

## DEVELOPMENT OF ACID SULPHATE SOILS IN NILWALA FLOOD PROTECTION AREA, MATARA, SRI LANKA

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### ABSTRACT

Development of acid sulphate soils was observed in some paddy fields of Nilwala flood protection area in Matara district. Field investigations, borehole data and chemical evidence that cause the abandoning of most of the paddy fields showed occurrences of sulphide-bearing sediments at depths ranging from 2 to 5m at Malimboda and Kapuduwa. Soils contain potentially acidic substances such as jarosite, ferric hydroxide, gypsum and aragonite. The pH of these soils is around 4.0. The total potential acidity values of the study area have very much exceeded the standard action criteria levels. The levels of potential and actual acid sulphate soils are also significantly higher than normal values in both study sites. The Eh-pH diagram representing the samples of Malimboda and Kapuduwa have shown that many points in this study fall within the Fe<sup>2+</sup> field, indicating possible disequilibrium with respect to Fe-bearing minerals. Preventive measures are suggested to reduce the harmful effects of toxic substances generated in the acid soils. Using proper soil management systems and selection of rice varieties tolerant to this specific environment, the abandoned paddy lands can be re-cultivated to increase the rice production of Matara district.

**Keywords:** acidic sulphate soils, toxic substances, soil management, rice varieties

### INTRODUCTION

The south-west coastal belt of Sri Lanka is subjected to frequent flooding and high urbanization with development activities which facilitate the formation of Acid Sulphate Soils (ASS) in most coastal belts. Acid sulphate soils are characterized by the occurrence of pyritic minerals in subsoil. When such soils are drained and aerated, pyrite is oxidized and hydrolysed, often releasing toxic quantities of sulphuric acid, iron, aluminium and heavy metals. The 'Nilwala Flood Protection Scheme (NFPS)' based on the Nilwala River basin near Matara, is a drainage project, implemented to protect the town of Matara and other villages from floods. Implementation of the project has led to abandoning of paddy lands and the rice yields of Matara district have been severely reduced. Investigations were carried out to find out the causes of such problems.

The term acid sulphate soil has been applied to soils and sediments in which sulphuric acid will be produced or has been produced in sufficient quantities to have a lasting effect on the main soil characteristics (Pons, 1973). Sedimentary materials that contain iron sulphide (usually pyrite, FeS<sub>2</sub>) in a reduced or waterlogged condition, in which no oxidation has taken place, are identified as Potential

Acid Sulphate Soils (PASS). Actual acid sulphate soils (AASS) contain pyrite that has oxidized to form sulphuric acid thereby decreasing the pH to less than 3.5 (Fitzpatrick *et al.*, 1998). The process of developing sulphuric acid in acid sulphate soils is accelerated by bacteria such as *Thiobacillus ferrooxidans*. Optimum conditions for the formation of ASS are; (i) oxidation of pyrite accelerated by iron oxidizing bacteria, in particular *Thiobacillus ferrooxidans*, (ii) oxygen concentration > 0.01 mole fraction (1%), (iii) temperature 5-55° C (tropical environment) and (iv) pH 1.5-5.0, optimally 3.2 (Fitzpatrick *et al.*, 1998). The characteristic mineral compounds formed in acid sulphate soils including jarosite, natro-jarosite, allunite, jurbanite, basaluminite, goethite, haematite, ferric hydroxide, gypsum, and pyrite (van Breemen, 1972). Jarosite [KFe<sub>3</sub>(SO<sub>4</sub>)<sub>2</sub>(OH)<sub>6</sub>] is an intermediate oxidation product of ferrous sulphate in an acid medium. Jarosite appears in the pores and cracks of the soil as pale yellow (or straw yellow) mottles, and is indicative of acid sulphate soils. Jarosite is further hydrolyzed in a less acidic medium eventually precipitating iron as hydrated ferric oxides, releasing more acidity. The acidity produced by pyrite oxidation may be neutralized if there is a large amount of lime (CaCO<sub>3</sub>) contained in the sediment or brought in by sea water. In some coastal areas, plenty of fine gypsum crystals can be seen in the soil as a

result of the neutralization reaction. However, in most of the humid tropics, the carbonate content is low or nil. Acidity remains in the soil to give a pH sometimes as low as 3 (Van Breemen and Wielemaker, 1974).

Disturbance and exposure of acid sulphate soils by inappropriate development in agriculture, new drainages, road constructions, excavations of canals and fluctuation of groundwater levels can facilitate the oxidation of pyrite. This leads to release of high amounts of acidity into the soils and the environment (Shamshuddin and Auxtero, 1991). This acid reacts with host clay minerals to release silica and metal ions, specially, aluminium, iron, potassium, sodium, magnesium, manganese and trace heavy metals (Sammut *et al.*, 1996). Detrimental impacts of sulphide oxidation include decreased plant growth, corrosion of engineering infrastructures, massive fish deaths and fish diseases and dramatic changes in the stream ecology (White *et al.*, 1997).

Deposits of acid sulphate soils are commonly found in low lying coastal areas of less than 5m above the mean sea level (MSL), such as estuaries, salt marshes, wetlands, lagoons etc. Such deposits are still forming today in such environments while some were formed millions of years ago and occur in ancient marine rocks. These were formed after the last major sea level rise within the past 10,000 years in the Holocene Epoch (Katupotha, 1998).

The western and south-western coastal belt of Sri Lanka encloses an area of 30,000 ha of low-lying lands with the potential for development of acid sulphate soils (ASS). Many lagoons in the southernmost part of Sri Lanka have turned in to salt lakes, salt marshes or even sand and mud flats. The western coast is composed mainly elongated lagoons separated from the open ocean by barrier islands, the area covered being about  $20 \times 10^3$  hectares. Among the largest open lagoons in the western coast are those at Negombo, Puttalam and Mannar. The barrier island which forms the Negombo lagoon can be traced further south, towards Colombo. Negombo lagoon is the largest open lagoon in the western coast and it also forms the western boundary of the Muthurajawela peat bog. This swamp extends to an area of 20 km<sup>2</sup> and is estimated to contain 50 billion MT of peat that contains about 25-40% carbon. Peat layers are extensively seen in Muthurajawela swamp. The occurrence of peat in other areas is less extensive and is found in an irregular manner (Senaratne *et al.*, 1989). The age of peaty layers is about 30,000 years. In Sri Lanka, wetlands and other peat forms environments occur mainly in the south-west coastal plains extending from Negombo to Panadura (Gurusinghe, 2006).

These areas are sites of high urbanization with many development activities carried out in the recent past.

