III oxides, and jarosite. Van Breemen (1976) argues that in severely acid, oxidised environments (pH less than 4.4, Eh greater than 400 mV), jarosite is more stable than amorphous iron III oxide. Field observations confirm that the more severe the acidity, the more dominant is jarosite deposition compared with iron oxide deposition. Acid generation according to Equation 3.11 is therefore pursued here. In terms of acid production, this equation predicts three moles of H^+ per mole of pyrite. Jarosite is ultimately hydrolysed to goethite, releasing a further mole of H^+, but under field conditions this reaction moves to completion over many years rather than months.

The estimation of net acid production requires the determination of both the total oxidisable sulphur and the neutralising capacity of the system.

3.6.2 A dynamic model

The rate of reaction will be controlled by the temperature, the surface area of the pyrite, and the rate of transfer of oxidants (oxygen and Fe^{3+}) into the system (Figure 3.1). In recently-deposited alluvial soils, the crystal size of pyrite is small (see Plates 1.5, 1.6, 4.8, and 4.9) and the rate-limiting factor is likely to be the diffusion of oxidants. The rate of acid production can thus be estimated using a simplified model of diffusion of oxygen through water-filled pores.

Simplifying assumptions:

- The rate of oxidation of pyrite is controlled by the rate of oxygen transport through water-filled pores, i.e. the potential rate of reaction is faster than the rate of diffusion;
- Oxidation of organic matter consumes negligible oxygen compared with oxidation of pyrite;
- No blockage of pores by precipitates;
- No hindrance of oxygen diffusion by collision and interaction with soil particles.

If the rate-limiting process is diffusion of oxygen, then the rate of oxidation at any point will be related to the distance from the air-water interface.

Unripe soils under mangrove vegetation are typically very permeable because of many burrows, coarse plant debris, and old root channels. (Auger holes bored to 1 m fill with water within a few minutes.) However, unless ripening and fissuring of the soil takes place, lateral drainage over longer distances may be very restricted. The early stages of ripening typically bring about fissuring of clay soils into prismatic peds up to 30 cm in cross-section, so a further assumption is made that:

- The soil fissures into prismatic peds of radius much less than length (Plates 3.1 and 3.2). The ped face is the air-water interface. Diffusion of oxygen into the soil can therefore be modelled approximately as the rate of diffusion into cylinders of equivalent radius. In the absence of fissuring, oxidation may be modelled using an horizontal oxidation front moving downwards through the soil. This will predict a much slower rate of acid generation and leaching than the cylindrical model.

3.6.3 Calculation of the rate of oxidation

At time $t = 0$, the water in pores opening to the surface of the ped becomes saturated with oxygen. The soil is then gradually oxidised from the surface inwards. The model assumes instantaneous reaction, so the effect of diffusion plus reaction is analagous to diffusion alone, but with a corresponding reduction in the rate of advance of the diffusing front of oxygen because it is consumed in the oxidation of pyrite.

If the time-diffusion coefficient of dissolved oxygen is D, then the appropriate value for the case of diffusion plus reaction is given by:

$$\frac{D}{R + 1}$$

where R is defined as below:

Concentration of oxidisable material, expressed as the number of moles of O_2 required for its oxidation = R x concentration of O_2 in water, expressed in moles

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 $J_o(a\alpha_n) = 0$. (J_o is the Bessel Function of order zero.)

Details of the calculation are given by Dent and Raiswell (1982). Figures 3.6 and 3.7 show predicted rates of oxidation for a range of ped sizes and total oxidisable sulphur content, calculated for unripe clay of 77 per cent water-filled pore space.

A rough test of the model can be made by comparing the residual sulphur contents of acid sulphate horizons, after various periods of drainage and leaching, with the sulphur contents of equivalent undrained horizons. In Hokianga, New Zealand, the mean sulphur content of virgin sulphidic clay horizons is 2.0 per cent (13 samples).

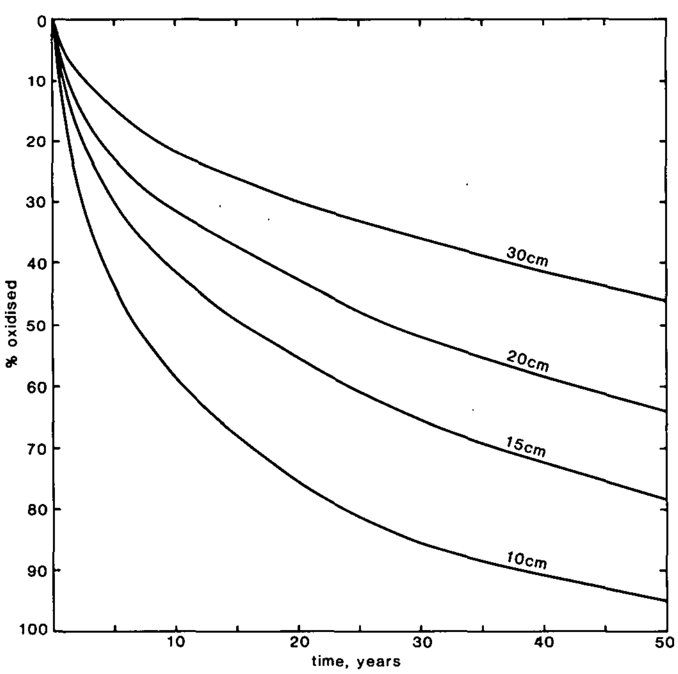


Figure 3.6 Rate of oxidation of pyrite in soils with 3.5 per cent by mass pyrite S in cylinders of different diameter.

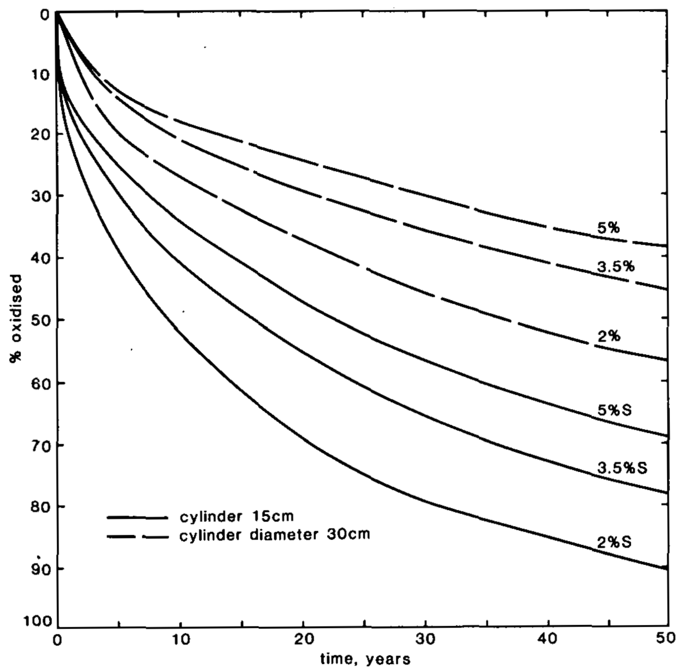


Figure 3.7 Rate of oxidation of pyrite in soils of different pyrite content in 15 cm and 30 cm diameter cylinders (from Dent and Raiswell 1982).

In polders drained to about 0.6 m below the sulphide datum (i.e. the level below which the soil is sulphidic) for 45 years, the mean sulphur content of the equivalent drained layer has been reduced to 0.95 per cent (7 samples). Ignoring the small amount of basic sulphate present, this is a loss of 52.7 per cent which agrees well with the model prediction for 30 cm peds of 54.4 per cent.

The model progressively underestimates the apparent rate of oxidation over shorter periods, so that after only 7 years of drainage the mean sulphur content was reduced by 37 per cent, compared with the model prediction of 26 per cent. This may be accounted for by a flux of oxygen moving down the profile from the upper surface, in addition to the flux from vertical fissures. However, total sulphur data from younger polders are limited and refinement of the model is hardly justified without better test data.

3.6.4 A case study: the Gambia Barrage Scheme

The model of pyrite oxidation was developed to answer practical questions in a major land development scheme in The Gambia. The river Gambia flows through a region of strongly seasonal climate with an average rainfall of about 1000 mm during a 5-month wet season and no rain during the 7-month dry season. The river is tidal for a distance of more than 200 km upstream. In the dry season, when freshwater 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. Lower-than-average freshwater flows, or any increase in the present low level of abstraction of water for irrigation, 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 between 13 and 19 thousand hectares.

A feasibility study proposed a barrage across the tidal river to intercept the salt water intrusion and create a reservoir of fresh water for irrigation in the dry season (Coode and Partners 1979). Figure 3.8 shows the calculated water levels of the reservoir assuming average river flow and different amounts of abstraction of water for irrigation.

Soil surveys revealed about 12900 ha of potential acid sulphate soils upstream of the proposed barrage site which would be drained at low reservoir levels (Dent 1979; Thomas et al. 1979). The sulphide datum was surveyed by levelling transects across the tidal zone along which stakes painted with red lead were implanted. Soluble sulphides turn red lead black, so the sulphide datum was taken to be the upper limit of blackening on the stakes. This corresponded with the field identification of a practically unripe, reduced horizon and was confirmed by determinations of total sulphur content.

The mean elevation of the sulphide datum at Sankwia, close to the proposed barrage, is + 1.3 m above Gambia datum. Under a conventional barrage operation, abstraction of water for irrigation of 24000 ha irrigated rice would lower the water level in the reservoir more than 2 m below the sulphide datum in a year of average river flow.

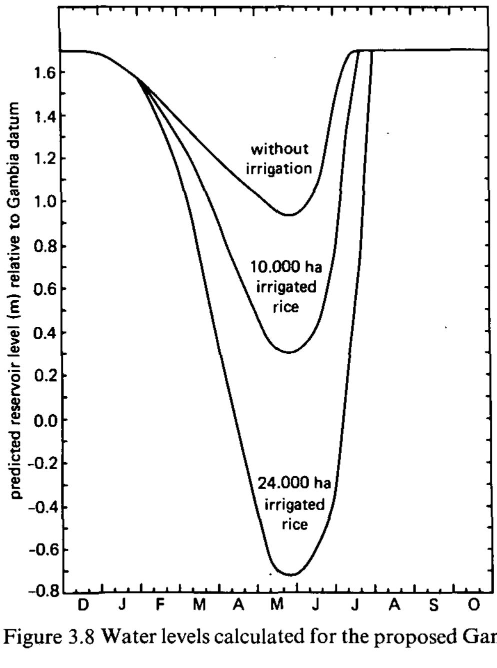


Figure 3.8 Water levels calculated for the proposed Gambia reservoir, assuming average river flow.

Under these conditions, severe soil acidification is inevitable.

The mean sulphur content of the Gambian sulphidic horizons analysed was 3.5 per cent, or 3.44×10^2 moles FeS_2 m^{-3}. By Equation 3.11, oxidation of this pyrite will liberate 10.31×10^2 moles H^+.

No calcium carbonate was present in the soils, but an effective neutralising capacity of 20 milliequivalents per 100 g was allowed for cation exchange capacity, leaving an excess acid production of 9.05×10^2 moles H^+ m^{-3}.

Evaporation will lower the reservoir level below the sulphide datum, even without abstraction of water for irrigation, so severe acidity will develop during the first year of barrage operations. The greater the abstraction of water, the greater the depth of drainage and the greater the acidification. If we assume abstraction of water for 24000 ha irrigated rice, fissuring of the soil into peds 30 cm diameter, and an horizontal watertable, then net *annual* acid generation will be 35.4 moles H^+ per square metre at the $T = 1$ year rate, decreasing to 6.6 moles H^+ m^{-2} where $T = 10$ years, i.e. after about 40 years of full operation of the scheme.

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 short-term buffering effect 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.

Fate of the acid

Figure 3.9 depicts the pH values of the reservoir in mid-July, assuming abstraction of water for 24000 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.

Implications of this severe acidity include:

- In the area of sulphidic soils upstream of the barrage, the development of acidity and changed hydrology will combine to kill all present vegetation and aquatic life;
- Loss of vegetation cover will lead to bank erosion and siltation of the reservoir;
- Engineering structures must be designed to cope with the effects of the acidity and high sulphate content of the reservoir water on steel and concrete;
- The ecological effects of the annual flush of acid will extend far downstream of the reservoir and will recur annually for many years.

Without the combination of soil survey and a quantitative model, the extent and effects of acidification would be difficult to envisage. On the basis of the model applied to data from the soil survey, two alternative design options were presented:

- Locate the barrage upstream of the most extensive areas of sulphidic soils;
- Apply a more sophisticated system of water management to maintain the water level in the reservoir above the sulphide datum. This may be done by a 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 evaporation and irrigation.

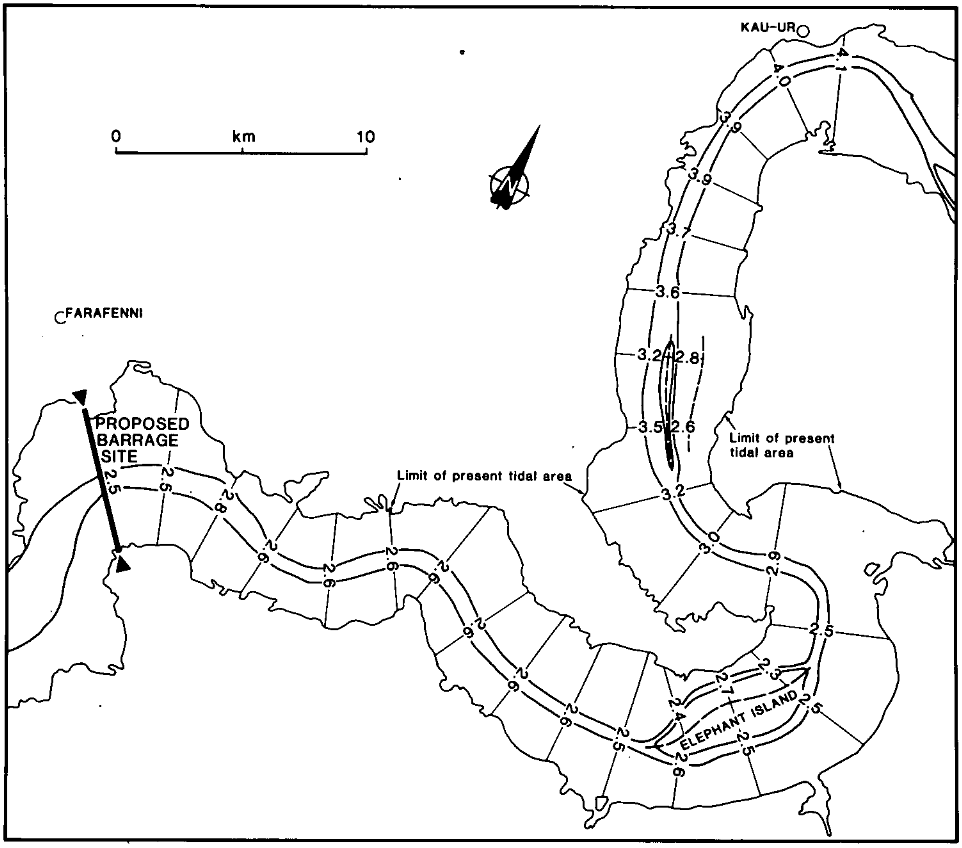


Figure 3.9 Gambia Barrage Project: predicted pH values for the reservoir in mid-July, assuming:
- Average river flow;
- Abstraction of water for 24 000 ha of irrigated rice;
- Soil fissured into 30 cm peds;
- Oxidation rate at T = 10 years;
- Complete washout of the annual increment of acid into the reservoir at the beginning of the rainy season.

4 Field relationships, soil horizons, and soil profiles

4.1 Field relationships and soil survey

Surveys for land reclamation and improvement have to identify those characteristics of land that will determine its performance under a range of new, alternative systems of management, especially those properties that will change as a result of drainage.

A definitive characteristic of acid sulphate soils is the amount and distribution of pyrite, but the determination of pyrite is exacting, time-consuming, and requires special laboratory facilities. Intensive sampling and determination of pyrite is therefore not a practical proposition. Where large areas are to be surveyed, it is more cost-effective to establish field relationships between the primary soil properties and surrogate characteristics that can be mapped quickly by hand and eye. In the case of pyrite distribution, a field relationship can be established with soil morphology and landforms (Dent 1980). Another soil property critical to land reclamation is the saturated hydraulic conductivity. Again, direct measurement is both exacting and slow, but a field relationship can be established with soil texture and ripeness.

Describing soil morphology and characterising the mapping units identified on the basis of morphology is therefore the essence of soil survey. But this requires a system of description and classification that takes account of the special features of acid sulphate soils – and a system that is widely understood.

The most widely used system of soil description and horizon nomenclature is that defined in the FAO Guidelines for Soil Profile Description (1977) and the FAO/Unesco Soil Map of the World (1974). This section will introduce some new horizon names to augment the FAO system by catering for unripe, potentially acid, and acid sulphate horizons. At the same time, the new names maintain the integrity of other, long-established horizon definitions, which otherwise would be stretched to accommodate acid sulphate soils.

In introducing the new horizon names, this section will describe the development of soil horizons and soil profiles, first in the tidal environment, and then during the course of drainage, ripening, and the oxidation of pyrite.

4.2 Sequential development of horizons in the tidal zone

Where the sea level is stable, a sequence of horizons is developed by the deposition of mud under mangrove or salt marsh vegetation.

The different horizons are recognised in the field by their morphology. They also have contrasting physical and chemical characteristics, notably differences in pyrite content, that affect their response to reclamation and drainage. The horizon designation summarised in Table 4.1 has been developed from Dent (1980) to be consistent with the legend of the FAO/Unesco Soil Map of the World (1974).

Table 4.1 Horizons of unripe saline clay soils

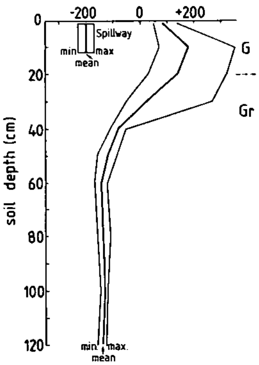
Gr	Practically unripe or half ripe; permanently reduced and accumulating pyrite
Gro	Half ripe; partly oxidised; iron pipes and ped coatings
Go	Nearly ripe; oxidised; mottled; nodules, pipes and coatings of iron oxide; not potentially acid
Gj	Severely acid; yellow mottles of jarosite; practically unripe or half ripe
G	Undifferentiated, unripe surface layer

4.2.1 Gr horizon

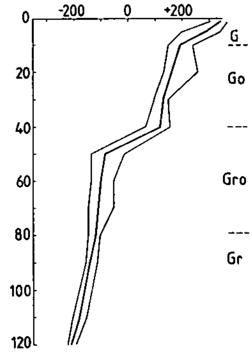
Once vegetation is established on a mud flat, sedimentation is promoted by the closely-spaced stems of the marsh vegetation, or the tangle of prop roots and pneumatophores of the mangroves (Plate 4.1). Below the surface, the dense mat of fibrous roots stabilises the mud and grows upwards as fresh mud is deposited.

Plate 4.1 *Avicennia marina*, Kaipara, New Zealand. The fibrous underground root system and pneumatophores poking up through the soil surface stabilise the sediment and promote further accretion of mud.

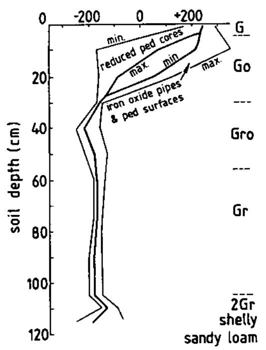
Under stable conditions, a distinctive soil horizon is developed:
- Dark grey or dark greenish grey in colour, commonly with black mottles around rotting roots;
- Usually practically unripe, structureless;
- With many fine to coarse dendritic pores and, under *Avicennia* mangroves, prominent coarse, vertical, tubular pores left by the decay of pneumatophores, and many crab or lobster burrows;



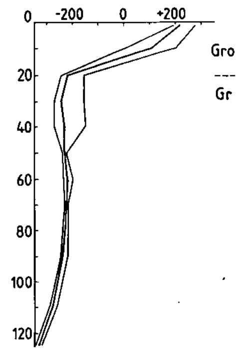
4.1 Unripe saline sulphidic clay



4.2 Half ripe saline sulphidic clay, levee site



4.3 Half ripe saline sulphidic clay, raised flat site



4.4 Unripe saline sulphidic clay, backswamp site

Figures 4.1 to 4.4 Eh profiles of virgin tidal soils, Kaipara, New Zealand

- In contrast with the underlying, finely-stratified mud-flat sediments, it does not show regular stratification.

The symbol Gr is proposed for this horizon: G denoting unripe, hydromorphic material, r for permanently reduced.

The finely-divided organic detritus deposited in the sediment and the huge amount of organic matter added by the swamp vegetation is broken down by sulphate-reducing bacteria (Section 3.1). In the field, pH values are generally between 6.2 and 6.7. Eh values drop rapidly from about +200 mV at the soil surface and in contact with living roots, to -200 mV within 20 to 40 cm (Figure 4.1).

Under these severely-reducing conditions, the breakdown of organic matter is incomplete. Fibrous roots and spongy tissues disappear rapidly, leaving blackened corky and vascular tissues. There is a strong smell of hydrogen sulphide. Inky black mud, sometimes with a white scum of colloidal sulphur, collects in surface depressions and oozes from the profile face.

This is the principal horizon of pyrite accumulation, but total sulphur contents vary widely. Figure 4.5 indicates the rate of accretion of sediment and pyrite accumulation in Kaipara Harbour, New Zealand, under *Avicennia* mangrove vegetation. The data, although from only three dated samples, indicate a rate of pyrite accumulation of the order of 1 per cent S by mass or 10 kg S per m^3 of sediment per 100 years. In New Zealand, there is also a general trend of increasing sulphur content in Gr horizons from south to north - from 1.4 $\pm$ 0.7 per cent dry mass in Kaipara Harbour, to 2.0

Colour plates

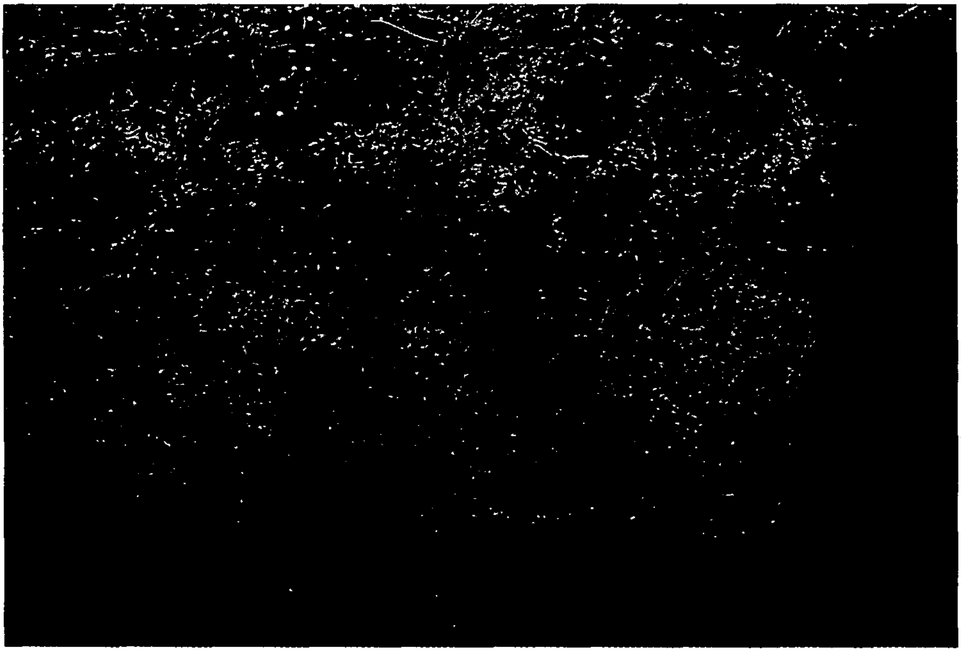


Plate 1.3
Raw acid sulphate clay, Hokianga, New Zealand. Yellow jarosite deposition is emphasised on exposed ditch sections. Gelatinous ochre deposition in the drainage water.

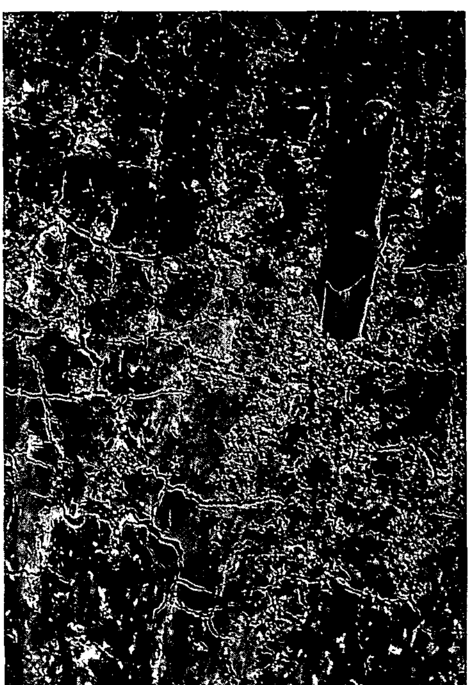


Plate 1.4
Ripe acid sulphate clay, Bangkok Plain, Thailand. Prominent red iron mottling in an old, ripe acid sulphate soil (Leen Pons)

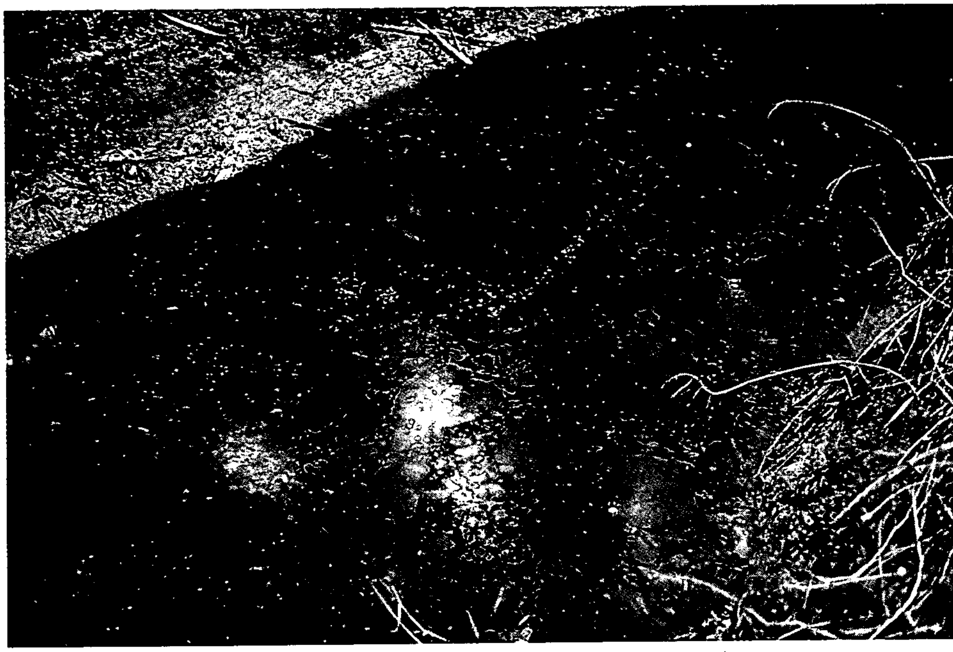


Plate 2.6
Acid, iron-rich drainage water. Oil palm plantation with controlled high watertable management, Selangor, Malaysia.

Plate 4.3
Half ripe saline sulphidic clay, Kaipara, New Zealand

Profile form: $p_3s_1Cw_2$
Vegetation: Mangrove (*Avicennia marina*) 15 per cent cover of 40 cm shrubs
Topography: Raised flat, 5 cm microtopgraphy, very poor surface drainage

Brief profile description:

G 0-16 cm Light olive brown 2.5Y 5/4 silty clay; nearly ripe; moderate medium blocky structure; many pores and crab burrows lined with olive clay; pH 6.6

Go 16-36 Dark bluish grey 5B 4/1 prominently mottled reddish brown and pale olive; silty clay; nearly ripe; weak coarse prismatic structure; brittle iron oxide pipes around medium and coarse dendritic pores; pH 6.5

Gro 36-56 Dark greenish grey 5GY 4/1; silty clay; half ripe; weak coarse prismatic structure; soft iron oxide pipes around coarse vertical tubular pores; pH 6.6

Gr 56-80 Dark bluish grey 5B 4/1 silty clay loam; practically unripe; structureless; many dendritic pores commonly occupied by partly-decomposed roots; pH 6.5

2 Gr 80-200+ Dark bluish grey 5B 4/1 loamy sand; abundant shells between 120 and 150 cm, common shells below this; pH 7.0 at 110 cm

Physical and chemical data:

Horizon	G	Go		Gro		Gr	2Gr
Sample depth, cm	0-10	15-25	30-35	40-45	50-55	70-75	110-120
Apparent density, g cm^{-3}	0.9	0.9	1.1	1.1	1.0	1.0	1.4
n-value	0.8	1.2	1.3	1.3	1.3	1.5	n/a
Shear strength, kPa, initial	40	40	37	35	34	26	35
remoulded	12	12	10	6	4	3	3
Organic matter, %	6.8	4.2	2.4	0.8	1.7	2.3	0.6
Salinity, EC_e, mS cm^{-1}	36	35	26	26	26	27	38
pH field	6.6	6.4	6.6	6.6	6.6	6.5	7.0
incubated	6.0	5.9	6.2			3.1	6.5-4.5*
peroxidised	5.5	5.9	6.0			2.0	2.3
Total S, %	0.14	0.07	0.06			1.4	1.06
kg m^{-3}	1.3	0.7	0.7			14.0	14.8

* High pH values adjacent to shell fragments

Plate 4.4
Raw saline acid sulphate clay, Carey Island, Selangor, Malaysia

Profile form $a_1s_2Cw_2$

Vegetation/Land use: Swamp forest dominated by nibung palm, *Oncosperma* sp., and *Nypa fruticans*, cleared within the last two years for oil palm plantation

Climate	J	F	M	A	M	J	J	A	S	O	N	D	Total
Mean monthly rainfall (mm)	123	112	128	123	94	123	141	147	188	207	270	279	1885

Mean monthly temp.: (Kuala Selangor, 12 m) 27 to 28°C throughout the year
Watertable: Maintained at about 50 cm over the last two years

Brief profile description:

Apj 0-10 cm	Pinkish grey 7.5YR 6/2 with occasional fine yellow mottles; clay; ripe; coarse blocky structure; pH 2.8
Gj 10-50/60	Light brown 7.5YR 6/4 with medium and coarse dark greenish grey 5BG 4/1 mottles and fine yellow and reddish brown mottles around pores and fissures; clay; nearly ripe; pH 2.9
Gr 50/60-110	Dark grey N4 clay; half ripe; abundant *Nypa* remains; many coarse dendritic pores oozing black FeS and some white colloidal sulphur; very strong smell of H_2S
Gr 110+	Dark greenish grey 5G 4/1 clay; practically unripe; abundant mangrove remains; very strong smell of H_2S; pH 5.6

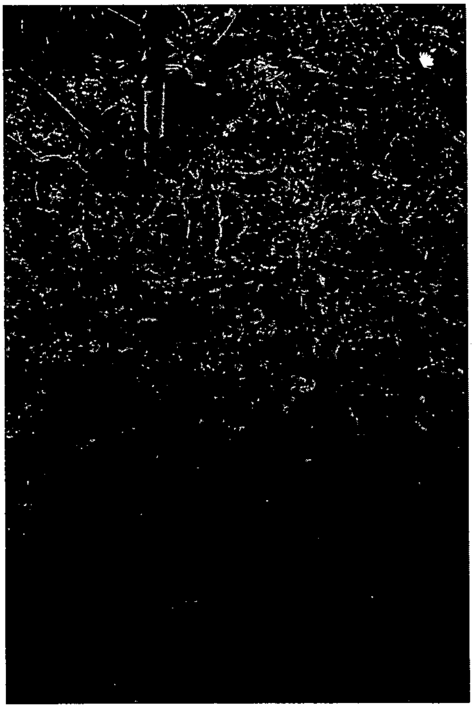


Plate 4.5
Raw saline acid sulphate clay, Hokianga, New Zealand

Profile form: $a_1s_2Cw_2$

Land use: Very poor pasture dominated by salt-tolerant species including *Juncus australis, J. bufonious, Lotus angustissimus, Polypogon monspeliensis*

Climate	J	F	M	A	M	J	J	A	S	O	N	D	Total
Mean monthly rainfall (mm), Kohukohu	76	91	89	130	155	168	157	168	119	124	104	94	1475
Mean monthly temp. (°C), Waipoua, 88 m	17	18	17	15	13	11	10	11	12	13	15	15	

Watertable: Maintained at about 70 cm, drained for 15 years

Landform: Raised flat

Brief profile description:

O	2-0 cm	Dark brown peaty root mat; pH 4.7
Bj	0-12	Grey 7.5 YR 5/1 with many fine and medium prominent pale yellow 5Y 7/3 and strong brown 7.5 YR 4/6 mottles; silty clay; ripe; coarse prismatic structure with continuous reddish brown 5 YR 3/2 iron oxide and yellow jarosite coatings on ped faces; pH 4 to 4.3
GBj	12-30	Grey 10YR 3/1 with pale yellow 5Y 8/4 mottles; silty clay; half ripe; weak very coarse prismatic structure with jarosite coatings on ped faces; pH 3.4
Gj	30-70	Dark greenish grey 5GY4/1 with coarse grey and fine yellow mottles; silty clay; half ripe; weak very coarse prismatic structure; many coarse tubular pores with soft, granular iron oxide pipes with jarosite aureoles; pH 2.5
Gr	70-100	Dark greenish 5GY 4/1; silty clay; practically unripe.

