CSIRO

East Trinity Acid Sulfate Soils
Part 1: Environmental Hazards

W.S. Hicks, G.M. Bowman and R.W. Fitzpatrick

CSIRO Land and Water
Technical Report 14/99, April 1999

CSIRO LAND and WATER

East Trinity Acid Sulfate Soils
Part 1: Environmental Hazards

W.S. Hicks, G.M. Bowman and R.W. Fitzpatrick

CSIRO Land and Water
Technical Report 14/99, April 1999

Contents

Disclaimer

1. *CSIRO gives no warranty and makes no representation whether express or implied that this report is error free.*
2. *CSIRO gives no warranty and makes no representation whether express or implied that this report will be suitable for any purpose other than the assessment of soil conditions at the East Trinity Site near Cairns.*
3. *CSIRO will accept no responsibility for any interpretation, opinion or conclusion that any person may form as a result of examining this report.*
4. *CSIRO accepts no liability to any person in respect of anything contained in this report whether negligent or otherwise in respect of anything and/or the consequences of anything done or omitted to be done by any such person in reliance whether partly or wholly on the contents of this report or part thereof.*

Summary

CSIRO studies at East Trinity, Queensland, have identified remaining acid sulfate and potential acid sulfate soils, ongoing pyrite oxidation and off-site export of leachate. A QDPI soil survey mapped the extent of these soils in the southern part of the site. Aluminium, arsenic, iron and zinc concentrations in water on the site exceed the ANZECC guidelines for the protection of aquatic ecosystems.

Prior to drainage these elements where immobilised in the soils and sediments. The initial and continuing oxidation of pyrite and acidification of the soils, has led to the formation of dissolved ferrous iron and soil mineral acid hydrolysis products in the soil leachate. The leachate collects in the drainage channels and moves off-site through tide gates. The highest concentrations of these elements occur in water at the site of production. Processes of dilution, precipitation and adsorption onto ferric hydroxy precipitates decrease the concentrations of these elements in the water as it moves from the soil into drains and then into the main site drainage channels. Although substantially lower, concentrations of iron and aluminium still exceed the ANZECC guidelines and discharge through tide gates into Trinity inlet. Water bodies on-site regularly have pH’s of 3.5 or less and have extensive iron precipitates. These iron precipitates are likely to have elements such as aluminium, arsenic and zinc adsorbed onto them and form a highly mobile reservoir capable of being flushed into Trinity Inlet as particulate matter. Natural processes in the sediments of the inlet will chemically reduce the iron in the particulate material from its ferric to ferrous state. This will release the adsorbed elements into the surrounding pore waters where they are mobile and likely to be taken up by benthic and bottom feeding organisms.

Our studies of a section of the site naturally re-flooded for long periods during the wet season, indicate that rehabilitation by simple re-flooding would not be successful as reductive processes are inhibited by site conditions. It is likely that viable management strategies are available for rehabilitation, including re-flooding, however these would require further research to determine the exact requirements of the East Trinity site.

Introduction

Acid sulfate soils

Formation and Occurrence

Acid sulfate soils (ASS) form in coastal estuarine and mangrove swamp environments because these waterlogged or highly reducing conditions are ideal for the build-up of the mineral iron pyrite (FeS_2). However, ASS are environmentally unfriendly soils if exposed to air by disturbance or over-drainage because they become strongly acidic ($pH < 3.5$) and acid drainage water is produced. They are widely distributed around the eastern, northern and northwestern Australian coastline. ASS underlie coastal estuaries, embayments and floodplains on or near which the majority of the Australian population and urban development is located. They also underlie significant fish nursery areas and coastal agricultural industries such as sugar cane, dairying and tea tree oil.

Left undisturbed ASS are benign, but disturbance exposes sulfidic compounds in the soil to air, resulting in the formation of damaging levels of sulfuric acid. Further deleterious effects come from the action of the acid on the soil, producing high concentrations of toxic metals especially aluminium and iron which end up in waterways. Nationally, there is an estimated 30,000 km^2 of ASS. (National Working Party on Acid Sulfate Soils, June 1998).

Acid runoff from these areas causes adverse impacts to the environment, coastal development, fishing and agricultural industries. Costs to local and regional communities are:

1. Poor water quality with attendant loss of amenity, damage to estuarine environments and reduction of wetland biodiversity;
2. Rehabilitation of disturbed areas to improve water quality and minimise impacts;
3. Loss of fisheries and agricultural production;
4. Maintenance of community infrastructure, particularly where affected by acid corrosion.

Major environmental impacts include fish and oyster kills, fish disease, destruction of fish nursery habitat as well as loss of aquatic biodiversity.

Economic impacts are broad and substantial. Coastal development, driven by the high value of waterfront investment, and associated infrastructure worth over $10 billion, is threatened by ASS impacts. Costs of treating and rehabilitating ASS associated with urban development and infrastructure projects total many millions of dollars. Consequently, many projects have stalled and some have been abandoned. Millions of dollars worth of infrastructure corroded by acid water has had to be replaced. Millions of dollars of oysters, prawns and fish have been destroyed, nursery areas have been decimated and land has been degraded by poor ASS management. Acid drainage and poor water quality also pose considerable threats to coastal tourism and communities reliant on good quality estuarine water to attract visitors.

Oxidation of Sulfidic Compounds

The predominant sulfidic compound in undisturbed ASS is the mineral iron pyrite. The overall equation for pyrite oxidation is:

$$FeS_{2(s)} + {}^{15}/_{4}\, O_{2(g,aq)} + {}^{7}/_{2}\, H_2O \rightarrow Fe(OH)_3 + 4H^{+}_{(aq)} + 2SO_4{}^{2-}{}_{(aq)} \qquad \ldots\ 1$$

with each mole of pyrite yielding 4 moles of acidity. Actual pyrite oxidation proceeds in stages. The first stage results in the formation of ferrous iron, sulfate and acid according to the equation:

$$FeS_{2(s)} + {}^{7}/_{2}O_{2(aq,g)} + H_2O \rightarrow Fe^{2+}{}_{(aq)} + 2SO_4{}^{2-}{}_{(aq)} + 2H^{+}{}_{(aq)} \qquad \ldots\ 2$$

The acid can be neutralised by reacting with soil carbonates (such as shell fragments) or by displacing exchangeable cations. Excess acidity then reacts with soil minerals releasing major constituents such as potassium, magnesium, aluminium and silicon, as well as trace elements such as arsenic, copper, cadmium, chromium, nickel and zinc. Remaining acidity is exported off-site. The ferrous iron produced in reaction can be exported off-site and produce a further two moles of acid (equation 5) and lower the dissolved oxygen concentration. When the pH drops below 4 the rate of pyrite oxidation is increased by the catalytic oxidation of ferrous iron by the bacterium Thiobacillus ferroxidans to ferric iron which acts as a pyrite oxidant (equation 4) with regeneration of ferrous iron. This reaction is fast compared with equation 2 (van Mensvoort and Dent, 1997).

$$Fe^{2+}{}_{(aq)} + {}^{1}/_{4}O_{2(g,aq)} + H^{+\ \text{T. ferrooxidans}} \rightarrow Fe^{3+}{}_{(aq)} + {}^{1}/_{2}H_2O \qquad \ldots\ 3$$

$$FeS_{2(s)} + 14Fe^{3+}{}_{(aq)} + 8H_2O \rightarrow 15Fe^{2+}{}_{(aq)} + 16H^{+}{}_{(aq)} + 2SO_4{}^{2-} \qquad \ldots\ 4$$

$$Fe^{2+}{}_{(aq)} + {}^{1}/_{4}O_{2(g,aq)} + {}^{3}/_{2}H_2O\ FeO.OH_{(s)} + 2H^{+}{}_{(aq)} \qquad \ldots\ 5$$

Aluminium released from the soil matrix can also hydrolyse to release acidity. The reactions proceed stepwise to release an overall 3 moles of acidity.

$$Al^{3+}{}_{(aq)} + H_2O \rightarrow Al(OH)^{2+}{}_{(aq)} + H^{+}{}_{(aq)} \qquad \ldots\ 6$$

$$Al(OH)^{2+}{}_{(aq)} + H_2O \rightarrow Al(OH)_2{}^{+}{}_{(aq)} + H^{+}{}_{(aq)} \qquad \ldots\ 7$$

$$Al(OH)_2{}^{+}{}_{(aq)} + H_2O \rightarrow Al(OH)_{3(aq)} + H^{+}{}_{(aq)} \qquad \ldots\ 8$$

Figure 1 shows the overall sequence of mineral reactions important in aqueous pyrite oxidation.

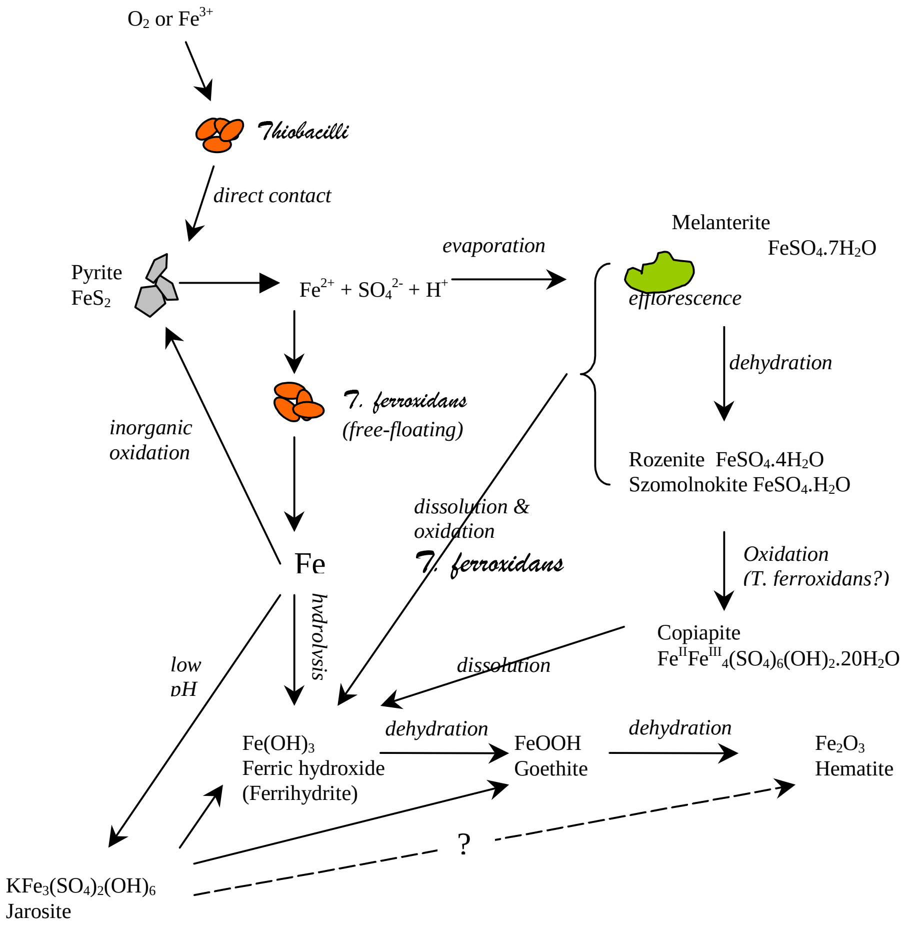


Figure 1 The overall sequence of mineral reactions for pyrite oxidation showing relationships between oxidising agents, catalysts and mineral products. (After Nordstrom, 1982)

Site

East Trinity Site a Prime Study Area

Production, export and fate of leachate from Australian ASS are poorly understood, especially in tropical Australia. Consequently, in 1995, CSIRO in collaboration with State and local authorities undertook research into the formation and degradation processes operating in Australian ASS to:

- obtain better and more quantitative information;
- relate the soil and water processes to environmental controls;
- provide more accurate environmental hazard assessment in order to develop improved methods of rehabilitation.

East Trinity, adjacent to Cairns City and within the World Heritage listed Great Barrier Reef Marine Park, provided a unique site for research. The study site is a tropical estuarine wetland drained for sugar cane production some 20 years ago by the construction of a bund wall and tidal floodgates (Hollingsworth Dames and Moore, 1993). Acidification and the production of acid leachates have severely degraded the land within the drained area. Outside the drained area, undrained soils were present in their original condition immediately adjacent to their drained counterpart. These formed a baseline for the measurement of change. The severe and ongoing environmental hazard posed by this site was identified from our detailed on-site geochemical monitoring and laboratory research data collected over a period of three years:

The southern corner of the bunded area, around Firewood and Magazine Creeks is the most severely affected part of the site. Here the undrained intertidal soils are rich in organic carbon and pyritic material. Occupying about 110 ha, this section contains the most severely acidified soils. More than 20 years after drainage the creeks and drainage lines in the area remain consistently acidic. Hills Creek, the major stream in the area, has an extremely low pH of <4 during late dry season periods of low flow.

Climate

Cairns has a tropical monsoonal climate with summer dominant rainfall. Evaporation (pan) exceeds rainfall from May to December, with a net yearly rainfall deficit of 63.1mm. Average daily maximum temperatures remain above 25 °C and average daily minimum temperatures remain above 17 °C. This compares with northern NSW where most research data on Australian ASS has been collected, with 18 and 9 °C as the comparative temperature values and a net excess of rainfall over evaporation of 286 mm with evaporation exceeding rainfall from August to January. (Cairns Airport Meteorological Office and Alstonville Tropical Fruit Research Station, Australian Bureau of Meteorology Data)

Table 1 Monthly Average Climate Data for Cairns

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Mean Daily Max. Temp (°C)	31.5	31.1	30.5	29.2	27.5	25.8	25.6	26.5	27.8	29.4	30.6	31.4	28.9
Mean Daily Min. Temp (°C)	23.6	23.7	23	21.5	19.9	17.6	17	17.5	18.6	20.5	22.2	23.3	20.7
Mean Rainfall (mm)	405.4	434.2	424.3	197.9	99.9	49.1	30	27.4	35.3	38.3	89.4	175.6	2007
Mean Monthly Evaporation(mm)	220.1	170.8	179.8	159	145.7	138	155	173.6	204	235.6	234	238.7	2254.3

Method of Investigation

Site Selection and Description

A range of potential and actual acid sulfate soil environments are present, from intertidal mangroves to supra-tidal saltflats. These environments represent stages in the geomorphic development of the estuarine system with elevations (outside the bund) from 0.87 to 1.23 m Australian Height Datum (AHD).
We selected three sites representing stages in the geomorphic development of the mangrove system. At each site, installations, measurements and samples were paired across the bund. Using this design, we were able to compare conditions before and after drainage. Sites and installations were levelled to AHD. Table 2 describes the sites and their position is shown in Figure 2. The sites were numbered 1 to 3, from south to north.

Table 2 Three paired monitoring sites at East Trinity

Site No.	**Undrained *or* Drained**	**Vegetation**	**Tidal influence**	**ASS *or* PASS**	**International System: Soil Taxonomy (1996)**	**Australian System Isbell (1996):**	**Elevation m AHD**
T**M**1	Undrained	**M**angroves	Intertidal: *mid tides*	PASS	Typic Sulfihemist	Sapric Histic-sulfidic Intertidal Hydrosol	0.87
T**C**1	Drained	**C**leared with *Melaleuca* forest	No tidal inundation	ASS	Hydraquentic Sulfaquept	Sulfuric, Extratidal, Hydrosol *or* Sulfuric, Redoxic Hydrosol	-0.39
T**M**2	Undrained	**M**angroves	Intertidal: *high and spring tides*	PASS	Typic Sulfihemist	Sapric Histic-sulfidic Intertidal Hydrosol	1.13
T**C**2	Drained	**C**leared with *Imperata cylindrica* Grassland	No tidal inundation	ASS	Hydraquentic Sulfaquept.	Sulfuric Extratidal Hydrosol *or* Sulfuric Redoxic Hydrosol	0.84
T**S**3	Undrained	**S**altflat: bare	Intertidal:, *spring tides*	PASS	Salidic Sulfaquept	Sulfuric Extratidal Hydrosol *or* Sulfuric, Salic Hydrosol.	1.23
T**C**3	Drained	**C**leared saline flat with salt couch grassland	No tidal inundation.	ASS	Hydraquentic Sulfaquept	Sulfuric Extratidal Hydrosol *or* Sulfuric Redoxic Hydrosol	1.21

Where: PASS = Potential Acid Sulfate Soils; ASS = Actual Acid Sulfate Soils (see Appendix 1.1)

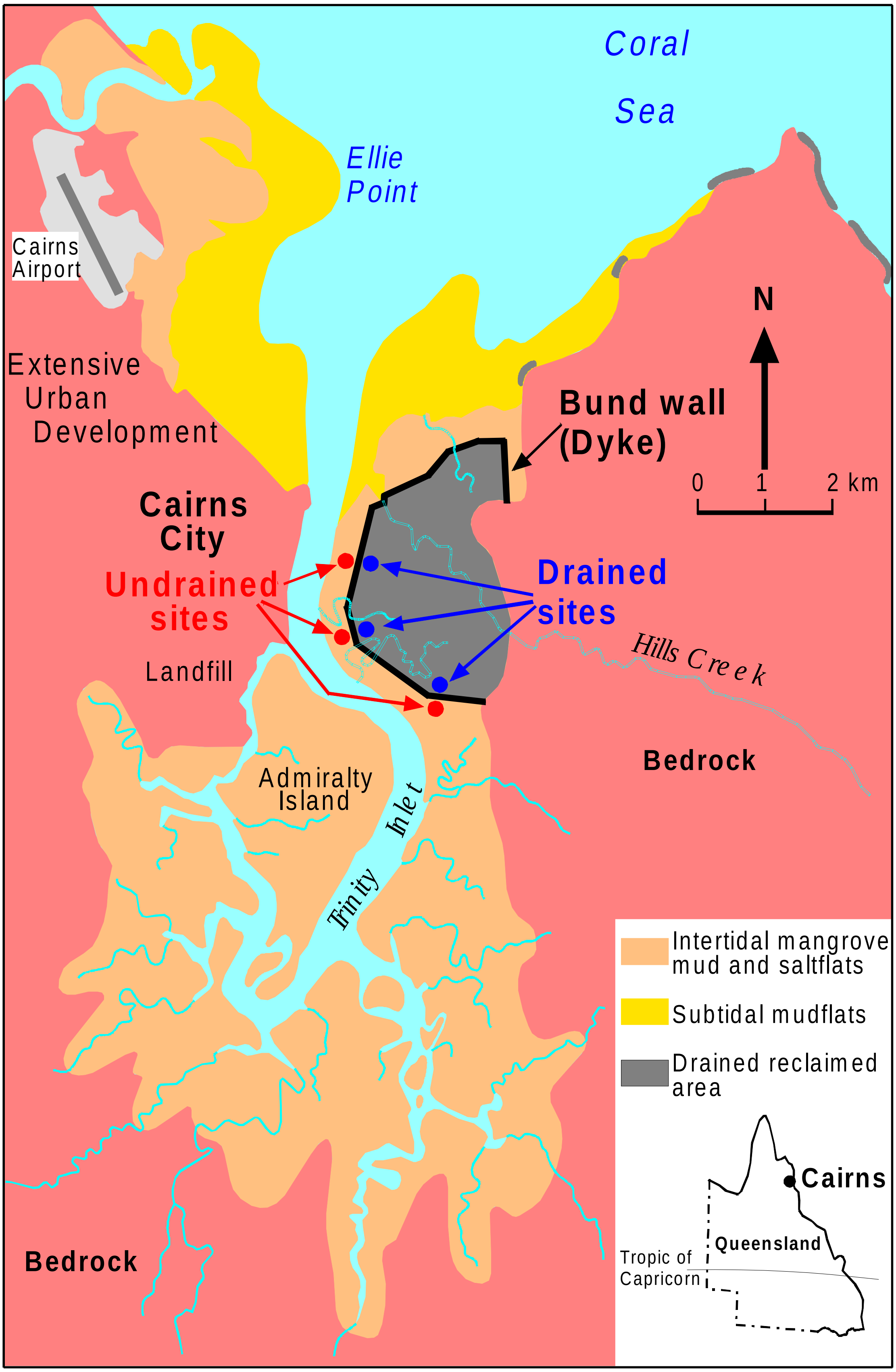


Figure 2 East Trinity Location Map

Period of Investigation

Field measurements of water levels and redox potentials commenced in January 1996 and water sampling and analysis began in November 1996. Sampling and field measurement ceased in April 1998.