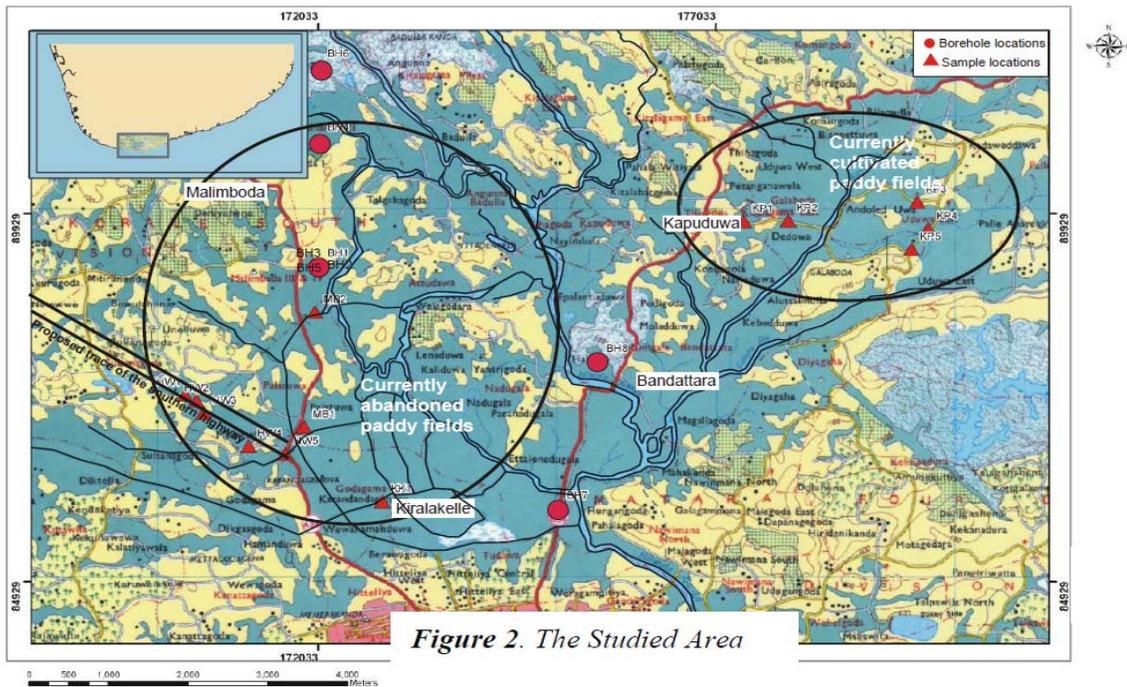
Hence, the possibility of the formation of ASS from potential acid sulphate soil (PASS) in the southern coastal belt is rather high. Major rice growing areas of the south-west coastal plain in Sri Lanka are coastal swamps or estuaries where seasonal flooding is often experienced.

The Nilwala Flood Protection Scheme (NFPS) is a drainage project, implemented to protect the town of Matara, and other villages from floods. Although the occurrence of major floods was curtailed, about 1,000ha of paddy fields in the right bank of Nilwala River have now been abandoned after the project and, rice yields sharply decreased (Balasuriya, 1987; Dent, 1987). Drainage and flood mitigation activities may have altered the natural hydrological regime of the floodplains. This project probably increased acidity by oxidising sulphides in large areas of floodplains and wetlands, which were drained for agriculture and urban development during the NFPS. It is unclear how much of the existing sulphide oxidation and its concomitant acidity is actually caused by excavations. Increasing salinity of water and soils has perhaps caused the abandoning of paddy fields. Although the processes and controls of pyrite oxidation are known, the spatial distribution of acidity in the landscape is not understood. Dent (1986) pointed out that ASS was not uniformly and equally debilitating, but only a few studies have investigated spatial variations in these soil properties and their causes.

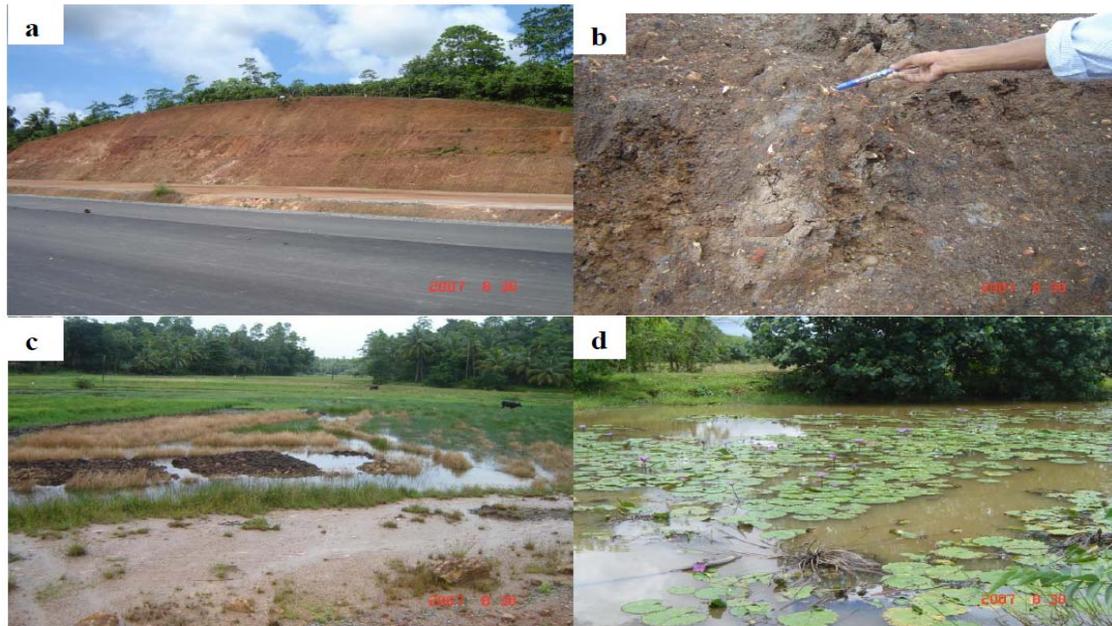
This paper describes the spatial distribution of total actual acidity (TAA) in areas affected by Nilwala Flood Protection Scheme and outlines the underlying physical reasons for the observed pattern. It also describes the determining factors controlling reducing conditions of acid sulphate soils of the NFPS and the effects of monsoonal rain, pH, Eh and solution chemistry.

#### **Study Area**

The study area (Figure 2) located in the flood plains of Nilwala River has a marked wet season from May to December (170 km -182 km E, 84 km-90 km N). The floodplain vegetation at the time of flood protection project comprised mainly paddy fields and mangrove forests. Mangroves were identified only at the marshy area of *Kirala Kele* (Figure 2). Very little natural vegetation is observed in the area of the flood plains. Two study sites (Malimboda and Kapuduwa) were selected based on field observations of the paddy cultivation. In Malimboda, most of the paddy fields have been abandoned in recent times whereas in Kapuduwa was selected because successful paddy cultivation observed before the NFPS had shown no effect even after the flood protection scheme. Constructions of the Southern Highway Development Project are under way in the vicinity of the Malimboda site.