Physical and chemical data:

Horizon	Bj	GBj	Gj	Gr	
Sample depth, cm	0-5	15-20	45-55	70-80	80-100
Apparent density, g cm^{-3}		0.87	0.87	0.7	
n-value		1.0	1.0	1.3	
Shear strength, kPa, initial	42	22	18	12	10
remoulded	9	4	3	2	2
Organic matter %	5.1	3.3	1.9	1.6	3.7
EC_e, mS cm^{-1}	0.5	2	5	10	24
pH field	4.5	3.4	2.5	5.0	7.0
incubated	4.7	3.4	2.1	2.9	3.1
Total S %	0.2	0.4	1.0	1.9	2.3

Plate 4.6
Ripe acid sulphate clay with raw subsoil. Thanyaburi clay, Amphoe Thanyaburi, Changwat Pathum, Thailand.

Profile form $a_2s_2Cw_1$

Land use: Abandoned rice paddy

Climate	J	F	M	A	M	J	J	A	S	O	N	D	Total
Mean monthly rainfall (mm)	5	31	46	77	219	173	114	210	256	205	41	15	1392
Class A pan evaporation, Bangkok	141	138	184	187	174	144	139	126	123	113	115	126	
Mean monthly temp. °C	25	29	30	31	32	29	30	29	28	26	26	26	

Watertable: Flooding to 30/40 cm for 3/4 months; dry season watertable drops to 90-140 cm

Brief profile description:

Ap	0-22 cm	Dark grey 10YR 4/1 mottled yellowish red 5YR 5/8 along channels and fissures; clay; ripe; moderate coarse blocky; pH 4.0 to 4.5; EC_e 3 mS cm^{-1}
Bg	22-40	Very dark greyish brown 10YR 3/2 with fine strong brown mottles; clay; ripe; very coarse prismatic structure with dark grey organic coatings on ped faces; pH 4.0 to 4.5; EC_e 3 mS cm^{-1}
Bj	40-90	Brown 7.5YR 5/2 clay; nearly ripe; massive; jarosite and iron oxide lining dendritic pores; pH 4.5; EC_e 4 mS cm^{-1}
Gr	135+	Grey 5Y 5/1 clay; half ripe; massive; at 150 cm pH 4.5, EC_e 5 mS cm^{-1}; at 250 cm pH 6.4, EC_e 8 mS cm^{-1}

Physical and chemical data:

Horizon	Ap	Bg	Bj	Gj	Gr	
Depth, cm	0-7	22-40	40-90	90-135	135-250	250-300
Clay, <2μm, %	64	63	63	65	71	68
Silt, 2-50μm, %	35	36	32	34	27	31
Sand, >50μm, %	1	2	5	1	2	1
Apparent density, g cm^{-3}	1.4	1.5	1.1	0.9		
n-value	0.2	0.4	0.6	0.7	0.9	1.1
Organic matter %	5.2	1.1	0.6	1.7	4.2	3.7
EC_e, mS cm^{-1}	3.4	3.0	2.7	4.3	5.1	8.3
pH, $CaCl_2$	4.1	3.6	3.4	3.4	4.0	5.0
Total S %	0.2	0.1	0.9	0.3	1.4	1.3

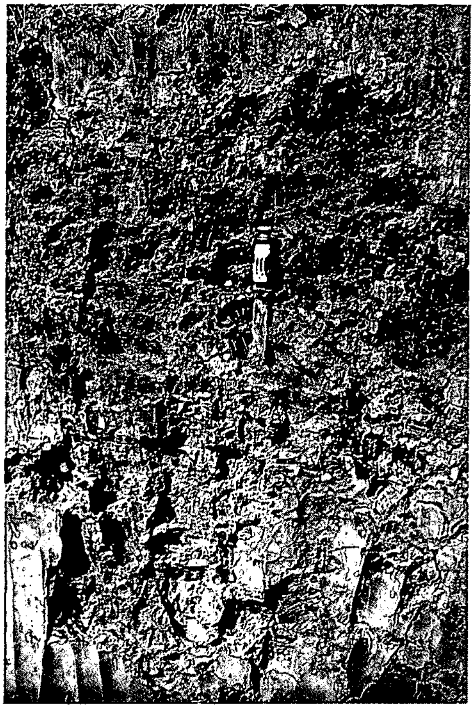


Plate 4.7
Ripe acid sulphate clay. Ongharak clay, Amphoe Nang Sua, Pathum Thani province, Thailand.

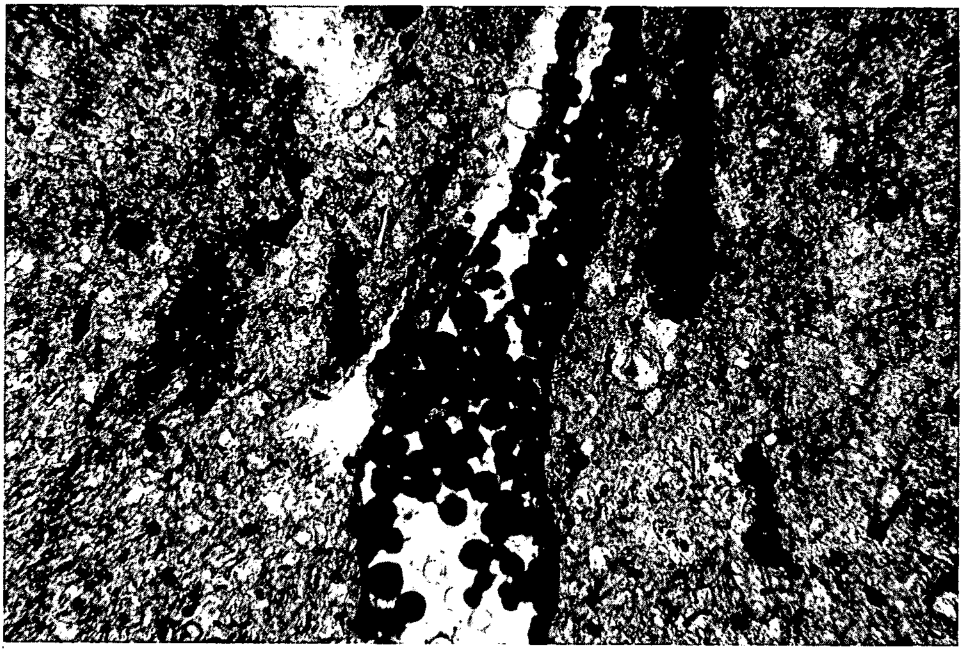
Profile form: a_3s_oC
Land use: Abandoned paddy field
Climate: as Plate 4.6
Watertable: Annual flooding to 15-20 cm for 2-3 months in the wet season; dry season watertable below 1 m

Brief profile description:

Ap	0-14 cm	Dark greyish brown 10YR 3/2 mottled yellowish red 5YR 5/8 along root channels; clay; ripe; moderate coarse subangular blocky; pH 4.0; EC_e 1.5 mS cm^{-1}
Bg	14-30	Greyish brown 10YR 5/2 mottled red 10YR 4/6 and strong brown 7.5YR 5/6; clay; ripe; moderate medium subangular blocky; almost continuous organic coatings on ped faces; pH 4.5; EC_e 2 mS cm^{-1}
Bg 2	30-60	Greyish brown with prominent coarse red 10YR 4/8 and strong brown 7.5YR 9/8 and few fine yellow 2.5YR 8/6 mottles; clay; ripe; coarse prismatic structure with slickensides and patchy organic coatings on ped faces; pH 4; EC_e 3 mS cm^{-1}
Bj	66-115	Brown 7.5YR 5/2 with fine yellow 2.5Y 8/6 mottles; clay; ripe; massive; jarosite and occasional iron oxide coatings lining pores; pH 4; EC_e 3.5 mS cm^{-1}
GBj	115-165	Brown 7.5YR 5/2 with few fine yellowish brown and yellow mottles; clay; nearly ripe; massive; pH 4; EC_e 4.4 mS cm^{-1}
Gr	195+	Grey 10YR 5/1 clay; nearly ripe; pH rising gradually from 4.5 at 180 cm to 7.0 at about 2 m

Physical and chemical data:

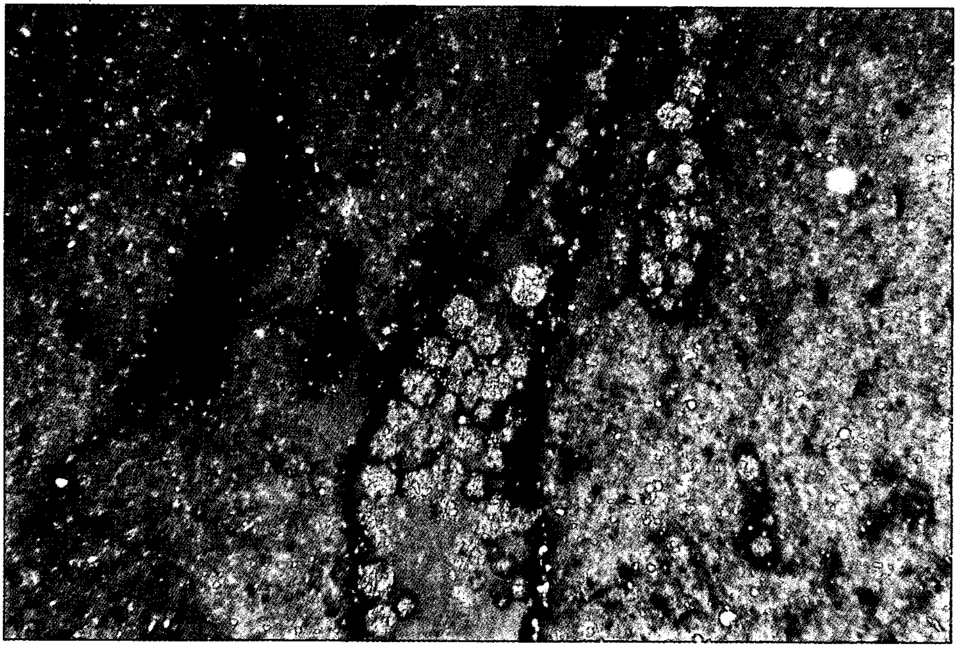
Horizon Depth, cm	Ap 0-14	Bg 14-30	 30-60	Bj 66-115	GBj 115-165	Gr 165-195	 195-315
Clay, <2 µm, %	56	63	68	70	75	70	80
Silt, 2-50 µm, %	43	33	29	27	24	29	19
Sand, >50 µm, %	1	4	3	3	2	1	1
Apparent density, g cm^{-3}	1.4	1.5	1.4	1.2	1.0		
n-value	0.3	0.3	0.6	0.7	0.9	0.9	0.8
Organic matter %	2.2	0.8	0.6	0.3	1.7	5.8	5.1
EC_e, mS cm^{-1}	1.5	1.9	2.7	3.5	4.4	5.5	7.0
pH, $CaCl_2$	3.7	3.5	3.5	3.4	3.5	3.6	4.2
Total S %	0.3	0.5	0.5	0.8	0.2	1.7	1.3



0,1 mm

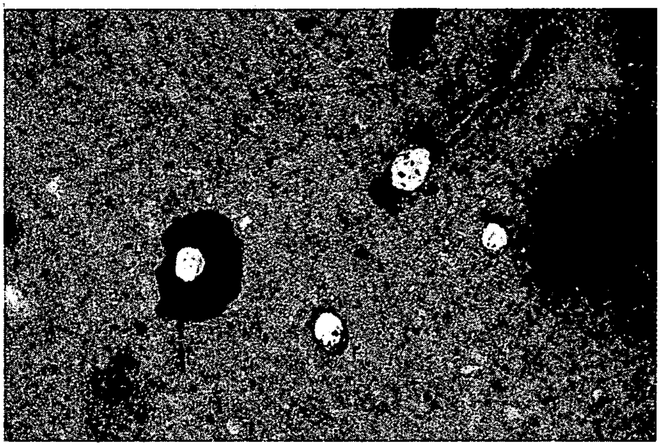
Plates 4.8 and 4.9

Gr horizon, unripe sulphidic clay from The Netherlands showing decaying roots almost filled by clusters of spherical pyrite nodules. In transmitted light (4.8), the pyrite is opaque and plant remains are dark reddish brown to opaque. In reflected light (4.9), pyrite crystals are easily recognised by their bright, silvery reflection whereas organic matter remains dark brown (photomicrographs by R. O. Bleijert)



0,1 mm

Plates 4.10 to 4.15 Ripe acid sulphate clay from Thailand (photomicrographs by R. O. Bleijert, interpretation by Dick Creutzberg)



1 mm

Plate 4.10
Bj horizon. Root channels in a clay matrix. The pores appear white. The matrix adjacent to some of the pores is impregnated with jarosite crystals, which appear black under low magnification. The black cloud in one corner is associated with a large void around which jarosite accumulations have been partly transformed to iron III oxides.

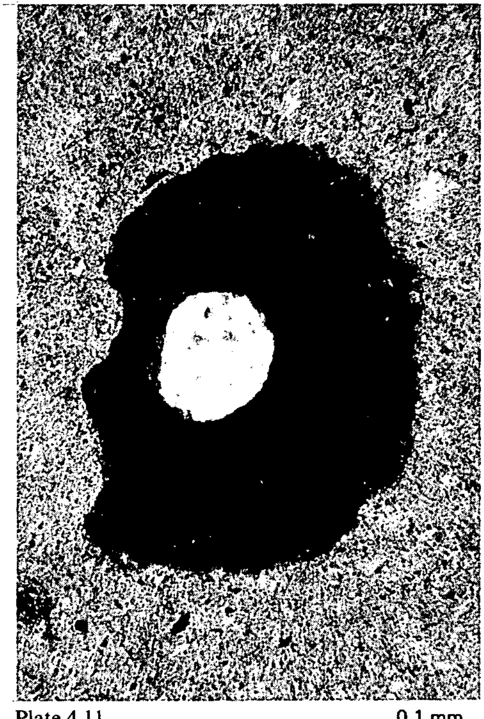


Plate 4.11 0,1 mm

A root channel from Plate 4.10. Even under this higher magnification, the jarosite appears black in transmitted light, although at very high magnifications many fine, colourless jarosite crystals (3-5 μm) can be recognised.

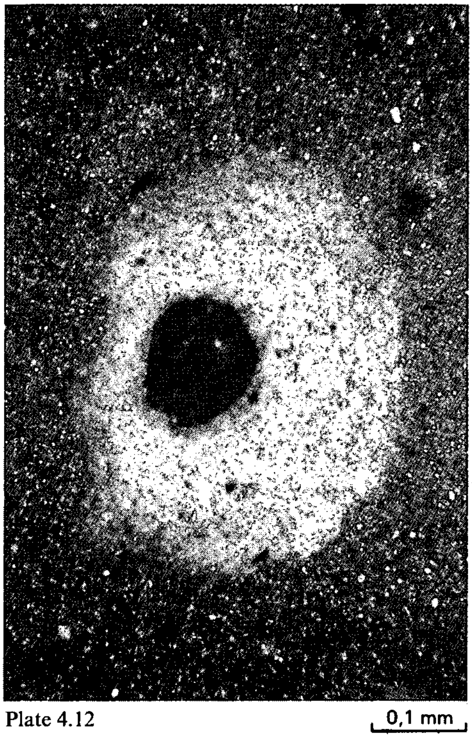
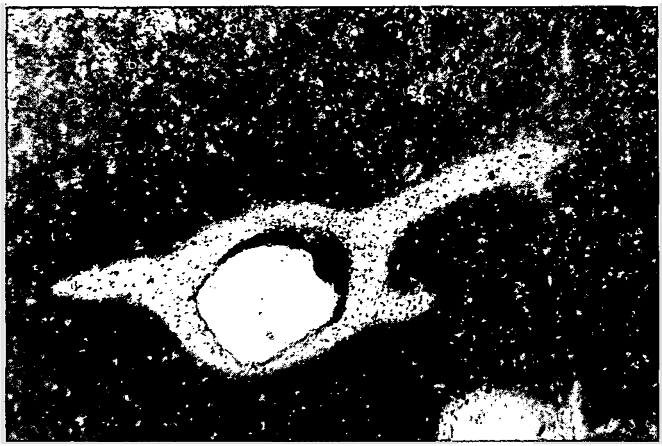


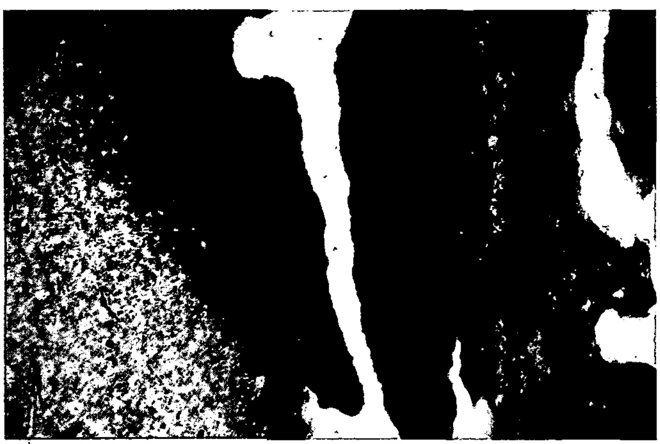
Plate 4.12 0,1 mm

Same as Plate 4.11 in reflected light. This illumination of the jarositic aureole around the pore produces a milky, slightly yellowish colour. Seen with the naked eye, the colour in this section is yellow.



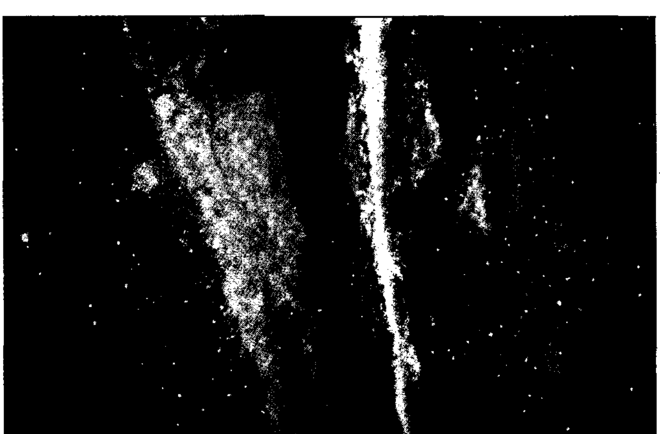
0,2 mm

Plate 4.13
A pore surrounded by jarosite deposition (black); a pale, leached zone; and dark reddish brown iron III oxide deposition. Probably the pore was first surrounded by jarosite, similar to Plate 4.10. Subsequently, the jarosite was hydrolised to iron oxide so that almost the whole field has aquired a dark reddish brown colour. During a period of reducing conditions, the iron III oxides immediately adjacent to the pore were reduced and removed in solution. A renewed phase of oxidation has resulted in further jarosite deposition.



0,2 mm

Plate 4.14
Bg horizon. A fissure (white) from which jarosite has at some time penetrated into the clay matrix. The 'clean' clay appears yellow in transmitted light. In the adjacent grey mottled zone, there are abundant jarosite crystals. Closer to the fissure, the jarosite has been transformed to iron III oxides that completely mask the colour of the clay.



0,2 mm

Plate 4.15
Same as Plate 4.14 in reflected light, showing that some of the iron has been transformed to haematite (bright red) in contrast to goethite (yellow)

Plates 3.1 and 3.2

Progressive oxidation following drainage of a compact sulphidic material on a Pleistocene marine terrace, Lelydorp, Surinam. Oxidation appears to be proceeding concentrically from the ped faces. The ped cores remain reduced and dark grey in colour. The pale grey band is presumed to be a diffusion zone through which Fe^2 and SO_4^{2-} move outwards and oxidant moves inwards. Jarosite and goethite are precipitated mainly on the ped faces. Plate 3.1 shows a vertical section with peds about 30 cm diameter. Plate 3.2 shows a cross-section with zones of oxidation across about 5 cm. (Robert Brinkman).

Plate 6.5
Orinoco Delta, Venezuela. Extensive areas of acid sulphate soils have developed as a result of drainage. In basins, iron oxides and alum accumulate as floodwaters recede. Vegetation is sparse, with few species (Leen Pons)

Colour plates 4.10 to 4.15 by courtesy of
International Soil Reference and Information Centre (ISRIC), Wageningen

± 0.6 per cent in Hokianga Harbour, to 3.5 ± 1.3 per cent in Rangaunu Harbour – in accord with increased temperatures and more luxuriant growth of the mangroves (Dent 1980). The location of these sites is shown on Figure 4.6. In The Gambia, the mean sulphur content of Gr horizons under *Rhizophora* and *Avicennia* mangroves is 3.5 per cent, but values range from 0.4 to 8.2 per cent (Dent and Raiswell 1982). The total S content of Gr horizons in temperate reed swamps, salt marsh, and gyttja is generally less than 2 per cent.

Pyrite is not uniformly distributed within the Gr horizons. Even analysis of bulk samples from different depths can show variations in pyrite content up to an order of magnitude. Microscopic examinations (Pons 1964; Eswaran 1967) show that pyrite is commonly associated with root channels and organic debris (see Plates 1.6, 4.8, and 4.9).

4.2.2 Gro horizon

Accretion of mud raises the land surface towards high-tide level. As a consequence of improved drainage, a new soil horizon is developed on top of the Gr. This horizon is both riper and more oxidised and does not accumulate much pyrite. It is designated Gro, indicating a partly oxidised condition. Its morphological characteristics are:

- Greenish grey or bluish grey colour, lighter than the Gr. A few black mottles may be present around rotting roots, especially where the Gro merges with the underlying reduced horizon;
- Physical ripening progresses to the half-ripe stage. A weakly-defined, very coarse prismatic structure may be developed;
- Iron oxide is deposited as thin, usually patchy, yellowish red coatings on ped faces and as soft, thick-walled pipes around coarse pores. Iron pipes are most conspicuous in soils developed under *Avicennia* mangroves where coarse, vertical, tubular pores are left by the decay of pneumatophores.

pH values vary between 6.1 and 6.9. Eh values range systematically between +300 mV close to ped faces and coarse pores, to −200 mV within the peds (Figures 4.2, 4.3, and 4.4).

4.2.3 Go horizon

Continued sedimentation on levees and raised flats builds them up towards the level of high-water spring tides. The surface is free of tidewater for increasing periods and a nearly ripe, essentially oxidised upper horizon is differentiated. This horizon is designated Go. Its morphological characteristics are:

- Grey colour, prominently mottled yellowish red to dark red;
- Nearly ripe;
- Yellowish red to dark red iron oxide coatings on ped faces, iron oxide pipes, commonly iron or iron/manganese nodules.

pH values of Go horizons range between 5.7 and 6.6. Eh values range widely from between +100 and +300 mV in oxidised zones adjacent to pores and ped faces, to between zero and −50 mV in ped cores (Figure 4.3). Under these conditions, pyrite

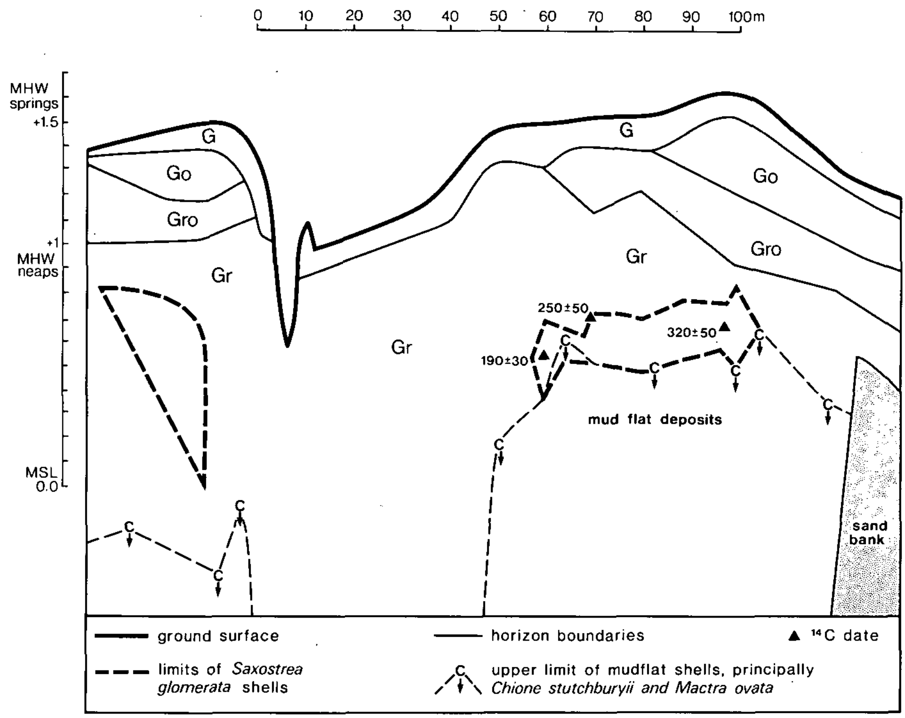


Figure 4.5 Rate of accretion of sediment and accumulation of pyrite, Kaipara Harbour, New Zealand

The section shows a stratigraphic sequence of:

1) Sand bank with beds of transported shells;

2) Mudflats characterised by shells of *Chione stutchburyii* and *Mactra ovata* in situ;

3) Mangrove swamp deposits, characterised in their early stages by shells of *Saxostrea glomerata* (oysters) that grow on trees lining clear water creeks. The oysters are ultimately killed by turbid water where sedimentation is heavy, and buried by unstratified mud rich in mangrove remains.
14C dating of oyster shells by the N.Z. Radiocarbon Dating Laboratory shows the progressive infilling of the creek, differentiation of soil horizons, and the accumulation of pyrite in the Gr horizon.

N.Z. 14C No.	Age(yrs)	%S	kg S m^{-3}
4034	190 ± 50	0.7	6 – 8
4033	250 ± 50	1.0	8 – 10
4032	320 ± 50	1.4	11 – 14

does not accumulate.

4.2.4 Transitional surface horizons, G

Gradually, the soil profile grows from the bottom upwards (Figure 4.7). Sediment at the soil surface passes through an ephemeral oxidised stage, ranging from an oxid-

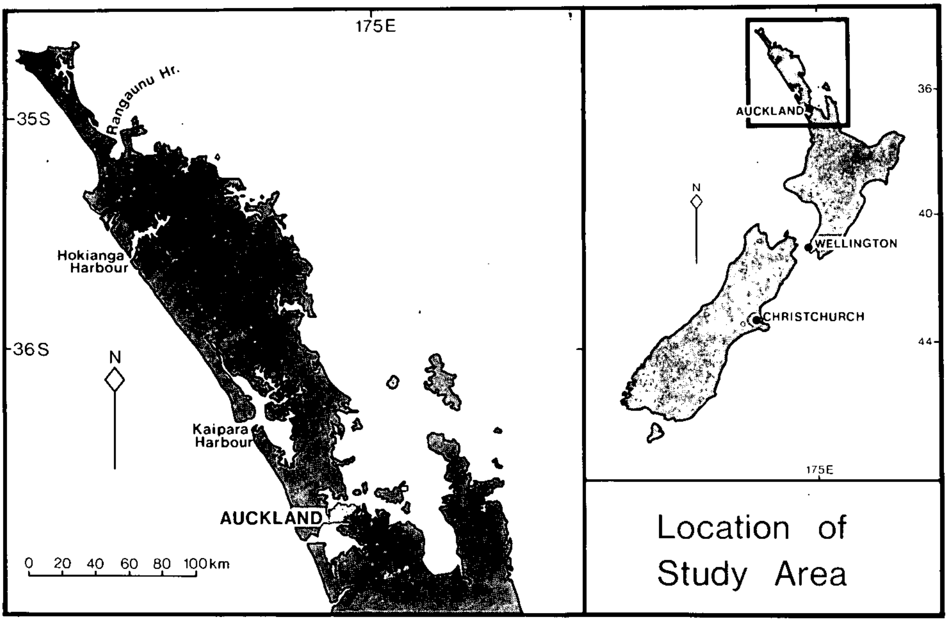


Figure 4.6 New Zealand, location of study areas

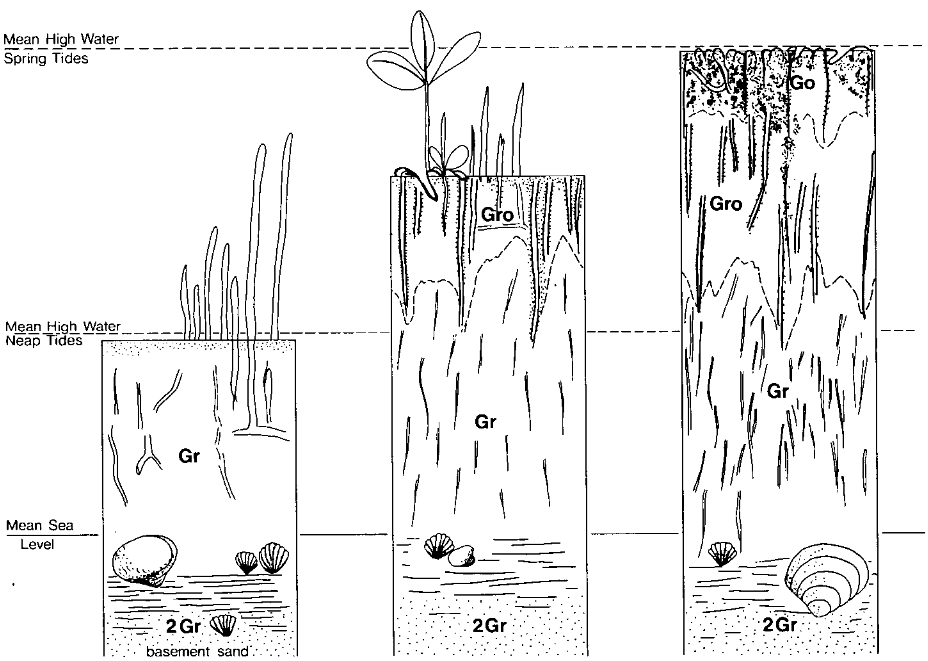


Figure 4.7 Schematic sequence of soil profile development in the tidal zone

ised layer only a few millimetres thick at the surface of backswamps and young raised flats, to distinct horizons up to 10 cm thick at the surface of mature levees and raised flats. As these surface layers are buried by fresh sediment, they are transformed to Go, Gro, or Gr horizons, depending on the natural drainage of the site.

The surface horizon of levees is never severely reduced. Freshly-deposited material is dark greyish brown, not prominently mottled, from half ripe to nearly ripe with a medium to coarse subangular blocky (nutty) structure and many crab or lobster burrows. Fissures and burrows are lined with soft, olive brown, freshly-deposited mud. In contrast, the surface of raised flats is subjected to greater reduction due to poor surface drainage and also, if the vegetation is sparse, to greater evaporation during neap tides when it may dry completely, developing a salt crust. The uppermost horizon of raised flats is greenish grey to olive grey, mottled yellowish brown; nearly ripe, sometimes with a ripe crust; with a platy structure carrying dark brown coatings on ped faces. These transitional surface horizons are designated G without any subscript differentiation. They always have low total sulphur contents.