Installations

We installed at each site, a piezometer cluster to measure depth to water table at different depths below ground level, Platinum electrodes to measure soil redox potential, soil solution samplers and a rain gauge. Details of site installations are given in Appendix 2.

Soil Sampling and Description

We described and sampled representative soil profiles at each site. Soil samples were taken with a gouge auger and immediately transferred to an air tight jar, stored in insulated container and frozen within 6 h of collection. Samples were stored frozen until freeze dried using a Dynavac Model FD12S Freeze Drier.

Field Measurement and Sample Collection

We established a fortnightly monitoring program that measured water levels and soil redox potential. Samples of soil-water and surface water were collected fortnightly for chemical analysis.

Sample Analysis

We analysed soil samples for the following parameters:

total actual acidity, total potential acidity, total carbon, total sulfur and acid extractable: aluminium; arsenic; boron; calcium; cadmium; chromium; copper; iron; potassium; magnesium; manganese; sodium; nickel; lead; zinc and bulk density;

and water samples for:

electrical conductivity, pH, redox potential, arsenic, total organic carbon, chloride, ammonia nitrogen, nitrate + nitrite nitrogen, aluminium, reactive silica, magnesium, boron, calcium, copper, total and ferrous iron, potassium, manganese, sodium, phosphorus, sulfur, zinc, titratable acidity and titratable alkalinity.

Sampling, preparation and analysis details are provided in Appendix 3.

Findings and Discussion

Soil

Description and Classification of soils

Profile descriptions of the profiles are presented in Appendix 1,Table 1. Soil horizons were demarcated and described as shown in Appendix 1,Table 1. Results of some chemical analyses for selected horizons are given in Appendix 1,Table 2. A key is presented in Appendix 1 to assist with identifying and classifying the soils into the following two categories: Actual Acid Sulfate Soils or Potential Acid Sulfate Soils. The soils were also classified using the international system called Soil Taxonomy (Soil Survey Staff, 1996) and as well as the new Australian system Isbell (1996) (Appendix 1, Tables 1 and 3).

The soils (TM1 and TM2) currently forming in the mangrove swamps, where there is active tidal influence, still contain high amounts of "sulfidic material". The sulfidic material oxidises when exposed to air and the pH levels drop to below 4 (i.e. after aging for 7 weeks: Appendix 1, Table 2). These two soils contain fine grained pyrite, which oxidises rapidly to form sulfuric acid when exposed to air. They also contain high amounts of organic carbon (generally > 20%) mainly in the form of either hemic or sapric materials (i.e Appendix 1.4). Consequently, these Potential Acid Sulfate Soils classify as Typic Sulfihemists or Typic Sulfisaprists (Soil Survey Staff, 1996).

In those areas where mangrove swamps have been cut off from the sea 20 years ago (bunded) the Potential Acid Sulfate Soils have transformed to Actual Acid Sulphate Soils (TC1 and TS3). These soils generally classify as Hydraquentic Sulfaquepts or Salidic Sulfaquepts (Soil Survey Staff, 1996).

Extent of Acid Sulfate Soils

The Queensland Department of Primary Industries (QDPI) undertook a soil survey in 1995 (QDPI, 1995). A series of transects from the bund wall were made south from Hills Creek. The longest transects were in the southern part of the bunded area, extending up to 600m from the wall. The survey mapped the extent of the acid soils by measuring soil pH, actual and potential acidity according to the method of Dent and Bowman (1996).

The results of the survey show that south of Magazine Creek, average soil pH’s are less than or equal to 5 from 0.1 to 0.9m below ground level (bgl). Surface pH’s are higher probably due to leaching of acid from the top few centimetres of soil. The most consistently acidified part of the profile was at 0.5 m with a range in pH over 13 samples of 3.1 to 3.7 with an average of 3.4. Acidification was found as deep as 1.8 m bgl where a minimum pH of 3.5 was recorded.

North of Magazine Creek, the average pH remains above 5 throughout the profile, although pH’s of less than 7 above 1m bgl indicate some acidification with in-situ neutralisation. This is consistent with the occurrence of shell fragments in the soil profile.

Measurements of actual soil acidity (total actual acidity or TAA) showed oxidation of pyrite to at least 1.1m bgl and substantial remaining potential acidity below 0.7m. Figure 3 shows the profile distribution of actual and potential acidity and the range in values at each depth. Using the survey data, we estimate the severely acidified area to be about 110 Ha corresponding to the area around Firewood and Magazine Creeks and their former distributaries.

The data from the QDPI soil survey are summarised in Table 3 and Table 4.

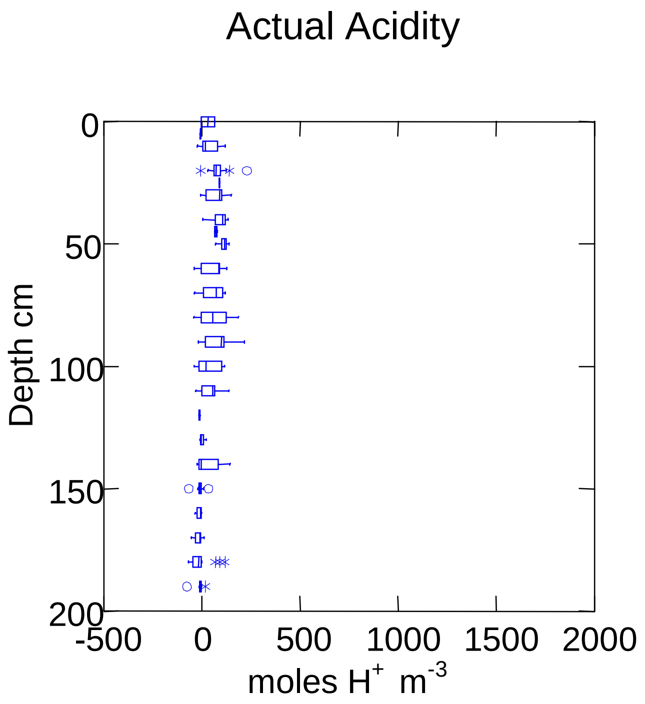
Table 3 Summary of QDPI Soil Survey pH Data

Depth	pH_{NaCl}					
cm bgl	N of cases	Min.	Max.	Median	Mean	Standard Dev
North of Magazine Ck.						
10	1	6.9	6.9	6.9	6.9	
20	2	5.9	8.0	6.9	6.9	1.5
30	3	4.2	8.5	5.1	5.9	2.3
40	1	6.1	6.1	6.1	6.1	
50	1	8.9	8.9	8.9	8.9	
70	3	5.3	7.3	6.3	6.3	1.0
80	1	7.5	7.5	7.5	7.5	
90	1	5.6	5.6	5.6	5.6	
100	2	4.1	8.3	6.2	6.2	3.0
140	2	8.2	8.3	8.3	8.3	0.1
150	2	8.3	8.3	8.3	8.3	0.0
160	1	7.5	7.5	7.5	7.5	
170						
180	1	8.1	8.1	8.1	8.1	
South of Magazine Ck.						
0	2	3.8	7.3	5.5	5.5	2.5
5	1	7.8	7.8	7.8	7.8	
10	31	3.2	7.9	4.3	4.6	1.1
20	19	3.0	6.3	3.7	3.8	0.7
25	1	3.7	3.7	3.7	3.7	
30	13	3.2	7.2	3.6	4.2	1.2
40	9	3.0	5.1	3.5	3.7	0.6
45	2	3.6	4.0	3.8	3.8	0.3
50	13	3.1	3.7	3.4	3.4	0.2
60	9	3.3	7.5	3.7	5.0	1.9
70	10	3.2	7.4	3.7	4.5	1.6
80	31	3.1	8.4	3.8	4.7	1.7
90	18	3.0	7.6	3.7	4.4	1.5
100	5	3.4	7.9	4.8	5.4	2.1
110	5	3.3	7.9	4.3	5.1	1.9
120	2	7.0	7.2	7.1	7.1	0.2
130	4	4.2	8.3	7.1	6.7	1.7
140	5	3.3	8.0	7.6	6.0	2.4
150	11	4.1	8.4	7.5	6.9	1.4
160	14	5.8	8.3	7.6	7.5	0.7
170	9	4.7	8.2	7.5	7.1	1.0
180	23	3.5	8.8	7.6	7.2	1.5
190	9	4.8	8.8	7.2	7.0	1.2

Table 4 Summary of QDPI Soil Survey Potential and Actual Acidity Data

Depth cm bgl	TPA moles H^+ m^{-3}							TAA moles H^+ m^{-3}				
	N of cases	N of cases	Min.	Max.	Median	Mean	Standard Dev	Min.	Max.	Median	Mean	Standard Dev
North of Magazine Ck.												
10	1	1	-62	-62	-62	-62		-5	-5	-5	-5	
20	2	2	-85	-48	-67	-67	26	-34	-1	-18	-18	23
30	3	3	-80	-9	-19	-36	38	-20	68	9	19	45
40	1	1	-62	-62	-62	-62		-4	-4	-4	-4	
50	1	1	-71	-71	-71	-71		-17	-17	-17	-17	
70	3	3	-65	618	510	354	367	-25	5	-3	-8	15
80	1	1	-67	-67	-67	-67		-22	-22	-22	-22	
90	1	1	1206	1206	1206	1206		-1	-1	-1	-1	
100	2	1	825	825	825	825		-17	45	14	14	44
140	2	2	-89	-65	-77	-77	17	-30	-18	-24	-24	8
150	2	2	-65	-62	-63	-63	2	-23	-22	-22	-22	0
160	1	1	-65	-65	-65	-65		-31	-31	-31	-31	
170	1	1	-65	-65	-65	-65		-26	-26	-26	-26	
180	1	1	-102	-102	-102	-102		-23	-23	-23	-23	
South of Magazine Ck.												
0	2	2	-83	57	-13	-13	99	-4	65	31	31	48
5	1	1	-61	-61	-61	-61		-9	-9	-9	-9	
10	31	31	-89	763	42	78	153	-23	118	17	39	43
20	19	19	-47	255	87	97	68	-7	230	73	83	48
25	1	1	407	407	407	407		89	89	89	89	
30	13	13	-61	156	108	85	76	-6	149	91	71	51
40	10	10	-17	928	123	194	264	4	133	107	94	38
45	2	2	93	120	107	107	19	65	77	71	71	8
50	13	13	28	732	116	147	184	69	139	115	111	22
60	9	9	-512	913	142	209	438	-41	127	86	48	67
70	10	10	-82	859	123	159	267	-37	118	74	58	55
80	31	31	-107	1093	181	213	288	-42	185	56	62	66
90	17	18	-58	1003	295	353	271	-19	217	99	81	67
100	5	5	-77	358	-6	92	184	-40	115	20	36	69
110	5	5	-63	1174	662	586	523	-31	137	56	45	65
120	2	2	-63	-33	-48	-48	21	-15	-11	-13	-13	3
130	3	4	72	721	506	451	274	-10	23	-4	3	17
140	5	5	-68	623	135	190	291	-25	143	-3	36	74
150	11	11	-119	1168	307	378	459	-67	34	-10	-10	24
160	14	14	-105	1396	757	570	527	-35	-2	-6	-14	13
170	9	9	-82	1062	279	372	436	-55	13	-9	-16	20
180	23	23	-116	1510	387	438	497	-69	118	-17	-12	48
190	9	9	-118	1415	259	534	562	-76	17	-8	-12	26

Note: negative values indicate neutralising capacity



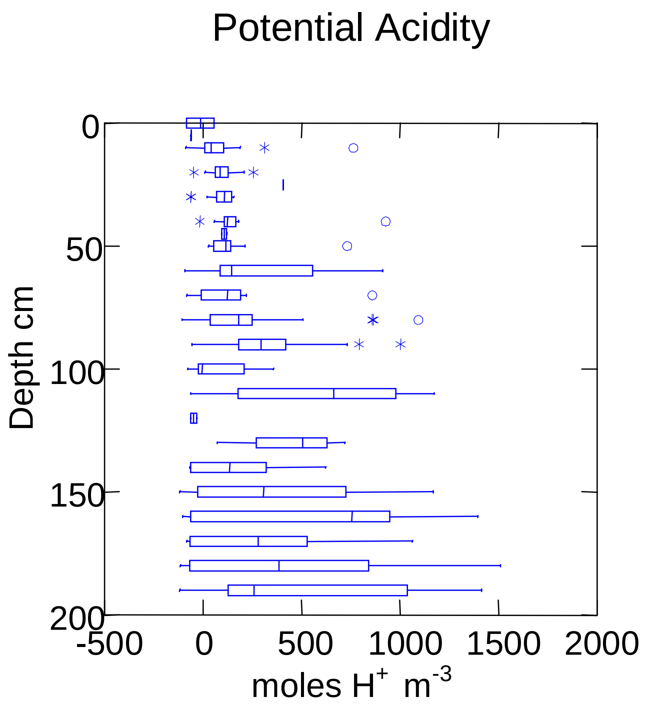
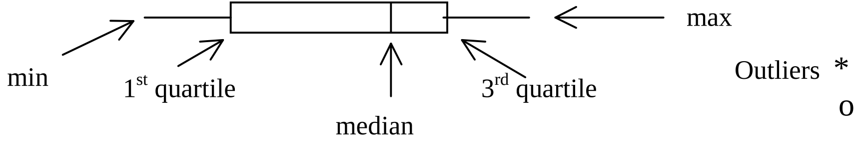


Figure 3 Box Plots of Actual and Potential Acidity South of Magazine Ck. See below for explanation of symbols.



Soil Profiles

We analysed soil profiles sampled either side of the bund for a range chemical elements and physical parameters. Drainage has resulted in the loss of material from the drained soil and some consolidation between the surface and 0.1m and between 0.6 to 0.7m below the surface. At our study site 1, the surface elevation has fallen from 0.869 m AHD before drainage to the current (1997) elevation of –0.389 m AHD. Soil profile characteristics indicate, that by –2.3 m AHD the drained profile is unchanged. We have therefore chosen this elevation as the reference level for all calculations. Using this level, we have calculated the soil profile store above for elements of interest in the drained and undrained soil profiles. The difference, gives an estimate of the release into the environment of the chemical elements measured.

Soil Hydraulic Properties

Soil hydraulic properties were measured from undisturbed cores in the laboratory and pumping down the piezometers, using methods described in Youngs, E.A. (1991). Results were consistent with profile descriptions. Saturated hydraulic conductivities (K_{sat}) ranged from ~10^{-4} m s^{-1} where there was surface cracking, through to10^{-7} to 10^{-8} m s^{-1} in muds with extensive biological activity. The surface of the saltflat had a K_{sat} of 10^{-5} m s^{-1} consistent with shallow surface cracking observed at the site, this compares with 10^{-3} m s^{-1} in the equivalent drained soil where extensive deep cracking is evident. In mangrove soils with reduced biological activity, K_{sat} was significantly reduced, dropping to 10^{-10}m s^{-1} at 0.3m bgl and further to 10^{-12} m s^{-1} below 3m. In the drained soils extremely low K_{sat} values from 10^{-11} to 10^{-12} m s^{-1}were measured below 0.75m. Hydraulic conductivities of 10^{-12} m s^{-1} (0.1 mm per year) below 0.8 m in the drained soils limit the downward movement of water and solutes. Therefore, any transport of oxidation products has been above this level, through the horizontal movement of water and solutes when the soil is saturated during the wet season. Measured hydraulic conductivities are listed in Table 5.

Table 5 Measured Hydraulic Conductivity

Site	Type	Depth m bgl	K_{sat} m s^{-1}
TC1	Drained	0.05	$7x10^{-5}$
		0.15	$5x10^{-4}$
		0.76	$5x10^{-12}$
		3.82	$3x10^{-11}$
TM1	Mangrove	0.28	$5x10^{-8}$
		0.80	$1x10^{-7}$
		3.70	$4x10^{-8}$
TC2	Drained	0.79	$2x10^{-11}$
		3.69	$1x10^{-11}$
TM2	Mangrove	0.33	$1x10^{-10}$
		0.82	$3x10^{-10}$
		3.71	$1x10^{-11}$
TC3	Drained	0.05	$2x10^{-3}$
		0.34	$2x10^{-11}$
		0.82	$3x10^{-11}$
		2.75	$8x10^{-12}$
TS3	Saltflat	0.05	$1x10^{-5}$
		0.28	$2x10^{-9}$
		0.84	$2x10^{-10}$
		3.86	$8x10^{-12}$

Production of Acid ASS by East Trinity ASS

The method of Dent and Bowman (1996) was used to analyse profile samples for total potential acidity (TPA). The profile store of TPA for both drained and undrained profiles was calculated from a baseline level of -2.3m AHD. Prior to drainage, the soil stored potential acidity of *$2.6x10^{7}$ moles H^{+} ha^{-1}* (equivalent of *0.69 Megalitres* or *1270 tonnes of sulfuric acid*). Drainage and oxidation of pyrite has resulted in this being reduced to *$1.3x10^{7}$ moles H^{+} ha^{-1} (0.35 ML or 620 t).* By difference, we estimate that from drainage until 1995, *$1.3x10^{7}$ moles H^{+} ha^{-1} (0.35 ML or 650 t)* has been released into the environment for every hectare of affected land. This equates to an annual rate *of $7.0x10^{5}$ moles $H^{+}ha^{-1}y^{-1}$ (19 kL or 34 t).* Applying this rate to the severely acidified area of 110 ha, we estimate the site has produced since drainage, *$1.5x10^{9}$ moles H^{+} (39 ML or 72 000 t),* at an average annual rate of *$7.7x10^{7}$ moles H^{+} (2.1 ML or 3800 t).*

This has resulted in the severe acidification of the site as demonstrated by the QDPI soil survey. Water analyses show soil water pH's of 3.2 and surface water pH's which average 3.4 in drainage channels and Magazine Creek and 4.4 in Firewood. Creek. Figure 4 shows the soil profile acidity stores.