**Figure 2:** Study area around Malimboda and Kapuduwa



**Figure 3:** Field observation of the Malimboda sampling site; (a) View of the newly constructed Matara-Colombo highway; (b) Peaty soil layer found below the ground level of the southern highway project; (c) Grey colour peaty soil was found at the middle of the abandoned paddy field where paddy is almost dead; (d) Huge canals excavated by the Nilwala flood protection scheme.

Malimboda site is located at 5 km away from the Matara town along Matara-Akuressa access road of the proposed Matara-Colombo highway where cut and fill sites are common (Figure 3a). Grey-black coloured peaty soil is heaped in both sides of the highway. Excavated sub soils can be seen in banks of canals (Figure 3b). Sea shells can also be observed in that soil. The abandoned paddy fields distributed over a large area of this site (Figure 3c). Red colour iron stains were found in shallow canals and drainages everywhere in the paddy fields (Figure 3d). Huge canals could be observed throughout the area in both study sites. However, successful paddy cultivation has been operated even after the flood protection scheme in the area around Kapuduwa site although the red colour iron stains were found in some paddy fields.

## METHODOLOGY

### *Sediment Collection and Handling*

Sample collections were performed from August to October, 2007, during the period of south-west monsoon. Samples from Nilwala River flood plain in Malimboda and Kapuduwa were collected from open pits, road cuts and drain sites using a hand auger. Borehole data obtained during the construction of the project was used for profile study (see Figure 2). Samples were taken at dense intervals around the groundwater table, where drastic changes in pH and redox potential were expected to occur.

Observations were made at each field site to determine the potential risk of ASS. Soil samples were collected for chemical analyses. Observations included: (i) nature of disturbance (ii) water logged conditions (iii) occurrence of fine clay and silts/peat (iii) presence of yellow jarositic mottles in the excavated soil; (iv) iron stain or red precipitate; (v) corrosion on concrete or steel structures; (v) presence of beach sediments; (vi) presence of needle like white crystals and (vi) soil field tests (texture, colour, mottling etc). A complete profile sample was taken from Malimboda site representing three groups of horizons, the lateritic and underlying transitional horizons and peaty soils (Figure 3a and b).

Twenty (20) sites were selected for the study based on the results of the best studies. These were investigated during field visits in late August and October 2007. Visual observations were made at each site, which resulted in twelve (12) locations being considered for sediment sampling. The profile sampling strategy at each site was based on the nature of sediments, changes in lithology and depth to standing water. Table 1 shows site information of the twelve selected sites.

### *Sample treatment and analysis*

Soil samples were collected properly into the polythene bags and labelled. All samples were taken to the laboratory for analysis. Bulk samples were packed in airtight conditions and transported to the laboratory for characterisation. Wet samples were used for chemical analyses and results were corrected to oven – dried moisture content.

Total actual acidity, total potential acidity and total sulphide acidity were measured as acidity parameters in soil samples. Also, fresh pH values and pH after the oxidation with hydrogen peroxide were measured and strength of the peroxide reaction was observed. The pH was measured on fresh samples after shaking the samples in de-ionised water (1:2.5) at room temperature. The remaining samples were dried at 35°C and sieved through a 2-mm mesh for remaining analyses. Titration method was used to measure acidity parameters. Total actual acidity (TAA) is determined by titration of a 1M KCl salt solution extract to pH 5.5. For each sample 1:5, sediment: water extracts were prepared using 10 g of soil and 50 ml of KCl solution. Aliquots of these extracts were used to measure TAA (Konsten *et al.*, 1988). For the samples with pH<5.5, a 25 ml aliquot was titrated using 0.01 M sodium hydroxide (NaOH) to an endpoint of pH 5.5, and the amount of total actual acidity present calculated in mol H<sup>+</sup> ton<sup>-1</sup> after correcting to the dry weight of soil for each horizon depth increment. All organic matter was oxidized before the titration. Total potential acidity (TPA) for each sample was determined by peroxide double oxidation method (Konsten *et al.*, 1988).

For the calculation of the potential acidity of soil sample, complete oxidation of total oxidisable sulphur method was used. However, other reduced forms of nitrogen, phosphorous etc may also form acidic compounds during peroxide oxidation there by contributing to the potential acidity. Nevertheless, the experience in other countries show the amount of sulphur based acidity is the key contributor of ASS. For each sample, 1:5 sediment: water extracts were prepared using 10 g of soil with 50 ml of KCl solution.

The samples were left to stand overnight and additional aliquots of 30% H<sub>2</sub>O<sub>2</sub> were added until oxidation ceased. The samples were heated to allow excess H<sub>2</sub>O<sub>2</sub> to decompose. The samples were returned to room temperature, filtered and de-ionized water was added to bring the sample to the original 1:5 composition. An aliquot was titrated using 0.01 M NaOH to an endpoint of pH 5.5, and the amount of total potential acidity present was calculated in mol H<sup>+</sup> ton<sup>-1</sup> after correcting to the dry weight of soil. Total sulphidic acidity (TSA) was determined by subtracting TAA from TPA.

Five representative samples taken from the Malimboda site were air dried, powdered and sieved using 63µm sieve for XRD analysis at the Department of Chemistry, University of Peradeniya. X-ray diffractograms were obtained for randomly oriented powders with a Cu X-ray tube. Samples were step scanned from 5° to 80° using a 0.05° step and a 4s count time. All the samples collected from the Malimboda and Kapuduwa sites were analysed

for Iron (total) using AAS. The samples were kept in an oven at 65°C until a constant weight was obtained. Then the dried sample was sieved using a sieve with the mesh size of 200 µm. 0.5000 g of each sample was weighed and digested using 5.00 ml of 1 % HNO<sub>3</sub> and 2.00 ml of H<sub>2</sub>O<sub>2</sub> for 30 min. Then it was filtered and transferred into a volumetric flask and diluted up to 25 ml using de-ionized water.

**Table 1:** Description of Sampling Sites at Malimboda and Kapuduwa (KP denotes sites from Kapuduwa whereas the rest are from Malimboda)

Location	Description	GPS position (National UTM Coordinates)
HW 01 A, B, C	Road cut. Soil profiles were taken from the top to bottom (A-C)	170.364 N, 087.469 E
HW 02 D, E	Abandoned paddy-field, grasses are dominant, some grass near the highway are destroyed	170.509 N, 087.390 E
HW 03 P, Q	Excavated peaty layer, thick band of peat layer had been exposed in the vicinity of the highway, sea shells observed	170.598 N, 087.223 E
HW 04	Excavated soil	171.165 N, 086.775E
HW 05	Excavated yellow soil	171.623 N, 086.671 E
MB 01	Canal bank of Unalla, Sea shells observed	171.863N, 087.034 E
MB 02	Abandoned paddy field of Jayanthipura	171.998 N, 088.595 E
KK	Kiralakelle, a marshy land	172.842 N, 086.021 E
KP 01	Paddy field and canal bank – Dedduwa	177.379 N, 089.826 E
KP 02	Cultivated paddy field – Dedduwa	177.938 N, 089.837 E
KP 03	Cultivated paddy field – Kapuduwa	179.558 N, 090.090 E
KP 04	Abandoned paddy field – Kapuduwa	179.695 N, 089.728 E
KP 05	Canal bank – Galaboda	179.484 N, 089.444 E

The iron concentration of each sample was measured using atomic absorption spectrophotometer at the Faculty of Fisheries and Marine Science, University of Ruhuna.