In areas with very active crab and mud lobster activity, notably in Malaysia and Indonesia, very large quantities of sulphidic mud are brought to the surface where they oxidise and acidify (Plate 4.2). The most active burrowing mud lobster, *Thalassina anomala*, burrows to a depth of about 1 m, injests reduced mud and organic material, and voids this as mounds up to 1.5 m high and 1 to 2 m in diameter. The mounds are mottled throughout with yellow jarosite and become severely acid – pH 2.7 to 3.9 (Andriesse et al. 1973). *Thalassina anomala* is restricted to backswamp sites close to mean high water (Diemont and van Wijngaarden 1974). The severely acid horizon

Plate 4.2 Mudlobster mounds, Selangor, Malaysia. *Thalassina anomala* injests organic-rich, reduced subsoil, and voids this at the surface in mounds up to 1 m high. Where the mud is also sulphidic, the mounds become severely acid (Robert Brinkman)

they produce, designated Gj (j for jarosite), may be thought of as a late-stage modification of the normal sedimentation and soil development.

Table 4.2, which summarises some of the morphological characteristics, and Table 4.3, which summarises chemical and physical properties of unripe saline gley soils, are based on field descriptions and measurements of more than 1000 profiles, supported by laboratory analysis of 40 profiles (250 samples) from New Zealand (Dent 1980). The same sequence of horizons occurs in tidal soils elsewhere, but some details of morphology and other properties will be different.

4.3 Soil profile development in the tidal zone

Figure 4.7 shows the sequence of soil horizon development, and also the sequence of soil profile development where the rate of sedimentation is greater than the rise of sea level. Soil profiles evolve through the stage of a profile with only a Gr horizon to a profile with Go horizons superimposed on top of the Gr. These profiles can be described by formulae, as suggested by FitzPatrick (1967; 1983), listing the horizons present and their thicknesses. For example, the profile shown in Plate 4.3 (p. 100) may be described as:

$$G_{16}\ Go_{20}\ Gro_{20}\ Gr_{100+}$$

With the horizon thicknesses omitted, the normal sequence of profile development can be described as:

G Gr → G Gro Gr → G Go Gro Gr

Different facets of the tidal environment develop at different rates. Backswamps scarcely develop beyond the stage of the Gr horizon. Raised flats with good surface drainage, and especially levees, may quickly develop a complex soil profile.

Although the rate of sedimentation at a particular site is much reduced as the land surface is built up towards high-tide level, the process of pyrite accumulation in the Gr horizon will continue as long as there is a supply of dissolved sulphate from tidewater.

Continued sedimentation and extension of the inter-tidal zone seawards may change the hydrology of older sediments in a number of ways, for example:

- By excluding seawater, so that potentially acid, brackish water sediments are buried by freshwater alluvium or peat. Examples are widespread on the coastal plains of Malaysia and Kalimantan, producing profiles of the type:
  - Peat Gr
  - Peat Go Gr
  - Bg Gr – where Bg represents ripe, non-sulphidic alluvium;
- By impeding drainage, impounding lagoons or backswamps that may be either fresh or seasonally brackish. Brinkman and Pons (1968) and Augustinus and Slager (1971) describe this situation in Surinam;
- By so reducing tidal influence that soils dry out to a considerable depth in the dry season, leading to the oxidation of pyrite in the Gr horizon and the development

Table 4.2 Standard horizons of virgin tidal soils, Northland, New Zealand: morphology described according to the FAO Guidelines for Soil Description (1977)
(Note: Where a range of values is given, the mode is italicised)

Symbol		G (levees)	G (raised flats)	Go	Gro	Gr	2Gr
Position		Surface	Surface	Upper	Upper	Lower	Lower
Thickness (cm)		9 ± 6	7 ± 3	22 ± 11	31 ± 27	Greater than 20	Greater than 20
Colour	hue	5Y, 2.5Y, 10YR	5G	5B, 5GY, 5Y	5B, 5G, 5BG, *5GY*	5B, 5G, *5GY*, 5Y	5B, 5BG, 5GY, *5Y*
	value	3,*4*, 5,	4, 5	4, *5*	4, *5*	2, 5, *4*, 5	4
	chroma	1, *2*, 3, 4	1, 2, 3, 4	*1*, 2	*1*, 2	*1*, 2	1
Mottles		*None*, few, common; fine, medium; diffuse, clear; 10YR 3, 4/3, 4	Few, *common*, many; fine, medium; clear; 2.5Y, 10YR4, 5/4 and 5G, 5Y 4/1	Many; fine, *medium*; sharp, clear, diffuse; 7.5YR, *5YR*, 2.5YR 2-3/5-6	Few to many increasing with depth; fine, medium, coarse; diffuse; black	None to many; fine, medium; *clear*, diffuse; very dark grey or black	*None*, few, common; medium, coarse; diffuse; very dark grey or black
Texture		Fine sandy clay loam or finer, usually silty clay					Coarser than fine sandy clay loam, usually sand to sandy loam
Degree of ripening		Practically unripe, half ripe or nearly ripe	*Nearly ripe* or ripe	Half ripe or *nearly ripe*	*Practically unripe* or half ripe	Practically unripe	Ripe
Structure		Structureless on young sites to medium or coarse subangular blocky under *Avicennia*; weak fine crumb under *Salicornia*	Weak fine to coarse platy or moderate fine to medium subangular blocky	Weak, moderate, *strong coarse*, very coarse prismatic	*Weak*, moderate, strong *coarse*, very coarse prismatic	Structureless	Structureless
Pores		Common to many fine and medium dendritic and coarse vertical tubular pores; common to may crab burrows		Common or many fine to coarse dendritic and coarse vertical tubular pores	Many fine to coarse dendritic and coarse vertical tubular pores, commonly with soft blackened root remains *in situ* and oozing fluid mud		

Pedological features	All pores opening at the surface carry film of recently-deposited olive mud; occasionally a few fine transported iron oxide nodules	Halite efflorescence at the surface in dry weather during neap tides; pores opening at the surface carry a film of recently deposited olive or reddish-brown mud; occasionally patchy thick dark brown coatings on platy ped faces	A few thick-walled soft to crisp 2.5YR, 5YR 3-4/2, 4-6 iron oxide pipes; commonly a few 1-3 mm soft to hard reddish-brown to black iron oxide or iron-manganese nodules; occasionally patchy thin 5YR 4/4 iron oxide coatings on ped faces	*Patchy*, broken or continuous thin or thick 2.5YR, *5YR*, 7.5 YR, 10YR 2.5-4/2-8 iron oxide coatings on ped faces; common to many coarse thick-walled *soft* to crisp 2.5YR, 5YR, or 7.5YR 3-5/2-8 iron oxide pipes	None	None

Table 4.3 Standard horizons of virgin tidal soils in New Zealand: psysical and chemical data (mean and standard deviation)

Symbol	G (levees)	G (raised flats)	Go	Gro	Gr - clay shell free	 shelly	2Gr - sand shell free	 shelly
Field pH	6.2 (5.9-6.6)	6.1 (5.7-6.7)	6.1 (5.7-6.6)	6.4 (6.1-6.9)	6.6 (6.2-6.7)	6.6 (6.5-7.2)	6.4 (6.0-6.6)	6.7
pH after incubation	5.8 (5.4-6.2)	5.4 (3.4-5.7)	5.6 (5.7-6.6)	3.9 (3.4-3.9)	2.7 (2.2-2.7)	4.8 (4.4-4.9)	2.5 (2.1-2.9)	4.8
Total C % by mass	2.4 ± 1.0	1.8 ± 0.6	1.7 ± 1.4	3.2 ± 1.9	Kaipara 1.9 ± 0.6 Hokianga 2.1 ± 1.0 Rangaunu 4.9 ± 2.7		0.8 ± 0.4	
Total S % by mass	0.16 ± 0.8	0.16 ± 0.7	0.09 ± 0.06	0.71 ± 0.58	Kaipara 1.43 ± 0.69 Hokianga 2.01 ± 0.58 Rangaunu 3.49 ± 1.25		0.85 ± 0.38	
EC (mS cm^{-1})	21 ± 9	37 ± 22	20 ± 8	23 ± 9	27 ± 9		23 ± 14	
Total pore space %	69 ± 10	60 ± 6	66 ± 8	73 ± 6	75 ± 7		50 ± 5	
Shrinkage on drying %	43 ± 16	30 ± 11	36 ± 14	47 ± 8	52 ± 10		16 ± 7	
Shear strength (kPa)								
initial	16 ± 9	22 ± 13	33 ± 9	27 ± 7	20 ± 10		30 ± 10	
remoulded	5 ± 4	6 ± 2	9 ± 3	6 ± 2	3.5 ± 1.5		3 ± 2	
n-value	1.0 ± 0.3	0.7 ± 0.2	1.0 ± 0.2	1.2 ± 0.2	1.6 ± 0.25		Not applicable	

of acid sulphate soils. This situation has been cited in the case of the acid 'tanne' soils of Senegal and The Gambia (Viellefon 1977; Marius 1984), which have profiles of the type Go Gj Gr.

Changes in relative sea level add a further dimension to soil profile development:

- Where sedimentation keeps pace with a slowly-rising sea level, very thick sulphidic horizons can accumulate;
- Peat soils of very high sulphur content (up to 15 per cent dry mass or 45 kg S m^{-3}) occur in North Western Europe where peat, developed primarily in freshwater conditions, has subsequently been flooded by brackish water (Dent and Turner 1981);
- In contrast, a fall in relative sea level results in the formation of terraces on which drainage and oxidation of sulphidic material produces natural acid sulphate soils.

4.4 Development of horizons following drainage

Drainage begins the leaching of soluble salts and quickens the process of ripening already begun in the tidal soil. Where acid sulphate soils do not develop, drainage enables the land to be used for normal farming within a few years. Where there is insufficient calcium carbonate to neutralise the acidity generated by the oxidation of pyrite, the soil pH falls rapidly, and acid sulphate horizons develop. The proposed nomenclature of the horizons that develop as a result of drainage is summarised in Table 4.4. A digest of morphological, physical, and chemical properties of horizons developed in polders in Northland, New Zealand, is presented in Tables 4.5 and 4.6.

Table 4.4 Horizons developing following drainage

Gj	Severely acid; black, dark grey or pinkish brown, usually with pale yellow jarosite mottles; practically unripe or half ripe; reserve of pyrite present
GBj	Severely acid; grey with pale yellow jarosite mottles; half ripe or nearly ripe; reserve of pyrite present
Bj	Severely acid; strongly mottled grey with reddish iron oxide and yellow jarosite mottles; ripe
Bg	Not severely acid; strongly mottled grey with reddish iron oxide mottles and nodules; ripe
Hj	Severely acid peat
A	Surface mineral horizon distinguished by a concentration of organic matter; not severely acid

4.4.1 Gj horizon

Drainage of sulphidic material initially produces coarse black mottling or an overall black colouration. The black colour may be due to the quick oxidation of organic matter. Alternatively, black iron monosulphide may be produced by the reduction of the sulphates just released by oxidation of pyrite in overlying horizons or locally within a newly drained layer.

Ultimately, thick yellow deposits of jarosite accumulate around fissures and coarse pores. pH values can range from 2.5, in oxidised zones, to about 6 in the reduced matrix. Eh values range from about +700 mV in areas of fresh jarosite deposition to negative values in the matrix.

Where drainage remains poor, the Gj stage may last for several years. Sometimes jarosite is not visible even though severe acidity develops.

Severely acid horizons without jarosite are usually poorly-drained and rich in organic matter. Possibly, the absence of visible jarosite is a function of concentration, since jarosite usually precipitates on or adjacent to evaporating surfaces; or Eh values may remain too low for the precipitation of jarosite but sufficient for the oxidation of pyrite. Sometimes a pinkish brown colour (*beurre marron*) is developed.

The soil remains unripe or half ripe, and there is little development of soil structure.

The symbol G is retained for this horizon, with a subscript j indicating the severe acidity and the liberation of soluble sulphates characteristic of an acid sulphate soil.

4.4.2 GBj horizon

When good drainage is maintained, the Gj horizon is changed within a few years to a distinctive new horizon:

- Grey with prominent pale yellow mottles and coatings of jarosite around pores and fissures. Sometimes, patchy very thin iron oxide deposits are superimposed on the jarosite and, in very young GBj horizons, granular remnants of iron pipes are seen, apparently dissolving and surrounded by jarosite aureoles;
- In young polders, pH values less than 2.5 have been recorded but generally the pH ranges between 3.4 and 4.5. (The mean value calculated from H^+ activity for more than 500 field measurements in New Zealand polders is 3.8 – Dent 1980.) Usually there remains some reserve of unoxidised pyrite, which can be demonstrated by a fall in pH in a sample incubated in a thin-walled polythene bag for three months.

In empoldered acid sulphate soils, physical ripening of the subsoil has often not progressed beyond the nearly ripe stage; structure varies from very coarse prismatic to coarse blocky, commonly with deep, wide vertical fissures; mechanical strength is low. In backswamps and other low-lying sites, salinity persists through lack of drainage.

This unripe acid sulphate horizon is designated GBj, G denoting that it remains physically unripe but B emphasising the far-reaching pedological changes that have been brought about by drainage of the initially sulphidic material.

4.4.3 Bj horizon

Bj horizons are physically ripe (n-value less than 0.7). Typically, they are prominently mottled grey and reddish brown, with iron oxide and jarosite coatings in pores and on ped faces.

pH values are higher than in GBj horizons (in New Zealand polders between 3.9 and 4.9) and total sulphur contents are lower. Usually, the original pyrite is spent, but jarosite and exchangeable aluminium represent significant reserves of acidity.

The presence of jarosite in Bj horizons suggests either an earlier phase of greater acidity, subsequently ameliorated by leaching and buffering; or localisation of relatively small amounts of pyrite in the initial unripe soil, for example in rotting plant remains.

Table 4.5 Standard horizons of polder soils from Hokianga and Kaipara Harbours, New Zealand: morphology description according to the FAO Guidelines for Soil Profile Description, 1977
(Notes: Where range of properties is given, the mode is italicised; n.d. = no data)

Symbol	Bg	Bj	GBj
Position	Upper, *middle*	Upper, *middle*	Upper, middle
Thickness (cm)	24 ± 10	23 ± 11	28 ± 13
Colour hue	5G, 5GY, *5Y*, 2.5Y, 10YR	*5Y*, 7.5YR	5Y, 2.5Y, *10YR*, 7.5YR
value	4, *5*, 6	*5*, 6	4, *5*, 6
chroma	*1*, 2	*1*, 4	*1*, 2
Mottles %	45 ± 15 Mostly fine and medium; *sharp*, clear; *5YR*, 7.5YR 3-4/2-6 and medium to coarse; clear; 5G 6/1, 10YR 4/3	30 ± 5 Fine, fine and medium; *sharp*, clear; 7.5YR, 5YR 3-4/3-6 and 5Y 7/3-4	20 ± 5 Fine, *fine and medium*; sharp, clear; 5Y 7-8/3-6, commonly also 5YR, 7.5YR 4-6/6-8, occasionally also coarse diffuse 5BG 3/1
Texture	Fine sandy loam or finer, usually silty clay		
Degree of ripening	Ripe	Ripe	Nearly ripe, *half ripe*
Structure	Strong; fine, *medium*, or coarse blocky; occasionally coarse prismatic, fissuring to blocky	Strong; *coarse* or very coarse *prismatic*, columnar; fissuring to blocky	Weak, moderate or *strong*; coarse or *very coarse*; prismatic; commonly fissuring to coarse blocky
Pores	Many fine to coarse dendritic	Common or many fine to coarse dendritic; occasionally with partly-decomposed roots *in situ*	Many fine to coarse dendritic and coarse tubular; commonly with partly decomposed roots *in situ*
Pedological features	Coatings - none to continuous, very thin to thick, 2.5YR, *5YR*, 7.5YR or 10YR 2.5/2-6 iron oxide; thin brown to black organic; rarely patchy thin black MnO_2 or pale yellow jarosite on ped faces Nodules - none to many, small soft iron oxide or manganese dioxide, rarely large crisp to hard 2.5YR 5/4 iron oxide Pipes - none to many medium and coarse thick-walled soft to crisp, 2.5YR, *5YR* or 7.5YR 2.5-4/4-8 iron oxide, commonly distorted and fractured	Coatings - patchy to continuous, thin to thick, pale yellow jarosite on ped faces and lining medium and coarse pores; patchy to continuous, thin 7.5YR or 5YR 3-5/1-2 iron oxide coatings superimposed; occasionally thin dark brown organic coatings Nodules - none to few, small soft, iron oxide Pipes - usually none, occasionally few, coarse, thick-walled soft, iron oxide	Coatings - patchy to continuous, thin to thick, pale yellow jarosite on peds and lining medium and coarse pores; sometimes with patchy to broken very thin 2.5YR, 5YR or *7.5YR* 4, 5/6 iron oxide superimposed. Where shell moulds are present they are lined with jarosite and iron oxide Nodules - none Pipes - usually none, occasionally few coarse thick-walled or granular soft iron oxide pipes with thick jarosite aureoles

Gj	Gr	2GBj	2Gj
Middle, rarely surface	Lower	Upper, middle	Middle
31 ± 12	20 to more than 180	24 ± 14	n.d.
5B, 2.5Y, *10YR*, 7.5YR	5B, 5BG, 5G, *5GY*, 5Y	5Y, 10YR, *7.5YR*	*5B*, 5G, 5Y
3, 4, 5	3, *4*, 5	3, 4, *5*, 6	*3*, 4, 5
1	1	*1*, 2, 4	1
15 ± 15			
Medium and coarse; diffuse; 5B, 5G 3/1 and up to 5% fine and medium; clear to sharp; 5Y 6-8/4-6 and 5YR, 7.5YR, 10YR 4/4-6	Only in upper 40 cm of the horizon, up to 20 per cent *fine*, medium; sharp, clear 7.5YR 4.5/4	Fine and medium, *medium and coarse* clear 5YR, 10YR 6-7/4-8 8 and 7.5YR 5/8	None
		Coarser than fine sandy loam	
Half ripe, practically unripe	Practically unripe	Ripe	
Structureless to *weak*, moderate or strong very coarse prismatic	Usually structureless; occasionally weak or moderate, very coarse prismatic in upper 40-60 cm	Usually structureless; occasionally weak very coarse prismatic in finer-textured materials	Structureless
Many fine to coarse dendritic and coarse tubular; commonly with partly decomposed roots *in situ*	Many fine to coarse dendritic and coarse tubular; commonly with partly decomposed roots *in situ*	Many to common, as G_j	Many to common, as G_j
Coatings - commonly absent, occasionally patchy to continuous thin soft pale yellow jarosite on ped faces and/or lining coarse pores; occasionally patchy to continuous very thin 2.5YR or 5YR 3-4/2-6 iron oxide on ped faces Nodules - none Pipes - none to many medium to coarse thick-walled soft 7.5YR 4/4 iron oxide; occasionally few coarse thick-walled crisp 2.5YR or 5YR 3/2-4 iron oxide with thick jarosite aureoles	Coatings - where ped faces are developed they carry patchy to continuous thin 5YR 4/6 iron oxide and commonly also very thin black MnO_2 coatings; shells in upper 40 cm may be outlined by thin iron oxide or iron oxide and MnO_2 coatings Nodules - usually absent but where abundant shell is present few to many, small to large, rounded, firm to hard $CaCO_3$ cemented mudstone nodules below GB_j and G_j horizons Pipes - as GB_j in upper 40 cm only	Coatings - none to continuous thin soft pale yellow jarosite lining pores, patchy thin jarosite on ped faces Nodules - none Pipes - usually none, occasionally few coarse thick-walled soft 7.5YR 5/8 iron oxide	Coatings - none to continuous thin jarosite and iron oxide coatings lining some pores and shell moulds Nodules - where abundant shell is present, few to many rounded soft to hard 5GY 4/1, 5/1 carbonate-cemented mudstone nodules occur Pipes - none to common coarse thick-walled soft to crisp strong brown iron oxide with jarosite aureoles

Table 4.6 Standard horizons of polder soils in Hokianga and Kaipara Harbours, New Zealand: physical and chemical data

Mean values and standard deviation are given for each property. In the case of acidity, pH values have been converted to H^+ activity for calculation, then returned to the pH scale. (Note: n.d. = no data)

Symbol	Bg	Bj	GBj	Gj	Gr	GBj (sandy)	Gj (sandy)
Field pH	4.9 (4.5-5.1)	4.3 (3.9-4.9)	3.8 (3.4-4.5)	4.0 (3.6-4.2)	5.6 (5.0-6.2)	3.8 (3.5-4.3)	4.4 (3.8-5.9)
pH after incubation	4.3 (3.9-4.6)	4.0 (3.7-4.5)	3.7 (3.4-4.1)	3.1 (2.8-3.3)	3.5 (3.2-3.6)	3.6 (3.5-3.7)	4.2 (3.8-5.9)
Total C %	1.8 ± 1.4	1.9 ± 1.0	1.7 ± 0.6	1.6 ± 0.8	1.3 ± 0.4	0.5 ± 1.1	0.5 ± 0.9
Total S %	0.08 ± 0.05	0.52 ± 0.23	0.49 ± 0.34	1.42 ± 0.46	1.75 ± 0.34	0.53 ± 0.65	n.d.
EC_e (mS cm^{-1})	0.7 ± 0.4	0.7 ± 0.4	3.7 ± 5.1	9.7 ± 7.7	15.8 ± 0.6	n.d.	n.d.
Total pore space %	59 ± 5	57 ± 3	68 ± 5	n.d.	70 ± 5	n.d.	n.d.
Shrinkage on drying %	23 ± 9	30 ± 6	39 ± 10	n.d.	47 ± 8	n.d.	n.d.
Shear strength (kPa)							
initial	52 ± 37	42 ± 35	27 ± 10	24 ± 8	17 ± 8	35 ± 5	n.d.
remoulded	21 ± 17	14 ± 12	6.5 ± 2.5	3.75 ± 1.0	1.7 ± 1.5	3 ± 2	n.d.
n-value	0.59 ± 0.09	0.53 ± 0.06	1.02 ± 0.20	1.25	1.5	Not applicable	Not applicable

4.4.4 Bg horizons

Go horizons of low pyrite content, and Gr horizons in which there is sufficient calcium carbonate to neutralise the acidity generated by the oxidation of pyrite, ripen normally. In clayey soils, ripening initially produces very large prismatic peds separated by wide fissures. These peds gradually break to a strong medium blocky structure.

The colour of ripe B horizons is typically grey to olive grey, prominently mottled reddish brown. Coatings of organic matter, iron oxide, and sometimes manganese dioxide are deposited on ped faces. The greater the pyrite content of the unripe soil, the greater the release of mobile iron during ripening. Thick, granular deposits of iron oxide sometimes develop in pores and fissures. Nodules and pipes of iron oxide are also inherited from the Go horizon, but pipes are fractured and distorted during ripening.

The ultimate pH depends upon the balance between pyrite and calcium carbonate. It can range from 4.0 at the acid end of the spectrum to 6.5 in calcareous soils. The total sulphur content is usually less than 0.1 per cent, unless gypsum is present.

The bearing strength of Bg horizons is sufficient to support conventional wheeled vehicles, but deficiencies of the drainage system may lead to waterlogging in wet weather. So long as ripening continues, new fissures are formed every year and compensate for loss of structure under cultivation or trampling by stock. Once ripening is complete, soils of heavy texture may suffer increasing drainage problems under continuous arable management (Dent et al. 1976).

4.4.5 Aluminium-saturated horizon, Bg

The duration of the phase of extreme acidity, characterised by the unripe GBj horizon, depends upon the reserve of pyrite to be oxidised and the rate of oxidation. A sequence of horizon development following drainage may be envisaged.

Firstly, an initial phase of extreme acidity, caused by the oxidation of pyrite generating free acid. This very toxic phase may last for decades, during which further ripening is inhibited.

Secondly, a phase of severe residual acidity, maintained by the slow hydrolysis of jarosite to goethite and by the periodic rise of free acid from deeper horizons, where pyrite oxidation takes place during periods of exceptionally low watertable. This stage may last for hundreds of years. Probably, ripening can take place because of the partial colonisation of the horizon by roots and, in climates with a marked dry season, by the slow transfer of water from the wet subsoil to the dry surface.

Ultimately, both pyrite and jarosite are exhausted, physical ripening is complete, and soluble sulphates are reduced to low levels by leaching. The former acid sulphate horizon is now a ripe, acid, aluminium-saturated horizon. In the old acid sulphate soils of the Bangkok Plain in Thailand, this horizon is characterised as follows (van der Kevie and Yenmanas 1972; van Breemen 1976; Soil Survey Division of Thailand 1981):

- Physically ripe, n-value less than 0.7;

- Prominent coarse mottling. Matrix colours range from dark greyish brown to brown and pinkish grey, mottles are red to yellowish red and strong brown or yellowish brown;
- Strongly-developed medium or coarse prismatic structure, commonly with slickensides. Coatings of black, organic-rich material on ped faces, burrows, and some root holes;
- Field pH between 4 and 4.5 This is not much higher than in acid sulphate horizons, but the lime requirement to raise the pH to optimum levels for crops is significantly less than for acid sulphate horizons of comparable clay and organic content;
- Low salinity, EC_e usually less than 2 mS cm^{-1};
- Low total sulphur, less than 0.5 per cent S by mass, commonly less than 0.1 per cent;
- Low base saturation, less than 40 per cent, aluminium is the principal exchangeable cation.

4.4.6 A horizons in ripe acid sulphate soils and acid aluminium soils

The overlying topsoil is black or very dark grey with dark yellowish brown mottles along root channels; very slow permeability when wet; drying to a medium blocky or subangular blocky structure; pH 4 to 4.5. In Thailand, where the topsoil is desiccated in the dry season, the organic matter content is in the range of 2 to 3.5 per cent.

4.4.7 Acid peat

Drainage of potentially acid peat causes the same severe shrinkage as with other peat soils, simply by loss of water. In contrast to mineral acid sulphate soils, jarosite mottles often do not develop in acid peats although a large amount of soluble iron may be liberated. Confirmation of acid sulphate status depends on pH measurements.

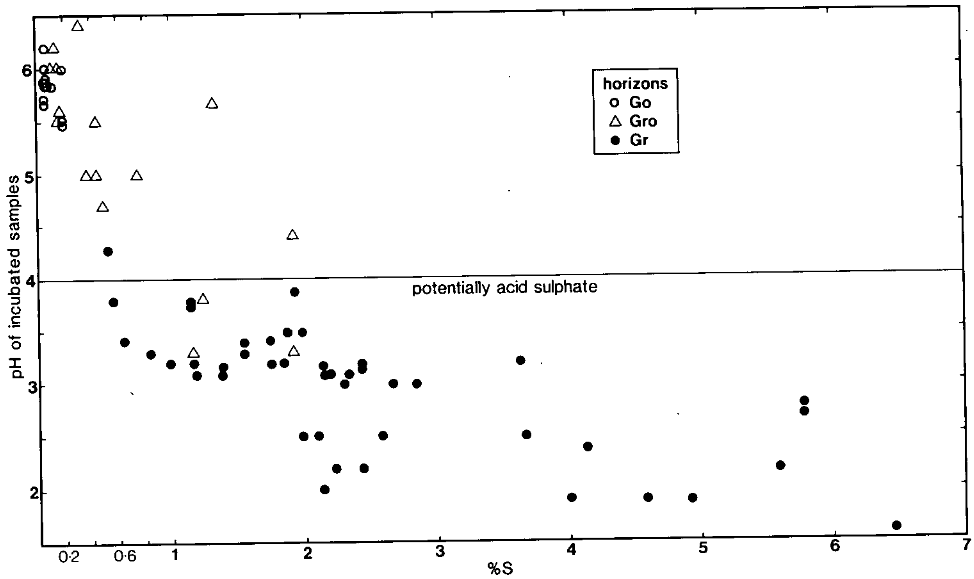
Acid sulphate peat layers are designated Hj.

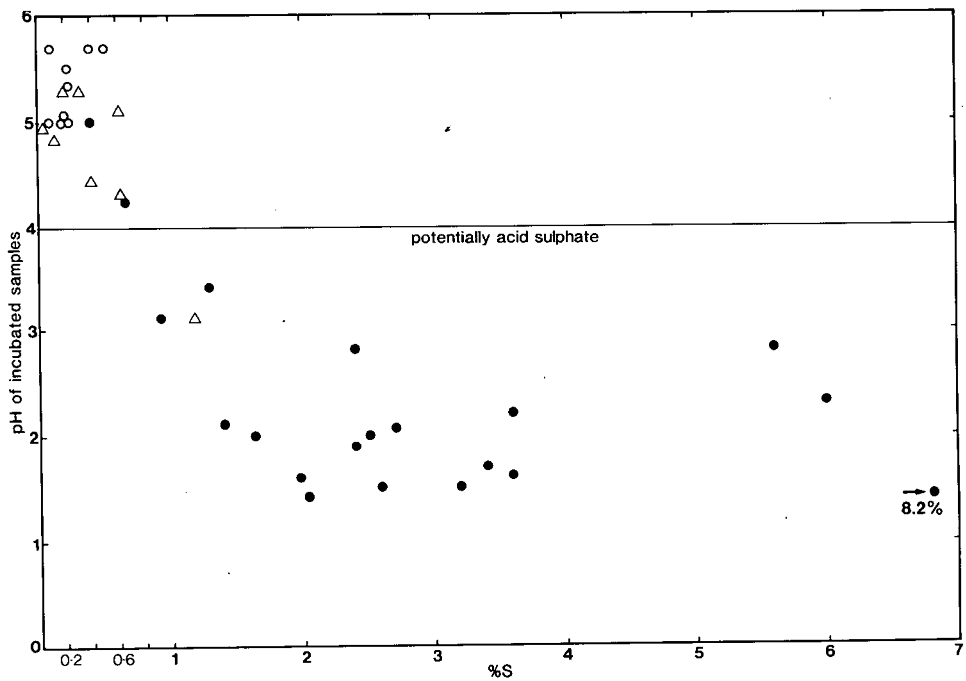
4.5 Sequential soil profile development following drainage

Figures 4.8 and 4.9 show that Go horizons are always low in pyrite and do not develop severe acidity following drainage. They can be expected to ripen normally to Bg horizons.

Predictions for Gro horizons, based solely on morphology are not so reliable, but extreme acidity does not usually develop. Gr horizons are always sulphidic and acid sulphate conditions will develop following drainage, unless abundant shell is also present.

For practical purposes, the upper boundary of the Gr horizon is the critical chemical interface in the landscape. So long as the watertable is maintained above this datum, severe acidity will not develop. If the watertable is drawn down below it, acidity is inevitable. Initially the acid sulphate horizons will increase in thickness, following the falling watertable. Over a much longer period, the raw, unripe acid sulphate horizon





Figures 4.8 and 4.9 Relationships between soil horizons, total sulphur content, and incubated pH for non-calcareous samples from New Zealand (4.8) and The Gambia (4.9)

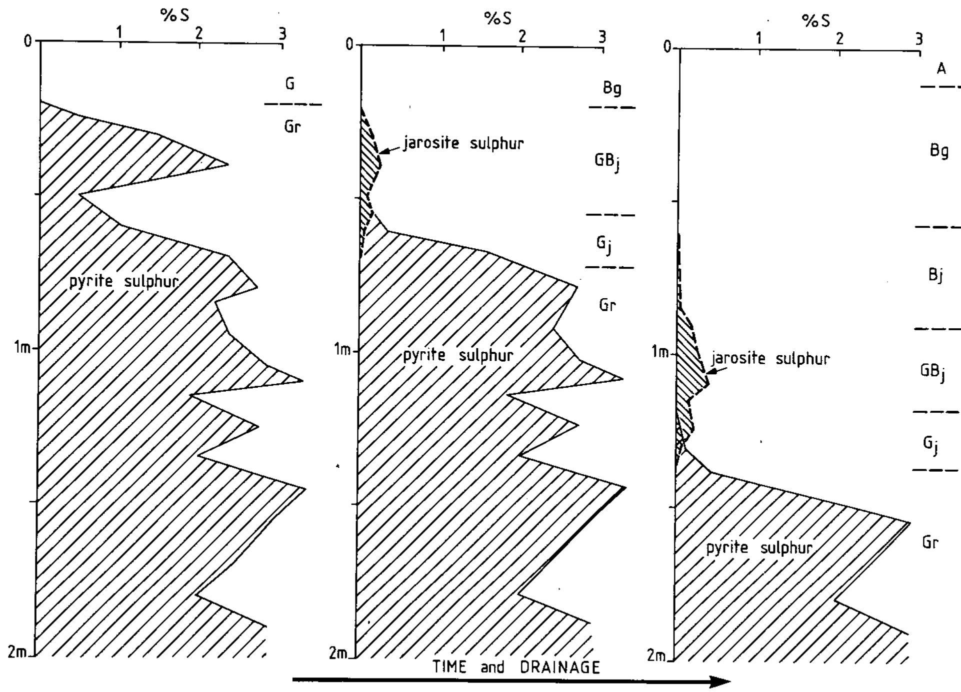


Figure 4.10 Schematic sequence of soil profile development by oxidation of pyrite and, ultimately, hydrolysis of jarosite (after van Breemen 1976)

will be leached and weathered, and will ripen to become an acid alumunium horizon. Figure 4.10 depicts schematically the transformation and ultimate loss of oxidisable sulphur in the course of the evolution of an acid sulphate soil. Figure 4.11 summarises the sequence of horizon development.