White et al., (1997) estimate the rate of acid production from sub-tropical ASS to be 300 kg H_2SO_4 $ha^{-1}y^{-1}$. Their estimate is based on pH and water volumes. We demonstrate later in the report, that pH alone underestimates acidity. Our data indicates much higher rates from tropical ASS. The comparative rate calculated for East Trinity is 34 000 kg H_2SO_4 $ha^{-1}y^{-1}$some 110 times higher. Actual in-situ acid production is higher than this, as the method used to determine the acidity measures net acid produced after any neutralisation by the soil.

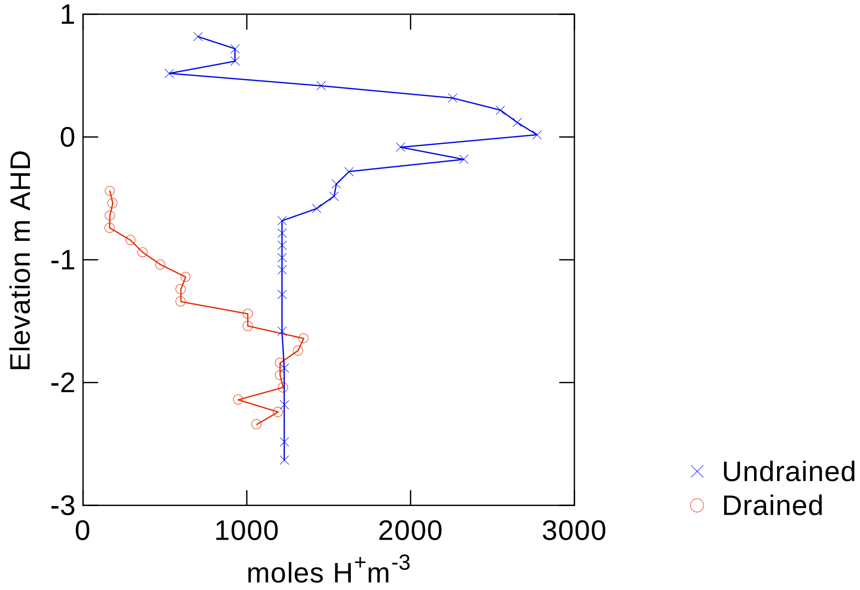


Figure 4   Soil Profile Acidity

Carbon Loss

In their undisturbed state, these soils are natural accumulators of carbon. In the southern corner of the East Trinity site, carbon accumulated in a sapric peat layer that extends from about 0.2 to 0.8 m bgl. In this layer carbon content exceeds 15%. We made calculations of the profile carbon store for the drained and undrained profiles as for acidity. Carbon profiles are shown in Figure 5. Our results show that 45% (0.07 Mt) of carbon in the profile has been lost as a result of oxidation and the acid dissolution of carbonates. The average oxidation (emission) rate since drainage is 33 t C ha^{-1}y^{-1}. Both these processes result in the emission of the greenhouse gas, carbon dioxide. The estimated total area of ASS in Australia is 30 000 km^2 (National Working Party on Acid Sulfate Soils, 1998). No estimate of the total area affected by drainage is available, however if we assume 10% and apply the rate calculated for Trinity, carbon emissions from Australian ASS may be as high as 10 Mt C y^{-1} compared with the current estimate of 16 Mt C y^{-1} for carbon emissions due to land use change (primary land clearing).

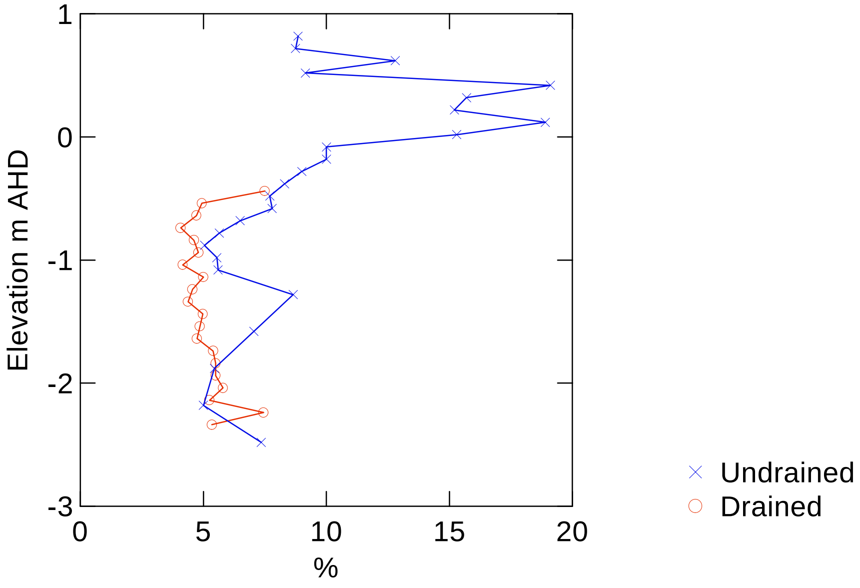


Figure 5 Carbon Profile

Iron

Conditions such as pH, redox status and drainage, determine the fate of the ferrous iron produced by the oxidation of pyritic sulfur. The iron may be oxidised in-situ to Fe^{3+}, or be transported distances of many kilometres before it is finally oxidised (Van Mensvoort and Dent, 1998). At East Trinity we found most of the iron remained in the soil profile, with slight gain (13%) for the drained site, probably through collection of runoff water as this site is a local low point. Iron previously in the top 1.6 m of the undrained profile is now concentrated in the top 40 cm of the drained profile (Figure 6). This is the result of oxidation, precipitation as iron oxides and concentration in the top of the profile where hydraulic conductivities are high. Further evidence of this process is found in the concentrations of dissolved ferrous iron in the soil water of the oxidising layer (>1000 mgL^{-1}) and a rapid decrease away from the site of production as illustrated in Figure 7.

The data in Table 6 shows that trace elements concentrate at the top of the soil profiles where elements are preferentially being adsorbed onto the surfaces of the poorly crystalline iron oxyhydroxides, which we have identified as currently precipitating. For example, the mineral ferrihydrite ($\approx Fe_5HO_8{\cdot}4H_2O$) is a poorly ordered Fe oxide that is common to the surface environments where waters rich in Fe(II) are exposed to rapid oxidation in the presence of compounds such as organic matter that block crystal growth. Ferrihydrite occurring in these soils has a rusty, reddish-brown color with Munsell hues in the 5 YR to 7.5 YR range and Munsell values < 6 (see Appendix 1, Plate 1 and Table 1). This mineral has a high specific surface area in the range of 200 to 600 m2/g. These trace elements can also be incorporated into the structures of the iron oxyhydroxides identified (see Part 2 report for more details).

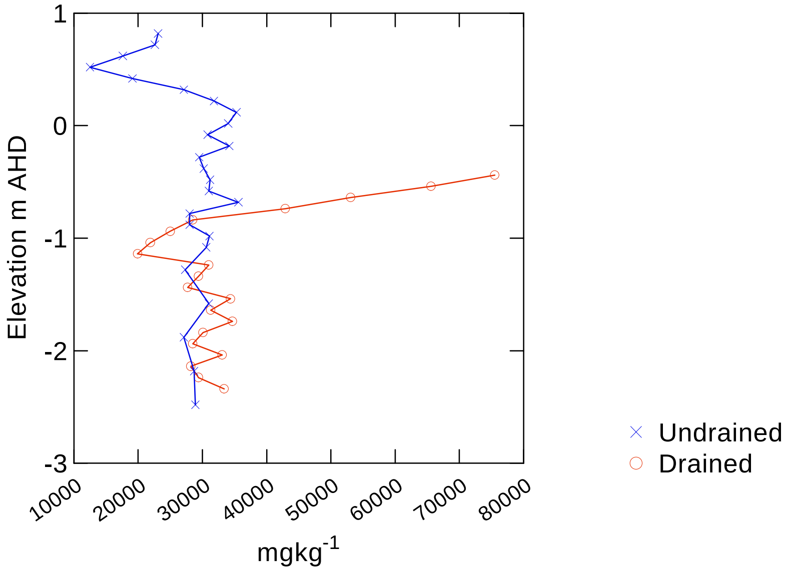


Figure 6 Iron Profile

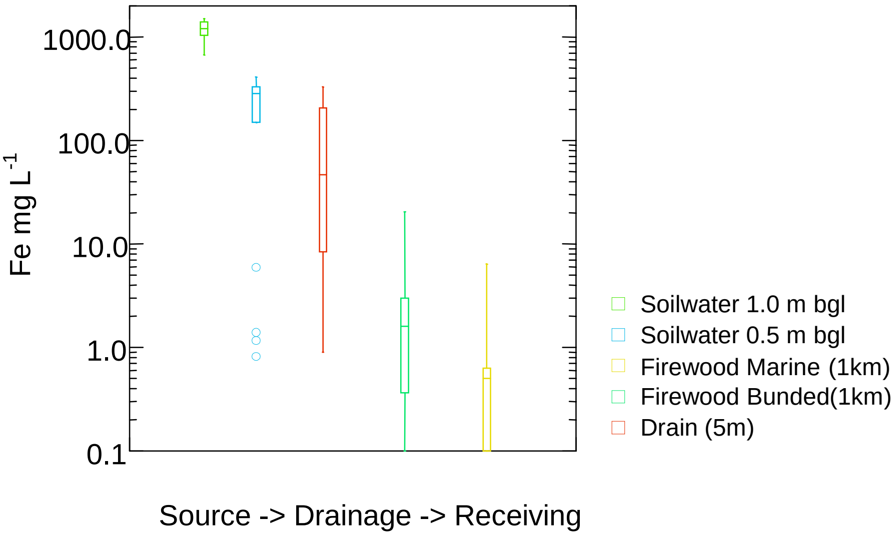


Figure 7 Box plots of Iron in surface and soil water.

Sulfur

Sulfur accumulates in the soil profile as sulfide, predominantly as iron pyrite. On drainage sulfide oxidises to sulfate (Equation 2). Sulfate can then leach from the profile, adsorb onto ferric hydroxide surfaces or remain in the soil profile as precipitates of calcium iron and aluminium minerals. These precipitates control the concentration of calcium, iron and aluminium in the soil solution. Minerals such as gypsum (Ca $SO_4.2(H_2O)$) and jarosite ($KFe_3(SO_4)_2(OH)_6$) have been identified and the minerals jurbanite ($AlOHSO_4$) predicted by our thermodynamic equilibrium calculations. In the profiles examined at East Trinity 53% of the sulfur is lost from the drained profile. Oxidation of sulfur is responsible for half the acidity generated on the oxidation of pyrite (equation 2). As expected the loss of sulfur from the soil profile closely matches the 51% loss of acidity.

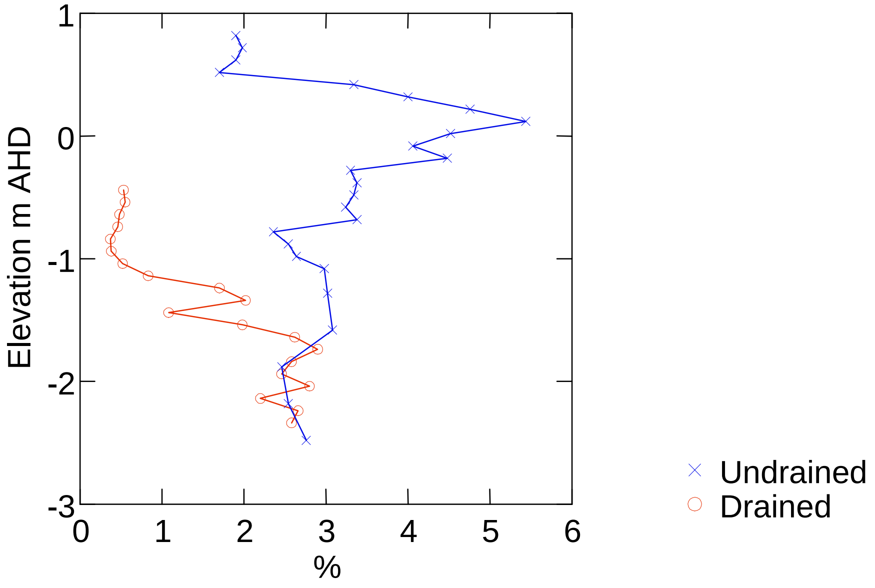


Figure 8 Soil Sulfur Profile

Arsenic and Zinc

The drained profile has lost 29% of the zinc originally present and arsenic has been concentrated in the top 0.4 m of the profile. Both elements are enriched in the top 1 metre (Table 6, Figure 9, Figure 10). This has occurred through the dissolution of these elements from soil minerals and their re-precipitation and adsorption onto iron oxyhydroxides.

Iron oxyhydroxides, have the strong ability to immobilise contaminants such as As because of their high surface reactivity (e.g.. Cornell and Schwertmann, 1996 p478). We have also recently identified a sulfur-containing iron mineral called schwertmannite ($Fe_8O_8(OH)_6SO_4$) these soils. It is likely that As is incorporated into the structure of this mineral.

Although remaining in the soil profile, these elements are no longer present in their biologically inactive natural form and could be released into the biota if conditions changed, for example through re-flooding or transport off-site.

Table 6 Arsenic and zinc concentrations (mg kg^{-1}) in undrained and drained soil profiles.

Elevation m AHD	Zn mg kg^{-1}	As mg kg^{-1}
Undrained		
0.819	55.3	10
0.719	52.9	12
0.619	42.1	11
0.519	26.3	8
0.419	27.1	17
0.319	30.8	26
0.219	29.8	29
0.119	30.1	29
0.019	29.9	22
-0.081	33.3	23
-0.181	33.4	22
-0.281	37.1	22
-0.381	45.6	23
-0.481	65.4	25
-0.581	47.4	23
-0.681	49.6	27
-0.781	46.4	21
-0.881	45.2	20
-0.981	52.7	17
-1.081	47.2	22
-1.281	37.7	23
-1.581	46.7	21
-1.881	45.3	19
-2.181	46.5	18

Elevation m AHD	Zn mg kg^{-1}	As mg kg^{-1}
Drained		
-0.439	105.5	39
-0.539	45.3	33
-0.639	48.9	36
-0.739	45.6	33
-0.839	35.7	23
-0.939	36.0	22
-1.039	34.7	20
-1.139	32.9	20
-1.239	95.0	31
-1.339	43.4	22
-1.439	120.5	23
-1.539	65.3	19
-1.639	70.0	19
-1.739	53.3	18
-1.839	45.1	13
-1.939	48.4	15
-2.039	52.4	16
-2.139	55.9	12
-2.239	59.2	15
-2.339	58.3	17

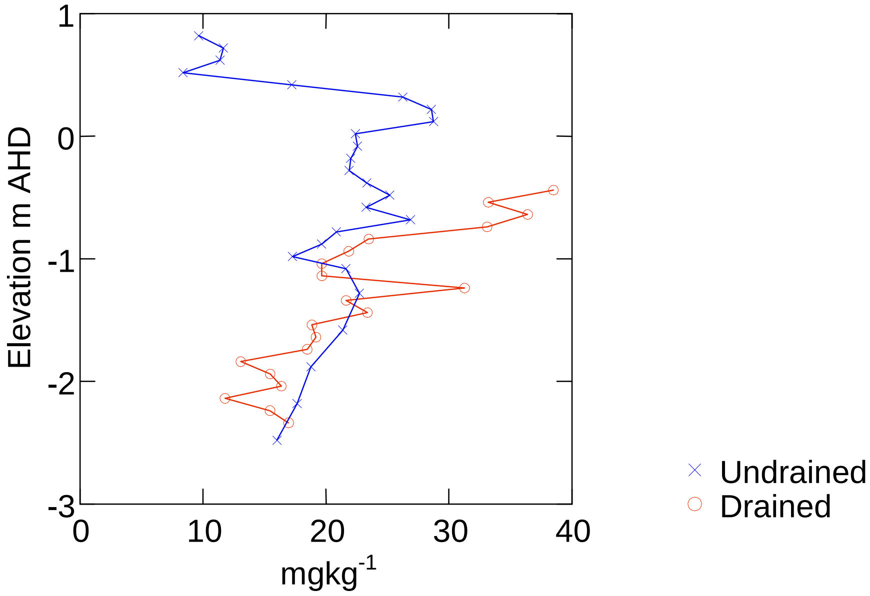


Figure 9 Soil Arsenic Profile

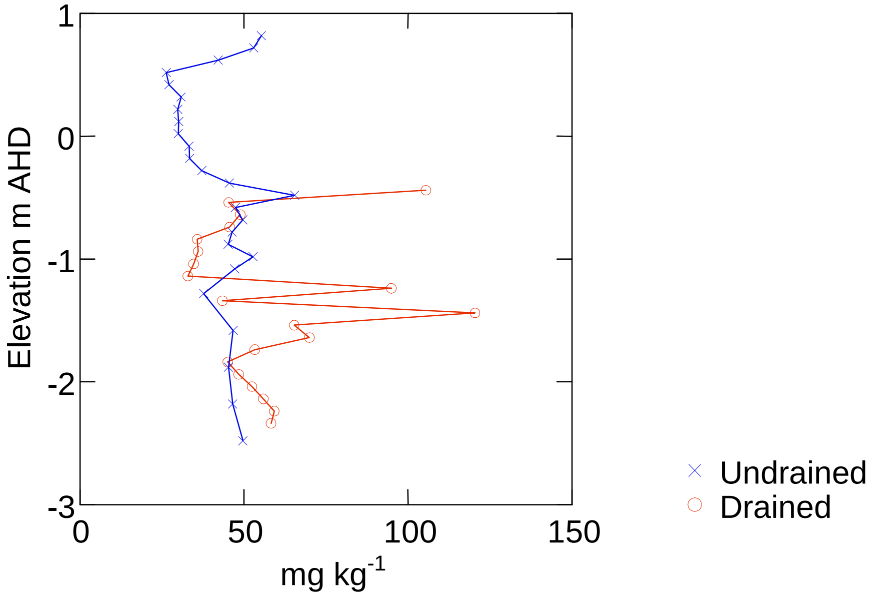


Figure 10 Soil Zinc Profile.

Water

Methodology and Detection Limits

We sampled and analysed soil solution and surface water collected from drainage lines, tidal pools and creeks. Prior to analysis all water samples were filtered through 0.2 micrometre membrane filters thus reported values represent the concentration of the dissolved fraction of each analyte. The sampling and analysis program was designed to gather data for research into process studies rather than environmental monitoring. Therefore, detection limits reflect the analytical method chosen to meet the objectives of the study, rather than the lowest available. Many samples were hyper-saline and required extra dilution prior to analysis, resulting in higher detection limits for those samples. Samples were routinely diluted 1:9 prior to analysis. Detection limits are given in Table 7

Table 7 Detection Limits

	As μgL^{-1}	Al μgL^{-1}	Fe μgL^{-1}	Zn μgL^{-1}
Method Detection Limit (* depends on dilution required by ICP technique)	2	* 100	* 100	* 50

Acidity Hazard

ASS water monitoring commonly uses pH to assess the acidity hazard. In ASS related water pH is a poor predictor of acidity hazard. Figure 11 shows that no relationship exists between pH and the actual acidity. pH only measures acidity due to hydrogen ion activity (approximately equal to concentration). In ASS discharge water there are other reduced or hydrolysable metal ions which contribute to acidity through oxidation of ferrous iron (equation 5) and the hydrolysis of aluminium (equations 7 through 9). Such cations can dominate the acidity of water samples from ASS affected sites (Figure 12) but are not considered when pH is used as the criteria of acidity hazard. The standard titration method for acidity (including the oxidation step), (APHA,1995) is a better measure of the hazard. Results obtained using this method were well correlated ($R^2=0.949$) with the sum of measured acidic cations, hydrogen, aluminium and iron at the East Trinity site (Figure 13). In ASS related water, titratable acidity is the best measure of acidity hazard.