Sediment pH and Eh (reported versus the standard hydrogen electrode; SHE) were determined, within 4 hr of sample collection, by preparation of KCl extracts. For each sample 1:5, sediment: KCl extracts were prepared using 5g of soil and 25ml of KCl solution. The pH and redox potential (Eh) values of the extracts were measured using the pH meter. The Eh–pH diagrams for iron (Fe) and sulphur (S) species were plotted and the standard Pourbaix diagrams were drawn.

## RESULTS AND DISCUSSION

### Soil characteristics

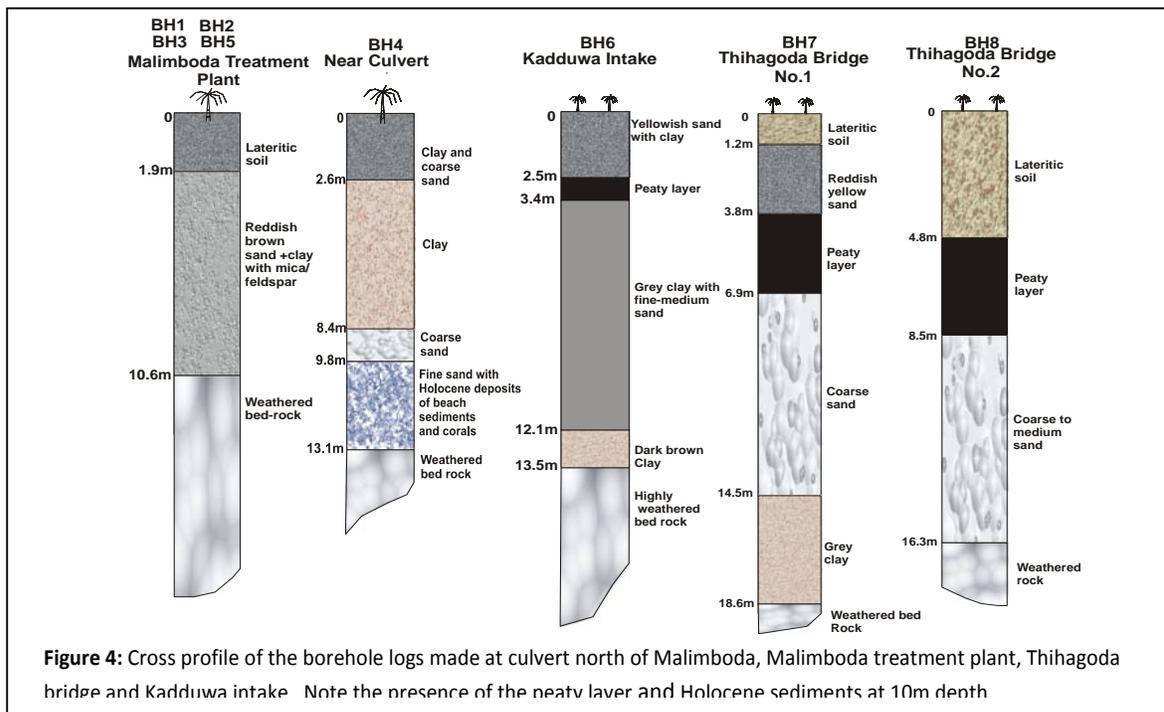
Coastal ASS can be found where elevation is below 5 m. ASS layers are common at or less than 1.5 m above high tide level but may be buried by many metres of alluvial material when located in major river systems. Figure 4 shows the generalised cross section of soil profile of 8 boreholes taken from the

Malimboda and Kapuduwa sites. The profile descriptions of BH-1, BH-2, BH-3 & BH-5 indicate a fairly consistent stratigraphy, although the boundaries between units vary in depth. Most profiles show fairly similar sequences with minor variations.

These profiles contain two distinct horizons: the A horizon made up of lateritic cap; and the B horizon, consisting of reddish brown sand with layers of weathered mica and feldspar. No peaty layer was observed in such profiles. A marshy land called ‘Kiralakelle’ is located near the Malimboda sampling site (Figure 1). However, the possibility of formation of ASS due to anthropogenic fluxes of sulphur in the marshy land is remote because it is an area protected by the Department of Wildlife. However, borehole logs taken from north and east of the site (BH-6, BH-7 and BH-8) at Malimboda, Kiralakelle, Bandattara and near Thihagoda bridge show up to 4m thick peaty layers (Figure 4 and see also Figure 1 for borehole locations). Lateritic soil caps underlain by several types of clay, silt and peat layers lying on bed rock were observed in such profiles. Discontinuous patches of Peaty layers were observed in locations situated northern, western and eastern parts of the

Malimboda site. Borehole log data and field studies showed a sub soil in the Malimboda site (BH-04) containing beach sediments (exo-skeletons of fossilised marine micro fauna). Although borehole logs were not available from Kapuduwa site, BH – 07

and 08 can be used as representative samples in this area. It clearly mentioned that peaty layers extended further towards Kapuduwa site through Galaboda and Deeyagaha areas.



**Figure 4:** Cross profile of the borehole logs made at culvert north of Malimboda, Malimboda treatment plant, Thihagoda bridge and Kadduwa intake. Note the presence of the peaty layer and Holocene sediments at 10m depth.

This is supported by the observation that peaty soil excavated by the NFPS could be seen on the canal banks even today, two decades later.

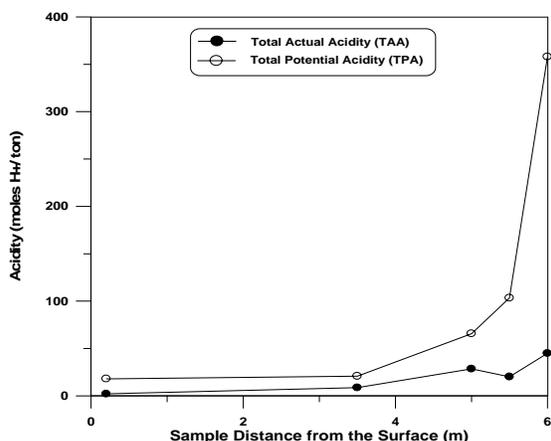
**Determination of Acidity Parameters**

Table 2 presents the results of acidity parameters and pH. The TAA, TPA and TSA were expressed in mol of acidity / tonne. Samples HW 01 A, B, C, HW 02 D and E were taken from the top and bottom respecting of a size profile in the Malimboda site. The acidity results showed that the potential acidity of those samples increased with depth from the surface as shown in Figure 5. The high TPA and TAA values were reported towards the bottom of the profile suggesting that acid sulphate materials have existed to a significant extent under reducing conditions. The TAA values may be further increased with time to increase soil acidity in the future. The TPA values of both Malimboda and Kapuduwa sites exceeded [6