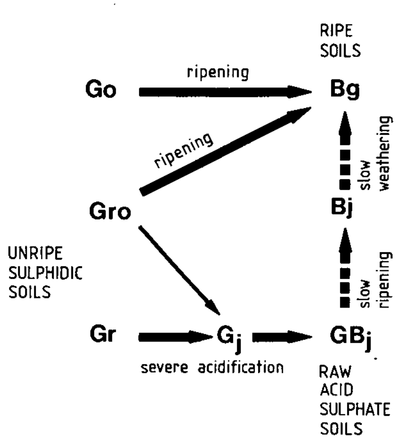


Figure 4.11 Schematic sequence of horizons developing following drainage. Horizon symbols are defined in Tables 4.1 and 4.4.

The range of soil profiles from raw saline acid sulphate clay in the first stage of drainage to a ripe clay with acid sulphate subsoil is illustrated by Plates 4.4 to 4.7; some micromorphological characteristics are illustrated by Plates 4.8 to 4.15. (pp. 102 to 109)

Soils with Bg horizons developed by ripening and leaching of acid sulphate horizons do not behave differently from other aluminium-saturated clay soils. Probably, the range of problems associated with them, such as acidity and phosphate fixation, occur to quite varying degrees. Field observations suggest that prominent, intense red mottling is associated with the most severe management problems (Pons, personal communication). Possibly, the intense mottling is associated with the liberation of large amounts of soluble iron from pyrite during a period of extreme acidity and intense weathering. This process will also bequeath a high proportion of exchangeable aluminium.

5 Soil classification

5.1 Purposes

The broad concept of acid sulphate soils encompasses unripe saline soils that will become acid if they are drained, unripe, severely acid soils, and ripe aluminium-saturated soils that are severely acid or potentially acid only in the deep subsoil. Each characteristic may be exhibited over a wide range of intensity and in combination with other properties that are common to all alluvial soils. In some cases, soil limitations are so severe that amelioration and cultivation are impracticable; in other cases, the limitations are slight or easily rectified; so it is useful to distinguish a range of categories of acid sulphate soils.
A soil classification serves two purposes:
- It enables us to order our own observations and ideas;
- It enables us to communicate with other people who need to use this information.

Soil survey involves grouping together soils that will behave in the same way, for the purpose in hand, and separating those soils that will behave differently. So classification is an integral part of soil survey. The two activities cannot be separated.

To be useful for management and land-use planning, a classification should be based on soil properties that are important to land use. The properties should also be measurable in the field or, failing this, measurable quickly and cheaply in the laboratory. Characteristics of acid sulphate soils that fulfil both criteria include:
- Acidity or potential acidity;
- Salinity;
- Composition and texture;
- Ripeness;
- Profile form, especially the depth and thickness of limiting horizons;
- Depth and seasonal variation of the watertable;
- Duration and depth of flooding.

None of the established international soil classifications considers these properties in combination, or in sufficient detail for land reclamation, management, or land-use planning. A new classification is therefore presented here, based on the first five of these properties. Two levels of classification are defined: the profile form – for detailed soil mapping and site characterisation – and a higher category classification – to group soils which present similar kinds of management problems. Correlation between this purely technical classification, Soil Taxonomy (1975), the ORSTOM classification (1982), and the FAO/Unesco legend (1974) is presented in Section 5.5.

5.2 Criteria of the ILRI classification

5.2.1 Acidity and potential acidity

Acidity is easily measured in the field (see Section 7.3). In mineral soils, severe acidity is usually associated with yellow mottles of jarosite; but in peat, muck, and clay rich in organic matter, the oxidation of pyrite may generate severe acidity without visible deposition of jarosite. (In peat, acidity may also develop independently of the occurrence of pyrite.)

Acidity generated by the oxidation of pyrite is associated with the production of soluble sulphate, iron, and aluminium. Soluble aluminium severely impairs crop growth at low concentrations. Crop response (for example Williams 1980), and measurements of pH and soluble aluminium on acid sulphate soils by Metson (1977) in New Zealand and by Allbrook (1973) in Malaysia, suggest that a pH value of 4 in the field, or with a dried sample in 0.01 M $CaCl_2$ (1:2.5 suspension), is low enough to cause acid sulphate problems. A pH value of less than 4 is therefore adopted here as the primary criterion of an acid sulphate soil. More severe acidity may be distinguished at phase level. In the absence of jarosite, a water-soluble sulphate content of at least 0.05 per cent serves to distinguish acid sulphate soils from other severely acid soils. This is a broader definition than that adopted by the USDA Soil Taxonomy (Soil Survey Staff 1975), which defines a diagnostic sulfuric horizon by a pH (1:1 in water) of less than 3.5 and jarosite mottles.

A prime distinction must be made between soils that are acid sulphate soils now, and soils that *will become* severely acid if they are drained. A *potential acid sulphate soil* is at present waterlogged and not severely acid, but contains so much pyrite that it will become severely acid if this pyrite is oxidised. The best criterion of potential acidity is a fall of pH to less than 4 during three months moist incubation. Soil Taxonomy defines sulfidic material as waterlogged material containing 0.75 per cent or more sulphur, and less than three times as much carbonate ($CaCO_3$ equivalent). Apart from requiring the determination of sulphur and carbonates, this definition does not make allowances for variations in the buffering capacity of clay minerals and exchangeable cations. It is better to let the soil 'speak for itself' with its pH after moist incubation.

A further distinction that is critical to management is between acid sulphate soils that still have a reserve of pyrite and those that do not. The term *raw acid sulphate soils* is proposed for those with a reserve of pyrite within the rooting zone. They can be identified by a fall in pH of at least 0.2 during incubation. The lime requirement to bring raw acid sulphate soils to a pH suitable for arable crops is normally prohibitive, and the pyrite will continue to generate acidity over many years. In contrast, soils that no longer have reserves of pyrite respond to normal applications of lime and fertilizer.

5.2.2 Salinity

Crop growth on tidal soils and on recently reclaimed land is limited by soluble salts. Because of the wide variation in crop tolerance of salinity, critical values for specific purposes should be selected according to the proposed management system. Production of grassland, rice, and many other arable crops is severely impaired by salinity (EC_e) greater than 4 mS cm^{-1}, so this value has been adopted as the standard. Phases may be distinguished according to the scale of the U.S. Salinity Laboratory (USDA 1954):

EC_e (mS cm^{-1} at 25° C)	Proposed classification
0–2	Non-saline
2–4	Slightly saline
4–8	Moderately saline
More than 8	Very saline

5.2.3 Soil composition and soil texture

Peat soils and mineral soils each have their own unique characteristics, and they respond differently to management in many ways. According to Soil Taxonomy, *peat* has more than 20 per cent organic matter by mass (if the mineral component has no clay) to more than 30 per cent organic matter by mass (if the mineral component is 50 per cent or more clay).

In mineral soils, the distinction between sandy and clayey materials is important because of their contrasting geotechnical properties, notably bearing strength, shear strength, ripening characteristics, and permeability. The 'Unified Soil Classification (U.S. Army Corps Eng. 1953; U.S. Dept. Defense 1968), which is widely used by engineers, makes a useful distinction between *clayey soils*, where more than half of the material less than 60 mm is smaller than 0.06 mm – i.e. more than half silt + clay – and *sandy soils* that are less than half silt + clay. Marine and estuarine sediments are nearly always well sorted, falling clearly into either the clayey or the sandy category. Layers of borderline texture are limited, except along river levees, but where this situation is extensive, a loamy category may be introduced.

5.2.4 Degree of ripening

The ripening of clay and peat soils critically influences drainage and mechanical strength (see Section 3.5). The categories defined by Pons and Zonneveld (1965) find wide application (for example de Bakker and Schelling 1966; Dent 1980):

Class	n-value	Remoulded shear strength (kPa)
Ripe	Less than 0.7	More than 20
Nearly ripe	0.7–1.0	7–20
Half ripe	1.0–1.4	4–6
Practically unripe	1.4–2.0	1–3
Unripe	More than 2.0	0

5.3 Profile form

The depths and thicknesses of limiting horizons, and their arrangement in the soil profile, are just as important as the degree of acidity, salinity, and ripening. Limiting depths of 20, 50, and 80 cm have been chosen to define ripeness categories in The Netherlands. These depths also correspond well with different degrees of management problems in respect of acidity and salinity for temperate soils and management systems.

The effects on crop growth of limiting horizons depend very much on the severity of the dry season. For dryland crops in the tropics, where there is a dry season longer than one month or a soil water deficit in excess of 150 mm, limiting depths of 20, 60, and 100 cm are more appropriate. Soil water deficit is defined as the maximum cumulative difference between rainfall and potential evaporation (see for example FAO 1977).

For special surveys, single properties may be mapped separately: for example, presence/absence of and depth to potentially acid material (Figure 6.6) or pH (Figure 6.15). For systematic, detailed soil surveys, different categories of acidity, potential acidity, salinity, composition or texture, and degree of ripeness can be combined in a shorthand *profile form*. Table 5.1 lists the limiting values applied to each property.

The profile form is written, for example, as:

$a_2s_0Cw_1$ or a_2Cw_1

where:
a_2 = severely acid at a depth of between 20 and 50 cm;
s_0 = not saline within 80 cm;
C = clay;
w_1 = ripe to at least 20 cm over an unripe subsoil.

Although there are a great many possible combinations of soil characteristics, those that distinguish acid sulphate soils and related alluvial soils are often closely related (for example, residual salinity in a polder is commonly associated with an unripe subsoil). So in practice, a manageable number of useful categories can be distinguished and only a few mapping units are required for soil survey in any particular locality (see Figures 6.5, 6.6, 6.10, and 6.12).

Soil series and phases of series can be established to encompass groups of profile forms that have distinct management requirements, for example:

a_2Cw_1	Omanaia Series	Ripe clay with unripe acid subsoil
$a_2s_2Cw_1$	Omanaia Series	Saline subsoil phase
$p_1s_1Cw_3$ $p_2s_1Cw_2$	Takahiwai Series	Unripe and half ripe saline sulphidic clay
$p_2s_1Cw_2$	Takahiwai Series, shallow phase	Sand within 65 cm

Table 5.1 Limiting values for individual characteristics of acid sulphate soils and related soils

Note that limiting depths are governed by the length and severity of the dry season. The lower values are applicable where the soil water deficit remains below 150 mm.

Acidity

Acid sulphate (pH < 4 and soluble sulphates)

within 20 cm	a_1
within 50/60 cm	a_2
within 80/100 cm	a_3

Very severe acidity may be distinguished as a separate phase

Potential acidity

Potentially acid (sulphidic) material

within 20 cm	p_1
within 50/60 cm	p_2
within 80/100 cm	p_3

Where an acid sulphate horizon has already developed in the upper part of the profile, this takes precedence in classification over sulphidic material at greater depth

Salinity

Saline ($EC_e > 4$ mS cm^{-1})

within 40/50 cm	s_1
within 80/100 cm	s_2
Not saline within 80/100 cm	(s_0)

Texture and composition

Clay	clay or silty clay more than 40 cm thick. Where a peaty surface horizon is present, this is less than 20 cm thick	**C**
Peat	peat more than 40 cm thick	**O**
Sand	sand to sandy loam more than 40 cm thick. Where a peaty surface is present, this is less than 20 cm thick	**S**
Muck	interlayered peat and mineral soil not fulfilling the above thickness criteria	
	organic topsoil	**O/C**
	mineral topsoil	**C/O, S/O**

Shallow phases may also distinguish clay or sandy topsoils that do not meet the thickness requirements of clay or sandy soils

Ripeness

In clay, peat, or muck

	n-value Depth 0-20 cm	Depth 20-50/60 cm	Depth 50/60-80/100 cm	
Unripe	>0.7	>1.4		w_3
Half ripe	>0.7	0.7-1.4		w_2
Ripe with unripe subsoil	<0.7	>0.7 and/or	>1.0	w_1
Ripe with ripe subsoil	<0.7	<0.7	<1.0	(w_0)

Soil series should be established only by national soil survey organisations, because they have the facilities for correlation and characterisation of mapping units. For this reason, the soil maps shown in Section 6 refer to acid sulphate soils only in terms of their profile form and higher category classification.

5.4 Higher category classification

Hierachical soil classifications are not well suited to the needs of land-use planning, land reclamation, or the transfer of detailed management experience from one place to another. Particular soil characteristics assume a different relative importance according to the climate, crop, or system of management. For example, the presence of potentially acid material below 60 cm is of no significance to irrigated rice or to grassland under high watertable management, but it is a severe limitation to dryland crops which rely on soil water storage.

Admitting that no single ordering of soil characteristics will serve all purposes equally well, it is still useful to distinguish a manageable number of categories of acid sulphate soils according to the nature of the problems they present and their distinct responses to management. A grouping of major categories of potential acid sulphate soils and acid sulphate soils is presented in Table 5.2.

5.4.1 Organic soils

Organic soils vary in density, hydraulic conductivity, degree of decomposition, available nutrients, mineral content, and thickness. Nevertheless, they form a distinct group. Organic soils may be separated from mineral soils on the basis of an organic matter content greater than 20 per cent dry mass, where the mineral component contains no clay, to greater than 30 per cent dry mass where the mineral fraction is 50 per cent or more clay. This corresponds to an organic matter content of well over 50 per cent by volume.

So far as reclamation and management are concerned, a further distinction should be made between, on the one hand, deep *peat* of low mineral content and, on the other hand, shallow peat (less than 40 cm thick), thin interlayers of peat and mineral soil (less than 40 cm mineral alluvium in the upper 60 cm of the soil profile), and organic soils of relatively high clay content (mineral content between 40 and 70 per cent dry mass). The three last categories behave in much the same way when cultivated and are here termed *muck*. Management problems common to all organic soils – low mechanical strength; massive shrinkage when drained, followed by continued loss by oxidation and erosion; low available nutrients; and trace element deficiences – are typically most severe in peat.

For the purposes of land reclamation and management, three classes of organic acid sulphate soils may be distinguished according to the long-term problems they present:

- *Unripe sulphidic peat and muck*: Unripe, sulphidic soils that are at present waterlogged but which will become severely acid when drained. They are unripe, with n-values more than 0.7 within 60 cm of the surface and more than 1.0 within 100 cm*;
- *Raw acid sulphate peat and muck*: Acid sulphate conditions, with pH less than 4 and with jarosite mottles or more than 0.05 per cent soluble sulphate, within 60

*Limiting soil depths are 50 and 80 cm under humid, temperate conditions; 60 and 100 cm under tropical conditions with a dry season longer than one month. See Table 5.1. All following definitions refer to seasonally dry tropical conditions.

Table 5.2 Major categories of potential acid sulphate soils and acid sulphate soils

	Organic soils		Sandy soils	Clayey soils			
Undrained not potentially acid	Unripe peat and muck		(Saline) sand	Unripe (saline) clay			
Potential acid sulphate soils	Unripe sulphidic peat and muck		Sulphidic sand	Unripe saline sulphidic clay			
Acid sulphate soils	Raw acid sulphate peat and muck	Ripe acid sulphate peat and muck	Raw acid sulphate sand Acid sulphate sand	Raw saline acid sulphate clay	Ripe acid sulphate clay with raw subsoil	Ripe acid sulphate clay	
Associated non acid sulphate soils	Peat and muck with unripe subsoil	Ripe peat and muck	Sand		Ripe clay with unripe subsoil	Ripe clay	Ripe acid aluminium clay

cm of the soil surface. Typically the subsoil remains unripe with n-values greater than 0.7 between 20 and 60 cm and greater than 1.0 between 60 cm and 100 cm. This subsoil contains a reserve of pyrite so that its pH will fall below 4 on incubation;
- *Ripe acid sulphate peat and muck*: Acid sulphate conditions, with pH less than 4 and with jarosite mottles or more than 0.05 per cent soluble sulphate, within 60 cm of the surface. The soil is ripe, with n-value less than 0.7 to a depth of 60 cm and less than 1 between 60 cm and 100 cm. There is no reserve of pyrite in the upper 100 cm; pH will not fall further on incubation.

5.4.2 Sandy soils

Sandy soils are mineral soils in which more than half of the material less than 60 mm is greater than 0.06 mm diameter, i.e. more than 50 per cent sand and gravel. Sandy soils are not cohesive but, except under exceptional conditions of water upwelling, they have great frictional strength. They do not shrink when drained. Sandy alluvial soils are of moderate or high permeability. They have a low available water capacity.

In addition to the physical differences between all sandy soils and all clayey soils, sulphidic sands are always low in pyrite, generally less than 1 per cent S by mass but, unless they are shelly, they have a low neutralising capacity, so that very severe acidity rapidly follows drainage. However, acidity and salinity are readily leached and, once oxidation of pyrite is complete, the lime requirement of acid sulphate sand is low.

Three classes of sandy acid sulphate soils may be distinguished. These are potential acid sulphate sands, severely acid sands with reserves of pyrite, and severely acid sands without significant reserves of pyrite:
- *Sulphidic sand*: pH greater than 4, but potentially acid (incubated pH less than 4) within 100 cm;
- *Raw acid sulphate sand*: pH less than 4 and jarosite mottling or more than 0.05 per cent soluble sulphate within 100 cm. The pH of some horizon within 100 cm falls to less than 4 and by at least 0.2 during incubation;
- *Acid sulphate sand*: pH less than 4 and either jarosite mottles or more than 0.05 per cent soluble sulphate within 100 cm. There is no further fall of pH during incubation.

5.4.3 Clayey soils

Clayey soils have more than half the mineral fraction finer than 0.06 mm (silt + clay). They have little frictional strength and their cohesive strength depends critically on their water content – unripe clays are fluid or soft, ripe clays are firm and tough. Permeability depends on structure. In well-structured clay, water drains readily so long as fissures between peds remain open. Even in unripe, structureless clays, permeability can be high if there are many coarse pores.

Clays exhibit the widest range of acid sulphate characteristics and offer a correspondingly great variety of possibilities for reclamation. It is useful to recognise several

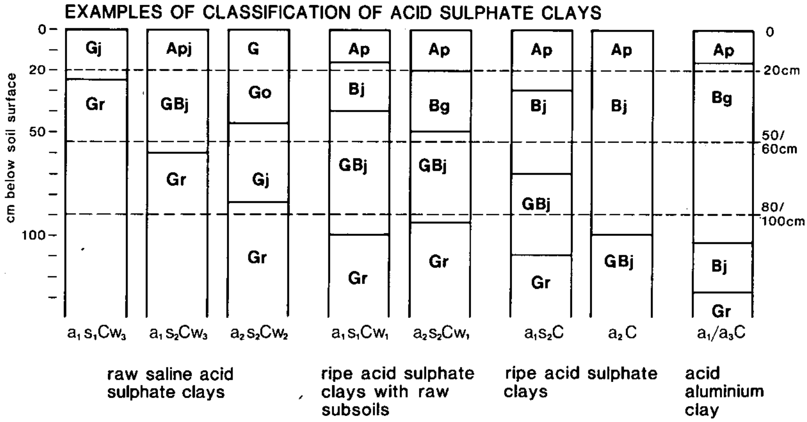


Figure 5.1 Classification of profile forms of sulphidic (potentially acid) clays

classes of clayey soils. The primary distinction is made between potential acid sulphate soils (sulphidic clays), acid sulphate soils that still have reserves of pyrite (raw acid sulphate clays), and those that do not. The same rules are followed as in the case of sandy soils and organic soils. Further distinctions are made according to physical ripeness and salinity:

– *Unripe saline sulphidic clay*: These soils are at present waterlogged, but contain pyrite that will oxidise following drainage and produce acidity in excess of the soil's neutralising capacity. The depth at which sulphidic material occurs and the total reserve of pyrite are critical characteristics for reclamation and must be distinguished by soil surveys. In tidal soils, ripening of clays does not proceed beyond the half-ripe stage so long as the soil profile remains almost continuously waterlogged.

  Figure 5.1 depicts a range of profile forms within the class of unripe saline sulphidic clays and proposed sub-classes based on the thickness of the more-ripened, more-oxidised horizons over the unripe sulphidic subsoil. Field identification of thick Go and Gro horizons can be interpreted as not potentially acid; Gr horizons are potentially acid unless rich in shell.

  The characteristics of unripe saline sulphidic clays are:
  - pH greater than 4, but potentially acid (incubated pH less than 4) within 100 cm;
  - Saline, EC_e more than 4 mS cm^{-1} within 100 cm;
  - Unripe; n-value greater than 0.7 in the upper 20 cm.

– *Raw saline acid sulphate clay*: These are very young acid sulphate soils in the initial phase of severe acidity, with reserves of pyrite remaining in the upper part of the profile. Plates 4.4 and 4.5 show examples of this kind of soil.

  Their characteristics are:
  - pH is less than 4 within 60 cm;
  - Jarosite mottles or more than 0.05 per cent soluble sulphate are present within 60 cm;
  - The pH of some layer within 100 cm will fall below 4 and by at least 0.2 during incubation;

- Typically, they are saline; EC_e greater than 4 mS cm^{-1} within 100 cm;
- Typically, they are unripe, with n-value greater than 0.7 within 20 cm.

– *Ripe acid sulphate clay with raw subsoil*: These are young acid sulphate soils with a ripe, severely acid topsoil and with reserves of pyrite in the subsoil. The topsoil may be leached of excess soluble salts. Plate 4.6 shows an example of a ripe acid sulphate clay with a raw subsoil.
Their characteristics are:
- pH is less than 4 within 60 cm;
- Jarosite mottles or more than 0.05 per cent soluble sulphate present within 60 cm;
- n-value less than 0.7 in the upper 20 cm, and greater than 0.7 within 60 cm or greater than 1.0 within 100 cm;
- The pH of the subsoil will fall to less than 4 and by at least 0.2 during incubation.

– *Ripe acid sulphate clay*: These are old acid sulphate soils that no longer have any reserves of pyrite within the crop rooting zone. Compared with young acid sulphate soils, their present acidity is typically less severe, but pH is still less than 4 within 60 cm. They are physically ripe, and may be completely leached of excess soluble salts. Sulphidic material may be present below 100 cm. Plate 4.7 shows an example of a ripe acid sulphate clay.
Their characteristics are:
- pH is less than 4 within 60 cm;
- Jarosite mottles are present within 60 cm;
- n-value less than 0.7 in the upper 60 cm and less than 1.0 in the 60 to 100 cm layer;
- The pH of the subsoil between 60 cm and 100 cm does not fall to less than 4 and by 0.2 during incubation.

– *Ripe acid aluminium clay*: These are not acid sulphate soils, although they may have developed from acid sulphate soils through a long period of weathering. They are severely acid, with pH less than 4 within 60 cm, but do not have jarosite or sulphidic material within 100 cm.
Their characteristics are:
- pH is less than 4 within 60 cm;
- No jarosite within 100 cm;
- n-value less than 0.7 in the upper 60 cm and less than 1 in the 60 to 100 cm layer;
- The pH of the subsoil between 60 and 100 cm does not fall to less than 4 and by 0.2 during incubation

The important characteristic of these soils is that the exchange complex is dominated by aluminium. At pH less than 4, soluble aluminium hampers crop growth, and aluminium can always be displaced from the exchange complex, for example by increasing salinity. So far as amelioration is concerned, the cation exchange capacity is crucial. If it is low, then relatively small amounts of lime will be required; if high, then amelioration may be too expensive.

Examples of the classification of acid clays are shown in Figure 5.2. The groups have been distinguished according to the nature of limitations to reclamation and crop growth. Within each group, more acid, less acid, or saline soils can be distinguished, according to local needs.

The soil groups distinguished above do not include all the possible combinations

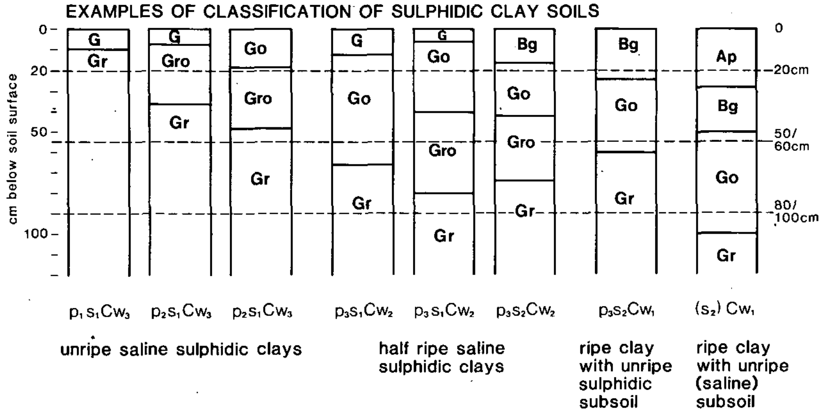


Figure 5.2 Classification of profile forms of acid clays

of composition, acidity, salinity, and ripeness. If other groups are found to be useful and widespread, they can be included easily in this scheme. However, because of the nature of sedimentation and also the rapid evolution of acid sulphate soils following drainage, intergrades will always bridge any arbitrary grouping, and extragrades will occur between acid sulphate soils and other soils with which they are associated in the landscape.

5.5 International classification of acid sulphate soils

5.5.1 Soil Taxonomy

In Soil Taxonomy (Soil Survey Staff 1975), *potential acid sulphate soils* are recognised by the presence of sulfidic materials – 'waterlogged mineral or organic soil materials that contain 0.75 per cent or more sulfur (dry weight) mostly in the form of sulfides and that have less than three times as much carbonate ($CaCO_3$ equivalent) as sulfur'.

Sulfihemists are potential acid sulphate soils that are dominantly organic. They have sulfidic materials within 100 cm of the surface.
Sulfaquents are mineral soils with sulfidic material within 50 cm of the mineral soil surface.
Sulfic Fluvaquents are ripe mineral soils with an irregular distribution of organic matter down the profile and with sulfidic material between 50 and 100 cm depth.
Sulfic Haplaquents are ripe mineral soils in which organic matter decreases regularly with depth below a depth of 25 cm and with sulfidic matter between 50 and 100 cm depth.
Sulfic Hydraquents are unripe or half ripe mineral soils with sulfidic material between 50 and 100 cm depth.

Acid sulphate soils are recognised by the presence of a sulfuric horizon, which is defined as 'mineral or organic material that has both a pH less than 3.5 (1:1 in water) and jarosite mottles (hue 2.5Y or yellower and chroma of 6 or more)'. The term 'per-

Table 5.3 Approximate correlation between Soil Taxonomy and ILRI classification of acid sulphate soils

Soil Taxonomy	Profile Form				ILRI nomenclature	Principal soil groups
Sulfihemists	p_1 p_2 p_3	O		w_2 w_3	unripe sulphidic peat	
		O/C C/O O/S S/O			unripe sulphidic muck	
Sulfaquents	p_1 p_2	S	s_1 s_2		saline sulphidic sand	
		C	s_1 s_2	w_2 w_3	unripe saline sulphidic clay	Potential acid sulphate soils
Sulfic Hydraquents	p_3					
Sulfic Fluvaquents and Sulfic Haplaquents	p_3	S	s_2		sand with saline sulphidic subsoil	
		C	s_2	w_1	ripe clay with saline sulphidic subsoil	
Sulfohemists	a_1 a_2	O	s_1 s_2	w_2 w_3	raw saline acid sulphate peat	
			s_2	w_1	peat with raw subsoil	Raw acid sulphate soils
		O/C C/O O/S S/O	s_1 s_2	w_2 w_3	raw saline acid sulphate muck	
			s_2	w_1	muck with raw subsoil	
		O			acid sulphate peat	
		O/C C/O O/S S/O			acid sulphate muck	
Sulfaquepts	a_1 a_2	S	s_1 s_2		raw saline acid sulphate sand	
		C	s_1 s_2	w_2 w_3	raw saline acid sulphate clay	
			s_2	w_1	acid sulphate clay with raw subsoil	
					ripe acid sulphate clay	Ripe acid sulphate soils
Sulfic Haplaquepts and Sulfic Tropaquepts	a_3	S			sand with acid sulphate subsoil	
		C	s_2	w_1	ripe clay with raw acid sulphate subsoil	
					ripe clay with acid sulphate subsoil	
					ripe acid aluminium clay	Acid aluminium soils

* Definitions of profile form are given in Table 5.1. Soil Taxonomy definitions of sulfidic material and sulfuric horizons are more rigorous than the definition of potentially acid and severely acid material used in the profile form.

Table 5.4 Summary of the ORSTOM classification of acid sulphate soils (from Segalen et al. 1982)

Grande sous-classe	-sous-classe	Grands groupes	Groupes	Sous-groupes
Thiosols	Halique saline ($EC_s > 8$ mS cm^{-1}) within 60 cm	Dystrique mineral, pH < 5.5	Amérisé thion at surface	Gravelleux
	Gypsique gypsum and secondary carbonate > 15 per cent within 60 cm	Eutrique mineral, pH > 5.5	Orthique subsurface thion	Caillouteux
	Carboxique secondary carbonate > 15 per cent within 60 cm	Sombrique organic, peat and muck	Graveleux ou Caillouteux gravelly or stoney	Arénique sandy
		Pallidique low-organic	Argilanique ou Bulgique with clay skins	Vertique clays with shrin-swell properties
			Halique	Prismatique prismatic structure
			Gypsique	Colonnaire columnar structure
			Carboxique	Hypohalique moderate salinity (EC_e 4-8 mS cm^{-1})
				Hypogypsique moderate gypsum carbonate
				Hypocarboxique moderate secondary carbonate
Sulfosols	Halique	Dystrique	Amérisé sulfon at surface	subsurface thion,
	Gypsique	Orthique Eutrique	Sulfuré subsurface sulfon	Other sub-groups as for Thiosols
	Carboxique	Sombrique	Thionique subsurface thion	
		Pallidique	Other groups as for Thiosols	

dysic horizon' has been used in the Mekong Delta to describe soils with sulphate acidity but without jarosite mottles (Pons, personal communication).

Sulfohemists are acid sulphate soils that are dominantly organic and have a sulfuric horizon within 50 cm of the surface.

Sulfaquepts are mineral soils with a sulfuric horizon within 50 cm of the surface.

Sulfic Haplaquepts are ripe mineral soils with jarosite mottles and pH between 3.5 and 4 within 50 cm of the surface, or jarosite mottles and pH (1:1 water, air dried slowly in shade) less than 4 in some part between 50 and 150 cm depth).

Sulfic Tropaquepts are ripe mineral soils with a mean annual soil temperature of 8° C or higher; jarosite mottles and a pH between 3.5 and 4 within 50 cm of the surface or jarosite mottles and a pH (1:1 water, air dried slowly in the shade) less than 4 in some part between 50 and 150 cm depth.

Table 5.3 shows the approximate correlation between Soil Taxonomy and the ILRI classification. Soil Taxonomy defines potentially acid materials by their sulphur and carbonate contents, as opposed to their incubated pH value; and defines acid sulphate horizons by a pH (1:1 in water) of less than 3.5, as opposed to a field pH of less than 4.

Separations introduced in the ILRI system that are not made in Soil Taxonomy include:

- Distinction of peat and muck within organic soils;
- Distinction of sandy and clayey groups within the mineral soils;
- Distinction of raw acid sulphate soils, ripe acid sulphate soils, and acid aluminium soils according to the reserves of pyrite and sulphate acidity;
- Separation according to salinity;
- The problem of separation according to climate has been tackled by adopting different diagnostic depth limits according to the potential soil water deficit.

5.5.2 ORSTOM

The ORSTOM classification (Segalen et al. 1979; 1982) distinguishes acid sulphate soils within the class of saline soils.