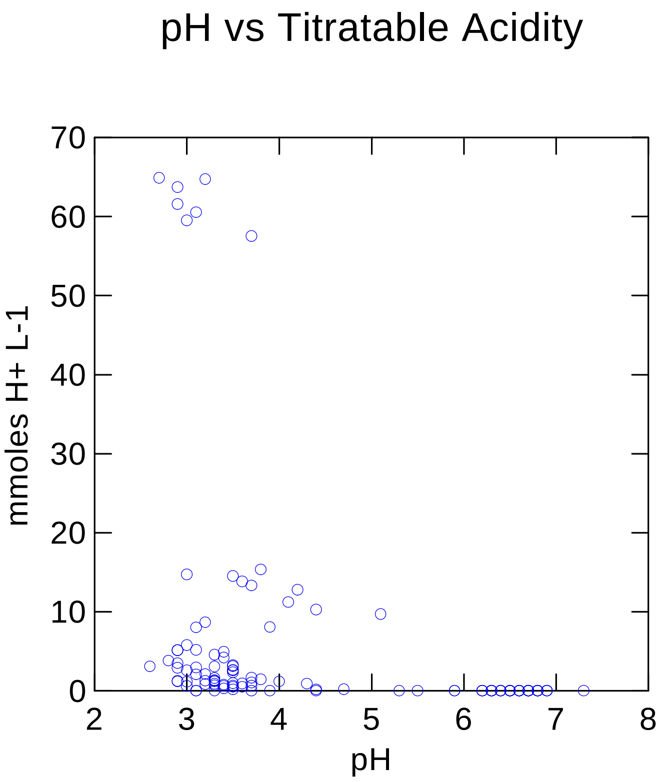
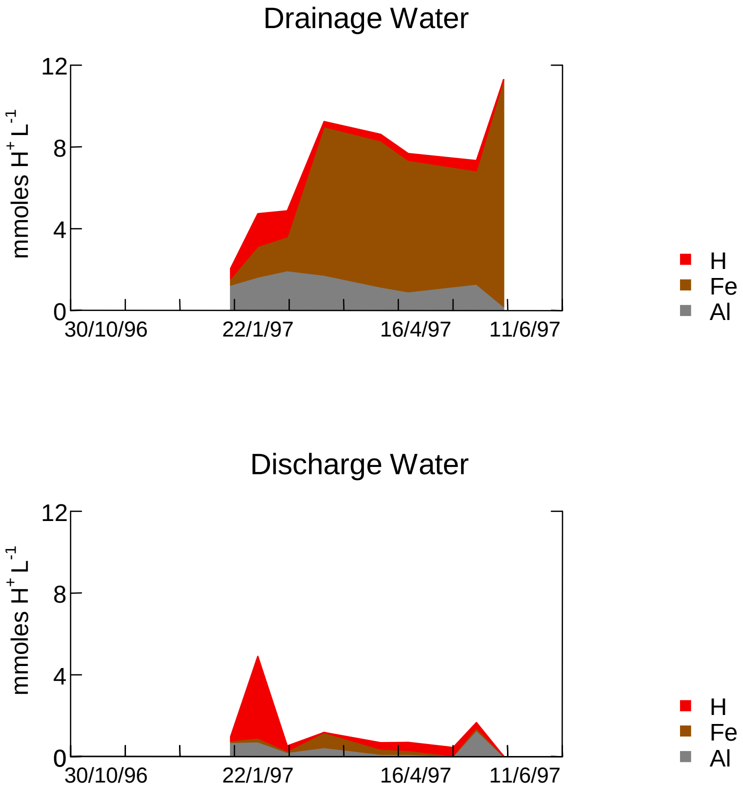


Figure 11 Plot of pH versus Titratable Acidity for East Trinity Waters



Drainage Water

Discharge Water

Figure 12 Acidic Species in Water Samples from East Trinity

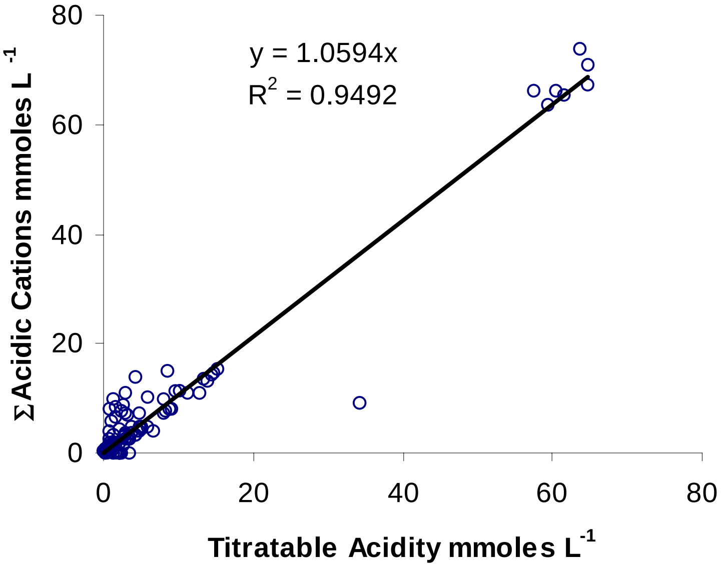


Figure 13 Relationship between titratable acidity and the sum of acidic cations (H^+, Al^{3+} & Fe^{2+}) for East Trinity water samples.

Aluminium

During the wet season, aluminium concentrations in waters inside the bunded area routinely exceed the Australia and New Zealand Environment and Conservation Council (ANZECC) Guideline for the protection of aquatic ecosystems (0.005 mg L^{-1} for pH<6.5) (ANZECC, 1992). The maximum concentration found in discharge waters was 31 mg L^{-1} in Magazine Ck on 1/12/97. Concentrations ranged from <0.1 to the maximum value of 31 mg L^{-1} and are consistent with values of 0.4 to 54 mg L^{-1} found by van Breemen in ASS from Thailand (Dent 1986). Seasonal variation in aluminium concentration is shown in Figure 14 and a statistical summary of data is given in Table 9. Magazine Ck. was sampled from October 1997 to April 1998 and concentrations consistently exceed ANZECC guidelines with a mean concentration of 13.6 mg L^{-1}. Firewood Creek was sampled from January 1997 to April 1998 and shows more variation, however concentrations consistently exceeded ANZECC Guidelines during the wet season. During the dry season when water levels were low the Firewood Creek sampling site was affected by leakage of seawater back through the floodgates. This is shown in the data as an increase in pH and in concentrations of sodium and chloride from June to November 1997 (Table 11).

Geochemical modelling using the chemical equilibrium program MINEQL$^+$ (Westall et al.,1976) indicated that in open waters, the aluminium in solution was present as free monomeric Al^{3+} and aluminium sulfates ($Al(SO_4)^+$ and $Al(SO_4)_2^-$) without any solid phase regulating its concentration. In the actively oxidising pyritic material the concentration of aluminium was controlled by jurbanite ($AlOHSO_4$). These findings are consistent with those of van Breeman (1993). In the presence of ferric iron and high silica concentrations, equilibrium calculations predict aluminium concentration in solution is regulated by a dioctahedral smectite mineral possibly Ca-nontronite with the overall formula $Ca_{0.2}Al_{0.3}Fe^{III}_2(Si(OH)4)_{3.7}$.

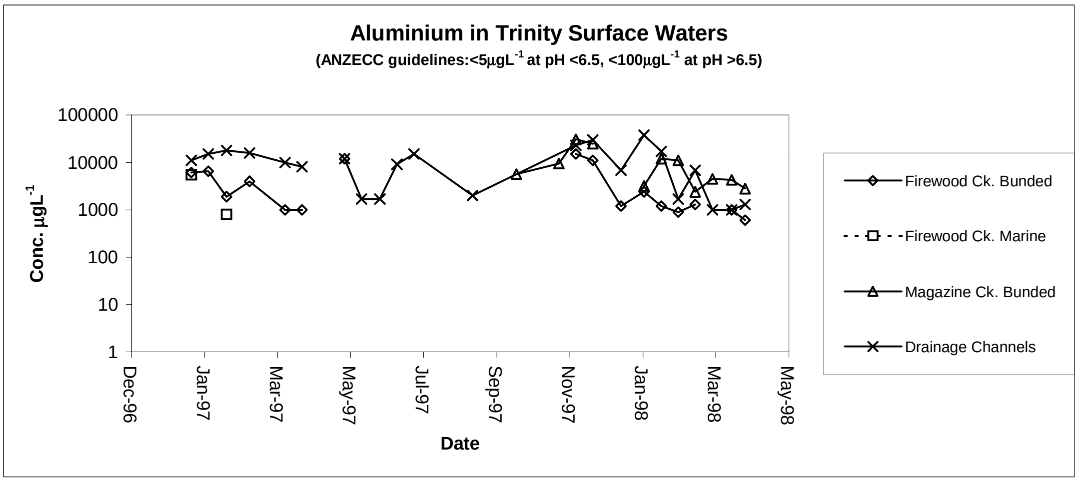


Figure 14 Concentration of dissolved Al (μgL^{-1}) in surface waters over the measurement period.

Iron

Ferrous iron is released into the solution by the oxidation of pyrite (equation 2). In the presence of organic matter and low pH, ferrous iron may migrate several kilometres before finally generating acidity (equation 5) under more oxidising conditions (van Mensvoort and Dent, 1998). Unwanted effects include depletion of oxygen in the water, acidification, clogging of fish gills and the blockage of drains. At East Trinity, substantial concentrations of soluble iron are present in discharge waters hundreds of metres to about a kilometre from their source. However concentrations are reduced from the very high (>1000 mg L^{-1}) concentrations found in soil solutions of pyritic horizons, to hundreds and tens of mg L^{-1} within a few metres. (*Figure 7*). These findings are consistent with measurements of total iron in the soil of the drained profile. Here the top 0.6 m is enriched in iron (with concentrations of up to 8%) with the iron released by oxidation of pyrite remaining in the profile. Precipitating ferric hydroxide will adsorb other trace metals such as arsenic and zinc released from soil minerals by the oxidation and acidification and result in their enrichment in the now unstable and highly mobile iron precipitates.

The ferrous iron present in discharge waters exceeds the ANZECC Guidelines of 0.5 mg L^{-1}. Geochemical predictions indicate ferrous iron is present as free Fe^{2+}, plus chloride and sulfate complexes. Seasonal variation in ferrous iron concentration is shown in Figure 15 and a statistical summary of data is given in Table 9. Significant concentrations of ferric iron were present only in drainage water and in an oxidising pyritic horizon at higher pH. Table 8 compares total and ferrous iron concentrations for a range of sites.

Table 8 Comparison of Total Iron and Ferrous Iron concentrations for samples collected on the 19/4/98.

Site	Total Fe mgL^{-1}	FeII mgL^{-1}
Firewood Ck. Bunded	2.6	2.7
Firewood Ck. Marine	0.8	1.1
Drain	5.9	2.9
Soil water TC 1 - 0.2 m	88.0	100
Soil water TC 1 - 0.5 m	410	415
Soil water TC 1 - 1.0 m	1500	1560
Soil water TC 1 - 1.5 m	61.0	41.2
Soil water TC 1 - 2.0 m	1.6	2.7
Soil water TC 1 - 3.0 m	0.5	0.1
Magazine Ck.	25.0	24.9
Soil water TC 2 - 0.2 m	0.5	0.9
Soil water TC 2 - 0.5 m	0.5	1.2
Soil water TC 2 - 1.0 m	20.0	19.2
Soil water TC 2 - 1.5 m	0.5	0.1
Soil water TC 3 - 0.5 m	120	157
Soil water TC 3 - 1.0 m	40.0	49.7

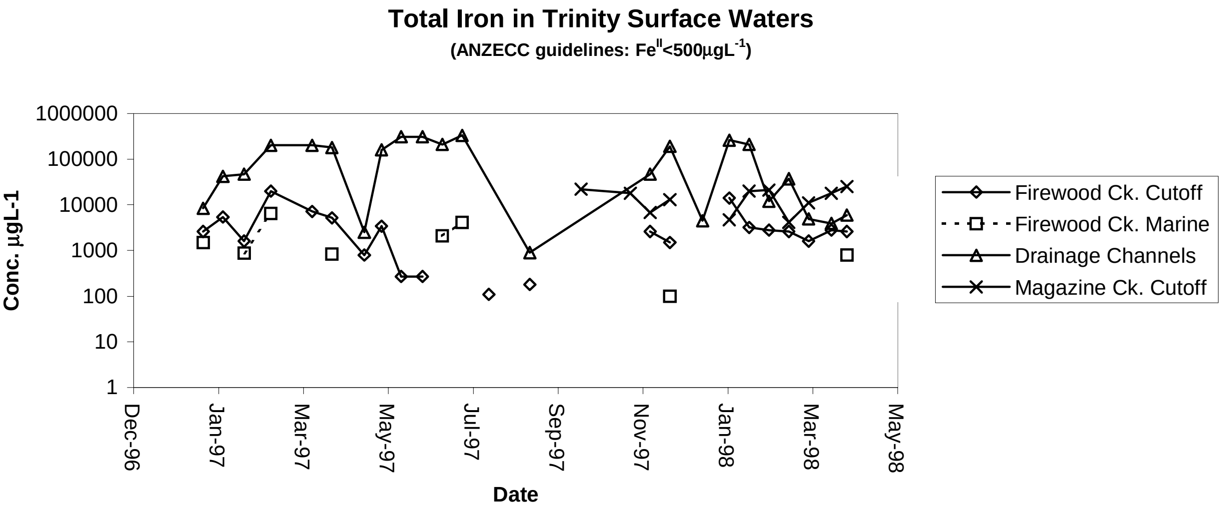


Figure 15 Concentration of ferrous iron (µgL^{-1}) in East Trinity surface waters over the measurement period.

Trace Metals-Arsenic and Zinc

Arsenic concentrations are only significant compared with the ANZECC Guideline value of 50 µg L^{-1} close to the site of pyrite oxidation, with ranges of 63 to 170 µg L^{-1} in soil water at 1 m bgl 2 to 280 µg L^{-1} at 0.5 m bgl and 2 to 130 µg L^{-1} in drainage water. Concentrations of arsenic in discharge waters are close to the detection limit of 2 µg L^{-1}. Arsenic is strongly adsorbed onto ferric hydroxide surfaces and any arsenic in solution would be removed from solution by precipitating ferric hydroxide. Thus arsenic concentration follows a similar pattern to that of ferrous iron. Although no longer in solution the arsenic in now readily available to biota when the conditions change. For example ferric hydroxides suspended in the water are discharged into Trinity Inlet where conditions in the sediment will reduce the iron to its ferrous state, releasing adsorbed heavy metals such as arsenic, which will then enter the food chain.

Zinc concentrations are similarly higher in the soil water close to where it is released by the acid hydrolysis of soil minerals. The highest concentrations occur at 1 m bgl where concentrations vary from 1.2 to 2.4 mg L^{-1}. Concentrations of zinc remain above the ANZECC guideline value of 0.05 mg L^{-1} in discharge waters. Figure 16 shows the seasonal variation in zinc concentration and a summary of data is given in Table 9.

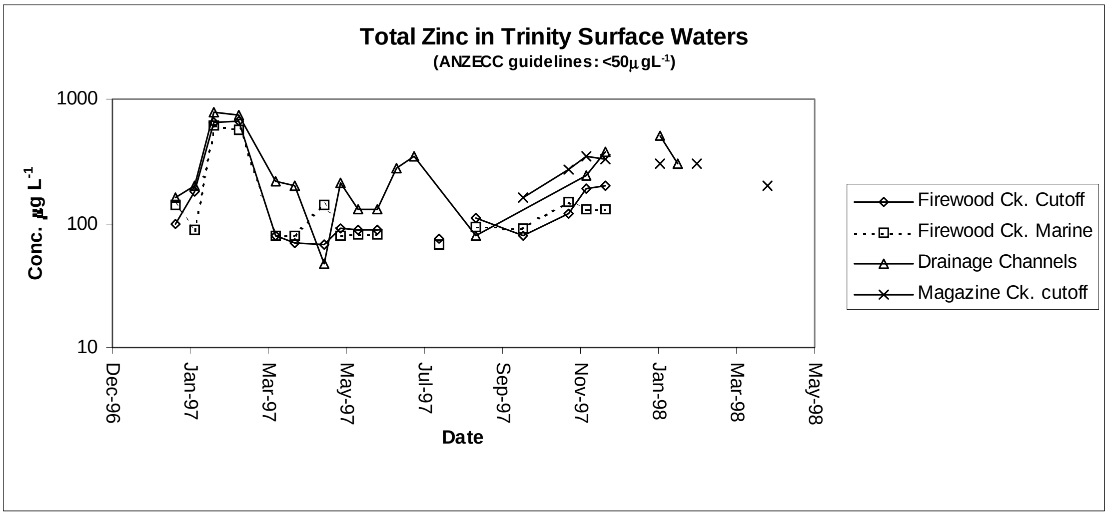


Figure 16 Concentration of Total Zinc (µgL^{-1}) in East Trinity surface waters over the measurement period.