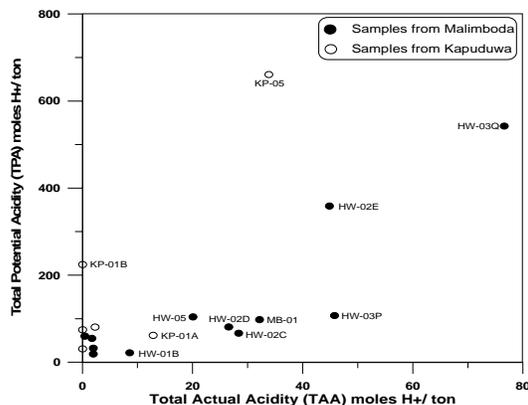
moles H<sup>+</sup>/ton] the action criteria levels suggested by Ahern *et al.* (1998), (Figure 6). Samples collected from excavated peaty soils of the Malimboda site show higher TPA values ranging from 20.77 - 541.72 moles H<sup>+</sup>/tone (HW 02E, HW 03P and HW 03Q). Apart from one sample (KP-05 33.92 moles H<sup>+</sup>/tone), TAA values from Kapuduwa site are negligible. Incidentally, sample KP-05 was taken from the excavated peaty soils. Although high values of PASS could be observed from many samples in both sites from the different proportions, considerable amount of ASS was reported mainly in Malimboda site. This suggests that extensive excavations during the NFPS in the Malimboda site may have caused the formation of ASS layer from PASS in the upper elevations

**Table 2:** Results of Chemical Analysis of Soil Samples

Sample Reference	pH before oxidation	pH after oxidation	Strength of the reaction with peroxide	Total actual acidity moles H <sup>+</sup> / t	Total potential acidity Moles H <sup>+</sup> / t	Total sulphidic acidity Moles H <sup>+</sup> / t
HW-01-A	4.22	3.45	Low	2.04	17.95	15.91
HW-01-B	4.07	2.57	Low	8.65	20.77	12.12
HW-01-C	3.88	2.42	High	28.44	65.62	37.18
HW-02-D	3.59	2.06	High	20.13	103.27	83.14
HW-02-E	2.98	2.13	Extreme	44.92	357.96	313.04
HW-03-P	2.55	1.89	Extreme	45.84	106.40	60.56
HW-03-Q	2.77	1.54	Extreme	76.68	541.72	465.04
HW-04	4.66	2.96	High	2.03	31.30	29.27
HW-05	3.27	2.15	High	26.62	80.23	53.61
MB-01	3.21	2.02	High	32.24	96.87	64.63
MB-02	4.58	3.41	Moderate	1.80	53.93	52.13
KK	5.47	3.25	Moderate	0.52	59.12	58.60
KP-01-A	3.58	2.24	High	12.92	60.93	48.01
KP-01-B	6.08	2.43	Extreme	0.0	223.58	223.58
KP-02	5.96	3.89	Low	0.0	29.72	29.72
KP-03	4.83	3.18	High	2.35	79.84	77.49
KP-04	5.76	3.11	High	0.0	73.85	73.85
KP-05	2.63	1.21	Extreme	33.92	660.16	626.24



**Figure 5:** Graph shows the variation of the potential acidity and actual acidity with increasing the depth of the soil profile (see also Figure 3).



**Figure 6:** Total potential acidity Vs total actual Acidity of the samples collected from the Malimboda and Kapuduwa area.

**Mineralogical Analysis**

The presence of jarosite was confirmed by XRD analysis for material from the sampling site HW-03P. Jarosite, gypsum, illite and bernalite (iron oxides) are minerals associated with ASS at Malimboda (Table 3).

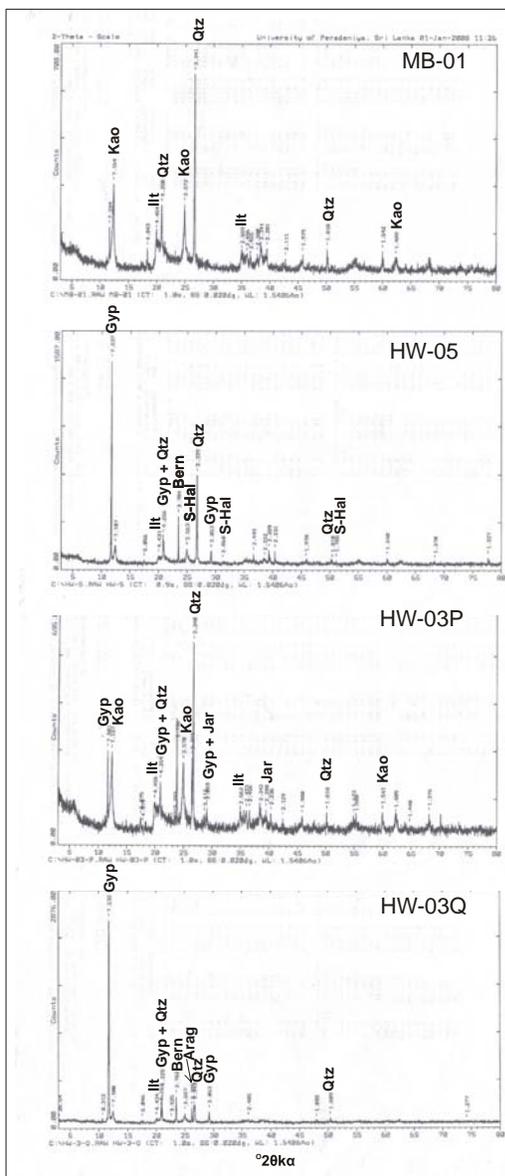
Most of the samples subjected to the XRD analysis were collected from excavated soils heaped on both sides of the southern highway handle construction. Therefore, those soil samples had been already oxidized by oxygen and pyrite may have oxidized to the secondary sulphide forms. As such pyrite was not detected by XRD analysis. However, the secondary minerals formed in ASS environment as gypsum and aragonite were detected in HW-03Q and MB-01 (Figure 7) Jarosite with goethite, hematite, ferric hydroxide, gypsum and pyrite minerals have also been observed in acid sulphate soils developed in other countries (van Breemen, 1972). In such countries, jarosite and pyretic minerals are common in mature soils at the deep of the horizons whereas the surface is characterised by soils with high pH.

**Eh-pH diagrams**

Pyrite (FeS<sub>2</sub>) oxidation is commonly described by the following equations (Evangelou and Zhang, 1995; Singer and Stumm, 1970). In equation (1), pyrite is oxidized by O<sub>2</sub> and water to produce dissolved ferrous iron, sulphate, and acidity.