Two sub-classes are distinguished:

- *Thiosols*-soils with a reduced 'thion' within 60 cm of the surface. A thion has more than 0.75 per cent oxidisable sulphur and becomes acid upon oxidation.
- *Sulfosols*-soils with an oxidised 'sulfon' within 60 cm of the surface. A sulfon has jarosite mottles, free sulphuric acid, more than 0.75 per cent sulphur, and a pH less than 3.5.

These correspond to potential acid sulphate soils and actual acid sulphate soils. The definitions are based on Soil Taxonomy and suffer the same difficulties. In addition, soils with diagnostic horizons deeper than 60 cm are not considered, which is unsatisfactory for land reclamation and management purposes.

Within each subclass, there is provision for four further hierachical subdivisions. These are summarised in Table 5.4. Most of the categories provided do not exist. A more serious drawback of this classification is that many groupings and separations that are made have no practical significance, although they may be of pedological interest.

5.5.3 FAO/Unesco

The FAO/Unesco Soil Map of the World legend (FAO/Unesco 1974) groups both potential acid sulphate soils and actual acid sulphate soils together as:

- *Thionic Fluvisols* – soils that contain sufficient sulphides to produce a pH less than 3.5 within 100 cm of the surface.

No subdivision of this group is required for the soil map at a scale of 1:5 million.

6 Soil patterns

6.1 Potential acid sulphate environments

Soil variation is always a problem for land-use planning and management. Acid sulphate soils are notoriously localised. Even within a single area of acid sulphate soil, the severity of acidity, or potential acidity, can vary significantly from point to point.

Relationships between soil characteristics and other facets of the landscape operate from the largest scale to the smallest. In this section, some generalisations are developed to help in identifying those parts of the landscape where acid sulphate soils can be expected. Because the detailed soil pattern of each area will be unique, this section can only give samples of the local links between acid sulphate soils and landforms, climate, ecology, and management.

The combination of factors required for the accumulation of sulphides occurs in three distinct environments (Pons and van Breemen 1982):

- *Marshy inland valleys and basins flushed by sulphate-rich waters* draining from older sulphidic sediments. These are not extensive, but there are several local examples including sulphidic peats in Uganda (Chenery 1954) and Leningrad (Krym 1982), and sulphidic sands in The Netherlands (Poelman 1973);
- *Bottoms of saline and brackish seas and lakes.* Organic-rich sediments deposited in saline or brackish water may accumulate significant concentrations of reduced sulphur, both as Fe (II) monosulphide and pyrite. The Littorina bottom sediments of the Baltic contain up to 2 per cent reduced sulphur. Isostatic recovery of the land, following glaciation, has brought some of these sediments above sea level, leading to the development of acid sulphate soils in coastal areas of Sweden and Finland (Wicklander et al. 1950; Kivinen 1950);
- *Saline and brackish water tidal swamp and marsh*, which includes tidal flats, salt marsh, and mangrove swamp. This is the principal potential acid sulphate environment.

6.2 Soil patterns in the tidal zone

6.2.1 Landforms

Sulphidic soils develop most extensively where clayey sediment accretes slowly in saline and brackish water and, simultaneously, copious organic matter is supplied by swamp vegetation. The longer the duration of saline or brackish swamp conditions, and the greater the input of organic matter, the greater the accumulation of pyrite. Shelter from strong currents and wave action is conducive to the accumulation of mud and to its colonisation by vegetation. Favourable conditions occur in deltas, sheltered estuaries, coastlines protected by offshore islands and bars, and even open shores where wave energy is dissipated across a broad, gently-sloping coastal shelf.

The lowest parts of the inter-tidal zone are flooded most of the time, so these soils are permanently reduced. In the higher parts of the tidal landscape, the upper horizons of the soil are predominantly oxidised. The tidal range, and the effectiveness of drainage, determine the thickness of oxidised, non-sulphidic material that will accrete above the permanently reduced, sulphidic substratum. The greater the tidal range, the broader the tidal zone, and the thicker the ultimate development of the oxidised surface horizon.

Several hundreds of years seem to be needed for pyrite to accumulate in excess of the neutralising capacity of the soil. Therefore, potentially acid soils are likely to develop only in relatively stable systems, where sediment is accumulating slowly. Rapidly-accreting systems, or systems subject to alternate erosion and deposition, will not accumulate high concentrations of pyrite.

Sandy sediments generally occur in less stable tidal environments. They rarely contain large amounts of pyrite, but only a small proportion of pyrite will produce severe acidity in a quartz sand, because there is little neutralising capacity.

Striking differences in chemistry between soils of a relatively straight mudflat coast and an estuarine area dissected by tidal creeks are reported by Diemont and van Wijngaarden (1974), working in West Malaysia. In the reduced horizon of the straight coast, field pH values varied between 8 and 8.4, reflecting high concentrations of HCO_3^- (10-26 mol m^{-3}) in the interstitial water, and pyrite S contents were less than 0.5 per cent. In contrast, in the estuarine swamps, pH values of the reduced horizon were between 6.2 and 6.8, interstitial water was lower in dissolved HCO_3^- (2-10 mol m^{-3}), organic matter contents were higher, and pyrite S contents were between 1 and 2.5 per cent. Concentrations of dissolved sulphide were similar in the two environments, except during spring tides when they were reduced to undetectable levels in the estuarine soils.

Pons and van Breemen (1982) attribute the apparent removal of dissolved sulphide and bicarbonate, and the increased accumulation of pyrite, to more effective tidal flushing. Flushing will be enhanced by the network of tidal creeks, and by greater soil permeability associated with a higher content of organic matter. Tidal flushing should promote pyrite formation, by removing HCO_3^-, supplying the limited amount of dissolved oxygen necessary to form pyrite from reduced sulphide, and by accelerating rate-limiting processes that are otherwise dependent on diffusion.

The different pyrite contents found along the Malaysian coast may equally be explained by the differing stability of the coastline. The straight coast is subject to strong tidal currents, and appears to be continually eroding and rebuilding.

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 conditions for pyrite accumulation have persisted over a long period, very high reduced sulphur contents may occur (up to 25 kg S m^{-3} under *Avicennia* mangrove in northern New Zealand; up to 50 kg S m^{-3} under *Rhizophora* mangrove in The Gambia). Rapid sedimentation and a rapidly-aggrading coastline result in a much shorter period of favourable conditions for pyrite accumulation and, consequently, in sediments of low sulphur content.

Plate 6.1 Reed swamp, East Anglia. *Phragmites* reedswamp has a world-wide distribution in fresh and brackish wetlands on unripe peat and alluvial soils. Thick peat deposits can accumulate in fresh water and these become potentially acid when subsequently flooded by brackish water, as in East Anglia and The Netherlands.

6.2.2 Vegetation

Vegetation fuels the process of pyrite formation by supplying readily-decomposed organic matter, mainly through the decomposition of the root systems since most surface debris is carried away by the tide. Both climate and salinity effect remarkable contrasts in the ecology of the tidal zone. Temperate salt marsh is mainly herbaceous; absent or much reduced in winter; and confined to the upper tidal zone by a combination of low temperatures, wave action, flooding, and the turbidity of the water, which reduces the amount of sunlight received. In brackish water, salt marsh gives way to reed swamp, where the dense, robust roots and rhizomes contribute to a high organic content in the reduced mud. At the freshwater margin, if the supply of mineral alluvium is low, peat accumulates (Plate 6.1).

The characteristic vegetation of inter-tidal swamps in the tropics is mangrove forest. Mangroves range from shrubs less than 50 cm high, at the cool margins of their range, to trees greater than 30 m high (see Plate 1.7). In favourable conditions, their productivity is comparable to that of rain forest. Mangroves extend lower into the tidal zone than salt marsh, sometimes below mean sea level in brackish waters. Where rainfall is high, they are succeeded in the upper part of the tidal zone by swamp forest or reeds. As in temperate regions, peat may accumulate at the brackish or freshwater tidal margin if there is little mineral sedimentation. A long dry season severely restricts

Plate 6.2 Mangroves, salt marsh, and barren tidal flats, Kerewan, The Gambia. Tall *Rhizophora racemosa* flank the tidal river and creeks. Where deposition of mud has raised the land surface so that it is flooded only by the highest tides, *R.racemosa* grows only to a small tree and is succeeded on the higher tidal flats by *R.mangle*, *Avicennia africana*, and the succulent *Sesuvium portulocastrum*. The highest tidal flats are bare of vegetation and are encrusted with salt during the dry season.

inter-tidal vegetation, especially in the tropics, where extreme salinity develops on the higher tidal flats that remain exposed for long periods during neap tides (Plate 6.2).

The organic matter contents of marine sediments are generally low in the tropics (0.5 to 3 per cent), but may be higher in temperate regions (up to 10 per cent). On bare tidal flats, pyrite formation may be limited by low organic matter content. But once marsh or mangrove vegetation is established, the dense mass of fibrous roots provides a copious supply of easily-decomposed organic matter.

Individual species or plant associations exert no specific effect on pyrite accumulation. However, different species do occupy particular niches related to climate, exposure, depth of flooding, drainage, and salinity (Chapman 1976). In temperate regions, marsh vegetation is much reduced in winter and is usually restricted to the upper part of the inter-tidal zone, above mean sea level. The most diverse and productive tidal swamp vegetation occurs in the humid tropics with a mean annual rainfall greater than 2000 mm and no dry season. Here mangroves may colonise the entire inter-tidal zone, and are succeeded inland by freshwater swamp forest. In dryer regions, the range and diversity of mangrove vegetation is reduced by very high salinity in the upper part of the tidal zone, which is flooded only during spring tides. Groundwater salinity in excess of about 10 per cent excludes mangroves. During the dry season, salinities in excess of 25 per cent occur on the highest part of the inter-tidal zone, where mangroves are succeeded by salt marsh and barren salt flats (Plate 6.2).

In a particular locality, the different swamp and marsh species indicate current differences in microtopography, hydrology, or salinity, which can be significant in land reclamation or management, but are not necessarily related to the pyrite content of the underlying soil, which may have developed under somewhat different conditions. In general, the largest areas of high pyrite content (more than 30 kg S m^{-3}) are formed under big mangroves and *Nypa*, or other brackish water plant communities, succeeding mangrove. Very high pyrite contents also occur in peat soils that have been subject to a long period of brackish water flooding.

6.2.3 Changing sedimentary environments

The relationship between post-glacial sea levels, the rate of sedimentation, and the regional distribution of acid sulphate soils was introduced in Section 1.3. During the last glacial period, the world sea level stood some 80 m below its present level. From about 18 or 19 000 years ago, the sea level rose rapidly, reaching about 5 m below the present level about 7 000 years ago. During the last 7 000 years, the sea level has risen more slowly with cyclical fluctuations of about 1 m amplitude (Morner 1971; Tooley 1976; Blackwelder et al. 1979). Against this background of a eustatic rise in sea level, many areas have been subject to isostatic or tectonic uplift or subsidence, resulting in a variety of regional trends of relative sea level (see Figure 1.1).

In each sedimentary basin, the combined effects of sea level changes and rates of sedimentation have affected the sedimentary environment, and also the time available for pyrite accumulation. Where sedimentation keeps pace with a rising sea level, a broad, stationary zone of tidal swamp or marsh vegetation may develop; tidal flushing remains active, and thick layers of sulphidic material can accumulate. Even under a stable sea level, strongly sulphidic sediments may accumulate if the rate of sedimentation is slow – so that favourable conditions for pyrite accumulation persist over a long period. Under the influence of a falling sea level, or very rapid sedimentation, accumulation of pyrite may be limited by the shorter period of suitable environment.

Regional and local changes in sea level, sedimentation, hydrology, or water chemistry can result in the burial of sulphidic material by non-sulphidic alluvium or peat, so that potential acid sulphate soils may be found in freshwater or dryland environments, or pyrite may accumulate in peat or alluvium originally laid down in fresh water.

6.3 Regional soil patterns

Contrasting regional patterns in South East Asia, resulting from different rates of sedimentation and rising sea level, were described briefly in Section 1.3.3. Figure 6.1 shows the general soil pattern of the Chao Phraya Delta in Thailand. Here the sulphidic older marine clays, laid down in a broad, stationary tidal zone under a rapidly-rising sea level, are succeeded, about 40 km from the present coastline, by younger marine clays, laid down along a rapidly-advancing coastline. The younger clays are mostly not potentially acid.

Inland, some of the older sulphidic clays are covered by a blanket of non-sulphidic

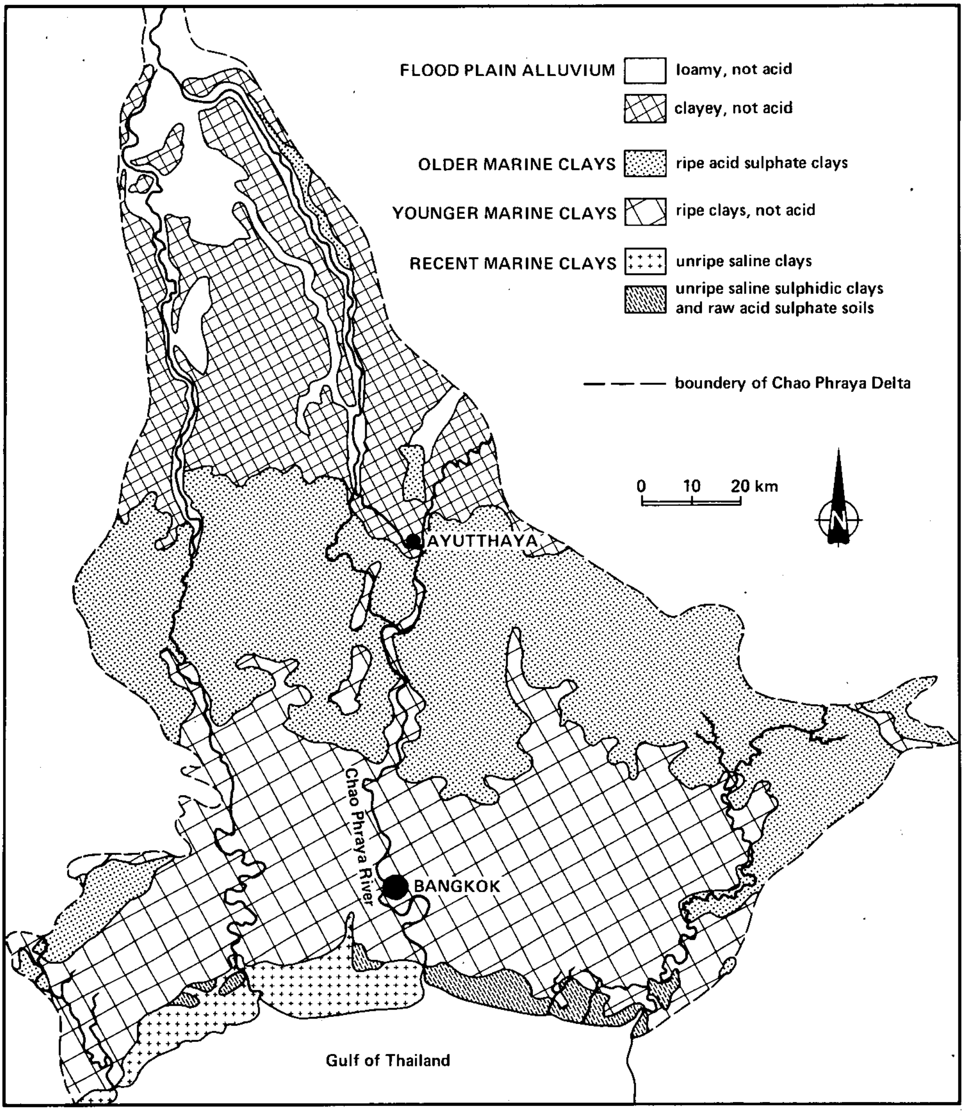


Figure 6.1 Generalised soil pattern of the Chao Phraya Delta, Thailand. Adapted from 1:40000 soil map of the Soil Survey Division, Department of Land Development, Bangkok 1977

river alluvium. The old marine clays that remain exposed have become acid sulphate soils, as a result of progressively falling watertables.

Figures 6.2 and 6.3 illustrate a very different soil pattern, in the middle reach of The Gambia estuary. Here the most recent sediments, accumulating in the broad tidal swamp on either side of the main river channel, are very sulphidic. The present tidal zone is flanked by low estuarine terraces, which suggests a recent slight fall in sea level. The terraces, which are still flooded at times during the wet season, carry ripe clays with only local occurrences of acid sulphate subsoils. Non-sulphidic half ripe

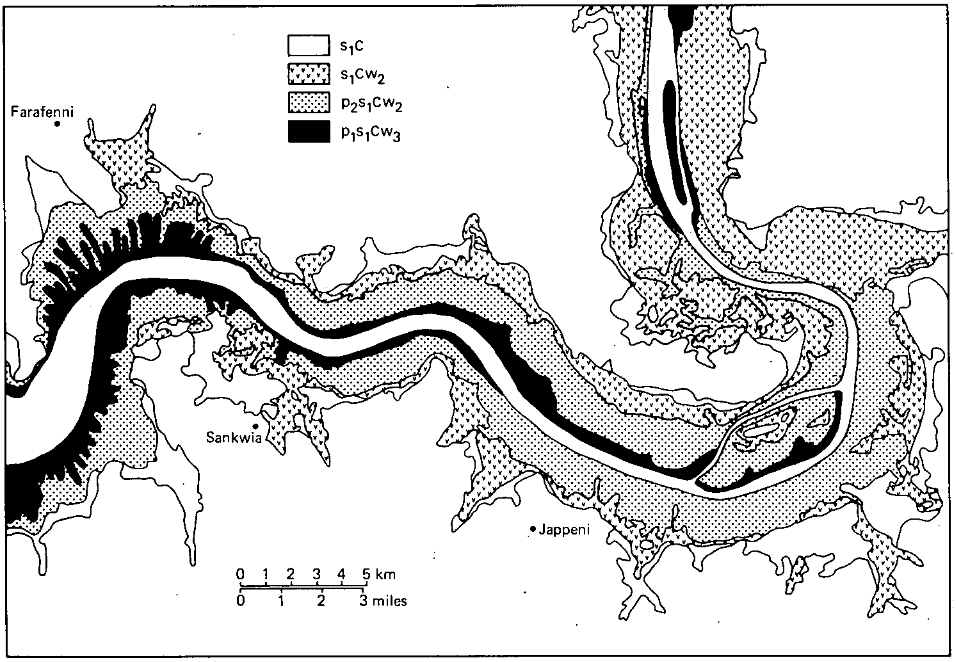


Figure 6.2 Generalised soil pattern of the mid-Gambia estuary, latitude 13° 25' to 13° 38'N, longitude 15° 15' to 15° 30'W (adapted from Thomas and Robinson 1979 and Dent 1979)

clays in the upper part of the present tidal zone appear to be planed-off remnants of these terraces, which must have been laid down under some combination of lower salinity and/or more rapid sedimentation than the present-day swamp sediments.

Certainly the most intensively-studied area of acid sulphate soils is the North Sea basin, especially in The Netherlands, where their fundamental chemistry was first elucidated by van Kerckhoff (1856) and van Bemmelen (1863; 1886). Here the sea level has continued to rise, intermittently, over the last 7000 years by a combination of eustatic rise of sea level and isostatic subsidence of the land (see Figure 1.1).

In both The Netherlands and East Anglia, the alternate formation and partial destruction of coastal sand dunes and spits has resulted in a complex pattern of sedimentation. Periods of subdued marine activity, during which extensive freshwater peat deposits accumulated, have alternated with marine incursions, when estuarine clays have been deposited and secondary pyrite accumulation has taken place in peats flooded by brackish water.

The general soil pattern of the Yare Flood Plain in East Anglia is shown by Figure 6.4. The most recent estuarine clay has been deposited broadly over the seaward part of the basin, and tongues inland along the tidal rivers. In the lower reaches, all the clay is calcareous. In the middle reaches, the clay is calcareous along the river and creek levees, but non-calcareous in the intervening basins, giving a complex pattern of potentially acid and non-acid soils (see Section 6.5.2).

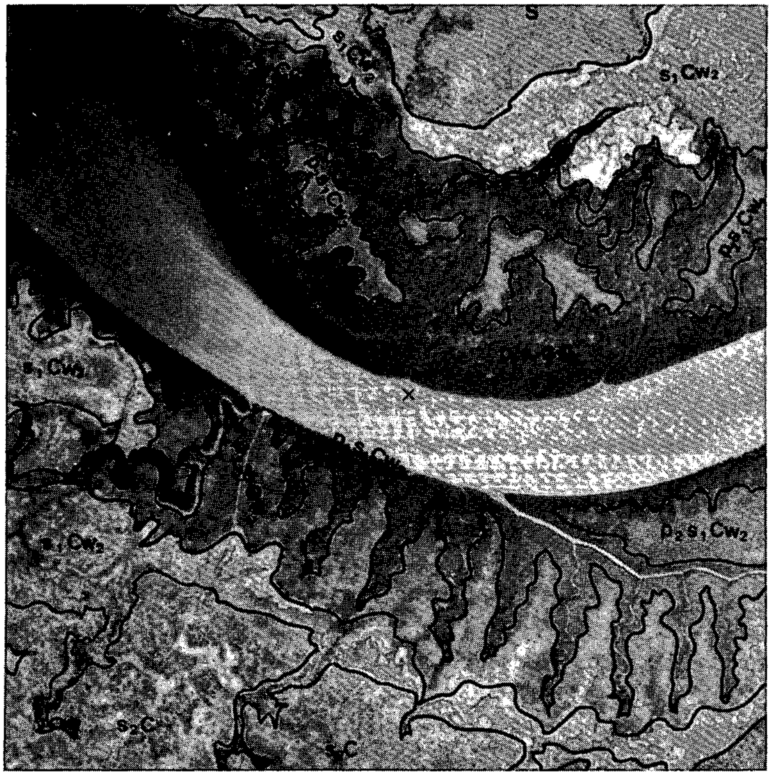


Figure 6.3 Detailed soil pattern at Sankwia Tenda, The Gambia. Base map by permission of the Superintendent of Surveys, The Gambia (For legend, see Figure 6.2)

Legend to Figures 6.2 and 6.3

Soil pattern in the mid-Gambia

Symbol	Soil	Vegetation and land use	Landforms and hydrology
S	Sandy and coarse loamy	Arable farming or woodland savanna	Colluvial valley slopes. Freely drained
$s_1C + s_2C + s_2Cw_1$	Association of ripe clay, ripe saline clay, and ripe clay with saline subsoil; rarely severely acid	*Mitragyna-Acacia* savanna with tall grass-herb vegetation in depressions. Formerly widespread rice cultivation in depressions	Estuarine terrace. Depressions flooded in the wet season
$s_1\ Cw_2$	Half ripe saline clay	*Sesuvium* and salt-tolerant grasses and rushes. Some barren salt-flats in lower reaches; *Phragmites-Echinochloa* reed swamp in upper reaches where salinity is less. Extensive clearance for tidal rice.	Planed-off estuarine terrace; upper tidal zone, not flooded during dry season neap tides

$p_2s_1Cw_2$	Half ripe saline sulphidic clay	*Avicennia africana*, *Rhizophora mangle* and *R. racemosa* mangroves; *Phragmites-Echinochloa* reed swamp. Extensive clearance for tidal rice.	
$p_1s_1Cw_3$	Unripe saline sulphidic clay	Tall *Rhizophora racemosa* mangroves	Tidal flats, flooded by every high tide

6.4 Detailed soil patterns in the inter-tidal zone

The soil patterns of the tidal zone evolve in concert with the sedimentary landscape. Regional soil patterns are related to changes in sea level and gross sedimentation. The characteristics of detailed patterns that are relevant to project feasibility and management commonly include:
- An intricate distribution pattern of acid and non-acid soils;
- Within any large area of acid sulphate or potential acid sulphate soils, a tenfold variation in pyrite content;
- Lower pyrite content in the topsoil than in the subsoil; variation in thickness of non-acid topsoil;
- Usually pyrite contents are greatest, and acid or potentially acid layers closest to the surface, in the lowest parts of the landscape (for example on the Bangkok Plain, van Breemen 1976);
- Depositional landforms, such as sand bars and levees, and erosional features, such as estuarine terraces and relict islands or shields of sediment deposited under a relatively higher sea level, are conspicuous features of the soil pattern (for example Andriesse and Sim 1968; Dent 1980).

Each sedimentary basin has a unique soil pattern. This is related to its particular environment and sedimentary history. The range of contrasting soil patterns is illustrated here by examples of detailed surveys from New Zealand and The Gambia.

In Northland, New Zealand (see Figure 4.6), relative sea level seems to have been fairly stable over the last 2000 years. Extensive tidal landscapes in wide harbours have developed an intricate pattern of meandering tidal creeks, levees, and backswamps, illustrated by Figure 6.5. A more disciplined pattern, representative of constricted tidal river landscapes, is illustrated by Figure 6.6.

In both landscapes, there is a correspondence between landform and soil morphology (Figures 6.7 and 6.8). Half ripe clays, with Go-Gro-Gr profiles, are developed on raised flats and levees that can drain quickly at low tide. Half ripe or unripe clays, with thick, sulphidic Gr horizons, are developed in the backswamps.

Soil profile morphology is indicative of a range of chemical and physical soil properties. Pyrite content has been discussed already in relation to the characteristic horizons of the tidal soils (see Section 4.2). A comparison between Figures 6.7 and 6.9 illustrate the field relationships of the important geotechnical property, shear strength. In this instance, the shear strength of the saturated tidal soils is determined firstly by soil texture; the characteristics of sandy materials are quite distinct from clays. Within the clay soils, shear strength is most closely related to ripeness.

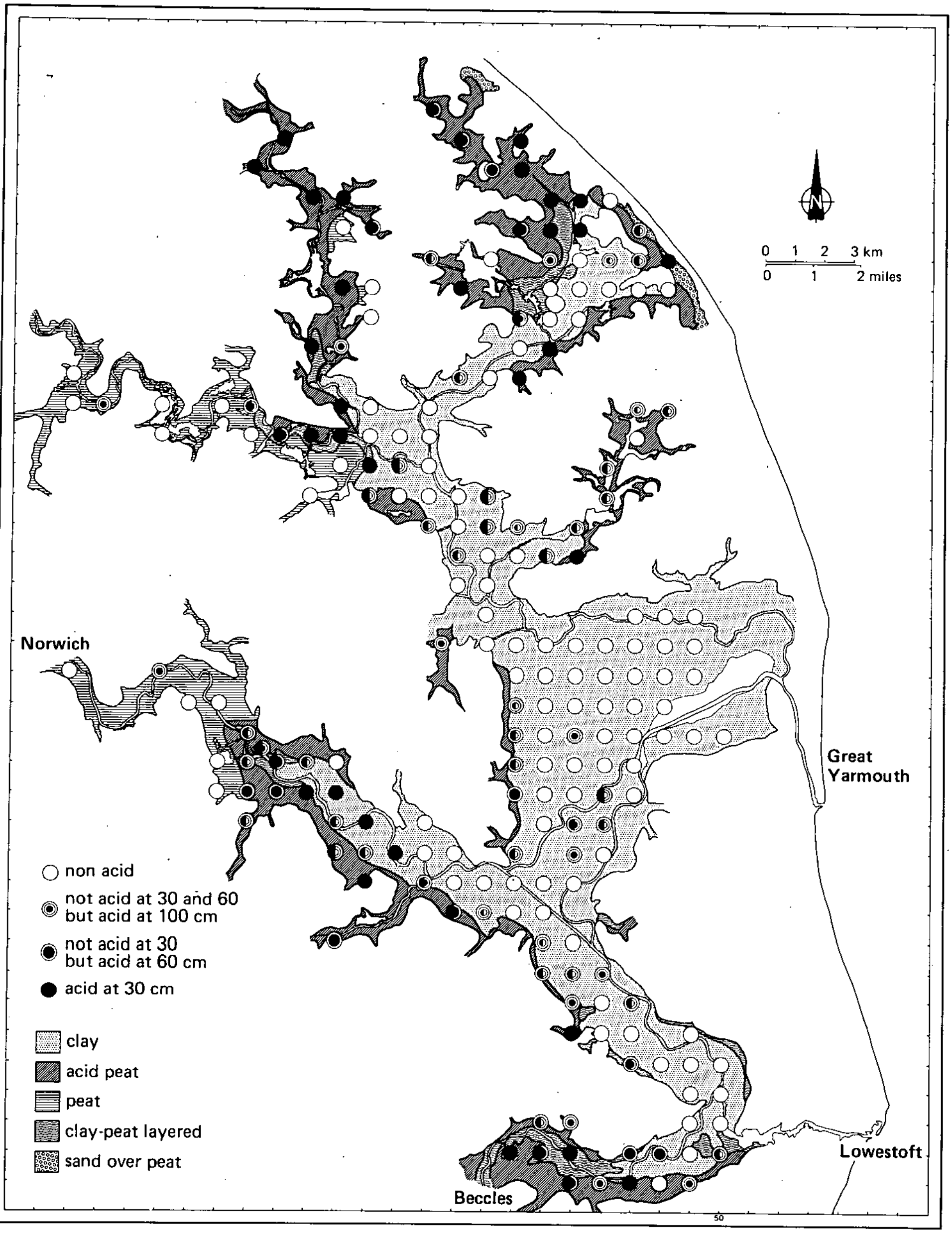


Figure 6.4 Generalised soil pattern of the Yare Flood Plain, East Anglia, U.K. Shaded circles represent the depth at which acid or potentially acid material occurred in duplicate samples from each 1 km grid intersect (from Dent 1981)

Only a small proportion of the sediment deposited in an estuary is deposited above mean sea level. The soil maps and sections illustrate the way that sand banks, colonised first by shellfish then by mangrove and salt marsh vegetation, often act as nuclei for the accretion of mud.

Terraces, islands, and planed-off shields of older sediment form upstanding features amongst more recent sediments. Typically, the upstanding soils that are no longer tidal have ripe, leached topsoils. Acid sulphate conditions may have developed initially on these elevated sites, but the phase of severe acidity has passed and, if acid sulphate conditions persist at all, they are deep in the profile.

6.5 Detailed soil patterns in reclaimed landscapes

Drainage of tidal and floodplain landscapes brings about aeration of the topsoil, leaching of soluble salts, quicker soil ripening, and subsidence. In the case of potential acid sulphate soils, drainage also causes severe acidification. The technical success of reclamation, and very often its economic and social success, is dependent upon the soil pattern. Many features of the soil pattern in a reclaimed landscape are inherited from the original tidal flats or floodplain. These include the distribution of effective drainage and poor drainage, saline and non-saline soils, acid and non-acid soils. A comparison of the soil pattern of virgin and reclaimed areas shows the development in polders of exaggerated relief, localised development of severe acidity, and differences in the degree and depth of ripening and salinity.

6.5.1 Exaggerated relief

The microrelief of polders is a result of unequal subsidence following drainage. Soil ripening involves shrinkage, through irreversible loss of water. This is greatest in peat soils, and in those parts of the landscape that are initially low and least ripe – such as backswamps and enclosed basins. Subsidence is least on mature levees and raised flats, where more ripening has taken place during sedimentation. The microrelief illustrated by Figure 6.12 is characteristic of a grazing marsh where the watertable has been maintained between 20 and 60 cm for hundreds of years. The deeper the drainage, the greater the subsidence, and the greater the microrelief. Areas underlain at shallow depth by sand shrink very little, and so form upstanding features in the drained landscape (Figure 6.13).

6.5.2 Localised development of severe acidity

Within any region of acid sulphate soils, there are significant local patterns that are related to the vertical and horizontal distribution of pyrite and calcium carbonate, soil texture, and the depth and length of time over which deep drainage has operated. The severity of acid sulphate conditions is always variable. Each locality has its own particular combination of soil and management factors which are responsible for its particular soil pattern.