Table 9 Summary of Selected Parameters in East Trinity Surface Water

	Statistic	pH	pe-	As ug/L	Si mg/L	Al mg/L	Fe mg/L	Mn mg/L	Zn mg/L
ANZEEC Guideline				50		0.005 0.100# # if pH>6.5	0.500		0.050
Drain	N of cases	24	6	8	24	24	24	24	24
	Minimum	2.8	6.6	2	4.0	0.1	0.9	0.4	0.05
	Maximum	5.1	11.7	130	63.6	38.0	329.1	4.9	0.79
	Median	3.2	8.8	2	37.7	9.7	46.8	1.7	0.20
	Mean	3.3	9.0	20	36.6	11.1	119.0	1.7	0.29
	Standard Dev	0.6	2.2	45	18.8	9.8	114.8	1.1	0.21
Soilwater 0.5 m	N of cases	36	38	16	35	35	35	35	35
	Minimum	3.0	-2.6	2	0.9	0.1	0.7	0.3	0.15
	Maximum	4.3	13.6	280	67.0	39.0	410.0	3.9	1.10
	Median	3.5	4.0	5	54.2	4.6	150.0	1.1	0.20
	Mean	3.5	6.3	74	51.9	8.7	151.8	1.4	0.30
	Standard Dev	0.4	4.2	104	13.3	10.0	137.2	0.9	0.19
Soilwater 1.0 m	N of cases	12	12	8	12	12	12	12	12
	Minimum	2.7	-2.6	63	46.0	110.0	670	16.3	1.20
	Maximum	3.7	4.0	170	110.0	270.0	1500	21.0	2.40
	Median	3.0	3.7	82	110.0	185.0	1200	19.5	2.30
	Mean	3.1	3.1	93	97.6	189.2	1186	19.2	2.04
	Standard Dev	0.3	1.8	34	21.8	44.0	256	1.3	0.48
Magazine Ck.	N of cases	12	6	8	12	12	12	12	12.00
	Minimum	2.6	5.2	2	8.0	0.5	0.5	1.0	0.16
	Maximum	6.2	11.6	3	26.9	31.0	25.0	4.7	0.35
	Median	2.9	7.5	2	19.0	5.1	15.5	3.5	0.20
	Mean	3.4	8.4	2	18.7	9.3	13.6	3.5	0.24
	Standard Dev	1.0	2.5	0	5.6	9.5	8.1	1.0	0.06
Firewood Ck. Bunded	N of cases	27	6	8	27	27	27	27	27
	Minimum	2.4	5.9	2	0.4	0.100	0.1	0.10	0.02
	Maximum	7.3	11.1	2	24.2	15.000	20.4	1.80	0.66
	Median	3.6	8.6	2	12.0	1.000	1.6	0.50	0.19
	Mean	4.4	8.6	2	11.3	2.595	3.1	0.57	0.20
	Standard Dev	1.5	2.3	0	6.5	3.999	4.5	0.44	0.17
Firewood Ck. Marine	N of cases	27	6	8	27	27	27	27	27
	Minimum	3.1	1.3	2	0.7	0.100	0.1	0.05	0.02
	Maximum	6.9	6.8	3	13.0	5.500	6.4	0.87	0.62
	Median	6.4	4.0	2	2.8	0.100	0.5	0.14	0.14
	Mean	6.1	4.0	2	4.1	0.511	0.8	0.30	0.19
	Standard Dev	0.9	2.2	0	3.6	1.037	1.4	0.24	0.16

Other Findings

Continuing ASS Oxidation

In the southern corner of the East Trinity site results show ongoing oxidation of pyrite to a depth of at least 2 m bgl.

Below 1 m bgl, the soil water pH remains above 5.9 indicating that the neutralising capacity of the soil has not yet been exceeded. However, soil pH in molar sodium chloride shows a drop in from 6.2 deeper in the profile and in the undrained profile to 4.9. This is probably due to the displacement of protons from the soil cation exchange sites.

The mole ratio of chloride to sulfur in water of marine origin is 19.2. As pyrite oxidises the relative amount of sulfur (sulfate) in solution increases and the mole ratio decreases. Results for site 1in the southern corner of the East Trinity site show the chloride to sulfur ratio is 10.7 at 2 m bgl, indicating a doubling of the sulfate concentration relative to chloride. The extremely low hydraulic conductivity of the soil (K_{sat}~10^{-12} ms^{-1}) means that the increase in sulfate concentration could not have come from downward leaching of sulfate and the increase in sulfate concentration must be from oxidising pyrite.

This evidence means that active oxidation is continuing and acidic discharges from the site are not from relict oxidation processes.

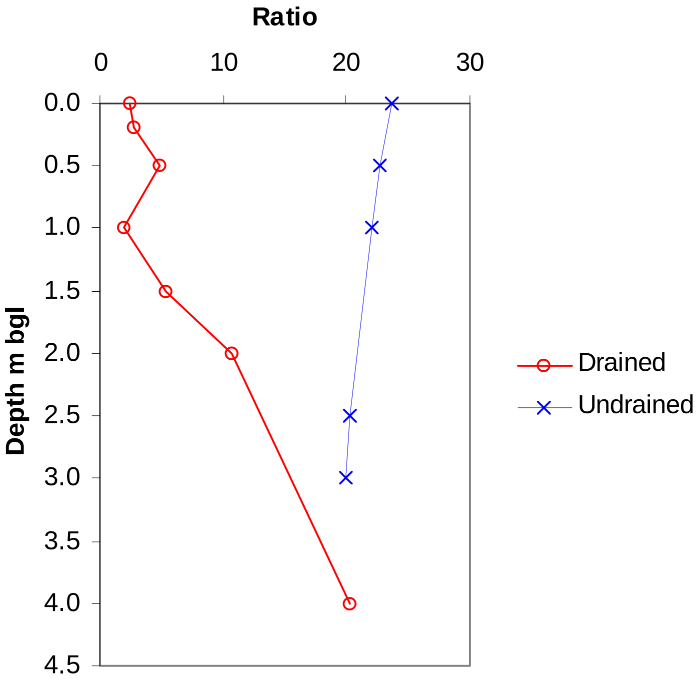


Figure 17 Mole ratio of chloride to sulfur in the East Trinity soil water. Ratio for seawater is 19.2

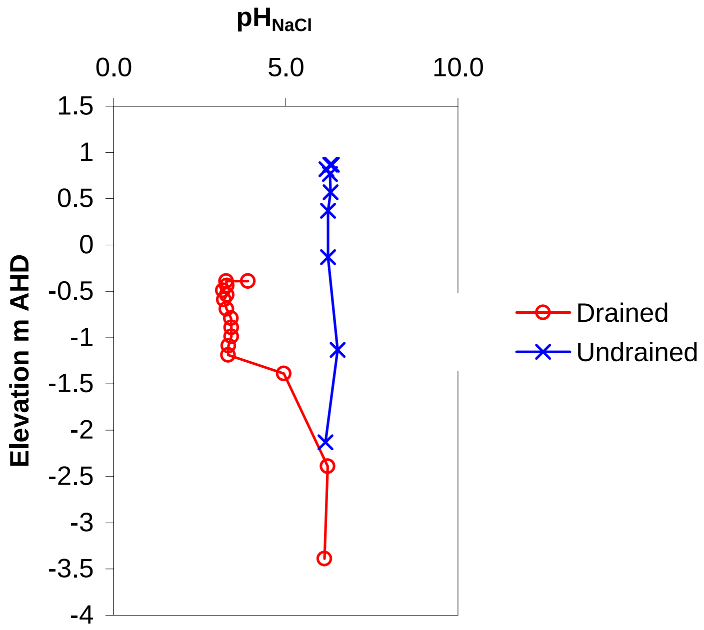


Figure 18 Soil pH profile for drained and undrained soil

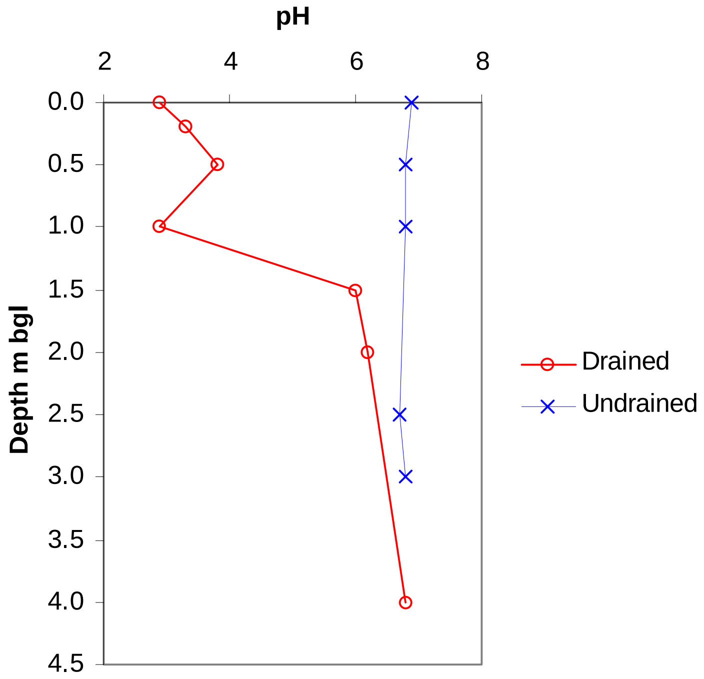


Figure 19 East trinity Soil water pH for Drained and Undrained profiles.

Seasonal Flooding

Study site TC1 was seasonally flooded and provided an opportunity to monitor the changes that would occur if the entire area were re-flooded. Once the soil above the electrode was flooded, there was an immediate drop in the redox potential and an increase in pH of about 1 unit. However the pH quickly returned to its original level and did not increase despite more than 100 days of inundation. This result is consistent with the observations of White et al 1997. van Breeman (1995) explained the failure of ‘old’ ASS to reach the theoretically predicted values of between 5.5 to 6.5 to either slow reduction or reduction in the absence of FeIII oxides. In the case of Trinity the latter does not apply and slow reduction due to either a low content of metabolizable organic matter and/or to adverse affects of low pH, high dissolved Al and poor nutrient status on the activity of anaerobes is the likely reason.

These results demonstrate that re-flooding of the site would fail to stop pyrite oxidation or decrease acidity.

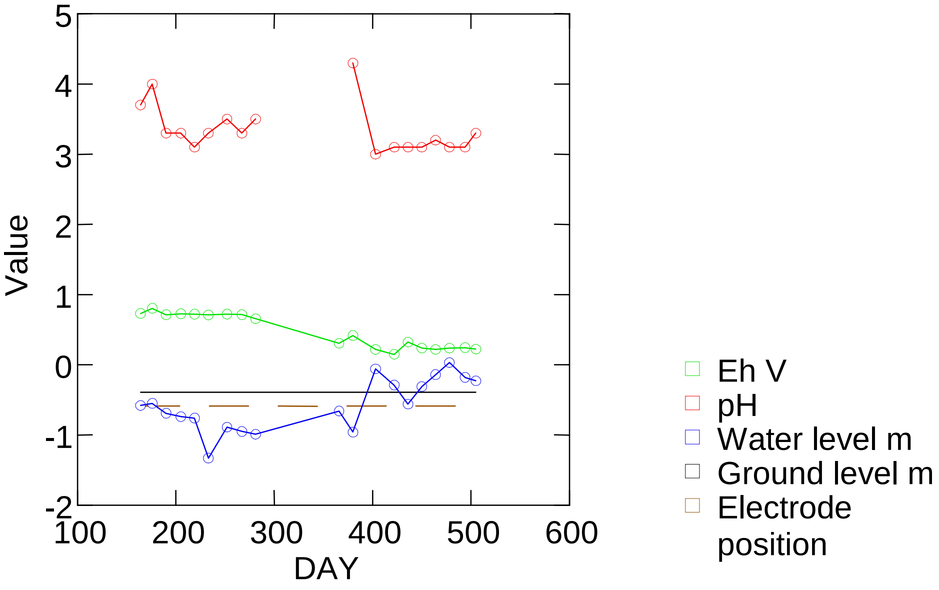


Figure 20 Change in pH and redox potential following flooding.

Conclusions

Acid Production

Acid production from the site is continuing, approximately one third of the original potential acidity remains. Results demonstrate continued oxidation of the remaining pyrite at around 1 to 2 metres below ground level. When the pyrite is finally exhausted, the accumulated acidity will continue to leach into the environment. Overseas examples indicate that the hazard could remain for decades.

Our results show that up to 1995 the site produced an estimated $1.5\text{x}10^9$ moles H^+ (72 000 t of sulfuric acid) an average annual rate of $7.0\text{x}10^5$ moles $H^+ha^{-1}y^{-1}$ (34 t $ha^{-1}y^{-1}$). This rate is 110 times the rate calculated for sub-tropical Australian ASS. It is not possible to estimate exactly how much of this acidity has been released into Trinity Inlet, however there has been severe acidification of the site and water released at the floodgates has an average pH of 3.4. Quantification of acid and other contaminant export would require flow measurements to be made at the floodgates.

Carbon Emissions

Carbon emissions from drained ASS are likely to have made a significant contribution to Australia’s carbon emissions over the past 20 to 30 years and have been underestimated.

Iron Particulates

Although we did not measure the concentration of suspended matter in the water column, suspended iron oxides can be readily seen in discharge water. This suspended material is almost certainly contains elevated concentrations of arsenic and zinc, with concentrations based on measurements made in soil profiles of 300 to 700 mg kg^{-1} of arsenic and from 100 to 500 mg $kg^{-1}$of zinc. Once this material is deposited in marine sediments adsorbed elements will be released into the marine environment. They can then be taken up by benthic and bottom feeding organisms and enter the food chain of animals within the Great Barrier Reef Marine Park.
The top 0.6 m of the soil profile inside the bunded area contains high concentrations of precipitated iron oxides (up to 8% iron) containing elevated concentrations of arsenic. Feral pigs feeding on the site may ingest sufficient quantities of arsenic to create a human health problem when they are hunted and consumed for food by indigenous Australians in the area.

Water Quality

Concentrations of aluminium, iron and zinc in discharge waters regularly exceed the relevant ANZECC Guidelines for the protection of aquatic ecosystems. Maximum concentrations occur during the wet season when oxidation products that have built up in the soil profile leach into the surface water. Water discharged into Trinity Inlet contains dissolved aluminium between 6000 and 120 times the ANZECC Guidelines. Patterns related to environmental factors are apparent in the composition of the discharge water, however further analysis of the data is required before the processes and factors can be quantified.

Rehabilitation

Basic Principles

The basic principles of rehabilitation are to curtail pyrite oxidation and to neutralise or leach existing acidity.

Pyrite oxidation can only be stopped by removing the oxygen supply. This can be done by re-flooding or capping. After the removal of the oxygen supply, oxidation of pyrite by FeIII may continue for some time. Pyrite oxidation can be slowed by decreasing the rate of FeIII production. Bactericides that inhibit *Thiobacilli* or amendments that complex or precipitate the iron are ways to do this. However, this is only a temporary solution more suited to short term requirements such as stockpiling during engineering works.

Neutralisation can be achieved by the addition of lime (or other alkaline substances) and by the reduction of FeIII oxides which consumes protons.

Leaching is only possible using a water management system that discharges acidic surface water. This is usually done at times of high flow to reduce the environmental impact. Most successful ASS rehabilitation schemes in S-E Asia rely on a combination of leaching through sophisticated water management and amendments to the leached soil. Management that relies on the discharge of acidic surface water containing toxic elements, may not be an acceptable option for Australian ASS.

Capping

Prior to capping the existing acidity would need to be neutralised. Capping has the advantage that only the existing acidity needs to be neutralised. However incorporating the lime to at least 1.5m bgl is required. Banding of lime is unlikely to be successful due to the low hydraulic conductivity of the soil and the precipitation of iron, which would block water movement and coat the lime surface stoping its neutralising action.

Liming

We estimated the remaining acidity to –2.3 m AHD to be $1.2\text{x}10^7$ moles H^+ ha^{-1}. Currently oxidation is occurring at –2 m AHD so neutralisation would be required to about the same level. This would require 600 tonnes of lime per hectare, incorporated to 1.5 m below the current ground level to neutralise the current acidity and remaining potential acidity.

The neutralisation of leachate with lime drains would require costly maintenance as iron precipitates clog drains and coat the surface of the lime making it inactive.

Re-flooding

Re-flooding has not been successful in reducing the production of acid or halting the continued oxidation of pyrite in Australian ASS. This is in contrast with the situation in S-E Asia where re-flooding of rice paddies is a successful management tool. Re-flooding as a management tool relies on establishing conditions where the reduction of the Fe, Mn, S and N can take place. The reduction of these elements consumes protons and is responsible for the increase in pH commonly observed in acid soils after waterlogging.

Evidence from elsewhere in Australia and the response of our study site to seasonal flooding indicate that simple re-flooding of the East Trinity site would not establish the reducing conditions necessary for neutralisation of acid or acidic by products. It is likely that a number of factors are involved in inhibiting reduction and no simple solution exists. If the conditions could be managed to establish reducing conditions, other problems would need to be overcome before environmentally acceptable rehabilitation plan could be devised. The increase in pH is favourable for the decrease in dissolved aluminium concentrations, however other changes such as the production of potentially toxic substances such as Fe^{2+}, organic acids and H_2S are not. In addition the reduction of FeIII oxides would result in the release of adsorbed elements such as arsenic and zinc.

It should be noted that removal and redistribution of soil materials during drainage works and post-drainage subsidence in the southern corner of the East Trinity site will complicate any re-flooding and a return to pre-drainage hydrology is impossible.

Acknowledgements

The authors wish to thank Norm and Edna Whitney. The project would have been impossible without their dedicated work in providing able and resourceful on-site technical assistance.

We also wish to thank the Queensland Department of Primary Industries in particular Doug Smith, for assistance in setting up the site and for making their soil survey data available for our use.

We gratefully acknowledge the assistance of Phil Davies and Damian Mowat for assisting us in the field with the installation of equipment and sampling of the soil pits.

References

ANZECC 1992. National Water Quality Management Strategy – Australian Water Quality Guidelines for Fresh and Marine Waters. Australian and New Zealand Environment and Conservation Council, Canberra.

APHA. 1995. Standard methods for the examination of water and waste water. 19th ed. pp 2-23 to 2-25. APHA-AWWA-WEF, Washington.

Bartlett, R.J. 1986. Soil Redox Behavior. *In:* Sparks, D.L. (ed) Soil Physical Chemistry, p200. CRC Press, Boca Raton.

Cornell, R.M., and U. Schwertmann. 1996. The Iron Oxides: Structure Properties, Reactions, Occurrence and Uses. Verlag Chemie, Weinheim.

Dent, D.L. 1986. Acid sulphate soils:a baseline for research and development. I.R.I. Pub. No. 39. pp31-32. Internat. Instit. For Land Reclam. and Imp. Wageningen.

Dent, D.L. and Bowman, G.M. 1996. Quick Quantitative assessment of acid sulfate hazard. CSIRO Division of Soils, Divisional Report 128

Hollingsworth Dames and Moore (1993). Royal Reef Project: Assessment of the distribution of acid sulfate soils. Report No. 28/92.

National Working Party on Acid Sulfate Soils. June 1998. Draft National Strategy for the Management of Coastal Acid Sulfate Soils. NSW Agriculture, Wollongbar Agricultural Institute, Wollongbar NSW.

Nordstrom, D.K. 1982. Aqueous pyrite oxidation and consequent formation of secondary iron minerals. *In:* Kittrick, J.A., Fanning, D.S. and Hossner, L.R. (eds), Acid Sulfate Weathering. SSSA Special Pub. No. 10, p52. Soil Science Society of America, Madison.

Queensland Department of Primary Industries. 1995. Unpublished

van Breeman, N. 1993. Environmental aspects of acid sulphate soils. *In:* Dent, D.L. and van Mensvoort, M.E.F. (eds), Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils, Mar. 1992, I.R.I. Pub. No. 53. pp. 391-402. Internat. Instit. For Land Reclam. and Imp. Wageningen.

van Mensvoort, M.E.F. and Dent, D.L. 1998. Acid Sulfate Soils. *In:* Lal, R., Blum, W.H., Valentine, C. and Stewart, B.A. (eds), Methods for assessment of soil degradation. Advances in Soil Science, pp301-335. CRC Press, Boca Raton.

Westall, J.C., Zachary, J.L. and Morel, F.M.M. 1976. MINEQL, A Computer Program for the Calculation of Chemical Equilibrium Composition of Aqueous Systems. Tech Note. 18, Dept. of Civil Eng., Mass. Inst. Technology, Cambridge, MA.