**Table 3:** Summary of the Results of X-Ray Diffraction Analysis

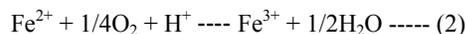
Sample Reference	Quartz SiO <sub>2</sub>	Kaolinite Al <sub>2</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	Jarosite KFe(SO <sub>4</sub> ) <sub>2</sub> (OH) <sub>6</sub>	Gypsum CaSO <sub>4</sub> .2 H <sub>2</sub> O	Illite	Bernalite Fe(OH) <sub>3</sub>	Arago nite CaCO <sub>3</sub>	Sulphohalide Na <sub>6</sub> (SO) <sub>4</sub> (F,Cl)
HW 02E	√	√	×	×	×	×	×	×
HW 03P	√	√	√	√	√	×	×	×
HW 03Q	√	×	×	√	√	√	√	×
HW 05	√	√	×	√	√	√	×	√
MB 01	√	√	×	×	√	×	×	×



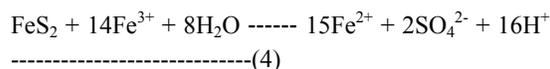
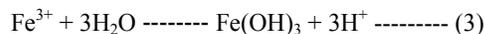
**Figure 7:** Representative X-ray powder diffractograms for soil samples from Malimboda at sampling sites: Qtz-quartz, Gyp-gypsum, Bern-bernalite, Ilt-illite, Arag- aragonite Kao-kaolinite, S-Hal- sulphohalite, Jar-jarosite



The ferrous iron is further oxidized to produce ferric iron (equation 2).



Ferric iron may hydrolyze to produce iron hydroxide precipitates and acidity (equation 3), or it may react with pyrite and water to produce ferrous iron, sulphate and acidity (equation 4). The oxidation of pyrite by ferric iron (equation 4) produces very high acidity. This reaction is pH dependent, since ferric iron becomes increasingly soluble and are less likely to precipitate as iron hydroxide, as pH decreases.



Under abiotic, acidic conditions, reaction 2 is slow (half-life ~ 1000 days) whereas reaction 4 is very fast (half-life ~ 20 – 1000 min.; Nicholson *et al.*, 1988). This means ferric iron is consumed faster than it is produced. Therefore, reaction 2 is considered the rate determining step in pyrite oxidation (Singer and Stumm, 1970). The Eh–pH diagram representing the samples of Malimboda and Kapuduwa, shown in Fig. 8, may help explain the iron chemistry during this study. Also indicated in this diagram are the Eh–pH stability field boundaries of Fe-bearing minerals considered important in acid sulphate soils.

These data indicate that many Eh–pH points in this study fall within the Fe<sup>2+</sup> field, indicating possible disequilibrium with respect to Fe-bearing minerals. Unfortunately, the control of Fe<sup>2+</sup> by sulphides could not be evaluated since sulphide measurement was not carried out. Moore and Patrick (1993) found that most of the Eh–pH points in their study of acid

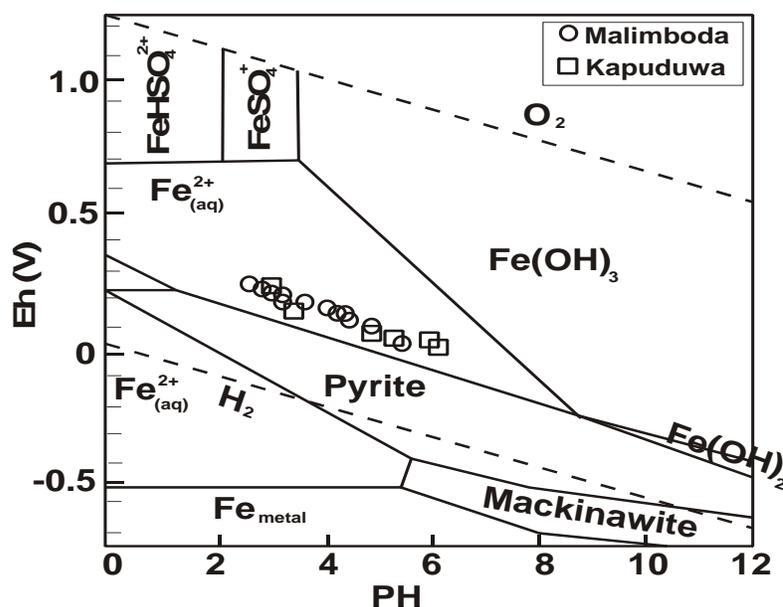
sulphate soils of Thailand fall within  $\text{Fe}^{2+}$  field and they concluded that  $\text{Fe}^{2+}$  activity was in disequilibrium with Fe–solid phase probably because of the possible existence of ill-defined ferric oxides. Other researchers, (Genon *et al.*, 1994), found that poorly crystallized Fe-oxides (ferrihydrite type) could control  $\text{Fe}^{2+}$  activity in highly organic soils.

One of the possible paradigms for  $\text{Fe}^{2+}$  control in this study would involve both precipitation/dissolution reactions as effected by redox condition of the soil and ion exchange phenomena. When the reduction condition is favourable (lower Eh and high pH), Fe (III) oxides or hydroxides would be reduced to  $\text{Fe}^{2+}$  (refer to the reverse step of equation 2 and 3). As  $\text{Fe}^{2+}$  is released into the solution, it exchanges with cations at exchange sites. If the rate of cation exchange exceeds that of mineral dissolution, then the  $\text{Fe}^{2+}$  activity would be governed by exchange process causing disequilibrium with respect to Fe-bearing minerals at the specific redox condition. The phenomenon of reducing conditions could have been occurring in the acid sulphate soils of Malimboda and Kapuduwa. In particular, Kapuduwa samples fall close to the  $\text{Fe}(\text{OH})_3$  field (Figure 8), suggesting that once the pH is raised the Fe in the Kapuduwa is concomitantly precipitated as  $\text{Fe}(\text{OH})_3$ , thus reducing its availability in the solution.  $\text{Fe}^{2+}$  is known to be toxic to the growing crops. For instance, the critical value for rice is 500 ppm (Nhung and Ponnampereuma, 1966) which has been exceeded in most soils of the Malimboda and Kapuduwa sites.

**Impact of acid sulphate soils on agriculture**

It was observed that with the completion of the engineering work of NFPS in 1983, the occurrence of major floods was eliminated and the drainage condition of the soils improved. Paddy fields located in the flood plains of Nilwala River contribute significantly to the rice production of Matara district (see Figure 1). However, with improved drainage of the paddy lands, accompanying problems such as the rice yield levels in these areas are still 1 ton/hectare lower than the national average of 3 ton/hectare (Department of Agriculture). Nearly 2000 hectares of paddy lands in the flood plains of the Nilwala River in Kiralakelle, Malimboda, Bandattara and Palatuwa were abandoned due to NFPS. For example, the total cultivated area of Matara district in ‘Yala’ season has decreased from 14,818 hectares in 1981 to 10,517 hectares after the establishment of NFPS in 1983 (Figure 9).