In Northland, New Zealand, shell beds are associated with the bare mud-flat stage of sedimentation in the core areas of raised flats. These shell beds oppose the development of acidity. Acid sulphate soils have developed only in material that has accumu-

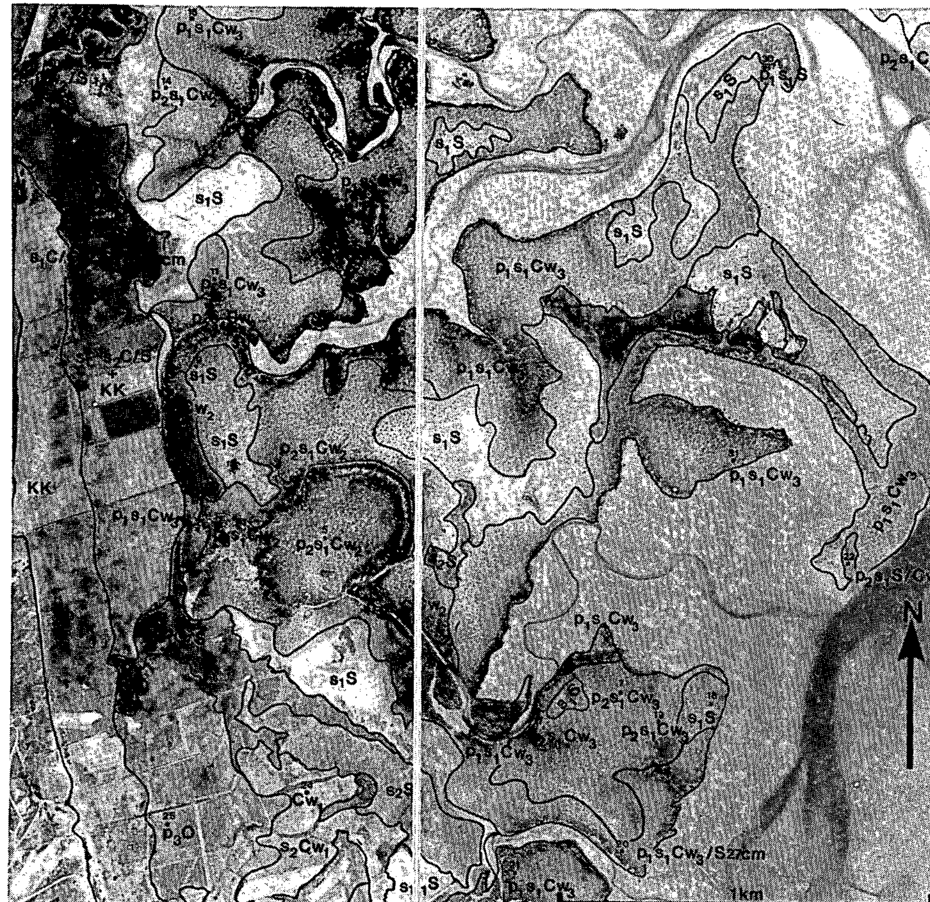


Figure 6.5 Detailed soil pattern, Rangaunu Harbour, New Zealand. Base map Crown Copyright.

Estuarine alluvial soils developed on low terraces

Symbol	Soil mapping unit	Associated properties
C	Ripe clay	
Cw_1	Ripe clay with unripe subsoil	
s_2Cw_1	Ripe clay with unripe saline subsoil	Usually with peat topsoil; may be acid (a_3) or potentially acid (p_3) within 80 cm; areas not empoldered may be saline throughout – s_1Cw_1
s_2S	Sand with saline subsoil	Includes gleyed sand and weakly-cemented sand; may be potentially acid within 100 cm
s_1C/S	Ripe saline clay (< 40 cm thick) on sand	
p_2s_2O	Half ripe and unripe, brackish peat and muck	Peat and muck subject to brackish water flooding and freshwater seepage

Tidal alluvial soils (unstable sand banks and mudflats have not been mapped)

Symbol	Soil mapping unit	Associated properties
ps_1Cw_2	Half ripe saline sulphidic clay	Levees and raised flats p_2 potentially acid within 40 cm p_3 potentially acid within 20 cm
$p_1s_1Cw_3$	Unripe saline sulphidic clay	Backswamps and low flats p_1 potentially acid within 20 cm
s_1Cw_2/S	Half ripe saline clay (< 40 cm thick) on sand	Raised flats
s_1Cw_3/S	Unripe saline clay (< 40 cm thick) on sand	Low flats
s_1S	Saline sand	
s_1O	Saline peat and muck	Peat usually < 60 cm thick, upper margins of tidal zone and backswamps

Other mapping units defined in the Northland Soil Legend (Taylor et al. 1982)

Symbol	Soil mapping unit	Genetic soil group	Landform
RK	Ruakaka peat	Organic soil	Waterlogged depressions associated with stable sand dunes and beach ridges, and estuarine terrace receiving freshwater seepage
KK	Kaikino sand	Groundwater podzol	Estuarine terrace
TT	Tangitiki sand	Podzolised yellow brown earth	Stable old dunes, beach ridges, and cover sand

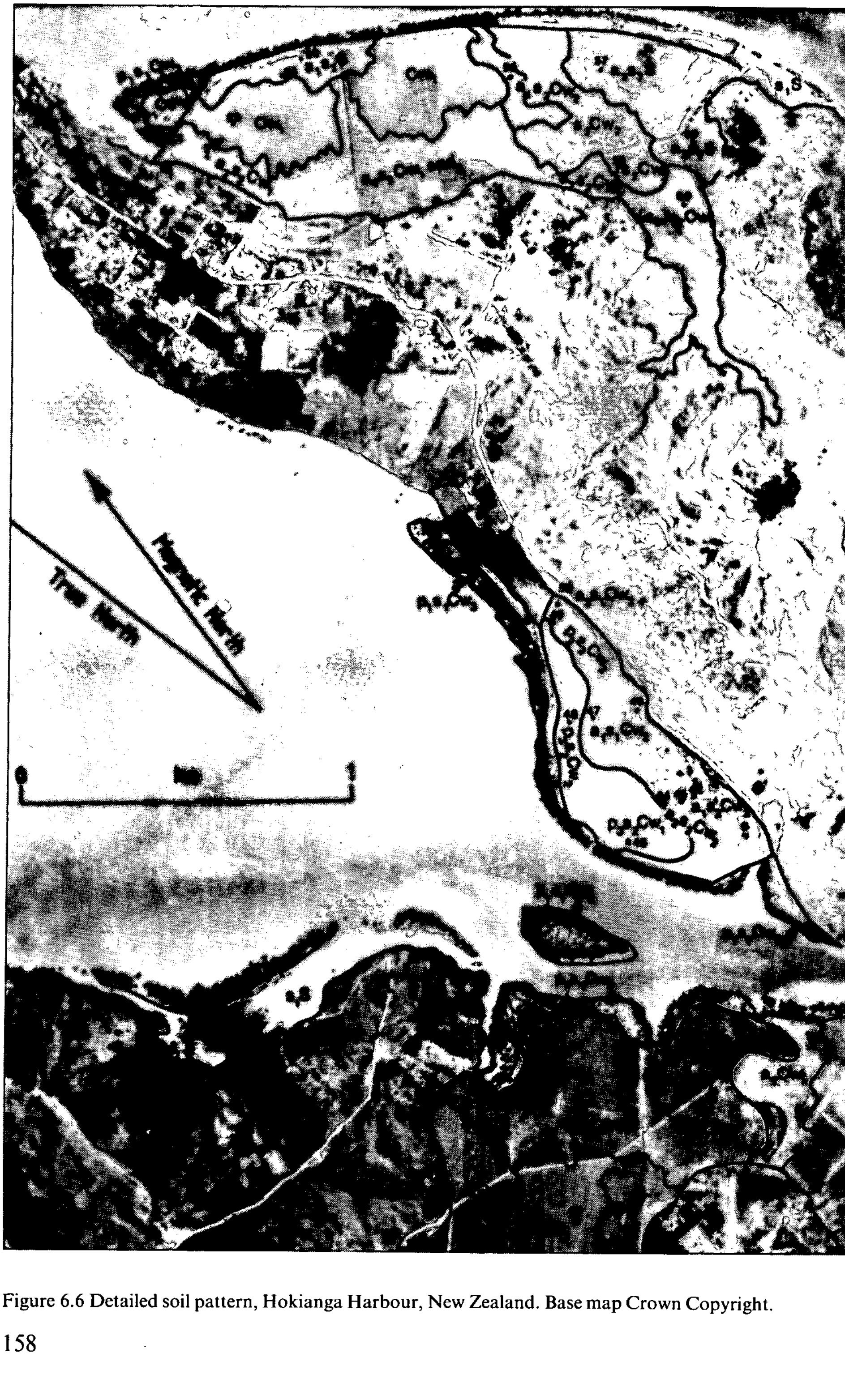


Figure 6.6 Detailed soil pattern, Hokianga Harbour, New Zealand. Base map Crown Copyright.

Soil legend

Tidal soils (unstable sand and mud flats are not mapped)

Symbol	Soil mapping unit
s_1S	Saline sand
s_1Cw_2	Half ripe saline clay
$p_1s_1Cw_3$	Unripe saline sulphidic clay

Polder soils

Symbol	Soil mapping unit
Cw_1	Clay with unripe subsoil
Cw_2	Half ripe clay
s_2Cw_2	Half ripe clay with saline subsoil
$p_3s_2Cw_1$	Clay with unripe saline sulphidic subsoil
$p_3s_2Cw_2$	Half ripe clay with saline sulphidic subsoil
$p_2s_2Cw_2$	Half ripe saline sulphidic clay
$a_1s_2Cw_1$	Raw acid sulphate clay with unripe saline subsoil
$a_2s_2Cw_1$	Clay with unripe saline raw acid sulphate subsoil
$a_1+a_2s_1+s_2Cw_2$	Half ripe saline raw acid sulphate clay
ax, s_2 S/Cw_2	Acid sand over half ripe saline acid sulphate clay
a_2s_2S	Sand with acid saline subsoil
a_3s_2S	

Salinity classes:

s_1 Saline (EC_e > 4mS cm^{-1}) within 50 cm
s_2 Saline between 50 and 80 cm

Potential acidity classes:

p_1 Sulphidic (incubated pH < 4) within 20 cm
p_2 Sulphidic within 50 cm
p_3 Sulphidic within 80 cm

Acid sulphate classes:

a_1 Severely acid (field pH < 4) within 20 cm
a_2 Severely acid within 50 cm
a_3 Severely acid within 80 cm

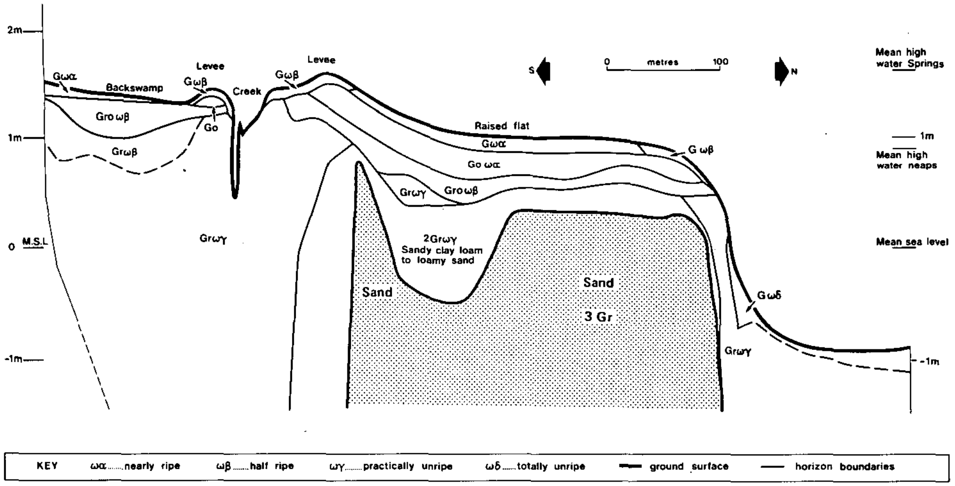


Figure 6.7 Relationships between topography and soil morphology, Ngapuke Creek, Kaipara Harbour, New Zealand. Transect levelled and sampled at 10 m intervals (from Dent 1980)

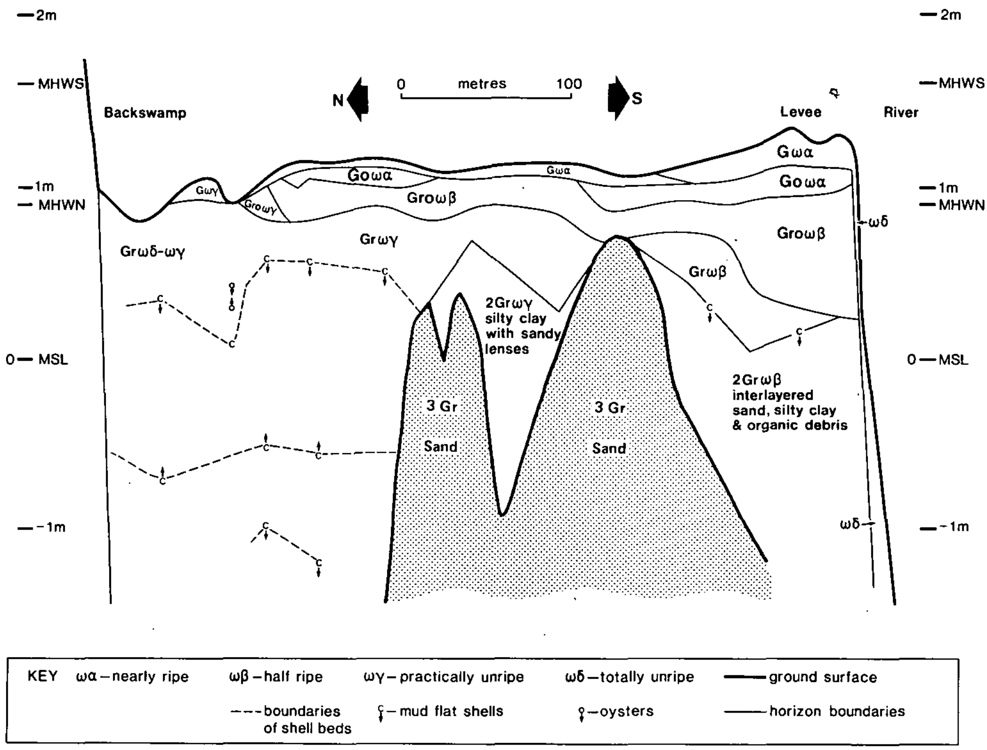


Figure 6.8 Relationships between topography and soil morphology, Mangawhero River, Hokianga Harbour, New Zealand. Transect levelled and sampled at 10 m intervals

lated entirely under mangrove vegetation, and acidity is invariably more severe in backswamps than on levees. The depth at which severe acidity is developed is related mainly to the thickness of the oxidised horizons in the virgin soil. Following drainage, severely acid horizons develop closest to the surface in basins, backswamps, silted creek channels, and on tidal flats that have been reclaimed at an early stage of sedimentation.

Even within a single estuary, a number of different soil patterns may be developed. On the Yare flood plain in East Anglia (Figure 6.4), the most recent phase of sedimentation has deposited marine clay over freshwater peat. At the seaward margin, the clay contains up to 20 per cent by mass of $CaCO_3$, and less than 1 per cent by mass total S. At its inland margin, the clay is non-calcareous and of higher pyrite content. It abuts and is interlayered by peat, also of variable pyrite content, but containing up to 15 per cent by mass or 40 kg S m^{-3}. Figures 6.10 and 6.11 show the soil pattern where marginal peats and basin clays are acid or potentially acid, while the levees are calcareous. Figures 6.12 and 6.13 depict a situation where both clay and peat are sulphidic and non-calcareous.

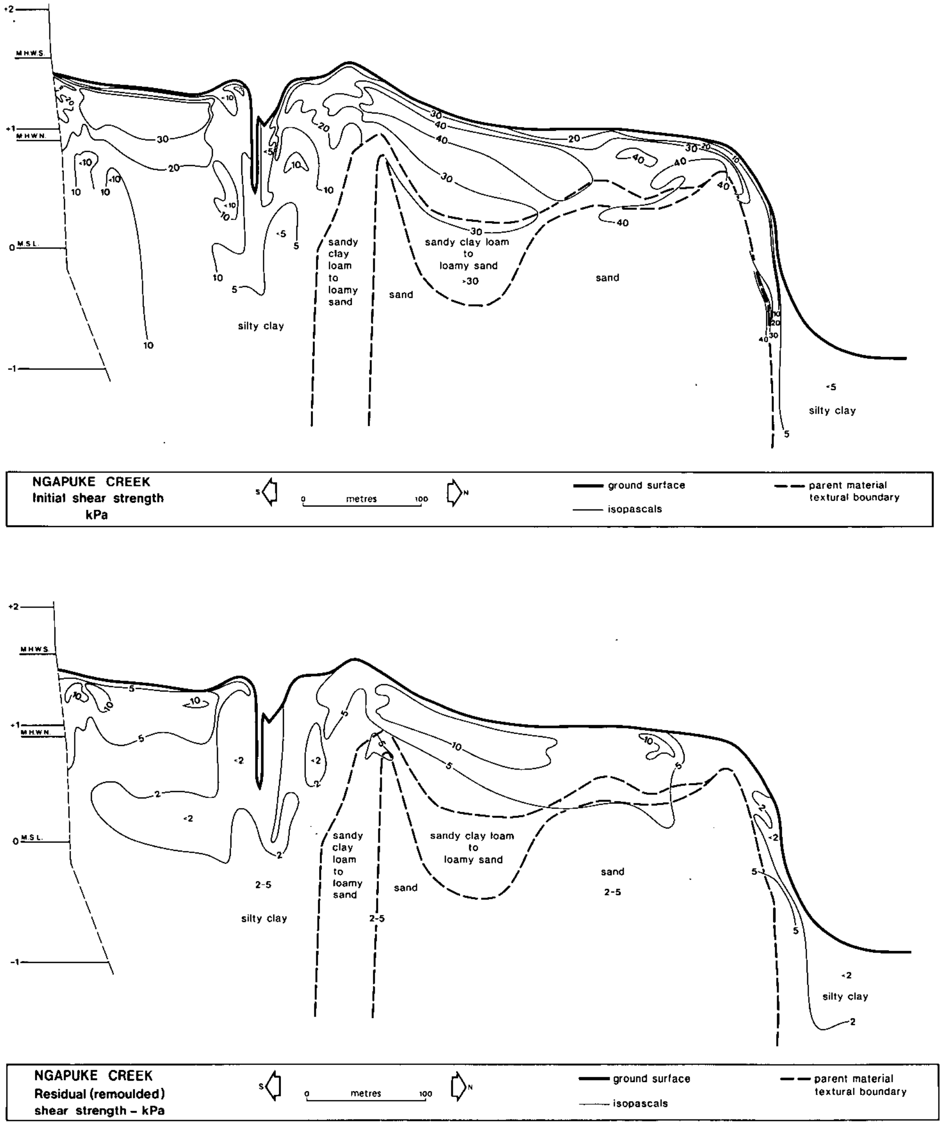


Figure 6.9 Relationships between topography and
1 initial shear strength
2 residual (remoulded) shear strength
Ngapuke Creek, Kaipara, New Zealand. Values measured using a hand shear vane at 10 cm vertical steps and at 10 to 20 m horizontal intervals

6.5.3 Efficiency of drainage

In both The Netherlands and East Anglia, soil patterns have been complicated by systematic land reclamation since the 16th century. The tidal rivers have been embanked, and drainage – first by tidal sluices and wind pumps, more recently by steam,

Figure 6.10 Soil pattern at Norton Marshes, Norfolk, England. Base map Copyright Cambridge University Collection.

Legend

Landforms	Map symbol	Soil group	Acid sulphate classes
Upland and sand bars exhumed by peat shrinkage	S	Sandy soils, not severely acid	
River and creek levees	Cw_1	Clay with unripe subsoil	
Basins and backswamps	a_2Cw_1	Clay with unripe raw acid sulphate subsoil	a_2 field pH <4 within 50 cm
	a_3Cw_1		a_3 field pH <4 within 80 cm
	p_3Cw_1	Clay with unripe sulphidic subsoil	p_3 incubated pH <4 within 80 cm
	a_2O/Cw_2	Half ripe muck with raw acid sulphate subsoil	
	a_2Ow_1	Peat with unripe raw acid sulphate subsoil	

diesel, and electric pumps – has lead to unequal land subsidence, unequal preservation of peat deposits, and unequal development of acid sulphate conditions.

Figure 6.14 shows the severity of acidity over an area of reclaimed marsh, 18 years after drainage to about 1.2 m. Figure 6.15 shows the acidity predicted when oxidation

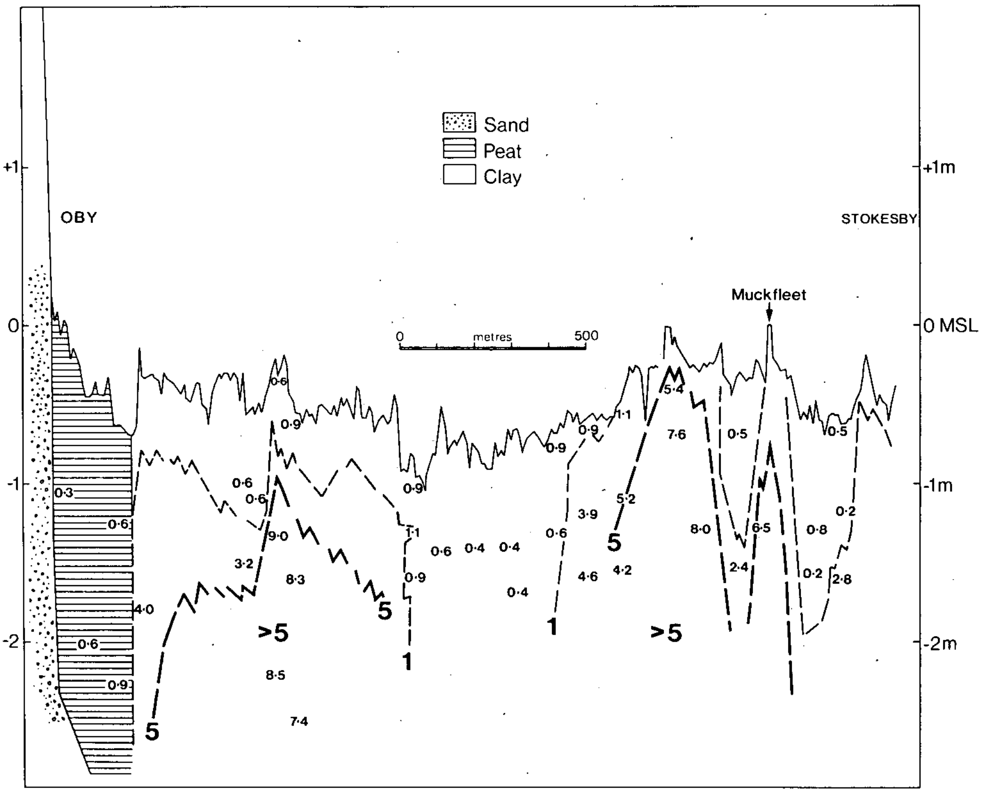


Figure 6.11 Relationships between topography and calcium carbonate content, Bure Marshes, Norfolk, England

is complete to a depth of 1.2 m. The contrast between these two patterns illustrates the influence of drainage efficiency on the development of acidity during several decades following reclamation.

6.5.4 Differences in the degree and depth of ripening

Soil ripening is most advanced where initial ripening in the tidal or floodplain landscape was most advanced; where abundant shell is present to counteract soil acidity and so enable deep and intensive rooting in the drained soil; and close to natural and artifical drainage channels. Soil ripening is arrested by severe acidity, so that acid sulphate soils may remain for many years unripe and, therefore, poorly structured and poorly drained.

6.5.5 Salinity

Salinity follows the same pattern as drainage. The highest, ripest soils are the most

Figure 6.12 Soil pattern at Beccles Marsh, Suffolk, England. Base map Copyright Cambridge University Collection

Legend

Landform	Map symbol	Soil group
Upland	S	Well drained sandy soils
Sand bars	a_2S	Acid sulphate sand
River and creek levees	$a_1 + a_2C$	Raw acid sulphate clay
	$p_2+p_3Cw_1$	Clay with unripe sulphidic subsoil
	p_2C/Ow_1	Muck with unripe sulphidic subsoil
	a_2C/Ow_1	Acid sulphate muck with unripe sulphidic subsoil
Basins	a_1+a_2C/O	Raw acid sulphate muck
	a_1+a_2O	Raw acid sulphate peat
	$p_1+p_2Ow_1$	Sulphidic peat
	p_1Ow_2	Half ripe sulphidic peat

Acid sulphate classes

a_1 severely acid, field pH <4 within 20 cm

a_2 severely acid, field pH <4 within 50 cm

p_1 potentially acid, incubated pH <4 within 20 cm

p_2 potentially acid, incubatd pH <4 within 50 cm

p_3 potentially acid, incubated pH <4 within 50 cm.

p_3 potentially acid, incubated pH <4 within 80 cm.

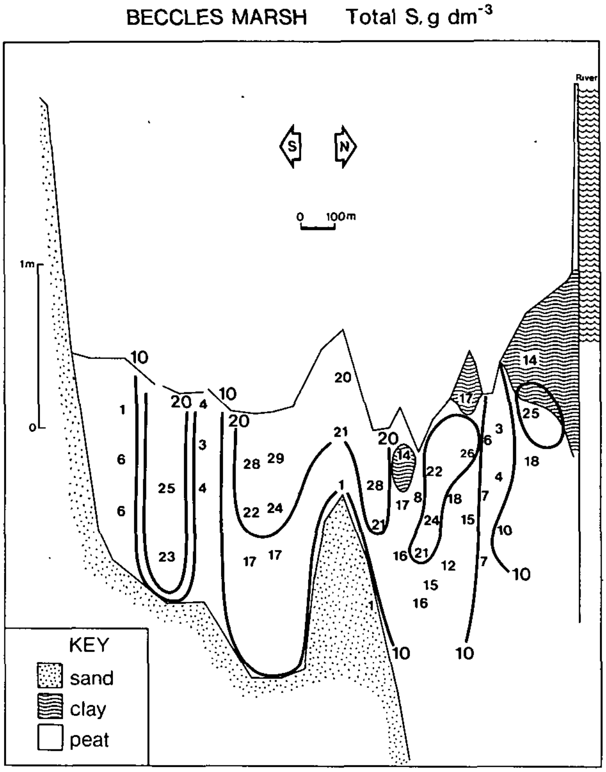


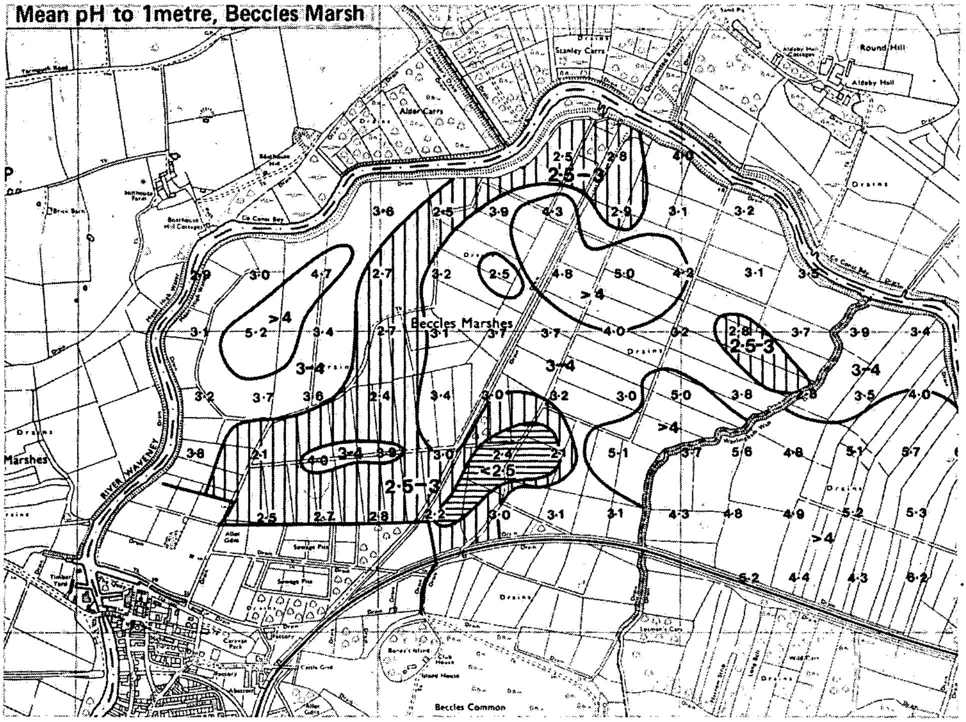
Figure 6.13 Relationships between topography, soil composition, and total sulphur (kg S m^{-3}), Beccles Marsh, Suffolk, England.
Note the increased shrinkage of the peat relative to the clay, and the influence of the sandy basement on the topography developed following drainage.

effectively leached. Low-lying, unripe, severely acid soils are most likely to remain saline after reclamation.

6.6 Interpretation of soil patterns from surface features

The differences in elevation over entire tidal and floodplain areas are usually slight. With the exception of drainage channels, landforms can be delineated reliably only by levelling. While this is essential in the research phase of a soil survey, it is not practicable for rapid survey of large areas. Vegetation patterns, on the other hand, are conspicuous in the field and on air photos. Soil surveyors must therefore make what use they can of correlation between vegetation and landforms and so, indirectly, with the soil pattern.

The pattern of vegetation has evolved in response to the same variations in elevation, drainage, salinity, and sedimentation as has the soil pattern. However, the relationships between soil and vegetation are not necessarily straightforward, and the soil characteristics that can be mapped by inference from the vegetation are not necessarily those of most interest to the surveyor. In particular, there is no direct relationship between the present vegetation and the amount and the distribution of pyrite. Present



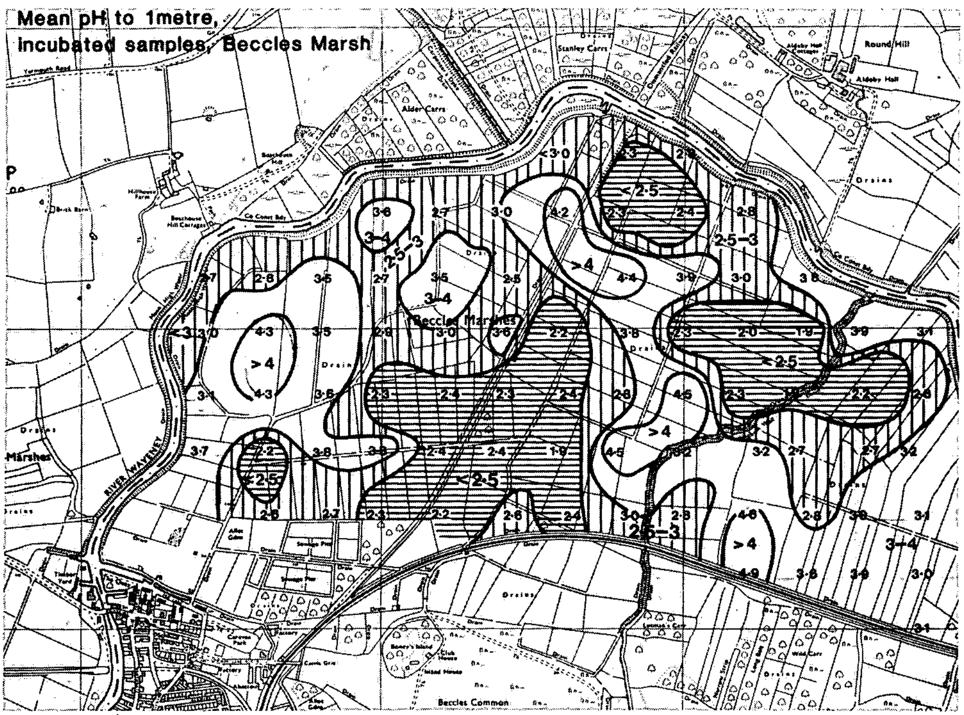


Figure 6.14 and 6.15 Beccles Marsh, Suffolk, England. Base map Crown Copyright

6.14 Acidity after 18 years of drainage to 120 cm

pH values are calculated from the mean H^+ activity of samples from 30, 60, and 120 cm depths on a 200 m grid.

6.15 Predicted acidity at completion of oxidation. pH values calculated from the mean H^+ activity of samples from 30, 60, and 120 cm incubated for three months.