White, I., Melville, M.D., Wilson, B.P. and Sammut, J. 1997. Reducing acidic discharges from coastal wetlands in eastern Australia. Wetlands Ecology and Management 5:55-72.

Youngs, E.A. (1991) Hydraulic conductivity of saturated soils. *In:* K.A. Smith and C.E. Mullins (eds), Soil Analysis Physical Methods, M Dekker, New York, pp161-207.

APPENDIX 1

PROPERTIES AND CLASSIFICATION OF ACID SULFATE SOILS

1 ***Acid Sulfate Soils***
2 ***Current National issues about Acid Sulfate Soils***
3 ***Field Methods***
4 ***Wet Chemical and mineralogical Methods of Analysis***

APPENDIX 1.1: IDENTIFICATION AND CLASSIFICATION OF ACID SULPHATE AND POTENTIAL ACID SULPHATE MATERIALS

APPENDIX 1.2: FIELD DESCRIPTION INFORMATION

APPENDIX 1.3: FIELD ESTIMATE OF MECHANICAL PROPERTIES AS RELATED TO SOIL MOISTURE OR WETNESS: n-VALUES

APPENDIX 1.4: ESTIMATION AND KINDS OF ORGANIC SOIL MATERIAL

APPENDIX 1.5: SALINITY

REFERENCES

PROPERTIES OF COASTAL ACID SULFATE SOILS

1 *Acid Sulfate Soils*

Acid sulphate materials are saline soils or sediments containing pyrites, which once drained (as part of land management or development measures), become acidic and release large amounts of acidity and other contaminants into the ecosystem with consequent adverse effects on plant growth and animal life. These soils are widespread around coastal Australia (especially when associated with mangrove swamps) and occur to an unknown extent in inland areas.

The source of acid sulfate problems is pyrite, FeS_2, which when oxidised generates sulfuric acid that brings the pH below 4, sometimes even below 3 (see Appendix 1.1 for sequence of reactions involved). Sulfuric acid may leak into drainage and floodwaters, corrode steel and concrete, and attack clay, liberating soluble aluminium and which kills vegetation and aquatic life. The off-site environmental implications means that more attention should be paid to these soils following soil drainage or excavation through areas where these soil conditions exist.

Acid sulfate soils are extensively developed around the Australian coastline, although they have only recently come to prominence in land use planning as a result of the detrimental environmental consequences that can arise from disturbing them. The recognition of acid sulfate sediments and soils in Australia and research into their behaviour has been limited. Hence, none of the published major Australian soil or geological classification systems has satisfactorily provided for such materials. However, an International Soil Classification System known as Soil Taxonomy (Soil

Survey Staff, 1996) does provide methods for describing, identifying and classifying acid sulphate and potential acid sulphate producing materials (i.e. sulfuric horizon and sulfidic materials).

Although a plethora of complex terminology and standards have evolved in the literature in relation to acid sulfate soils, in this report these have been simplified to the following two concepts as outlined in the flow-diagram in Appendix 1:

- ***Actual Acid Sulfate Soil*** (i.e. sulfuric horizon) are coastal sedimentary materials that once contained pyrites and may still contain some, but which have been exposed to the atmosphere by drainage or disturbance so that the pyrite has oxidised to form sulfuric acid, thereby decreasing the pH to less than 3.5. These materials are also characterised by bright yellow or straw coloured mottles of the mineral jarosite and often contain dark reddish coloured streaks.

- ***Potential Acid Sulfate Soil*** (i.e. sulfidic material) are coastal sedimentary materials that contain iron pyrites that has not been oxidised. Consequently, the pH is usually near neutral (approximately 7.0).

The hazards presented by acid sulfate soils are magnified by their location and specific properties. For example, the depth to the actual acid sulfate (i.e. sulfuric horizon) or potential acid sulfate (i.e. sulfidic materials) materials as well as the concentration of salts or minerals (e.g. sodium chloride, jarosite or pyrite) are critical.

2 *Current National Issues about Acid Sulfate Soils*

The Australia wide distribution of Acid Sulfate soils unknown at any scale. There is no consistent standard for mapping their extent or severity. It is difficult to frame a national strategy for dealing with them without knowing where they are and how extensive (an estimate of 2 million ha). Acid Sulfate soils are not all the same and nearly all characterisation has been in northern NSW and SE Queensland. For regulation and management, the range of soils likely to be encountered and the way they function must be known. For example, Acid Sulfate soils under a 10m tidal range in tropical NW Australia will be in a very different situation from one in SE Australia with a 2m tidal range. Consequently, there is an urgent need for more pedological, chemical, mineralogical, physical and microbiological information about Acid Sulfate soils and degradation processes especially in southern Australia.

3 *Field Methods*

A simplified technical soil classification system is outlined in the flow-diagram in Appendix 1.1. The international soil classification system known as Soil Taxonomy (Soil Survey Staff, 1996) is commonly used as a basis to provide the methods for describing, identifying and classifying acid sulfate soil (*sulfuric horizon*) and potential acid sulfate producing soils (*sulfidic materials*) (Appendices 1.1 to 1.5).

Soil pits should be excavated using a backhoe across the site to be investigated or surveyed. The first step of the procedure is to identify distinct horizons in each profile, photograph the profile and describe the following characteristics for each separate horizon: Horizon thickness, matrix colour, mottle colour, mottle type (abundance, size contrast), texture, structure, coarse fragments (type, abundance, size), reaction or fizz to HCl (McDonald *et al*. 1990); n-Value (Appendix 1.3), organic matter type (Appendix 1.4).

After completing the profile description each soil horizon or layer is sampled for chemical and mineralogical analyses. The simplified soil classification key is used to identify and classify the soils into the following two categories: Actual Acid Sulfate Soils and Potential Acid Sulfate Soils (Appendix 1.1). The process simply uses pH data and recognising specific visual soil features (soil colour). Methods and procedures used to classify these materials are simple and cost effective. Finally, it is possible to use this information to construct a simple soil map of the survey area with legend.

4 *Wet Chemical and mineralogical Methods of Analysis*

Moisture

The moisture content was calculated from the measured weight loss on drying a weighed, representative sub-sample of the as-received soil sample at 105°C.

Electrical conductivity and pH

A 4 g sub-sample was placed in a screw cap container, 8 mL water added and the suspension shaken for one hour (1:1 soil:water ratio). Similarly, a 4 g sub-sample was extracted with 40 mL water (1:5 soil:water ratio). The electrical conductivity was measured after calibrating the conductivity meter using 0.1M KCl (12.9 dSm^{-1}). Then the pH meter was calibrated using pH 4.00 and pH 9.00 buffers before measuring the pH of the sample extracts. Method 2B1, Rayment and Higginson (1992).

Aged pH

A separate sub-sample was set aside and kept moist (field capacity) as a layer 1 cm thick while maintaining contact with the air at room temperature. After two weeks, a 4g sub-sample was extracted with 20 mL water and the pH determined as above. This was repeated after 2, 4, 7 and 9 weeks (see Appendix 1.1 below).

Air-dried pH

A sub-sample was dried at 35°C then ground and sieved through a 2 mm sieve to prepare an air-dry, <2 mm sample for further analysis. The pH was measured by extracting a 4g sub-sample of air-dry soil with 20 mL water for one hour and measuring the pH as above. Method 4A1, Rayment and Higginson (1992).

Carbonate content Air

An air-dry sub-sample was weighed into a polypropylene cup, placed in the reaction vessel of a Collins Calcimeter and reacted with 2M HCl. The volume of CO_2 given off was measured to determine the carbonate content calculated as calcium carbonate.

Organic carbon

An air-dry sub-sample was weighed and then combusted in an atmosphere of oxygen in a Leco CR-12 carbon analyser at 1200°C. The quantity of CO_2 produced was measured by the I.R. detector and the total carbon content calculated automatically by the instrument. Method 6B3, Rayment and Higginson (1992). The organic carbon content was calculated by subtracting the inorganic (carbonate) carbon from the total carbon.

Soluble sulfur

A 10 g air-dry sub-sample was extracted with 50 mL of deionised water. Sulfur was measured by Inductively Coupled Plasma Spectrometry on the centrifuged supernatant. Method 10 B3, Rayment and Higginson (1992).

Total sulfur

An air-dry sub-sample was weighed, mixed with vanadium pentoxide and then combusted in an atmosphere of oxygen in a Leco CR-132 sulfur analyser at 1370°C. The quantity of SO_2 produced was measured by the I.R. detector and the total sulfur content calculated automatically by the instrument.

Extractable salts and trace elements (including heavy metals)

A 4 g sub-sample was placed in a screw cap container, 20 mL deionised water added and the suspension shaken for one hour (1:5 soil:water ratio). The extract was analysed using Inductively Coupled Plasma Spectroscopy (ICPS).

Mineralogical Methods

Selected samples were ground to a fine powder using an agate mortar and pestle.

X-ray diffraction (XRD)

X-ray diffraction patterns were obtained on the fine powder fraction of ground soil samples packed into aluminium holders. XRD data was also obtained for small subsamples of surface precipitates and other components of soil horizons (e.g. bright yellow mottles). The XRD instruments were Philips PW1710 and PW1800 microprocessor-controlled diffractometers with Co radiation, automatic-divergence slits and graphite monochromators. XRD patterns were collected as digital data and logged to permanent data files using instrument control programs developed by Self (1988, 1989). Analysis of the data was carried out using the program XPLOT (Raven, 1990).

Scanning electron microscopy (SEM)

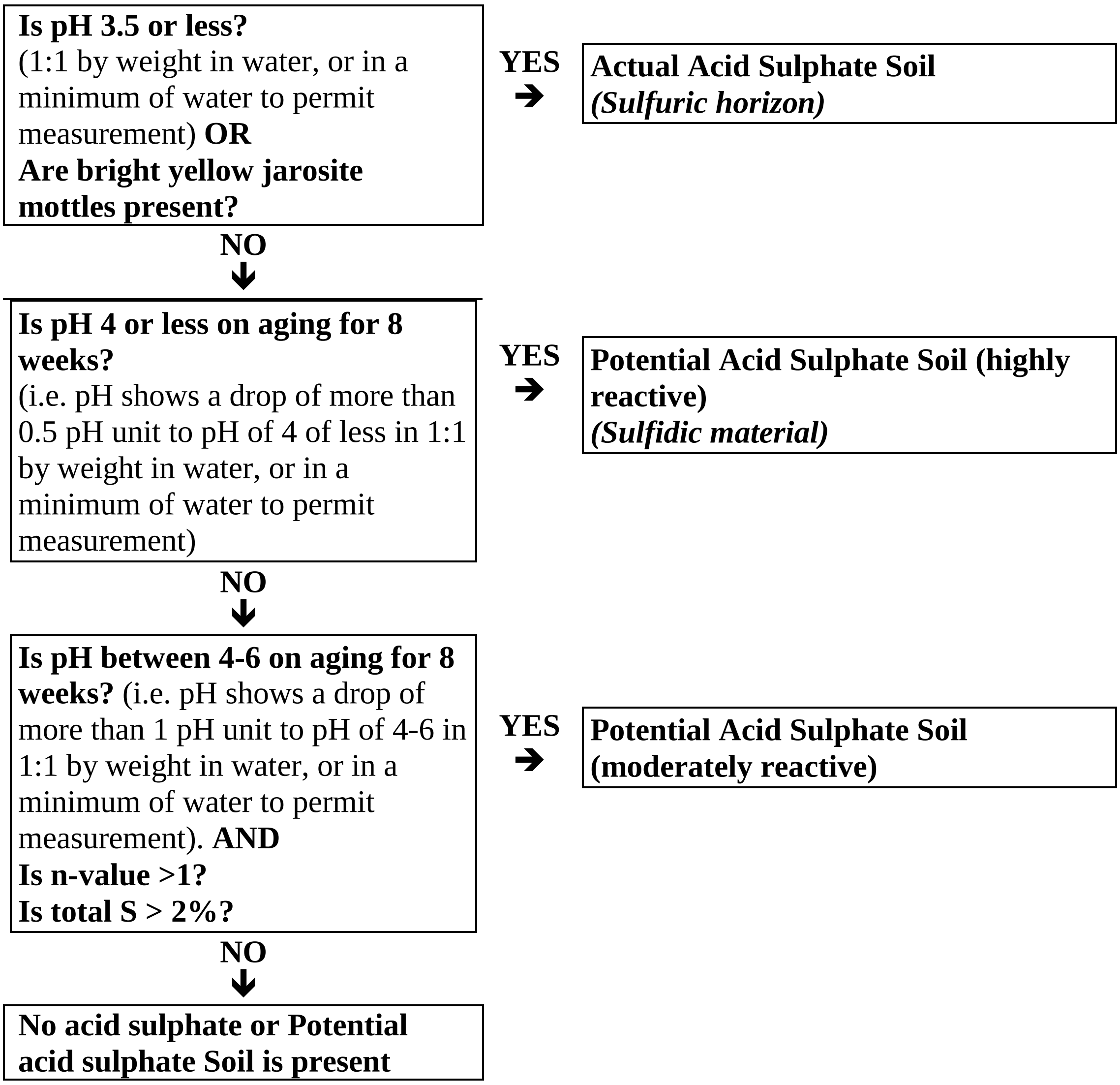
Scanning electron microscope (SEM) studies of either small flakes of the air-dried sample mounted on aluminium stubs and sputter-coated with gold or carbon-coated were made using a Cambridge Stereoscan 250 Mark 3 instrument fitted with a Be-windowed, Link energy-dispersive x-ray spectrometer (EDS). An attached Link EDS was used to provide elemental analyses of elements with atomic number greater than 9.

APPENDIX 1.1

IDENTIFICATION AND CLASSIFICATION OF ACTUAL ACID SULPHATE SOIL AND POTENTIAL ACID SULPHATE SOIL

Acid sulphate materials are saline soils or sediments containing pyrites, which once drained (as part of remedial land management measures, or as part of coastal development), become acidic releasing large amounts of acidity into the ecosystem with consequent adverse effects on plant growth, animal life etc. These soils are widespread around coastal Australia (especially when associated with mangrove swamps) and occur to an unknown extent in inland areas.

THE FOLLOWING KEY CAN BE USED TO HELP IDENTIFY AND CLASSIFY "ACTUAL ACID SULPHATE" AND "POTENTIAL ACID SULPHATE" SOILS:



Is pH 3.5 or less? (1:1 by weight in water, or in a minimum of water to permit measurement) **OR Are bright yellow jarosite mottles present?**

YES ➔ **Actual Acid Sulphate Soil *(Sulfuric horizon)***

NO ↓

Is pH 4 or less on aging for 8 weeks? (i.e. pH shows a drop of more than 0.5 pH unit to pH of 4 of less in 1:1 by weight in water, or in a minimum of water to permit measurement)

YES ➔ **Potential Acid Sulphate Soil (highly reactive) *(Sulfidic material)***

NO ↓

Is pH between 4-6 on aging for 8 weeks? (i.e. pH shows a drop of more than 1 pH unit to pH of 4-6 in 1:1 by weight in water, or in a minimum of water to permit measurement). **AND Is n-value >1? Is total S > 2%?**

YES ➔ **Potential Acid Sulphate Soil (moderately reactive)**

NO ↓

No acid sulphate or Potential acid sulphate Soil is present

Soil Survey Staff (1996) method to identify a *Sulfuric Horizon* or Acid Sulphate material

- 15 cm or more thick.
- Samples are identified as having sulfuric horizons (or acid sulphate properties) if the **pH is 3.5 or less** (1:1 by weight in water, or in a minimum of water to permit measurement) and shows evidence that the low pH is caused by sulfuric acid.

The evidence is one or more of the following:

- **Jarosite** concentrations, **or**
- Directly underlying sulfidic materials (defined above), **or**
- 0.05 % or more water-soluble sulfate.

Soil Survey Staff (1996) method to identify: *Sulfidic Material* or Potential Acid Sulphate material

(pH decrease after ageing in laboratory)

- Sample kept moist (field capacity) as a layer 1 cm thick while maintaining contact with the air at room temperature.
- After two weeks, a 4g sub-sample is extracted with 4 mL water and the pH determined (i.e. 1:1 by weight in water, or in a minimum of water to permit measurement).
- This is repeated after 4, 6 and 8 weeks.
- Samples are identified as having sulfidic materials (or potentially acid sulphate properties) if the pH on aging for 8 weeks shows a drop more than **0.5 pH unit or more to a pH value of 4.0 or less.**
- Thus if these soils were drained, or otherwise exposed to aerobic conditions (e.g. by earthwork excavations) the sulfides in these materials will oxidise to form some reactive sulfuric acid Fe^{2+} will undergo hydrolysis, as follows:

$FeS_2 + 7/2\ O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$ ....[1]

$FeS_2 + 15/4\ O_2 + 7/2\ H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$ ...[2]

However, these reactions greatly simplify the description of pyrite oxidation which includes several redox reactions, hydrolysis and complex ion formation, solubility controls, as well as kinetic effects.

The initial oxidant of pyrite is O_2 and elemental sulfur is produced:

$FeS_2 + 3/4\ O_2 + 3/2\ H_2O \rightarrow Fe(OH)_3 + SO_2$ ....[3]

the oxidation of elemental sulfur produces acidity:

$S_2 + 3O_2 + 2H_2O \rightarrow 2SO_4^{2-} + 4H^+$ ....[4]

As the pH decreases to below 3.5, which allows Fe^{3+} to remain in solution, Fe^{3+} becomes the dominant oxidant:

$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$ ......[5]

This reaction is biologically mediated by some thiobacilli such as *Thiobacillus ferroxidans* which functions well under highly acidic conditions to oxidize most reduced forms of sulfur, including sulfides (Trudinger 1979). *Thiobacillus ferroxidans* can also grow by oxidation of Fe^{2+}. The activity of such organisms results in an acceleration of the rate of pyrite oxidation (van Breemen, 1982). In addition, it is possible that the supply of Fe^{3+} had to build up to a certain level before the bacteria became active.

APPENDIX 1.2

FIELD DESCRIPTION INFORMATION

Colour: Soil: Description of soil colour has been standardised through the use of Munsell notations (colour charts produced for use with soils are available from Munsell Color Company, Inc., Baltimore 18, Md., USA). Accordingly, colour is usually given for moist soil in a descriptive term (eg. yellowish brown) and as a notation (eg. 10YR 5/4), the latter being compounded from charts for hue (10YR) and notations for value (5) and chroma (4).

Mottled: having, blotches of soil with a different colour.

Texture: HC = Heavy clay; MC = Medium Clay; LC = Light Clay; SCL = Sandy Clay Loam; L = Loam; S = Sand. (McDonald *et al*. 1990).

Behaviour of moist bolus (ball) for some common heavy soils.