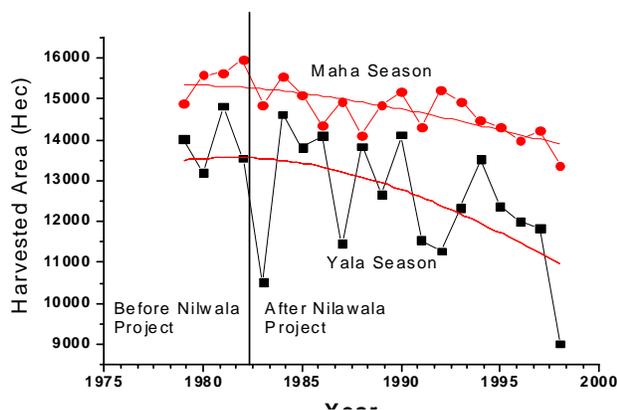
Southern coast including Matara experiences rains during the ‘Maha’ season whereas the ‘Yala’ season is regarded as a dry period in paddy cultivation.



**Figure 8:** Stability relations of Fe-bearing minerals in the Malimboda and Kapuduwa soil with Eh-pH measurements

## DISCUSSION

Since the water required for paddy cultivation in the 'Yala' season is supplied only by irrigation systems, the rice production is generally lower in this season. However, paddy cultivation in the 'Yala' season may have further been hampered by the excess acidity generated by acid sulphate soils due to NFPS (Figure 9). Dry season provides favourable environment to develop AAS and such acidity that may not be diluted and drained-off by water. The excess soil acidity could be drained-off with the monsoonal rains in the 'Maha' season. Therefore, the paddy production in 'Maha' season is considerably higher than that of 'Yala' season and impacts of the ASS soils are minimal.



**Figure 9:** Rice production of the Matara district during the 'Yala' and 'Maha' seasons (source: Department of Agriculture)

With the construction of new large scale drainage canals by NFPS, the ASS-rich sub soils exposed to air and oxidation persist. It is clear that the low productivity of the rice lands and abandoned rice lands in the scheme are mainly due to excessive drainage and oxidation of ASS rich sub soil. In dry periods, sulphuric acid and other ions such as iron, aluminium and potassium move vertically upwards by capillary action and are deposited in the surface layers as secondary minerals (jarosite, iron and aluminium hydroxides, aluminium sulphates) (Slavich and Chin, 2000). During run-off events, these iron and aluminium products may then be hydrolysed and transported to Nilwala River and eventually to the sea.

Field investigations relevant to borehole data and chemical evidences in the areas affected by Nilwala Flood Protection Scheme, especially at the Malimboda and Kapuduwa showed that the depth at

which sulphide-bearing sediments occurs is variable, ranging from approximately 2 to 5m by predominantly Holocene deposits. Problems associated with acid sulphate soils are increasingly being recognized in the paddy fields described here. The TPA values of the both Malimboda and Kapuduwa sites very much exceeded the standard action criteria levels. The level of PASS and AASS are also significantly higher than normal values in both study sites. However, extensive excavations during the NFPS in the Malimboda site may lead to form AASS layers from PASS in the upper elevations.

There are many reasons for the development of greater amounts of ASS in the paddy fields near Malimboda and Kapuduwa. First, the construction of numerous road cuts and canals exposed the sulphide mineral-bearing peaty soils producing ASS over the past few decades. Secondly, the fluvial deposits over these low-lying areas are thinner than on the canal banks (levees). Thus PASS was closer to the surface and, therefore, more prone to oxidation, particularly in drought periods. Further, the acidity of water generated by above processes has been moved from higher elevated areas to low-lying areas by surface flow or natural and artificial drains. Essentially, the low points in the swamps like 'Kiralakele' represent large acid sinks within the landscape. Due to NFPS, tidal inflow of saline water through the canals into these low-points was limited, and so there was no natural neutralisation of the acidity. Except in extended drought periods, water table levels in the fields are maintained above the PASS, thereby minimising further generation of acid by pyrite oxidation and reducing acid release.

Rice cultivation is known to tolerate relatively high acidity. In soils, the pH had to be less than 4 for rice to be adversely affected (Ponnamperuma *et al.* 1973). Reduction of Fe (III) to Fe(II) is quantitatively the most important process involved in raising the pH (Patrick and Reddy, 1978). Increased pH upon flooding is the main reason why wetland rice cultivation is successful on normal acid sulphate soils. Once the natural increase of pH is controlled by flood protection scheme, like NFPS, Fe(III) developed in soils produce ASS at a faster rate. Rate of cation exchange exceeds that of mineral dissolution, and then the  $Fe^{2+}$  activity would be governed by exchange process causing disequilibrium with respect to Fe-bearing minerals at

the specific redox condition. Nevertheless, it is clear that artificial drainage for flood mitigation or water table control in ASS landscapes has increased the rate of transmission and provides the conduit by which acidity is transferred from the canal banks to the waterlogged paddy fields.

The following measures may be effective in reducing the harmful effects of toxic substances generated by ASS: (a) preventing the oxidation of pyrites contained in potentially acid sulphate sediments; (b) draining harmful substances out of the rooting zone after allowing oxidation to occur; and, (c) deactivating aluminium by raising the pH of the medium by liming. This will also reduce the concentration of Fe (II) ion in the soil solution. All these measures have been recommended by researchers working with acid sulphate soils, to ameliorate them for rice cultivation. However, the first measure, preventing the oxidation of pyrite, is one of the best positive solutions to the acid sulphate soil problem. The other method required to control the development of Fe (III) is artificial treatments.

Two issues must be addressed for management of ASS landscapes: (a) how to eliminate further sulphide oxidation, and (b) how to minimise the export of acidity from existing stores in the landscape. Atkinson and Tulau (2000) proposed four ways of decreasing export of acidity: containment, neutralisation, dilution and transformation. At Matara, where total annual rainfall usually exceeds evaporation, it is not possible to design completely closed containment systems. We suggest that neutralisation is the only viable option available. It involves addition of pH increasing substances to the acid soils, particularly to the cultivated paddy lands. ASS management at the areas affected by NFPS should further concentrate on containing acidity within the soil profile and minimising subsoil discharge from the acidified zone into nearby drains. The sustainable use of the ASS landscapes depends upon having perennial crops that provide an adequate evapo-transpiration pump, and can survive these chemically hostile environments.