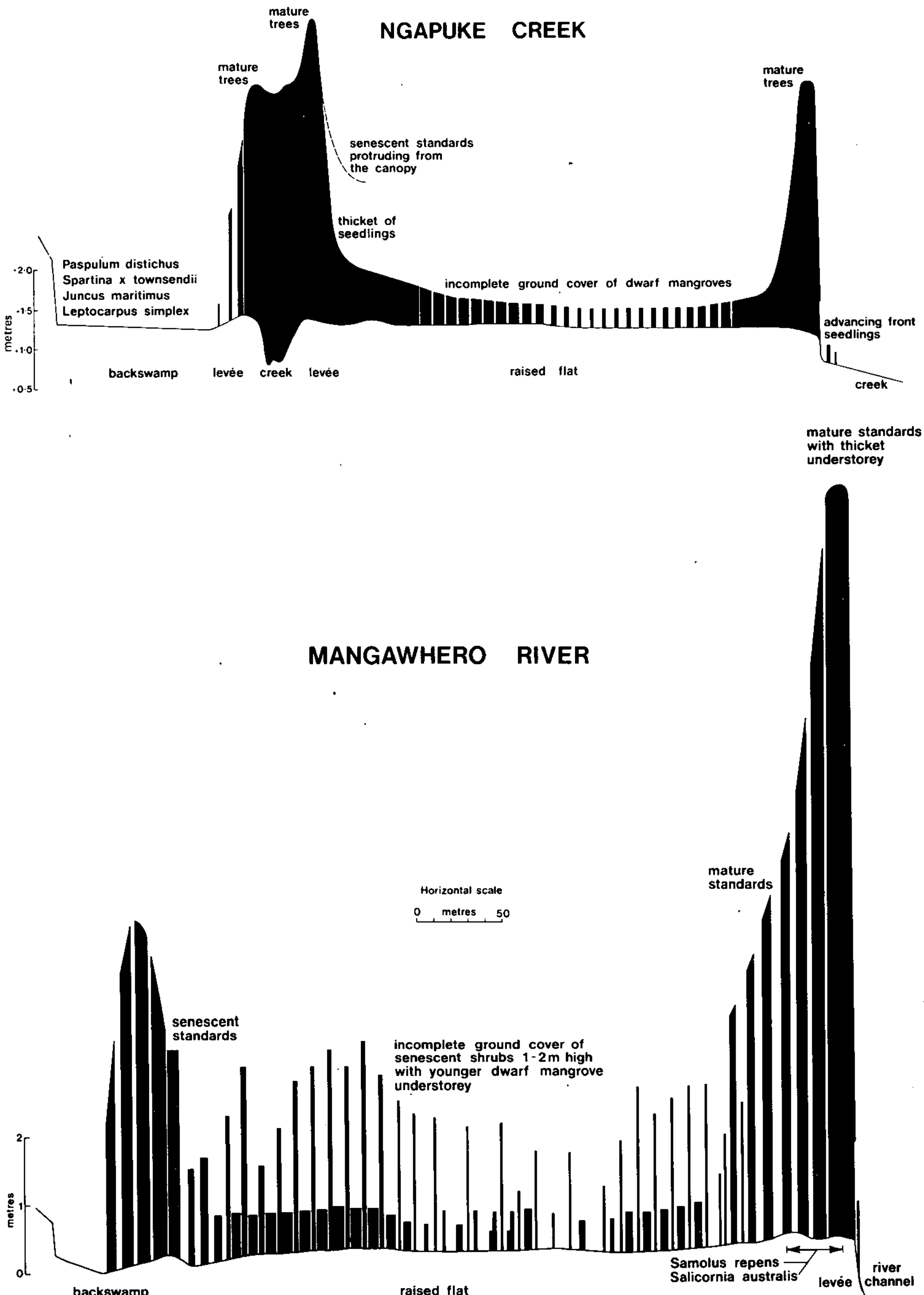


Figure 6.16 Relationships between topography and vegetation, Northland, New Zealand
1 Ngapuke Creek – corresponds to Figure 6.7 and represents a broad, sheltered tidal zone
2 Mangawhero River – corresponds to Figure 6.8 and represents a constricted estuary
Transects levelled and vegetation measured at 10 m intervals

Plate 6.3 Tall mature *Avicennia marina* on a creek levee in Rangaunu Harbour, New Zealand. This vegetation is characteristic of half ripe saline sulphidic clays with thick Go horizons, profile form $p_3s_1Cw_2$

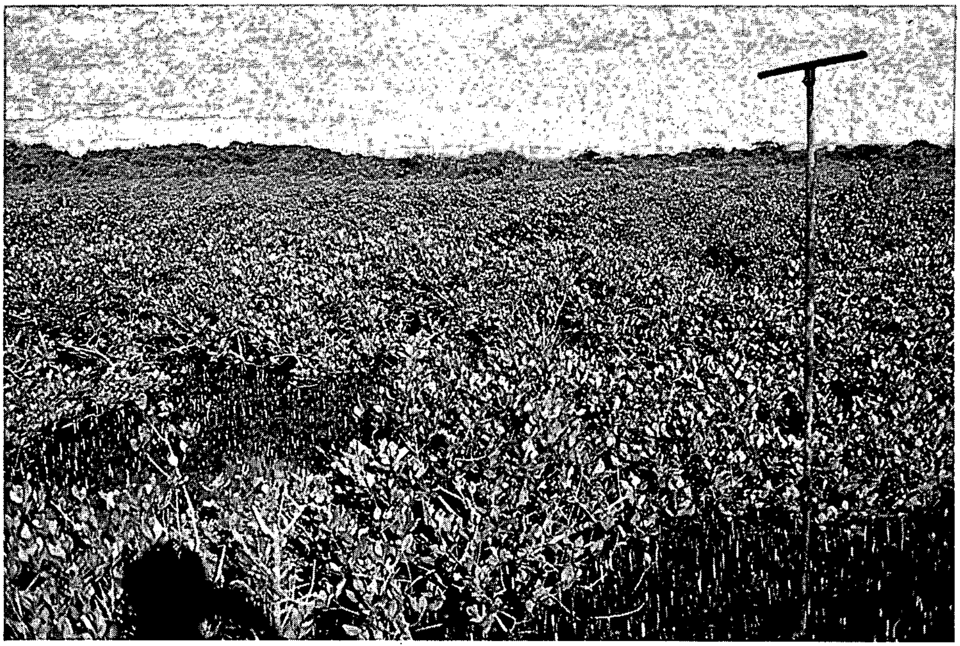


Plate 6.4 Dwarf *Avicennia marina* on a broad raised flat, Kaipara Harbour, New Zealand. The tall trees in the background mark a creek levee

vegetation is in equilibrium with the present environment, which may include management: pyrite may have accumulated over a long period, possibly under somewhat different conditions.

Figure 6.16 shows the relationships between vegetation and topography in Northland, New Zealand. The vegetation is remarkable in that there is only one species of mangrove, *Avicennia marina* var. *resinifera*, which extends from near mean sea level to high water level. The trees respond dramatically to variations in site drainage. A thicket of saplings precedes big, vigorous trees on the rapidly-accreting margins of raised flats and on young levees, with no associated species except algae on the trunks and pneumatophores below high-water neap tide level. In these situations, the soil is unripe, with only the Gr horizon developed, although surface drainage is good at low tide.

Mature levees also carry big mangroves, festooned with the lichen *Usnea* and occasional epiphytes, and with a ground cover of *Salicornia australis*, *Samolus repens*, and *Triglochin striatum* (Plate 6.3). On these sites, the soil is half ripe, with thick Gro and Go horizons.

On broad raised flats and in backswamps, surface drainage is poor, and the mangroves are stunted shrubs covering as little as 20 per cent of the ground surface (Plate 6.4). Continued accretion of sediment extends the flats and may infill the creeks, degrading the surface drainage. In such cases, well-grown trees are succeeded by stunted shrubs. It is important to be able to distinguish between raised flats and backswamps, although their vegetation can appear similar on air photos. The soils of backswamps are always unripe, with only the Gr horizon developed; typically, they have the greatest pyrite content in the landscape. In contrast, the soils of raised flats ultimately develop Go horizons; they have natural surface drainage to the creeks, which is important to reclamation; and the core region of a raised flat may be sandy or shelly close to the surface.

In tropical regions, there is a great variety of mangrove, reed, and swamp forest species. Plant communities which occupy specific niches are often easily identified on air photos. The relationships between plant communities, landforms, hydrology, and soils have to be established by field study for each landscape before they can be used to indicate soil boundaries.

In The Gambia, *Rhizophora racemosa* mangroves, up to 35 m high, occupy those tidal sites with the best surface drainage, along the river and creek channels that are flooded by each daily tide. Inland, these giants are succeeded by smaller trees of the same species and also *Rhizophora mangle*. Above high-water neap tide level, these are succeeded by a more open tidal forest of *Avicennia africana*, with a ground cover of the succulent *Sesuvium portulacastrum* or, in areas that do not experience high salinity, *Phragmites karka*.

The boundary between *Rhizophora* and *Avicennia* forest, which can be distinguished clearly on air photos, does not coincide exactly with the boundary between unripe and half ripe sulphidic clays. This boundary usually lies within the *Rhizophora* zone (Thomas et al. 1981). The most critical soil boundary, between potentially acid clays and non-sulphidic clays, is even less obvious in the field. Their morphology is similar, and they both occupy the upper part of the inter-tidal zone under *Sesuvium* or *Phragmites – Eleocharis* swamp and barren flats. Once the existence of the boundary had been established by field study, a reasonable correlation could be made between, on

Plate 6.6 The Plain of Reeds, Vietnam. A vast tract of rush vegetation and acid sulphate soils, dry season (Leen Pons)

the one hand, potential acid sulphate soils which occur under the regular vegetation and drainage pattern of recent sediments and, on the other hand, non-sulphidic soils which occur under the distinct vegetation and drainage patterns of the planed-off platform.

In contrast, the boundary between the half-ripe tidal soils and the ripe soils of the surviving low terrace is picked out sharply by the change from tidal communities to savanna with scattered *Mitragyna* and *Acacia* trees, which is very easily mapped on air photos (Figure 6.3).

In many areas, the interpretation of soil pattern from a complex vegetation pattern is further complicated by the clearance of natural vegetation for rice growing, or by mangrove forestry.

Soil mapping in reclaimed landscapes shares, with that in tidal areas, the problem of slight microtopography. Once again, the surveyor must seek correlation between soils and vegetation. In principle, the interpretation of vegetation patterns in relation to existing acid and saline soils should be easier than for potential acid sulphate soils, since we can expect direct correlation between vegetation, or crop performance, and severe soil problems (Plates 6.5, p. 111 and 6.6). An example of such relationships in a reclaimed landscape is given in Table 6.1, which summarises the correlation between rice performance, soil acidity and salinity, and vegetation in the Mekong Delta of Vietnam.

Table 6.1 Relationships between rice performance, soil conditions and natural vegetation, Láng Biên, Mekong Delta, Vietnam (van Mensvoort, personal communication

Raw saline acid sulphate clay	Raw acid sulphate clay	Ripe clay with acid sulphate subsoil	Ripe clay and ripe clay with acid sulphate subsoil	Ripe clay
Saline and severely acid	Very severely acid, no rice crop possible	Severely acid	Moderately acid, poor rice growth	Not acid, normal rice growth
Acrostychum aureum				
needle-leaved *Eleocharis* sp.				
	Eleocharis dulcis *Ceratopteris thalictroides* *Cyperus rectangulus*			
	Cyperus haspens *Xiris indica*			
		Phylidrium languinosum *Ischaemum magrum*		
		Panicum repens *Scleria paemorphis*		
			Saccarum spontanum	
			Oryza spontana *Sesbania* sp.	
				Iponaea aquatica *Lepironica articulata* *Phragmites karka*

7 Soil survey and land evaluation

7.1 Objectives and survey requirements

This section discusses: the different needs for soil information of land-use planners, project managers, farmers, and engineers; the methods by which surveyors can provide this information, including practical details of methods of analysis relevant to acid sulphate soils; and, finally, some of the problems of assessing the performance, or potential performance, of the land.

Soil surveys identify the different kinds of soil in a landscape, group like soils into homogeneous units, and map their distribution. These mapping units are then characterised so that their performance can be predicted and an effective system of management worked out. By dividing a landscape into units, a soil survey enables more accurate predictions to be made about soil properties and their response to management than would be possible for the landscape as a whole.

Soil survey is not a simple process of mapping discrete parcels of land. There are no discrete parcels waiting to be mapped. Each soil property changes more or less gradually, both vertically and horizontally; change in one characteristic is not always in phase with changes in others; so identical combinations do not necessarily reappear in the landscape. Also, acid sulphate soils change palpably, over a few months or years once reclamation is begun. However soil mapping units are defined, many boundaries will be arbitrary.

Clearly the first task of the surveyor and the user of the survey, working together, is to define the specific purpose of the survey. Then it can be decided what characteristics of the landscape should be surveyed, what kind of soil mapping units will be used, and what scale will be suitable.

7.1.1 Land-use planning

Land-use planning objectives may include:

- Reclamation and settlement, or more intensive use, of areas that will support new communities and will yield a good return for the effort and cost of development;
- Conservation of the existing productive capacity of areas that cannot support viable developments. Avoidance of long-term environmental damage;
- Improvement of the productive capacity of acid sulphate soils that are already being farmed.

For strategic planning, we need to know whether or not there is enough potentially useful land to make development worthwhile. Not all areas containing acid sulphate soils are useless and unproductive. Soil surveys can show which areas are potentially useful, and which are not. They can also identify the nature and severity of the problems.

Where large areas are involved, survey scales between 1:100000 and 1:50000 are appropriate. Uniform coverage is needed, but not necessarily a soil map. Point observations along equally-spaced transects, using a general purpose classification, will be sufficient to estimate the extent of the area affected by soil hazards.

For project feasibility studies, we need to know the distribution of suitable and unsuitable soils and the kind and severity of soil problems. These should be shown on a map. (Figures 6.2 and 6.4 are examples from soil surveys in support of project feasibility studies.) A soil map alone, however, is not enough. Planners and decision-makers require interpretations of the mapping units in terms of:

- Projected production, probably under a range of alternative management systems;
- The initial and ongoing cost of obtaining this production;
- The time scale involved in any land reclamation or improvement;
- The social and environmental impact of alternative systems of land use.

At this stage of planning, a decision must be made; either the project can support a limited extent of unfavourable soils, or the area affected by the soil problems and the cost of reclamation will be so great as to abort the project.

7.1.2 Project design and implementation

For project design and implementation, we need to know more details on a range of soil properties, so as to have a basis for the design of engineering works and to predict the response of the land to the projected management. Usually, a range of crops, management systems, and farm sizes will be considered. Critical soil characteristics will include:

- Existing or potential acidity;
- Lime requirement;
- Salinity;
- Soil texture;
- Ripeness;
- Available water capacity.

This basic survey should be at a scale between 1:25000 and 1:10000 and should show simple mapping units (series and phases of series) or specified individual soil characteristics.

Very detailed data may be required for special purposes. At the sites of major engineering works, for example, a precise topographic survey will be needed, as well as a geotechnical survey to provide data on particle-size distribution, unit weight, shear strength, compressibility and settlement, permeability, and liquid and plastic limits – all to a depth of several metres – while attention also has to be given to the corrosive effects of acid and sulphate-rich waters. However, the measurement of some soil engineering attributes can be incorporated easily in a general purpose soil survey and problem materials such as deep peat and unripe mud (low strength) and sand (excessive permeability) will be identified.

Geomorphological interpretation of basic soil survey data can narrow the required field of special investigation, and seismic survey can provide some information about the depth, thickness and general nature of subsurface layers. But for many purposes, there is no alternative to closely-spaced field measurements and sampling for laboratory tests.

7.2 Soil survey

Methods of soil survey are discussed in detail by Dent and Young (1981) and in summary by Ilaco (1982) and Landon (1984). The discussion here is confined to topics of special relevance to acid sulphate soils. A check list for survey planning is given in Table 7.1.

Table 7.1 Check list for survey planning

Activity	Responsibility
1. Identification and definition of objectives: – Location and boundaries of survey area; – Problems to be solved; – Time available.	User
2. Survey design: – Publication scale; – Observation intensity, location, depth and data recorded; – Role of air photos and other remote sensing; – Laboratory requirements; – Recording and handling of data; – Soil classification and map legend; – Land evaluation and other interpretative studies.	Surveyor initially, details agreed in consultation with user
3. Organisation: – Check availability and suitability of air photos, topographic base, climatic, geological, and agronomic data; commission photography as required; – Survey schedule; – Staffing; – Mobilisation and logistics – field base, travel and transport for field parties and equipment, personal services, communications; – Equipment; – Laboratory facilities, treatment and transport of samples.	Surveyor
4. Publication of results	User
5. Costing	Surveyor, firm agreement or contract with user

7.2.1 Survey design

Soil survey is always a compromise between speed, or cost, and the excellence of the data. Properties that can be assessed by hand and eye – such as texture, ripeness or colour – and those that can be measured easily in the field – such as pH or shear strength – can be mapped more cheaply and accurately than properties requiring laboratory tests – such as levels of soluble aluminium and iron, n-value, liquid limit, or mineralogy. Properties that are closely related to surface features (i.e. to topography, vegetation, surface colour or wetness), can be mapped quickly and precisely, especially if their surface expression can be identified on air photos. One of the first tasks of soil survey is to establish the field relationships between critical soil properties and surface features or other easily-mapped characteristics (see Sections 4 and 6).

Even when a survey is limited to soil characteristics that can be measured quickly, there is a practical limit to the number of observations that can be made. Some sampling strategy must be adopted. Statistical sampling techniques can establish the range of variation of soil properties and the sampling intensity needed to map any selected property or category. If critical soil properties are not obviously related to surface features, the optimum intensity of field observation can be assessed statistically from randomly selected pairs of sample sites located at fixed distances apart, for example 10, 50, 250, 1 000 m. Where difficulties of access and precise location of sample sites prevent rigorous application of this procedure, quite effective coverage of a survey area can be achieved by sampling along two intersecting transects.

At each site, the soil properties of interest are measured. These data can be subjected to nested analysis of variance (Webster 1977; Nortcliff 1978). Alternatively, the semi-variance of difference between all pairs of sampling points separated by each chosen distance, can be plotted against their distance separation. Semi-variance is a measure of the average similarity between sample points that are a given distance apart: the more alike the samples, the smaller the semi-variance (Burgess and Webster 1980).

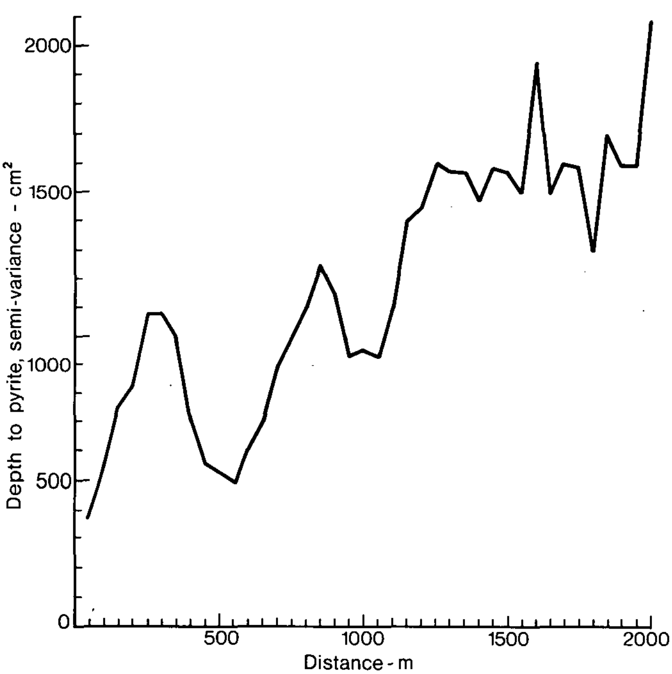


Figure 7.1 Semi-variogram showing the relationship between depth to pyrite and distance separation of sample sites, Do Hoa, Saigon Delta, Vietnam (from Bos and van Mensvoort 1984)

Bos and van Mensvoort (1984) have applied these techniques to acid sulphate soils in South Vietnam. Figure 7.1. shows one of the relationships they found between the semi-variance of the depth of pyrite, and the distance between sites. In this example:

- There is little increase in semi-variance at separation distances greater than 1 200 m. To obtain any useful information on the distribution pattern of this property, the sample interval needs to be less than 1 200 m;
- There appears to be a recurring pattern at separation distances of 500 and 1 000 m;
- There is a significant variation between sites at even the closest interval – in this case the sample spacing is 35 m and semi-variance at this spacing is 400 cm^2 (average variation of depth to pyrite is 20 cm). To reduce this uncertainty, a sampling interval closer than 35 m will be needed.

A rigorous statistical sampling exercise is itself a major research task. Computing facilities and suitable programmes are essential (for example Burrough 1981), and interpretation of the data is not straightforward. Nevertheless, we should know about the scales of variation of critical soil properties. Even where sophisticated statistical analysis is not appropriate, much insight may be gained by sampling at clusters of points at different intervals along transects, and simple plotting of raw data, such as depth to the potentially acid layer, against the separation distance of samples.

In the absence of a special determination of optimum survey intensity, the following rules of thumb apply: for mapping at a scale of 1:10000, the average observation spacing should be 100 to 200 m (one per 1 to 4 ha); for scale 1:25000, the average spacing should be 250 to 500 m (one per 6 to 25 ha). The time needed for surveys at different intensities is indicated in Table 7.2.

Mapping can be undertaken by making observations on a rectangular grid or, alternatively, by free survey. Grid survey achieves even coverage; it can be carried out by inexperienced staff; and there is no alternative where there are no adequate topographic maps or air photos.

A danger of using a grid is that the sampling interval may coincide with some underlying regularity of the soil pattern. For example, in the area represented by Figure 7.1, observations on a 500 m grid would give a wrong impression of the depth to pyrite. This risk can be avoided by random location of observation sites within each grid square, but this technique requires good access and precise location of sites. Very often, exact site location is impossible unless determined by measurement. In these circumstances, statistical validity is lost if the man on the ground ends up by choosing sites subjectively in the general area of the grid intersections.

Grid survey is also inherently wasteful; access may be interrupted by creeks and ditches, and many sites may be unrepresentative. Only someone who has been compelled to map by grid observations can know the frustration of not having information from other points where it would be more useful.

An alternative method is to establish field relationships between soil characteristics and visible features of the landscape that can be mapped directly in the field or on air photos. In this way, the surveyor builds up a conceptual model of the way the landscape functions. Using this model, he decides which characteristics to look for, selects each observation point where it will yield the most useful information, and interpolates soil boundaries between observation points. Later, the model will assist him in producing a range of predictive or interpretative maps from the basic data.

Table 7.2 Observation density and time requirements associated with different intensities of survey on alluvial soils

Purposes	Scale	Average of observations 0.5 per cm^2 of final map	Rate of progress per 22-day month*	Approximate time (days per month) required for different activities**			
				Field survey	Representative profile description and sampling	Field tests	Office and laboratory
Implementation of land reclamation or irrigation projects; management problems; urban and industrial development; soil problems critical	1:5 000 1:10 000	2 per ha 1 per 2 ha	250 – 500 ha 450 – 800 ha	8	2	8	4
Project planning; simple soil pattern; limited extent of problem soils	1:25 000	1 per 12.5 ha	1 000 – 1 500 ha	11	3	5	3
Project feasibility and regional land-use planning	1:50 000	1 per 50 ha	30 – 150 km^2	11	3	5	3

* Time requirements are increased by about 30 per cent for difficult access, for example boat work and delays due to tides and crossings of creeks and rivers. A further 10 to 30 per cent should be added for contingencies such as bad weather.

** Time exclusive of final report preparation, which may take up to 6 months, depending on the size and complexity of the project.

7.2.2 Remote sensing

LANDSAT *satellite imagery* is inexpensive, and is readily available for all parts of the world from EOSAT, Eros Data Center, Sioux Falls, SD 57198 U.S.A., and from several regional ground stations. Useful analysis of regional landforms and vegetation patterns can be carried out, without any special equipment, using 1:250000 false-colour images. Better definition, and so larger scale images, will be achieved by the new generation of satellite-born sensors. Because repetitive coverage is available, it is possible to identify progressive changes in land use.

Air photographs are almost indispensable for navigation on the ground, and make excellent base maps for field survey and final publication. Difficulties of access, and working conditions in tidal swamps and other undrained wetlands, encourage reliance on air-photo interpretation for the mapping of soil boundaries. (What lies within these boundaries still has to be found by field observations.)

Since topography is usually slight and is often concealed by vegetation, air-photo interpretation of wetlands boils down to the interpretation of vegetation and drainage patterns. This is most useful in virgin swamp, where there are direct relationships between current soils, hydrology, and vegetation, and in drained areas where acid sulphate soils have already developed. Interpretation is more difficult where there has been a degree of management, such as mangrove forestry or sporadic burning, which can produce spurious patterns, or uniform pasture management that imposes a uniform vegetation.

If the photographs are to be used as field survey sheets, it is useful to have photography at about twice the intended publication scale of the map. This leaves ample room for writing on the field sheets. It also allows for a reduction in scale from field survey to publication, to reduce the imperfections of mapping (or to counter the misleading impression of accuracy).

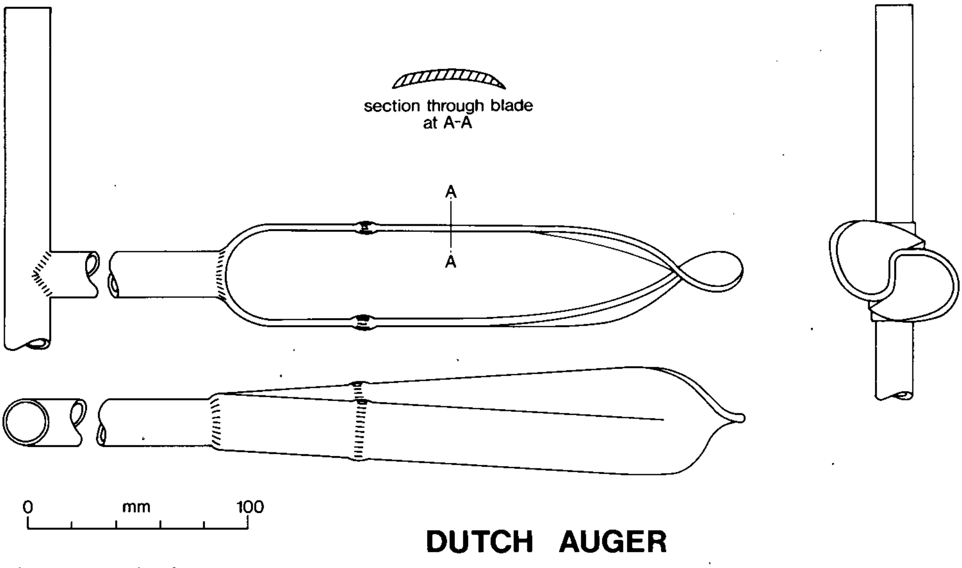


Figure 7.2 Design for a Dutch auger

Good quality, panchromatic 'black-and-white' photography is suitable, but film sensitive to infra-red, either 'black-and-white IR' or 'false-colour', affords greater contrast in wetland environments. Water and wet soil absorb infra-red radiation strongly, so they appear very dark on air photos; and there is more contrast between the reflectances of different plant species in the infra-red range, compared with visible light. On false-colour photography, this appears as a range of colours, depending on the kind of film used, through blue, green, orange, and red. Crops suffering stress or disease commonly show very clearly on infra-red photography. Where aerial photography is to be specially commissioned for soil survey of wetland areas, specification of infra-red-sensitive film should be seriously considered.

7.2.3 Equipment

Transport arrangements are of prime importance in any large survey. Where the survey area is tidal and intersected by creeks, field work is regulated by the tides, and a shallow-draught boat provides the most convenient transport.

A check list of equipment is given in Table 7.3. The basic equipment for surveys in moist, ripe soils includes a Dutch (Edelman) auger (Figure 7.2). It collects samples which are sufficiently undisturbed for identification of most morphological features and large enough for most laboratory purposes. However, a Dutch auger will not bring up samples from half ripe or practically unripe soils. For these, a gouge auger is needed. The large model shown in Figure 7.3 can be made cheaply from cold-drawn, seamless steel tube, 60 mm diameter, 2 mm wall thickness. This is cut as shown and formed to a conical shape by hand-beating on a round steel bar. The handle is cut and welded from steel tube approximately 20 mm diameter (Dent and Robinson 1982). As described, the auger weighs 2.7 kg. The dimensions are not critical, but the conical shape enables 10 to 20 cm of wet sand to be brought up, as well as any overlying cohesive material.

Undisturbed profiles of 1 m can be collected from half ripe soils in a few seconds by pushing the gouge auger vertically into the soil, turning through 180°, and lifting out gently. Undisturbed sub-samples can be collected in 45 mm diameter alloy cylinders, sharpened at one end, by pushing these down from the top of the sample in the auger and cutting out with a knife. The clean auger hole can be used directly for measurement of saturated hydraulic conductivity below the watertable. Since the auger core is removed at once, no bailing is needed.

For collecting deep samples of unripe soils, a variety of specialist equipment is available, of which a conventional peat sampler is the simplest to maintain and operate.

A bailer is necessary to pump out soil profile pits below the local watertable. A length of pipe with a one-way flap at the end, used in an auger hole sump, is simple and effective.

7.3 Characterisation of soil and site

Acid sulphate soils are easy to identify; often they are of striking appearance. It is more difficult to identify potential acid sulphate soils. But identification is not enough.

If we are to make use of experience gained on similar soils elsewhere, or apply technology developed elsewhere, adequate characterisation of soil and site is essential. This means a full description of:

- Thickness of non-acid topsoil;
- Depth, thickness, and reserves of acidity in acid or potentially acid layers;
- The kinds of acidity present:
  - Free (sulphate) acidity;
  - Soluble iron II and aluminium;
  - Exchangeable iron and aluminium;
  - Potential (pyrite and organic) acidity;
- The lime requirement;
- Soil texture profile;
- Ripeness;
- Salinity;
- Microtopography;

Table 7.3 Check list of field equipment

Standard field kit	Additional items, for special purposes
Air photo field sheets	Heavy, pointed spade; for unripe soils, a long-handled shovel; bailer; peat sampler and extension rods
Pencils (B and photo marker), pencil sharpener and rubber	
Clipboard or map case	
Notebook or pro-forma description cards	Hydraulic conductivity (auger hole) kit
Dutch auger	Infiltration equipment
Gouge auger for peat and unripe soils	Sampler and cylinders for undisturbed samples
Broad-bladed knife	Hand shear vane
Soil colour charts	pH/mV meter, electrodes, buffer solutions, distilled water
2-m tape	
Field pH kit	EC meter
Wash bottle	Surveying level, tripod and staff, 30-m tape, ranging poles
Acid bottle	
Sample bags and spirit marker	Stereoscope
Compass, waterproof wristwatch	Camera
Personal comfort and survival kit	Dictaphone

- Present and projected watertable;
- Crop water requirements;
- Amount, distribution, and reliability of rainfall, and especially the duration of drought periods;
- Availability and quality of irrigation water.

Much of this information can be obtained in the field or in a simple field laboratory. If sufficient field tests are performed to indicate the distribution, severity, and variability of acid and potentially acid soils, laboratory studies can be reserved for detailed analysis of a small number of representative samples.

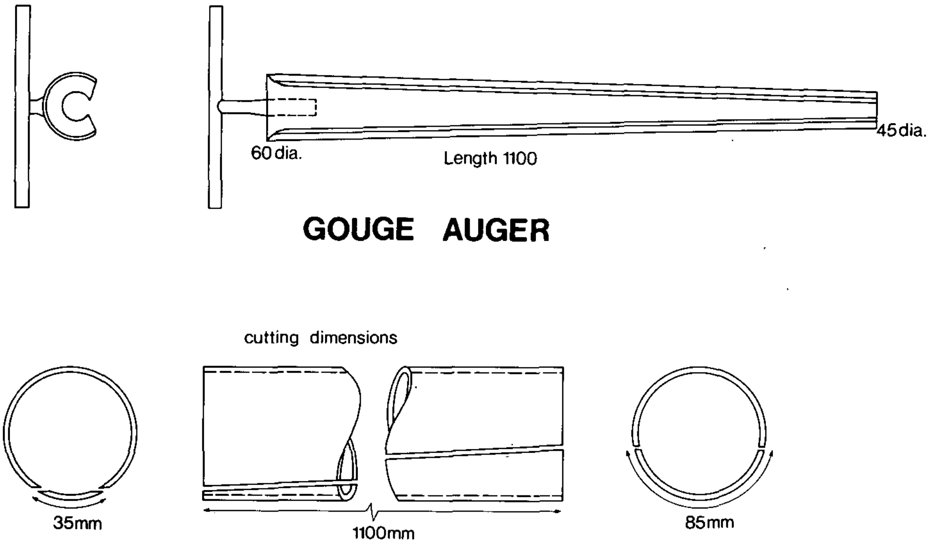


Figure 7.3 Design for a gouge auger

7.3.1 Morphology

The morphology of acid sulphate soils and potential acid sulphate soils was discussed in detail in Section 4. The salient points are as follows:

Acid sulphate soils:

- In mineral soils, acid sulphate conditions are characterised by pale yellow mottles of jarosite in a grey or pinkish grey matrix. Yellow mottles are often first seen in spoil from ditches. However, yellow mottles are not an infallible indication of severe acidity. Ultimately, in ripe soils, they lose their sharp outline and fresh, pale yellow colour, becoming ragged and associated with reddish brown iron oxide deposition. Jarosite may persist in the soil long after the phase of severe acidity has passed;
- In poorly-drained soils, especially in peat and muck, severe acidity may develop without yellow mottles;
- Large amounts of mobile iron are associated with all young acid sulphate soils. The iron appears as ochre on ped faces and in drainage waters. Sometimes, pipe drains and ditches can be blocked by gelatinous iron deposition;
- In young acid sulphate soils, both the severely acid horizon and underlying layers

remain unripe;
- Acid peats tend to dry irreversibly once they are drained, and a crunching sensation is felt and heard when they are augered. The peat below the oxidised layer is commonly intensely black.