Soil texture	**behaviour of moist bolus**
Sand (**S**)	Coherence nil to very slight, cannot be moulded; Clay is < 5%
Loam (**L**)	Bolus coherent and rather spongy; smooth feel when manipulated but with no obvious sandiness; may be greasy to touch if organic matter is present; will form ribbon of about 2.5 cm. Clay is about 25%
Sandy clay loam (**SCL**)	Strongly coherent bolus, sandy to touch; medium size sands grains visible in finer matrix; will form ribbon of 2.5 - 4.0 cm. Clay is about 30% - 35%.
Clay loam (**CL**)	Coherent plastic bolus; smooth to manipulate; will form ribbon of 4 - 5 cm. Clay is about 20% - 30%.
Light clay (**LC**)	Plastic bolus; smooth to touch; slight to shearing between thumb and forefinger; will form ribbon of 5 - 7.5 cm. Clay is about 35% - 40%.
Medium clay (**MC**)	Smooth plastic bolus, handles like plasticine and can be moulded into rods without fracture; has some resistance to ribboning shear; will form ribbon of 7.5 cm or more Clay is about 45% - 55%.
Heavy clay (**HC**)	Smooth plastic bolus: handles like stiff plasticine; can be moulded into rods without fracture; has firm resistance to ribboning shear; will form ribbon of 7.5 cm or more. Clay is about >55%.

Structure

Cracks will not be evident within a wet cracking clay soil. However peds will still be able to be removed by prising them from the core. What would have been a crack-line when the soil was dry will now be a line of weakness that will break to enable the clod to be removed. Once the ped is removed, examine the newly exposed face of the pit and ped. *Small angular shiny faces* show **good ped structure (eg prismatic**). However if the soil has a very dull, finely-grained appearance it indicates that the lump has been removed by tearing through the fabric of the soil rather than by breaking it along natural lines. This is a sign that the natural soil peds or clods are large or **massive (M)**.

Lime/gypsum

Usually present as shell or coral fossils. Remove these nodules and place them in dish of acid (eg. HCl). If the material causes the liquid to bubble it indicates that the nodule is composed of lime (calcium carbonate). If bubbling does not occur the deposit may be gypsum especially if there are clear, needle shaped, crystalline formations which turn white when crushed.

APPENDIX 1.3

SIMPLE FIELD ESTIMATE OF MECHANICAL PROPERTIES AS RELATED TO SOIL MOISTURE OR WETNESS: n-VALUES

n-Value (mechanical properties related to soil moisture or wetness)

The n-value (sometimes referred to as ``index of squishiness") concept was developed by Pons and Zonneveld (1965) to simply define the degree of physical ripening of soft sediments (i.e "**pelagic ooze**" materials, sulfidic materials and sulfuric horizons) as they dewater. It is a measure of the physical bearing capacity of a soil material. The following definition has been modified from Fanning and Fanning (1989) and Soil Survey Staff (1992):

n= <0.7: Ripe material is firm, not particularly sticky, and cannot be squeezed between fingers.

n= 0.7 to 1.0: Nearly Ripe Material is fairly firm; it tends to stick to the hands, and can be kneaded but not squeezed between fingers. Its water content is between 55 and 65%. It is not churned up, it will support by weight of stock and ordinary vehicles;

n= 1.0 - 1.4: Half Ripe Mud is fairly soft; sticky; and can be squeezed between fingers. Its water content is between 65 and 75% and its mechanical strength when disturbed is low. A man will sink ankle to knee deep unless supported by vegetation.

n= 1.4 - 2.0: Practically Unripe Mud is very soft; sticks fast to everything, and can be squeezed between fingers by very gentle pressure. Its water content is between 70 and 80%. A man will sink to his thighs unless supported by vegetation.

n= > 2.0: Totally Unripe Mud is fluid; it flows between fingers. In predominantly mineral sediments the water content is >80% by mass.

It is mathematically defined for Soil Taxonomy for soil materials that are not thixotropic as follows:

$$n=(A-0.2R)/(L+3H)$$

A=% water in soil in field condition, calculated on a dry-soil basis;
R=% silt + sand;
L=% clay (<2 μm);
H=% organic matter (organic carbon x 1.724).

An n-value of 0.7 of more is used in Soil Taxonomy (Soil Survey, 1992) to define certain classes considered to have ***a low bearing capacity.*** Sandy materials are considered to be physically ripe regardless of their water content.

APPENDIX 1.4

ESTIMATION AND KINDS OF ORGANIC SOIL MATERIAL

(from Soil Survey Staff, 1996).

Organic soil material either:
1. Is saturated with water for long periods (or artificially drained) and, excluding live roots, has an organic-carbon content (by weight) of:

a. 18 percent or more if the mineral fraction contains 60 percent or more clay; or

b. 12 percent or more if the mineral fraction contains no clay; or

c. 12+ (clay percentage multiplied by 0.1) percent or more if the mineral fraction contains less than 60 percent clay; or

2. Is never saturated with water for more than a few days and contains 20 percent or more (by weight) organic carbon.

Item 1 in this definition covers materials that have been called peat and muck. Item 2 is intended to include what has been called litter or an O horizon.

KINDS OF ORGANIC SOIL MATERIALS

Three different kinds or organic soil materials are distinguished in Soil Taxonomy, based on the degree of decomposition of the plant materials from which they are derived. The three kinds (defined below) are: (1) fibric, (2) hemic, and (3) sapric. Because of the importance of fiber content in the definitions of these materials, fibers are defined before the kinds of organic soil materials, as follows.

Fibers

Fibers, in the terminology of this taxonomy, are pieces of plant tissue in organic soil materials (excluding live roots) which:

1. Are large enough to be retained on a 100-mesh sieve (openings 0.15 mm in diameter) when the materials are screened after dispersion in sodium hexametaphosphate; and

2. Show evidence of the cellular structure of the plants from which they are derived; and

3. Are either 2 cm or less in their smallest dimension, or are undecomposed that they cannot be crushed and shredded with the fingers, such as large branches, logs, and stumps, are not considered to be fibers but coarse fragments (comparable to gravel, stones, and boulders in mineral soils).

Fibric soil materials (L. *fibra*, fiber)

1. Contain 75 percent or more (by volume) fibers after rubbing, excluding coarse fragments; *or*
2. Contain 40 percent or more (by volume) fibers after rubbing, excluding coarse fragments; and yield color values and chromas of 7/1, 7/2, 8/1, 8/2 or 8/3 (Munsell designations) on white chromatographic or filter paper that is inserted into a paste made of the soil materials in a saturated sodium pyrophosphate solution.

Hemic soil materials (Gr. *hemi*, half; implying intermediate decomposition)

Hemic soil materials are intermediate in their degree of decomposition between the less decomposed fibric and more decomposed sapric materials. Their morphological features give intermediate values for fiber content, bulk density, and water content. They are partly altered both physically and biochemically.

Sapric soil materials (Gr. *sapros*, rotten)

These are the most highly decomposed of the three kinds of organic soil materials. They have the smallest amount of plant fiber, the highest bulk density, and the lowest water content on a dry-weight basis at saturation. Sapric soil materials are commonly very dark grey to black. They are relatively stable, i.e., they change very little physically and chemically with time in comparison to other organic soil materials.

Sapric materials have the following characteristics:

1. Their fiber content, after rubbing, is less than 16 percent (by volume), excluding coarse fragments; and

2. Their sodium-pyrophosphate-extract colour on white chromatographic or filter paper is below or to the right of a line drawn to exclude blocks 5/1, 6/2 and 7/3 (Munsell designations). If few or no fibers can be detected and the colour or the pyrophosphate extract is to the left or above this line, the possibility that the material is limnic must be considered.

APPENDIX 1.5

SALINITY

Scale of salt severity in soils (from electrical conductivity measurements: 1:5 OR 1:1 soil: water extract)

Electrical conductivity

This measurement will give an indication of the salinity of the soil or sediment.

Electrical conductivity readings received from the laboratory will either be in dS/m or mS/cm. (these units are equivalent). The measurement refers to the extract obtained from 1 part soil to 5 parts water ($EC_{1\ 5}$). The texture of the soil will influence the level of salinity that can be tolerated.

***Mildly saline**:* <0.6 dS/m

-reduced vigour or stunting in pasture of crop species.

Moderately saline: 0.6-2 dS/m

- white salt stains are visible when soil surface is dry.
- small bare areas up to 1 square metre are present.

Highly saline (Hypersalic; Isbell, 1996***):*** >2 dS/m

- only highly salt tolerant plants are present - e.g samphire and mangrove swamps
- large areas of bare ground often with a salt crust.
- trees dead or dying.

Severely saline (Suprasalic): >30dS/m **OR**

Salic horizon (Soil Survey Staff, 1994) (measurement from an extract obtained from 1 part soil to 1 parts water ($EC_{1\ 1}$).

A salic horizon is 15cm or more thick and has for 90 consecutive days of more per year, in 6 or more years of 10:

(i) An electrical conductivity (EC)* equal to or greater than 30 dS/m in an extract obtained from 1 part soil to 1 part water ($EC_{1\ 1}$)*; AND

(ii) The product of the EC in dS/m and thickness in cm equal to 900 or more.

- *Alternatively an EC equal to or greater than 8 dS/m in an extract obtained from 1 part soil to 5 parts water ($EC_{1:5}$).
- only very highly salt tolerant plants are present - e.g samphire
- large areas of bare ground often with a thick salt crust.

References

Fanning, D.S. and Fanning, M.C.B. (1989). Soil: Morphology, genesis, and classification. John Wiley and Sons, New York.

Isbell R.F. (1996) The Australian Soil Classification. Australian Soil and Land Survey Handbook volume 4. CSIRO Publishing, Melbourne.

McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S., (1990). Australian Soil and Land Survey Field Handbook, 2nd Edition, Inkata Press, Melbourne. pp. 87 - 183.

Pons J.L. and Zonneveld, I.S. (1965). Soil ripening and soil classification. Initial soil formation in alluvial deposits and classification of the resulting soils. Inst. Land Reclam. and Impr. Pub. 13. Wageningen, The Netherlands. 128pp.

Raven, M.D. (1990). XPLOT version 3.2 user manual. Manipulation of X-ray powder diffraction data. CSIRO Division of Soils Technical Report No. 24/1990.

Rayment, G. E. and Higginson, F.R. (1992). Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata Press. Melbourne.

Self, P.G. (1988). PC-PW1710 - user manual. PC based system for the control of a Philips PW1710 X-ray diffraction system. CSIRO Division of Soils Technical Memorandum No. 41/1988. 32pp.

Self, P.G. (1989). PC-PW1800 - user manual. PC based system for the control of a Philips PW1800 X-ray diffraction system. CSIRO Division of Soils Technical Memorandum No. 1/1989. 29pp.

Soil Survey Staff (1996). Keys to Soil Taxonomy, Seventh edition. United States Department of Agriculture, Soil Conservation Service, USA.

Trudinger, P.A. (1979). The biological sulfur cycle. In: P.A. Trudinger and D.J. Swaine (Eds.) Biogeochemical Cycling of Mineral Forming Elements. Ch 6.1, pp 293-313. Elsevier, Amsterdam.

Van Breemen, N. (1982). Genesis, morphology and classification of acid sulfate soils in coastal plains. In: Acid Sulfate Weathering. pp 95-108, Soil Science Society of America. Special Publication No. 10. Madison, Wisconsin.

Table 1. Profile descriptions and classification of soil profiles at the East Trinity monitoring sites

Site No.: TM1 **Potential Acid Sulfate Soil.**
Site Description: Inter-tidal mangrove forest inundated at mid tide
Elevation AHD (m): 0.869
Date described: 20/5/1995.
Soil Taxonomy: Typic Sulfihemist.
Isbell (1996): Sapric Histic-sulfidic Intertidal Hydrosol.

Depth/ thickness (cm)	Horizon	Matrix colour (moist)	Primary Mottles: (Secondary Mottles)				Tex-ture	Structure	shells	n-value	Segre-gations	Reac-tion HCl	Roots No. 100^2 mm	Boun-dary
			Colour (moist)	%	Size (mm)	Contrast								
0-5	Ag1	10YR 2/1	5YR 4/4	2	1	D	ZCL	V	0	1-1.4	0	N	4	G
5-10	Ag2	10YR 3/2	10YR 3/2	1	1	F	ZCL	V	0	1-1.4	0	N	4	G
10-30	Bg1	10YR 3/2	10YR 3/2	2	2	F	LC	V	0	1-1.4	0	N	3	G
30-50	Bg2	[1]2.5 Y 5/4	10YR 3/1	2	2	F	LC	V	0	1-1.4	0	N	2	D/S
50-100	Bg3	[1]5Y 4/1	10YR 3/1	2	2	F	MC	V	0	1.4-2	0	N	1	D/S
100-150	Bg4	[1]5Y.4/1	10YR 3/1	2	2	F	MC	V	0	1.4-2	0	N	1	D/S
200-240	2Cg1	[1]5Y.4/1	10YR 4/2	1	2	F	MC	V	5%	1.4-2	0	N	1	D/S
300-400	2Cg2	[1]5Y.4/1	10YR 4/2	1	2	F	MC	V	10%	1.4-2	0	S	N	D/S

[1] Clayey sulfidic material

Site No.: TC1 **Actual Acid Sulfate Soil**
Site Description: Drained low lying *Melaleuca sp*. forest protected from tidal inundation.
Elevation AHD (m): -0.389
Date described: 20/5/1995.
Soil Taxonomy: Hydraquentic Sulfaquept.
Isbell (1996): Sulfuric Extratidal Hydrosol or Sulfuric Redoxic Hydrosol.

Depth/ thickness (cm)	Horizon	Matrix colour (moist)	Primary Mottles: (Secondary Mottles)				Tex-ture	Structure	Shells	n-value	Segre-gations	Reac-tion HCl	Roots No. 100^2 mm	Boun-dary
			Colour (moist)	%	Size (mm)	Contrast								
0-5	Ap1	7.5YR 3/1	7.5YR 4/6	4	2	P/S	ZCL	GR	0	<0.7	0	H	3	
5-10	Ap1	7.5YR 3/1	7.5YR 4/6	4	2	P/S	ZCL	GR	0	<0.7	0	N	3	C/S
10-15	Ap2	7.5YR 3/2	7.5YR 5/6	4	2	P/S	ZCL	GR	0	<0.7	0	N	2	G/S
15-20	B2w1	7.5YR 3/2	7.5YR 5/6	3	2	P/S	ZCL	GR	0	<0.7	0	N	2	G/S
20-30	B2w2	7.5YR 3/2	7.5YR 5/6	3	2	P/S	ZLC	GR	0	<0.7	0	N	1	G/S
30-40	[1]Bg3	7.5YR 3/2	7.5YR 5/6	3	2	P/S	ZLC	V	0	<0.7	0	N	1	G/S
40-60	[1]Bgyz4	10YR 4/2	2.5Y 8/6	3	2	P/S	ZLC	V	0	0.7-1	0	N	1	C/S
60-70	[1]Bgyz5	10YR 4/2	2.5Y 8/6	3	2	P/S	MC	V	0	0.7-1	0	N	1	G/S
70-80	[1]Bgy6	7.5YR 3/2	2.5Y 8/6	3	1	P/S	MC	V	0	1-1.2	0	N	1	G/S
80-100	[1]Bgy7	10 YR 3/2	2.5Y 8/6	2	1	P/S	MC	V	0	1-1.2	0	N	1	G/S
100-200	Bg8	10 YR 4/1	10YR 3/1	2	1	P/S	MC	V	2	1-1.2	0	N	N	G/S
200-300	[2]Bg9	10 YR 3/1	10YR 3/2	2	1	P/S	MC	V	3	1-1.2	0	S	N	G/S
300-400	[2]Bg10	10YR 3/1	10YR 4/1	1	1	P/S	MC	V	3	1-1.2	N	S	N	C/S

[1] Sulfuric horizon.
[2] Clayey sulfidic material.

Site No.: TM2 **Potential Acid Sulfate Soil**
Site Description: Inter-tidal mangrove forest only inundated at spring high tides.
Elevation AHD (m): 1.125
Date described: 20/5/1995**;**
Soil Taxonomy: Typic Sulfihemist.
Isbell (1996): Sapric Histic-sulfidic Intertidal Hydrosol.

Depth/ thickness (cm)	Horizon	Matrix colour (moist)	Primary Mottles: (Secondary Mottles)				Tex-ture	Structure	Shells	n-value	Segre-gations	Reac-tion HCl	Roots No. 100^2 mm	Boun-dary
			Colour (moist)	%	Size (mm)	Contrast								
5-10	Ag2	7.5YR 4/2	7.5YR 5/6	2	1	D	ZCL	V	0	1-1.4	0	N	3	
10-40	[1]Bg1	7.5YR 4/2	7.5YR 5/6	2	2	F	ZCL	V	0	1-1.4	0	N	2	C/S
40-115	[1]Bg2	5 Y5/1	5Y4/2	1	2	F	MC	V	0	1-1.4	0		1	C/S
115-250	[1]Bg3	5Y 5/1	5Y4/2	1	2	F	MC	V	1	1.4-2	0	N	1	G/S
250-370	[1]Bg4	5Y4/1	2.5Y4/3	1	2	F	MC	V	1	1.4-2	0	N	1	G/S

[1] Clayey sulfidic material.

Site No.: TC2 **Actual Acid Sulfate Soil**
Site Description: Grassland (*Imperata cylindrica*) protected from tidal inundation.
Elevation AHD (m): 0.835
Date described: 20/5/1995;
Soil Taxonomy: Hydraquentic Sulfaquept.
Isbell (1996): Sulfuric Extratidal Hydrosol or Sulfuric Redoxic Hydrosol.

Depth/ thickness (cm)	Horizon	Matrix colour (moist)	Primary Mottles: (Secondary Mottles)				Tex-ture	Structure	Shells	n-value	Reac-tion HCl	Roots No. 100^2 mm	Boun-dary
			Colour (moist)	%	Size (mm)	ontrast							
0-5	Ap	7.5YR 5/2	5YR 5/4	3	2	P/C	ZCL	GR	0	<0.7	N	3	
5-10	Ap	7.5YR 5/2	5YR 4/4	2	2	P/C	ZCL	GR	0	<0.7	N	3	C/S
10-30	[1]Bg	7.5YR 4/2	2.5Y 8/6	3	2	D/C	ZCL	SB	0	<0.7	N	2	C/S
30-100	[1]Bg	7.5YR 4/2	2.5Y 8/6	2	2	D/C	MC	SB	0	0.7-1	N	2	C/S
100-170	Bg	7.5YR 4/2	7.5YR 4/4	1	2	F/C	MC	V	0	0.7-1	N	1	C/S
170-230	Bg	7.5YR 4/2	7.5YR 4/4	1	2	F/C	MC	V	0	0.7-1	N	1	G/S
230-400	Bg	7.5YR 4/2	7.5YR 4/4	1	2	F/C	MC	V	1	0.7-1	N	1	G/S

[1] Sulfuric horizon.

Site No.: TS3 **Potential Acid Sulfate Soil**
Site Description: Bare inter-tidal saltflat only inundated at spring tides.
Elevation AHD (m): 1.232
Date described: 20/5/1995.
Actual Acid Sulfate Soil
Soil Taxonomy: Salidic Sulfaquept
Isbell (1996): Sulfuric Extratidal Hydrosol or Sulfuric Salic Hydrosol.