## CONCLUSIONS

This was a pilot study to identify the risk of acid sulphate soils having a negative impact on Nilwala Flood Protection Scheme (NFPS). Study revealed that potential acid sulphate soils are found throughout the paddy fields extending to Malimboda and

Kapuduwa. The NFPS has not taken any precautionary measures to protect/exclude most areas of ASS from development. Incidentally, more peaty soils were also exposed at the western part of the Malimboda site due to construction of southern highway project. Therefore, the site at Malimboda had high potential for active acid sulphate soils (AASS) whereas Kapuduwa was considered to have potential acid sulphate soils (PASS). Potential for having ASS during infrastructure development in the low lying coastal areas should be checked and a management plan proposed before the major development projects (mostly industrial). Investigations should specifically target potential development areas where ASS may affect the regional assets. Further work may be needed to assess the extent of ASS in the entire paddy fields of Matara district. Using a proper soil management system and selection of rice varieties tolerant to this specific environment, these abandoned paddy lands can be re-cultivated to increase the rice production of Matara district.

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## REFERENCES

- Ahern, C.R., Ahern, M.R., and Powel, B., 1998. Guidelines for sampling and analysis of lowlands acid sulphate soils in Queensland. Available at <http://acidsulfatesoils.environment.wa.gov.au>
- Atkinson, G. and Tulau, M., 2000. A framework for integrating ASS remediation strategies. In: Slavich, P.G. (Ed.), Proceedings of Workshop on Remediation and Assessment of Broadacre Acid Sulfate Soils, held at Southern Cross University, Lismore, 31 August– 2 September, 1999. ASSMAC, Australia, pp. 29–36.
- Balasuriya, I., 1987. Reclamation and development of rice cultivation on coastal low-lying lands of Southern and Western Sri Lanka, Tropical Agriculture Research Series 20: 213-224

- Dent, D. L., 1987. Environment impact report on the Nilwala Ganga Flood Protection Scheme, Land Use Policy and Planning Division, Ministry of Land and Land Development, Colombo
- Dent, D.L., 1986. Acid sulfate soils: a baseline for research and development. ILRI Publication 39, ILRI, Wageningen, The Netherlands.
- Evangelou, V. P. and Zhang, Y. L., 1995. A review: pyrite oxidation mechanisms and acid mine drainage prevention. *Crit. Rev. Env. Sci. Tech.* 25(2):141-199.
- Fitzpatrick, R.W., Merry, R.H., Williams, J., White, I., Bowman, G. and Taylor, G., 1998. Acid Sulfate Soil Assessment: Coastal, Inland and Minespoil conditions. National Land and Water Resources Audit Methods Paper. Canberra, Australia.
- Genon, J.G., de Hepcee, N., Delvaux, B., Dufey, J.E., and Hennebert, P.A., 1994. Redox condition and iron chemistry in highland swamps of Burundi. *Plant. Soil*, 166, 165–171.
- Gurusinghe, D.I.C., 2006. Occurrences and environmental impacts of acid sulfate soils in Colombo suburbs M.Sc. Thesis (*unpublished*), Postgraduate Institute of Science, University of Peradeniya, 82 p.
- Katupotha, J., 1988. Hiroshima University radiocarbon dates-1, west and south coast of Sri Lanka, *Radiocarbon*, 30(1):125-128
- Konsten, C.J.M., Brinkman, R. and Andriessse, W., 1988. A field laboratory method to determine total potential and actual acidity in acid sulphate soils. In: Dost, H. (Ed.), *Selected Papers of the Dakar Symposium on Acid Sulphate Soils*. ILRI Publication 44, ILRI, Wageningen, The Netherlands, pp. 106–134.
- Moore, P.A. and Patrick, W.H., 1993. Metal availability and uptake by rice in acid sulfate soils. In: Dent, D.L., Van Mensvoort, M.E.F. (Eds.), *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulfate Soils*, ILRI Publ., vol. 53. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, pp. 205–224.
- Moorman, F.R. and van Breemen, N., 1978. Rice: Soil, water and land, International Rice Research Institute, Manila, Phillipine
- Nhung, M.M. and Ponnamperuma, F.N., 1966. Effects of calcium carbonate, manganese dioxide, ferric hydroxide and prolonged flooding on chemical and electrochemical changes and growth of rice in a flooded acid sulfate soil. *Soil Sci.* 102, 29–41.
- Nicholson, R. V., Gillham R. W, and Reardon E. J, 1988. Pyrite oxidation in carbonate buffered solution. I. Experimental kinetics. *Geochem. Cosmochim. Acta.* 52:1077-1085.
- Patrick, W.H. and Reddy, C.N., 1978. Chemical changes in rice soils. *Soils and Rice*, IRRI, Los Banos, Philippines, pp. 361–379.
- Ponnamperuma, F.N., Attanandana, T., and Beye, G., 1973. Amelioration of three acid sulfate soils for lowland rice. *Proc. Intern. Symp. Acid Sulfate Soils*, ILRI Publication No. 18. Wageningen, The Netherlands, Vol. II: 391-406.
- Pons, L.J., 1973. Outline of the genesis, characteristics, classification and improvement of acid sulphate soils. In: Dost, H. (Ed.), *Proceedings of the International Symposium on Acid Sulphate Soils*, 13–29 Aug. 1972, Wageningen. ILRI Publication 18, vol. 1. ILRI, Wageningen, The Netherlands, pp. 3–27.
- Sammut, J., Callinan, R.B. and Fraser, G.C., 1996. An Overview of the Ecological Impacts of Acid Sulfate Soils in Australia. *Proceedings 2nd National Conference on Acid Sulfate Soils*. Robert J.Smith and Associates, ASSMAC, Australia.
- Senaratne, A., Tobschal, H.J. and Dissanayake, C.B. 1989. Diagenesis of sulphur in peat forming environment, *Fuel*, 64: 327-334.
- Shamshuddin, J. and Auxtero, E.A., 1991. Soil solution compositions and mineralogy of some active acid sulfate soils as affected by laboratory incubation with lime. *Soil Sci.* 152 (5), 365–376.
- Singer, P. C. and Stumm, W., 1970. Acid mine drainage: rate-determining step. *Science.* 167: 1121-1123.
- Slavich, P.G., and Chin, T., 2000. Designing drainage to reduce acid export from agricultural land with acid sulfate soils. In: Slavich, P.G. (Ed.), *Proceedings of Workshop on Remediation and Assessment of Broadacre Acid Sulfate Soils*, held at Southern Cross University, Lismore, 31 August–2 September, 1999. ASSMAC, Australia, 49 -58.
- Van Breemen, N., 1972. Soil forming processes in acid sulphate soils. In: Dost, H. (Ed.), *Proceedings of the International Symposium on Acid Sulphate Soils*, 13–29 Aug. 1972, Wageningen. ILRI Publication 18, vol.1, ILRI, Wageningen, The Netherlands, pp. 66–129.
- Van Breemen, N. and W.G. Wielemaker. 1974. Buffer intensities and equilibrium pH of minerals and soils. II. Theoretical and actual pH of minerals and soils. *Soil Sci. Soc. Amer. Proc.*, 38: 61-66.
- White, I., Melville, M.D., Wilson, B., and Sammut, J., 1997. Reducing acidic discharges from coastal wetlands in eastern Australia. *Wetlands Ecology and Management* 5, 55–72.