Potential acid sulphate soils:
- Waterlogged;
- Dark grey to dark greenish grey colours, commonly with black mottles;
- Typically unripe;
- Usually contain a lot of blackened, partly decomposed organic matter;
- Smell strongly of hydrogen sulphide;
- Do not contain a lot of shell.

7.3.2 pH

Under dryland crops, severe acidity can be identified on the spot with pH indicator paper. MERCK Spezialindikator is mounted conveniently on plastic tabs and is supplied in wide range (pH 0 to 6) and narrow range (2.5 to 4.5 and 4.0 to 7.0). To estimate the pH, press the indicator directly onto the wet soil for 20 seconds, then compare the colour of the indicator with the standard chart. If the soil is too dry, wet it with distilled water. In practice, it is difficult to estimate pH close to the limit of the indicator's range. In this case, check the pH using an indicator of the next overlapping range. A problem sometimes encountered with near neutral soils is the bleaching of the indicator dye when the paper is left in contact with the soil for more than a few seconds.

A battery-powered pH meter fitted with a combination electrode may also be used in the field, but in swamps and flooded rice fields it is difficult to keep equipment clean and to check readings against a buffer solution. In peat and unripe mud, the electrode may be inserted directly into the soil. Hard, sandy, and shelly materials may damage the sensitive tip and, in these cases, it is best to measure the pH in a paste made up with distilled water. Commonly, there is significant point-to-point variation in pH within any horizon. In raw acid sulphate soils, very low values develop along pores and fissures, while the soil matrix may remain 2 or more pH units higher. Obviously, it is worthwhile making several determinations on each soil horizon, but very precise measurements are not justified because of the inherent variability.

In waterlogged acid sulphate soils, for example in flooded rice fields, pH is raised by reduction processes. A pH determination after a few days or weeks of flooding may give no indication of acidity under oxidised conditions. This also applies to undrained potential acid sulphate soils. So long as they remain waterlogged, no acidity will develop. Potential acid sulphate conditions can only be positively identified by comparing the initial pH with the pH following incubation, or treatment with hydrogen peroxide.

Incubation

Potential acid sulphate soils can be identified by incubating moist samples in open, thin-walled polythene bags. This procedure simulates oxidation under natural conditions: although no leaching can take place in the bag, neutralisation by carbonates and some finely-divided silicate minerals does occur. A sample size of about 500 cm³ is suitable. Sometimes, pH drops rapidly within a few days and, with samples of this size, may continue to drop for at least a year if the sample is kept moist. For the sake of standardisation, three months incubation should be allowed.

Hydrogen peroxide

Treatment of a small sample with hydrogen peroxide (van Beers 1962) offers a quicker method of prediction. About 5 cm³ of soil is treated with 20 cm³ of 100 volumes hydrogen peroxide, heating if the mixture does not heat spontaneously to a temperature high enough to decompose the peroxide. The pH is determined after the peroxide is completely spent. pH values obtained by this method are usually lower than those obtained by incubation, and certainly lower than those developed in the field, because only finely-divided calcium carbonate is instantly effective in neutralising the acidity. In the field, and during several months incubation, coarse particles of calcium carbonate and more-slowly-acting minerals buffer the soil pH. This is not reflected by the peroxide test. Incomplete oxidation of organic matter also produces acidity.

Brinkman and Pons (1973) suggested a tentative limit for dangerous acid sulphate soils of pH 2.5 after peroxide treatment. This works well in practice – Figures 7.4 and 7.5 compare the pH values produced by incubation and peroxide treatment of peat and mineral soils.

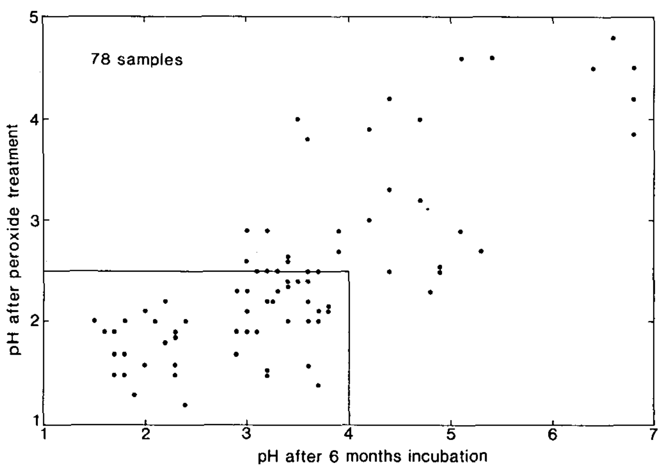


Figure 7.4 Relationship between pH after incubation and pH after peroxide treatment for peat soils, Norfolk, U.K.

Driessen (personal communication) has used hydrogen peroxide to test the microvariability of potential acid sulphate soils in the field as follows:

Clean the soil-profile face or gouge-auger sample and spray with universal soil pH indicator. Where the pH is in the range 6 to 8, an overall green colour is produced. Spray with hydrogen peroxide. Spray again with indicator. This time, concentrations of pyrite show as bands or patches of yellow or red.

BEWARE: 100 volumes hydrogen peroxide is a very hazardous reagent. Avoid contact with the skin and wash off any splashes immediately.

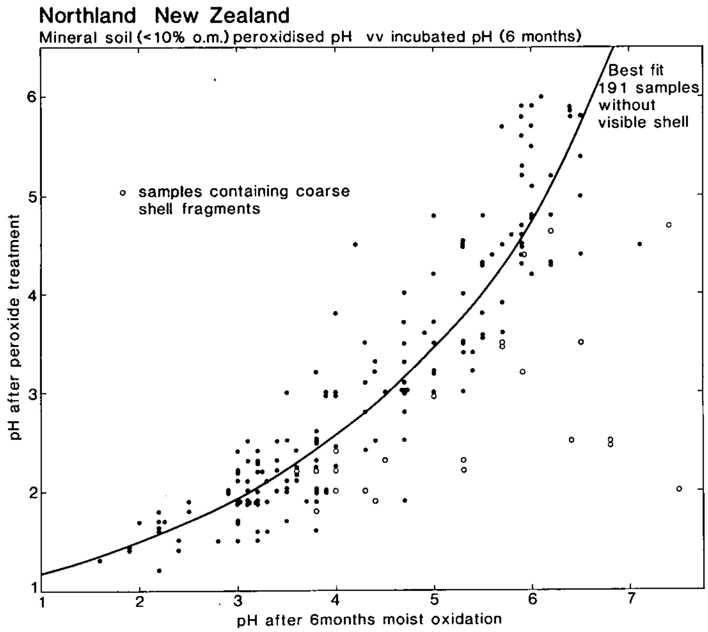


Figure 7.5 Relationship between pH after incubation and pH after peroxide treatment for mineral soils, Northland, New Zealand

7.3.3 Red lead

Wiedeman (1973) and others have used stakes painted with red lead to detect sulphidic material. Red lead is blackened within a few days by FeS and H_2S evolved in reduced sulphidic horizons. This indicates a pyrite-accumulating environment, but not the amount of pyrite present.

7.3.4 Sodium azide

Edelman (1971) developed a semi-quantitative method to estimate pyrite using sodium azide solution. Brinkman and Pons (1973) describe it as follows:

In a test tube, add 1 cm^3 concentrated soap solution (liquid detergent) and about 0.5 cm^3 sodium azide solution. (To prepare this solution, dissolve 1.27 g sublimated iodine and 2.4 g KI in 8 cm^3 water; dilute to 100 cm^3; add 3 g NaN_3 and dissolve; keep in brown bottle; prepare new solution frequently.) Add sample material equivalent to 0.2 g dry soil; stir carefully to avoid making bubbles, three times in 1 minute. The nitrogen gas, formed by the catalytic action of any sulphides present, makes foam.

The quantity of foam after 2 minutes is an indication of the sulphide present. For a few samples from Thailand, the following relation applied:

Foam 2 cm high	1.4 per cent sulphide S
Foam 0.3 cm high at margin and covering whole surface of liquid	0.8 per cent sulphide S
Foam 0.3 cm at margin not covering centre of liquid surface	0.4 per cent sulphide S
No foam	No sulphide S.

Coarse pyrite crystals will have less effect than an equal mass of finer crystals or aggregates. Other sulphides or organic sulphur compounds present might cause an exaggerated reaction, especially finely-divided FeS, or organic matter with a relatively high S content. However, within a local area, the size of pyrite crystals, the kind of organic matter, and other modifying factors might be fairly constant.

7.3.5 Calcium carbonate

Whether or not an acid sulphate soil develops depends upon both the amount of pyrite present and the amount of neutralising minerals, especially calcium carbonate. Shells can be seen in the soil profile. Finely-divided carbonates can be detected by the application of 10 per cent hydrochloric acid. The guidelines adopted by the Soil Survey of England and Wales (Hodgeson 1979) are as follows:

$CaCO_3$ %	Audible effects (hold close to ear)	Visual effects
0.1	None	None
0.5	Faintly to slightly audible	None
1	Faintly to moderately audible	Slight, just visible effervescence confined to individual grains
2	Moderately to distinctly audible; heard away from ear	More general effervescence visible on close inspection
5	Easily audible	Moderate effervescence; obvious bubbles up to 3 mm diameter
10	Easily audible	Strong effervescence; ubiquitous bubbles up to 7 mm diameter

Where FeS is present, treatment with hydrochloric acid gives rise to the characteristic smell of hydrogen sulphide. Pyrite does not react with hydrochloric acid.

7.3.6 Shear strength

The strength of materials can be measured on site most conveniently with a hand shear vane. Insert the vane vertically into the soil, and turn the spring-loaded dial until shear failure occurs in the soil. The instrument records the value at which failure occurs (the undisturbed shear strength), and the vane springs back. Continue turning the vane. Now the dial will record a reduced resistance following shear failure, equivalent to the shear strength of the remoulded or disturbed material. By using standard extension rods, shear vane readings may be obtained to depths of 1 m from the surface. Allowance can be made for the cohesive resistance of the extension rods for different depths of testing.

The shear strength of muddy sediments is due to their cohesion, which is directly related to their water content. Ripe and nearly ripe muds have a useful strength when remoulded. The remoulded shear strength must be used for calculations involving disturbed, excavated materials.

The shear strength of sand is due to the frictional resistance to individual grains moving past one another, which increases as the load applied increases. Sands have no cohesion and fail abruptly under shear stress.

Tables 4.3 and 4.6 include the range of undisturbed and remoulded shear strengths measured in tidal and empoldered soils in Northland, New Zealand.

7.3.7 Saturated hydraulic conductivity

The most suitable method to determine the saturated hydraulic conductivity (or permeability) is usually the auger hole method described by van Beers (1979). For in-field drainage, data may be required to depths of as much as 3 m. Even deeper borings may be needed for regional drainage studies or to assess the likelihood of seepage into a polder beneath the dikes. Measurements may be made in 8 to 10 cm diameter holes bored to the required depth. For measurements above the watertable, the test is best performed following saturation of the site. The hole is filled with water and the rate of fall of the watertable measured.

Measurements below the watertable are made by bailing out the auger hole and measuring the rate at which water flows in. Measurements should begin immediately after bailing and be completed before three-quarters of the water removed has been replaced by in-flowing groundwater, otherwise a funnel-shaped watertable develops, which reduces the rate of inflow.

Auger holes are difficult to make in practically unripe or half ripe mud, or in sand below the watertable. Holes in sand can be cased with perforated metal tube, inserted a few centimetres at a time as the hole is bored. For practically unripe and half ripe muds, a gouge auger can be used to obtain data for depths to 1 m.

7.3.8 Handling of samples

Sulphidic materials oxidise rapidly when removed from their natural environment. The most obvious chemical changes are the destruction of sulphides, evolution of acid, loss of carbonates, and changes in soluble salts and adsorbed cations. Where only a few samples are involved, oxidation can be avoided by complete filling of gas-tight containers, or removal of air with nitrogen gas, followed by rapid freeze drying; but these procedures are not practicable for a survey involving the collection and processing of hundreds of samples.

Drastic changes in the chemistry of the sample may be inhibited by collecting the fresh sample in a thin-walled polythene bag from which air can be squeezed, and securing the sample by knotting the neck of the bag. This bag should be enclosed in another, from which as much air as possible is removed before sealing. Labelling is best performed with a waterproof spirit pen on the outer bag. Muddy conditions and occasional leakage render paper or cardboard labels unsatisfactory.

Cold storage of the samples reduces oxidation prior to laboratory treatment, but a quick and reliable system of transport is obviously desirable. Once received, samples should be dried as quickly as possible. A forced-draught oven at 105° C is effective. To assist drying, unripe soils should be diced into small cubes as soon as they are sufficiently firm. Dry samples should be finely ground and stored in sealed bottles. Once a dried, ground sample has been prepared, most standard analytical procedures are appropriate. Only methods specific to acid sulphate soils are outlined below.

7.3.9 Organic matter

Wet oxidation with dichromate reagent is unsuitable for sulphidic soils because the dichromate reacts with pyrite. If a large number of samples are to be processed, organic matter is most conveniently estimated by ignition of finely-ground, oven-dry samples (5 to 10 g) in a muffle furnace for 16 hours at 375° C. At this temperature, carbonates, pyrite, and most clay minerals are stable, so the loss in weight is attributable mainly to the oxidation of organic matter.

7.3.10 Total sulphur

Where a large number of samples have to be processed, either oxidation in an induction furnace with automatic titration, or X-ray fluorescence may be used. Varley (personal communication) describes the induction furnace method used by the Tropical Soils Analysis Unit of the ODA, Reading, U.K. as follows:

Mix 0.05 g of finely ground soil with iron and tin, and place the mixture in a muffle furnace at 450° C for 30 minutes to destroy organic matter. When cool, place a 0.05 g copper ring on top of the sintered mixture and heat rapidly in a 'Leco' induction furnace to 650° C in a stream of oxygen. This converts the sulphur in the sample to sulphur dioxide, which is absorbed in hydrochloric acid containing sodium azide, potassium iodide, and starch. Remove halide interferences by passing the evolved gases through crushed antimony. Sulphur dioxide destroys the starch-iodide blue complex. To restore the original blue colour, add iodate solution from the automatic titrator as combustion proceeds. The volume of the potassium added is proportional to the sulphur content of the sample. (See also Tabatabai 1982).

For the X-ray fluorescence technique, take a dried sample, ground to less than 30 micrometres, and press it directly into pellets, using borax as a carrier. Then compare the X-ray fluorescence with a range of standard samples (Darmody et al. 1977; Tabatabai and Bremner 1970).

Besides sulphide S, total sulphur includes sulphur in stable organic compounds as well as acid sulphates and gypsum. However, in most sulphidic soils, nearly all the sulphur occurs as pyrite.

7.3.11 Pyrite

The determination of pyrite is more difficult and time-consuming than the determination of total sulphur. Pyrite may be estimated by the difference in the sulphate content of a sample before and after oxidation with hydrogen peroxide.

A rapid semi-quantitative microscopic method of estimation was developed by Pons (1964) and modified by Slager (1967) as follows:

Take a sample of about 1 g of dry soil and place it in a small plastic tube or bottle with 10 cm^3 water. Add some steel balls, 4 to 5 mm diameter, to speed dispersion, and shake. Immediately after shaking, place a drop of suspension (0.05 cm^3) on a microscope slide, using a small pipette. Evaporate most of the water by heating gently, then add a drop of glycerine. Make a homogeneous suspension by stirring with a needle, and cover with glass of known surface area. In the preparation, pyrite bodies can be recognised as spheres, clusters of spheres, or – more rarely – angular fragments, opaque in transmitted light, or very bright metallic green in incident mercury light (see Plates 4.8 and 4.9). Count all the pyrite bodies with their centres within strips of, for example, 400 micrometres wide and 10 mm long. Count the pyrite bodies in size classes , diameters of 2 to 6, 6 to 10, ...58 to 62...... micrometres. These would be equivalent to 1, 2, ...15,....units of an ocular micrometer (10 mm in 10 division) with a 25 × objective magnification.

Calculation:

mg FeS_2 pyrite sphere of D micrometres diameter equals:

$$5.0 \times \pi/6 \times D^3 \times 10^{-9} = 2.6 \times 10^{-9} \times D^3$$

mg S in pyrite sphere of D micrometres diameter equals:

$$64/120 \times 5 \times \pi/6 \times D^3 \times 10^{-9} = 1.4 \times 10^{-9} \times D^3$$

Percentage by mass of FeS_2 or S equals:

$$20 \times B/A \times (\text{total mass of } FeS_2 \text{ or S counted, mg})$$

B is the surface area of the cover glass and A is total surface of strips counted, in square millimetres.

7.3.12 Lime requirement

The lime requirement is the amount of limestone needed to raise the pH of the soil to a level satisfactory for crop production. Usually, it is expressed as tonnes $CaCO_3$-equivalent per hectare. Because of the great point-to-point variation in acidity or potential acidity and the difficulties of applying the very large amounts of lime and incorporating it throughout the desired rooting zone, very precise determination of the lime requirement is not justified.

Depending on the speed required and the facilities available, the lime requirement may be determined by incubation with powdered $CaCO_3$ or by peroxidation followed by titration.

Incubation

Take several 100 g samples of dry soil or 100 cm^3 of soil in field condition. Mix each sample thoroughly with powdered $CaCO_3$. A range of 0.1 to 10 g $CaCO_3$ should be suitable. Incubate under moist conditions in glass jars or polythene bags for three months, stirring monthly. If the lime required for flooded conditions is wanted, incubate under flooded conditions.

Measure the pH at the end of the period of incubation. Plot a graph of pH against the mass of $CaCO_3$ added and select the lime requirement to achieve the desired pH. Table 7.4 gives the lime requirement that corresponds to a range of $CaCO_3$ additions to the sample, assuming an apparent soil density of 1 g cm^{-3}.

Table 7.4 Lime requirement determined by incubation

g $CaCO_3$ added to 100 g sample	0.1	0.5	1	2	5	10
t $CaCO_3$ ha^{-1} per 10 cm depth	1	4.8	9.1	19.6	47.6	90.9

During incubation, some of the residual pyrite in the sample will be oxidised and this will be reflected in the lime requirement.

Rapid titration

Take 10 cm^3 soil and add 25 cm^3 100 volumes hydrogen peroxide. Titrate back to pH 5.5. Disposable syringes of volumetric alkali can be used. 10 cm^3 of 0.1 molar sodium hydroxide is equivalent to 5 tonnes $CaCO_3$ ha^{-1} per 10 cm depth.

7.3.13 n-value

Field assessment of ripeness and its more precise determination in terms of n-value (the quantity of water in grams absorbed by one gram of clay) were described in Section 3.5. To obtain the n-value, we need to know water content, organic matter content, and particle size distribution. Water content is easily determined by weighing a sample in field condition, drying at 105° C, and reweighing.

Particle size distribution is most conveniently determined by the hydrometer method (for example British Standard Institution 1977). It is best not to dry the sample before-hand, but to correct for the mass of water in the field sample. Dispersion may still be difficult because of the presence of soluble salts and the aggregation of clay and organic matter. Hydrogen peroxide treatment intended to destroy organic matter produces a vigorous reaction with sulphides. Satisfactory dispersion can usually be achieved by washing to remove soluble salts, addition of sodium hexametaphosphate dispersing agent, and ultrasonic treatment.

7.3.14 Apparent density

The apparent density, or dry bulk density, is a useful indication of ripeness (Figure 7.6). To determine it, weigh, dry, and reweigh samples of known volume, correcting for the mass of the container:

$$\text{apparent density (g cm}^{-3}\text{)} = \frac{\text{mass of oven dry soil (g)}}{\text{volume of soil in field condition (cm}^3\text{)}}$$

Samples can be collected from unripe soils in light alloy cylinders, sharpened at one edge, which are pressed directly into the profile face or into a sample collected with a large gouge auger. Cylinders, 50 mm long, cut from 40 mm diameter tube (62.8 cm^3) are suitable for sampling unripe soils (Section 7.2.3). A crude estimate of shrinkage during ripening may be made by measuring the core sample after drying.

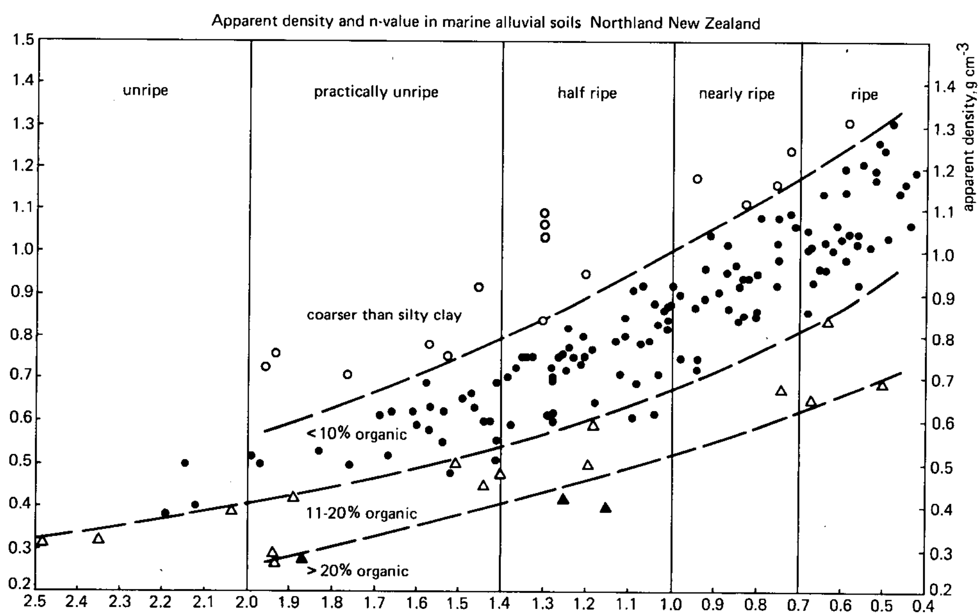


Figure 7.6 Relationship between apparent density and n-value in marine alluvial soils, Northland, New Zealand

7.3.15 Unit weight (γ)

The unit weight of a material is derived from the wet soil density multiplied by g, the gravitational constant. To determine it, collect an undisturbed sample of known volume, weigh it, and correct for the mass of the container.

$$\gamma(\mathrm{kNm}^{-3}) = \frac{\text{mass (kg)}}{\text{volume (m}^3\text{)}} \times g \; (6.673)$$

The unit weight of unripe mud usually lies between 15 and 18 kNm^{-3}; the unit weight of ripe materials is greater.

7.4. Land Evaluation

Land evaluation is the assessment of the performance of the land, or its potential performance, under specified kinds of management. The purposes of land evaluation are:

- To enable a choice to be made between alternative development options;
- To specify the extent and distribution of land suitable for any selected land use;
- To predict the consequences of applying specified kinds of management to particular areas of land, in terms of:
  - Inputs and other costs;
  - Crop yields or other benefits;
  - Environmental impact.

A Framework for Land Evaluation has been put forward by FAO (1976); its procedures are described in detail by Dent and Young (1981) and by FAO (1984). Essentially, the stages are:

- Establishment of development objectives;
- Identification of alternative systems of land use (land-use types);
- Establishment of the requirements of each land-use type in terms of:
  - Produce;
  - Technology;
  - Scale of operations;
  - Labour intensity;
  - Capital investment;
  - Management;
  - Physical land qualities;
- Survey of critical land qualities and other requirements;
- Matching of the land requirements of each land-use type with the land qualities of specific areas of land – usually these areas will be soil mapping units;
- For each land suitability unit, which may be a group of several soil mapping units, prediction of:
  - Production;
  - Kinds and amounts of inputs required (for example seed, fertilizer, drainage, labour, machinery;
  - Benefits and costs;

• Social consequences (for example opportunities for employment);
• Environmental impact.

The land-use types most likely to be considered on acid sulphate soils, were discussed in Section 2. They are:

- Conservation of the existing ecosystem or landscape;
- Systematic exploitation of natural products (especially fishing and mangrove forestry);
- Rain-fed rice;
- Arable crops other than rice;
- Tree crops (oil palm, coconut, cocoa);
- Intensive grassland management (in temperate regions);
- Ranching (extensive grazing in sub-tropical regions);
- Forestry (*Casuarina*, *Melaleuca*, in sub-tropical regions);
- Fish ponds (including shellfish);
- Reservoirs;
- Salt pans;
- Industry and urban development.

A lot of work is needed to establish what the requirements are for each land-use type, in terms of physical land qualities, and of soil characteristics in particular. Table 7.5 lists the land qualities that are relevant to most kinds of agricultural development and are limited by the special characteristics of acid sulphate soils. These unfavourable qualities do not necessarily exclude successful development, but they do impose strict demands on engineering and management, especially in respect of control of the watertable.

Usually, acid sulphate soils will be evaluated in the context of land reclamation, which involves control of the watertable, protection against flooding, and the introduction of a more productive system of land use. This investment of people and resources deserves a detailed evaluation of alternative systems of management. Often, in the past, acid sulphate soils have not been recognised at the planning stage of land development projects, and this has led to failure, or unacceptable social, economic, or environmental costs. In other cases, when they have been recognised, the immediate reaction of soil specialists has been to dismiss the prospect of successful reclamation. Neither case is of service to land development.

Usually, response to management is determined by the interaction of soil characteristics and climatic factors. So the response of land to drainage depends on climate, topography, hydraulic conductivity, acidity or potential acidity, and the depths at which limiting soil horizons occur.

The value of systematic land evaluation lies in:

- Consideration of the *interactions* between soil and water. Brinkman (personal communication) has identified four contrasting environments, each with different implications for the use of acid sulphate soils:
  • Wet, big water surplus;
  • Wet, no water surplus;
  • Seasonally dry, > 1 month dry season, seasonal water surplus;
  • Dry, no water surplus.

  Where there is a big water surplus, the main management problem is drainage. Aci-

Table 7.5 Land qualities affected by characteristics of acid sulphate soils

Quality	Soil characteristic
Water availability	*Available water capacity* – reduced by restriction of rooting. Either effective soil depth is limited, or the ramification of roots is restricted.
Oxygen availability to roots (Drainage)	*Topography* – flat or depressional relief and high watertable. Conventional drainage techniques will exacerbate acidity; *Saturated hydraulic conductivity* – often low in unripe clay subsoils, reducing drainage through the soil; ochre deposition in field drains.
Nutrient availability	*Low absolute nutrient levels*, as a result of prolonged acid leaching in sands and in ripe acid sulphate clays, peats, and mucks; low Ca, Mg, K, and micronutrients; *Low mineralisation* of nitrogen and organic phosphate, as a result of acidity; *Immobilisation of phosphate* by iron and aluminium under acid conditions.
Rooting conditions	*Toxicity* and *poorly-structured clay subsoils* limit effective rooting depth and ramification.
Flood hazard	*Topography* and *hydrology* – risk of tidal flooding by saltwater, and river flooding during the wet season; *Saturated hydraulic conductivity* – low in clays, leading to surface ponding after heavy rain.
Excess of salts	*Salinity* – in saline sulphidic and saline acid sulphate soils, reduces uptake of water by the crop.
Soil toxicity	*Aluminium toxicity* – at pH values <4; *Iron (II),* CO_2 *and* H_2S *toxicity* in flooded soils.
Potential for mechanisation and access	*Low strength* and *low saturated hydraulic conductivity* of disturbed, unripe, and puddled clays, demanding costly all-weather roadways; limited period of workability.
Engineering stability	*Excessive consolidation* and *low bearing strength* – in unripe soils; *Poor colonisation* of earthworks by vegetation – erosion hazard from rain and floodwaters.
Corrosivity	*Acid, high-sulphate soil and drainage waters.*

Table 7.6 Current land suitability, Láng Biên Farm, Mekong Delta, Vietnam: provisional suitability based on field observations (van Mensvoort, personal communication)

Soil mapping unit	Soil Taxonomy classification	ILRI classification	Land-use type					
			Irrigated double-cropped rice	Floating rice	Lotus	Jute	Cattle grazing	*Melaleuca* forestry
Mý Hôi series	Typic and Humic Tropaquepts	Ripe clay	S1	S1	S1	S1	S1	S1
Bin Thanh Trung series	Typic Tropaquepts, inclusions of Sulfic Tropaquepts	Ripe clay, inclusions of clay with acid sulphate subsoil	S3	S2	S2	S2	S2	S1
Kháng Chiên series	Sulfic Tropaquepts	Ripe clay with acid sulphate subsoil	N	S3	S3	S2	S2	S2
Láng Biên series	Sulfic Tropaquepts and Sulfaquepts	Ripe clay with raw acid sulphate subsoil	N	N	N	N	N	S3
Xáng series	Sulfaquepts	Raw acid sulphate clay and muck	N	N	N	N	N	S3

Land Suitability Classes:

S1 most suitable
S2 suitable
S3 marginally suitable
N not suitable

dification can be limited by maintaining a high watertable (Section 2.5). Acid sulphate conditions exert increasingly severe constraints where there is a dry season of more than a few weeks. The available water capacity, determined mainly by the thickness of the non-acid topsoil, then becomes a critical land quality. Land-use possibilities are also determined by the duration of flooding, and whether the flood is of tidal saltwater, alternating salt and freshwater, or fresh river water.
- Recognition of the diversity of soils that are grouped under the heading of acid sulphate soils. Potential acid sulpate soils, raw acid sulphate soils, ripe acid sulphate soils, and acid aluminium-saturated soils present different management problems and have different capabilities. Likewise, peat, muck, sand, unripe clay, and ripe clay present quite different engineering problems.
- Identification of both the unfavourable and favourable qualities of areas of acid sulphate soils. Favourable qualities can include climate, topography, technically-easy reclamation, slow permeability, and proximity to other land of high value or intensive use.

For land-use planning, a reliable prediction of the performance of a tract of land under each viable, alternative system of management is needed. In the case of agricultural systems, this involves an estimate of crop yield and the inputs required to achieve this yield. These can be ascertained by trials, or by analogy with similar systems elsewhere. At present, there are many weak links in the procedures of land evaluation. These include:
- Vagueness of information on crop requirements;
- Scarcity of information on crop performance in relation to many specific soil characteristics, such as tolerance of soluble aluminium and iron;
- The lack of any rational, generally-applicable way of modelling the combined effects on crop yield of several limiting characteristics;
- Inadequate site characterisation for most existing trial data, which makes it difficult to transfer information on crop response to other areas.

However, even where systematic crop data are not available, useful guidelines can be produced by relating observation of crop performance to soil type and water regime (for example Table 7.6).

To translate land evaluation into financial or economic terms, the production and inputs of each alternative system of management must be costed. This involves an estimate of crop yields, or other benefits, and prescriptions of the land improvements and management practices that are needed to avoid, or overcome, acid sulphate problems (for example Turner et al. 1983).

It is not possible to stipulate any general level of production that will be economic. There may be social reasons for an investment in major land improvements that will not yield a financial return, but a land reclamation or improvement project should at least be able to support the people directly involved and cover the continuing costs of maintainance of dikes, floodgates or pumps, drains, and roads.

Much work, theoretical and practical, remains to be done if we are to manage acid sulphate soils with confidence....which brings us full circle, to the Recommendations for Action and Targets for Research that were presented at the beginning of this book.

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