Depth/ thickness (cm)	Horizon	Matrix colour (moist)	Primary Mottles: (Secondary Mottles)				Tex-ture	Structure	Shells	n-value	Reac-tion HCl	Roots No. 100^2 mm	Boun-dary
			Colour (moist)	%	Size (mm)	Contrast							
0-5	A11	2.5Y 5/3					ZCL	PL	0	1-1.4	N	Q/Sc/	C/S
5-10	A12	2.5Y 5/3					ZCL	PL	0	1-1.4	N		
10-20	E	2.5Y 5/2	7.5 YR 4/6	2	2	P/S	ZCL	PR	0	1-1.4	N		
20-35	E	2.5Y 5/2	7.5 YR 4/6	2	1	P/S	ZCL	PR	0	1-1.4	N		
35-60	2Btg1	5Y 6/1	7.5 YR 5/6	3	1	P/S	LC	V	0	1.4-2	N		
60-100	2Btg2	5YR 4/1					LC	V	2	1.4-2	N		
100-180	2Btg3	5Y 3.5/1					MC	V	3	1.4-2	S		
180-200	2Btg4	5Y 3.5/1					MC	V	4	1.4-2	S		
200-300	2Btg5	5Y 3.5/1					MC	V	4	1.4-2	S		
300-400	2Btg6	5Y 3.5/1					MC	V	4	1.4-2	S		

Site No.: TC3 **Actual Acid Sulfate Soil**
Site Description: Saline flat with salt couch grassland protected from tidal inundation.
Elevation AHD (m): 1.209
Date described: 20/5/1995**.**
Soil Taxonomy: Hydraquentic Sulfaquept.
Isbell (1996): Sulfuric Extratidal Hydrosol or Sulfuric Redoxic Hydrosol.

Depth/ thickness (cm)	Horizon	Matrix colour (moist)	Primary Mottles: (Secondary Mottles)				Tex-ture	Structure	Shells	n-value	Reac-tion HCl	Roots No. 100^2 mm	Boun-dary
			Colour (moist)	%	Size (mm)	Contrast							
0-5	A11	2.5Y 5/2					ZLC	PR	0	0.7-1	N	2	
5-10	A12	2.5Y 5/3					ZLC	PR	0	0.7-1	N	2	C/S
10-35	E	2.5Y 5/2	7.5YR 4/6	3	2	P/S	ZLC	PR	0	0.7-1	N	1	C/S
35-57	[1]Btg1	6N 5Y 6/1	7.5YR 5/2 2.5Y 8/6	2	1	P/S	MC	V	0	1-1.4	N	1	C/S
57-75	[1]2Btg2	2.5Y 5/2	10YR 5/4 2.5Y 8/6	2	2	P/S	MC	V	0	1-1.4	NN	0	G/S
75-150	[2]2Btg3	2.5Y 5/2					MC	V	4	1-1.4	S	0	C/S
150-300	[2]2Btg3	2.5Y 5/2					MC	V	4	>2	M	0	G/S
300-400	2Btg4	2.5Y 5/2					MC	V	4	>2	M	0	G/S

[1] Sulfuric horizon

[2] Clayey sulfidic material.

Mottles: ABUNDANCE (%): 0=None; 1=Very few(<2)**; 2=Few**(2-10)**; 3=Common**(10-20)**; 4=Many**(20-50)**.**
SIZE (mm)**: 1=Fine**(<5)**; 2=Medium**(5-15)**; 3=Coarse**(15-30)**; 4=Very Coarse**(>30)**. CONTRAST: F=**Faint**, D=**Distinct**, P=**Prominent**. / S=**Sharp**, C=**Clear**, D=**Diffuse**.**

Texture: S=Sand, **LS**=Loamy Sand, **CS**=Clayey Sand, **SL**=Sandy Loam, **L**=Loam, **ZL**=Silty loam, **SCL**=Sandy Clay Loam, ZCL =Silty Clay Loam, **LC**=Light Clay, **MC**=Medium Clay, **HC**=Heavy Cclay.

Structure: Apedal (**G**= Single grain; **V**=Massive)**; PL**=Platy**; PR=**Prismatic**; CO=**Columnar**; AB=**Angular blocky**; SB=**Subangular blocky**; PO=**Polyhedral**; LE=**Lenticular**; GR=**Granular**; A=Cast.**
Pedal (**W**=weak; **M**=moderate; **S**=strong). **Size (**mm**): 1**(<2)**; 2**(2-5)**; 3**(5-10)**; 4**(10-20)**; 5**(20-50)**; 6**(50-100)**; 7**(100-200)**; 8**(200-500)**; 9**(>500).

Consistency (dry/force/strength): 0=Loose; **1**=Very Weak; **2**=Weak; **3**=Firm; **4**=Very Firm; **5**=Strong; **6**=very strong; **7**=Rigid.

Cutans: TYPES: **Z**=Zero, **U**=Unspecified, **C**=Clay skins, **M**=Mangans, **S**=Stress cutans, **K**=Slikensides, **O**=Other cutans. **ABUNDANCE (%): 0=None, 1=few**(<10)**, 2=Common**(10-50)**,**
3=Many(>50). **DISTINCTNESS**: **F=**Faint**, D=**Distinct**, P=**Prominent**.**

Voids: CRACKS (mm): **1=Fine** (<5), **2=Medium** (5-10), **3=Coarse** (10-20), **4=Very Coarse** (20-50), **5=Extremely Coarse** (>50). / **MACROPORES** of DIAMETER (mm): **1= Very fine**(<1),
2=Fine(1-2), **3=Medium**(2-5) & **4==Coarse**(>5) / ABUNDANCE (per 10x10mm) of Very fine (<1) & Fine (1-2) macropores: **0=None**, **1=few**, (<1), **2=Common** (1-5), **3=Many**(>5); *OR*
ABUNDANCE (per 10x10cm) of Medium (2-5) & Coarse (>5) macropores: **0=None, 1=Few** (<1), **2=Common**(1-5), **3=Many**(>5).

Segregations: C=Concretions, **N=**Nodules, **F=**Fragments, **X=**Crystals, **K=** Lime, **Y=**Gypsum, **Q=**Quartz**, F=**Iron**, M=**Manganese**, Sl=**Shells**.**
SIZE (mm)**: 1=Fine(**<2**); 2=Medium(**2-6**); 3= Coarse(**6-20**); 4=Very Coarse(**20-60**); 5=Extremely Coarse(**>60**).**
STRENGTH: 1=Weak, 2=Strong. ABUNDANCE (%): 0=None, 1=Very few(<2**), 2=Few(**2-10**), 3=Common(**10-20**), 4=Many(**20-50**), 5=Very many(**>50**).**

Reaction or fizz to HCl/calcareous: N=Non- calcareous; S=slightly; M=moderately; H=highly; V=very highly.

Coarse Fragments: SIZE (mm**): 1=Fine gravelly** (2-6)**, 2=Medium gr(**6-20**), 3= Coarse(**20-60**), 4=Cobbly(**60-200**), 5=Stony(**200-600**), 6=Bouldery(**600-2m**), 7=Large boulders(**>2m**)./**
TEXTURE: F=Fragmental, X=Crystalline (non-porphYRitic), P=PorphYRitic, A=Amorphous / STRUCTURE: V=Massive, S=Vesicular, C=Concretionary, P=Platy,
R=Vermicular, B=Bedded, F=Fissile, L=Foliated / POROSITY: 0=Non porous; dense, 1=Slightly porous, 3=Porous / MINERAL COMPOSITION: Q=Quartz, F=Feldspar,
M=Mica, D=Dark minerals, L=Clays (argillaceous), K=Carbonates, S=Sesquioxides, G=Glauconite, C=Carbonaceous material, Y=Gypsum / STRENGTH: see table 24, p. 156. /
SHAPE: see p.99.

Roots: (No./100x100mm)**: 0**=No roots; **1**=Few (1-10); **2**=Common(10-25); **3**=Many(25-200); **4**=Abundant(>200).

Boundary: (mm)**: S**=Sharp (<5), **A**=abrupt(5-20), **C**=Clear (20-50), **G**=Gradual (50-100), **D**=Diffuse (>100). **/ S**=Smooth, **W**=Wavy, **I**=Irregular, **T**=Tongued, **B**=Broken

Plate 1 Colour photograph of TC3 (Actual Acid Sulfate Soil) showing the bright yellow coloured jarosite-rich mottles in the sulfuric horizon between 35 cm and 45 cm overlying the darker sulfidic material

Table 2. Chemical data (pH, EC and chloride) for samples aged moist for 7 weeks

Site	Horizon depth/ thickness (cm)	pH					EC (dS/m)	Cl
		Air dried	0 wks moist	3 wks moist	5 wks moist	7 wks moist		
TC1	0 - 5	3.72	7.41	3.10	3.25	3.26	0.28	94.8
TC1	5 - 10	3.64	3.41	3.05	3.20	3.24	0.36	138.8
TC1	10 - 15	3.61	3.24	3.00	3.20	3.25	0.45	193.5
TC1	15 - 20	3.64	3.28	3.02	3.23	3.28	0.56	340
TC1	20 - 30	3.63	3.32	3.00	3.21	3.29	0.7	516.8
TC1	30 - 40	3.62	3.29	2.95	3.19	3.25	0.9	759.3
TC1	40 - 50	3.71	3.27	2.94	3.17	3.27	1.26	1294.7
TC1	50 - 60	3.85	3.35	2.97	3.19	3.28	1.51	1565.8
TC1	60 - 70	3.8	3.34	2.98	3.20	3.26	1.5	1552.4
TC1	70 - 80	3.75	3.33	2.94	3.16	3.21	1.63	1643.7
TC1	80 - 90	3.45	3.08	2.70	2.95	2.98	2.56	2398.5
TC1	100 - 200	4.67	5.44	3.38	3.16	2.88	6.4	6936.8
TC1	200 - 300	5.19	6.04	4.40	3.57	3.28	7.4	10247.3
TC1	300 - 400	5.16	5.51	3.95	3.55	3.20	7.3	10145.7
TM1	0 - 5	6.22	6.19				4.1	6429.7
TM1	0 - 5							
TM1	5 - 10							
TM1	10 - 0.3	5.33	6.29				11.8	18620.8
TM1	30 - 50	5.73	6.44	4.80	4.41	4.26	10.1	15489.2
TM1	50 - 100	5.11	6.38	4.50	3.87	3.44	11.4	17660.1
TM1	100 - 150	5.15	6.04	3.99	3.55	3.30	10.9	16854.5
TM1	200 - 240	5.24	6.26	4.28	3.72	3.49	9.6	13955.9
TM1	300 - 400	5.37	6.19	4.70	4.36	3.73	9.9	15019.6
TC2	0 - 5	6.15	5.79	5.63	5.72	5.56	0.08	19.8
TC2	5 - 10	5.73	5.22	4.87	5.12	4.95	0.08	12.9
TC2	10 - 30	4.68	4.30	4.06	4.31	4.15	0.13	53.8
TC2	30 - 100	3.79	3.32	2.92	3.11	2.94	1.3	1621.55
TC2	100 - 170	8.19	6.85	6.94	7.00	6.98	9.1	15165.3
TC2	170 - 230	8.28	6.94	7.17	7.10	7.03	11.9	20026.9
TC2	230 - 400	8.52	7.22	7.26	7.19	7.14	14.9	27807
TM2	0 - 5	7.12	6.71	6.60	6.47	6.48	9.4	16884.7
TM2	5 - 10	6.95	6.63	6.26	6.39	6.26	8.5	14636.9
TM2	10 - 40	6.56	6.45	6.76	6.85	6.59	12.3	21700.1
TM2	40 - 115	5.13	6.30	4.74	4.95	4.09	20.4	32949.7
TM2	115 - 250	8.17	6.94	7.21	7.08	7.02	14.7	26627.3
TM2	250 - 370	8.48	7.16	7.31	7.21	7.12	14.7	27384

Table 2 continued

Site	Horizon depth/ thickness (cm)	pH					EC (dS/m)	Cl
		Air dried	0 wks moist	3 wks moist	5 wks moist	7 wks moist		
TC3	0 - 5	7.85	7.13	7.32	7.58	7.59	0.76	822.1
TC3	5 - 10	8.34	7.58	7.92	7.92	7.93	0.99	1168.8
TC3	10 - 35	8.13	7.43	7.84	7.78	7.72	2.38	3433.2
TC3	35 - 57	7.28	6.73	6.34	6.51	6.65	6.5	10546.2
TC3	57 - 75	3.82	3.43	3.43	3.43	3.43	12.3	19850.1
TC3	75 - 150	7.84	6.79	7.17	7.09	7.04	23.4	37675.2
TC3	150 - 300	8.35	6.90	7.25	7.12	7.13	16.4	31981.9
TC3	300 - 400	8.42	7.07	7.19	7.16	7.13	18.4	31725.8
TS3	0 - 5	8.13	7.42	7.84	7.81	7.83	6.1	10481.5
TS3	5 - 10	8.23	7.30	7.64	7.68	7.65	7.1	12869.7
TS3	10 - 20	8.16	7.26	7.48	7.42	7.29	10.0	17788.9
TS3	20 - 30	8.15	7.17				14.7	28306.9
TS3	30 - 60	8.16	7.52	7.26	7.22	7.18	130	23841.1
TS3	60 - 100	7.24	6.84	6.80	6.90	6.89	25.1	40033
TS3	100 - 180	8.01	6.82	7.02	7.08	7.00	25.2	43017.1
TS3	180 - 200	8.14	6.73				19.5	33526.7
TS3	200 - 300	8.38	7.11	7.18	7.27	7.09	12.2	22520.6
TS3	300 - 400	8.4	7.12	7.27	7.24	7.14	12.6	22473.5

APPENDIX 2

SITE INSTALLATIONS

Monitoring & Sampling Equipment

Piezometer Clusters

Piezometers were manufactured from 25mm UPVC pipe with 200mm of slots and a 100mm sump at the end. Slots were covered with drainage sock.

Soil Solution Samplers

Undrained soils and neutral horizons

Soil solution samplers were manufactured from 40mm ceramic tips (Coinda Ceramics) and 40mm electrical conduit (Figure 21).

Acid horizons

Soil solution samplers were Prenart Super Quartz, quartz impregnated teflon supplied by Prenart.

Platinum Electrodes

Platinum electrodes were manufactured from platinum thermocouple wire soldered to single core copper wire and sealed in 100 microlitre pipette tips with epoxy resin. Individual electrodes were cleaned with a 1:1 hydrochloric acid/liquid detergent solution followed by 10% hydrogen peroxide and the potential checked against a suspension of quinhydrone in a 0.1M potassium acid phthalate buffer at pH 4 according to Bartlett ,1986

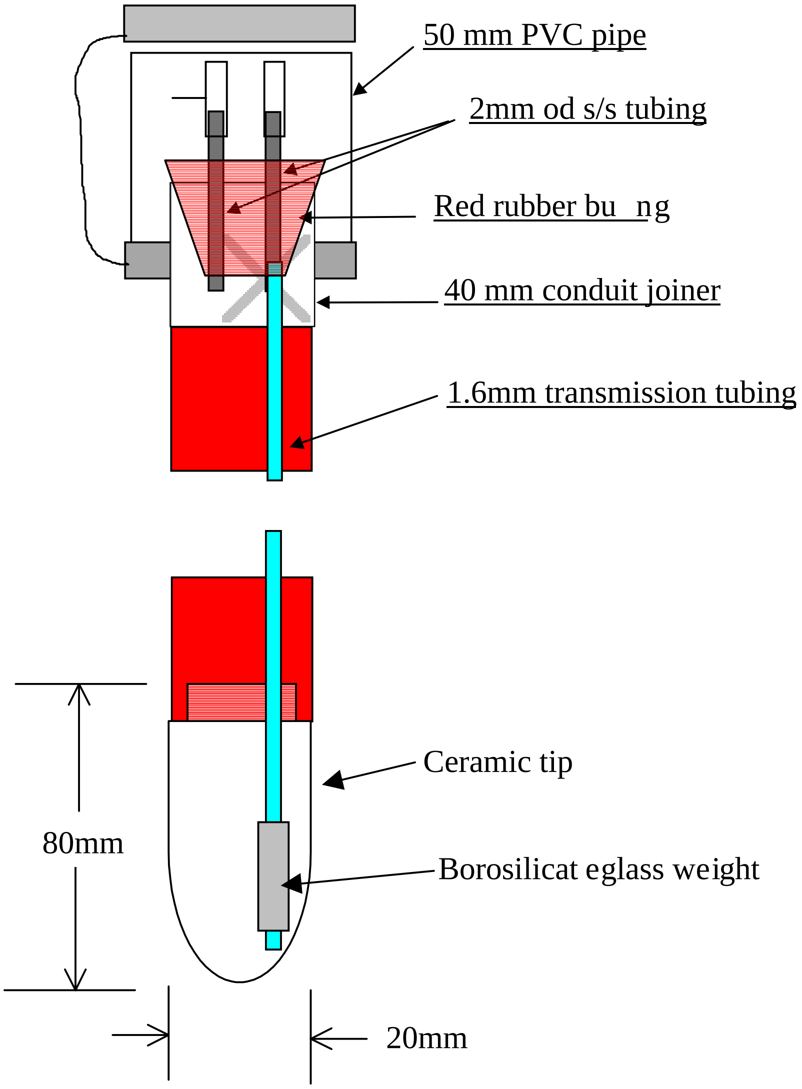


Figure 1 Ceramic soil solution samplers.

APPENDIX 3

MEASUREMENT, SAMPLING AND ANALYSIS

Measurement

Water levels in piezometers and surface water

Water levels were measured using a tape and ‘water whistle’ against a surveyed reference point.

Rainfall

Rainfall was recorded fortnightly at each site using Nylex Raingauge 1000 gauges.

Redox potential

Redox potential was measured using permanently installed Pt electrodes using a millivoltmeter and silver/silver chloride reference electrode with a potential equal to that of a saturated calomel electrode (0.244 V vs SHE)

Sampling and Analysis

Water

Collection

Soil solution samples were obtained using either teflon (Prenart Super Quartz, installation = 'T') or ceramic (Cooinda Ceramics, installation = 'C') soil solution samplers. Before collecting the sample, samplers were emptied and then placed under vacuum (-60kPa) for 24h to obtain a soil water sample.

Surface water samples from drains and creeks were grab samples taken just below the surface.

Preparation

Immediately on collection, a 10mL sub-samples were filtered through a 0.2mm PVDF syringe filters (Millipore). Samples were acidified with 40mL of BDH analytical reagent grade Nitric acid. Unfiltered samples were stored in a 100mL LDPE bottles filled to overflowing. Samples were refrigerated and then packed in insulated boxes prior to dispatch to the laboratory by overnight airfreight. Samples were refrigerated immediately on receipt. Based on expected conductivity, samples for segmented flow analysis and ICP-OES analysis were diluted 1:9 or 1:99 prior to analysis.

Analysis

pH and Eh were measured in the field using an Activon field pH meter and Tandy digital multimeter.

EC and alkalinity or acidity were determined on unfiltered samples using a Radiometer CDM83 conductivity meter and TitraLab 900 titrator respectively according to APHA standard methods 2310 and 2510.

Chloride and molybdate reactive silica were determined by segmented flow analysis using an Alpkem Flow Solution 3000 Analyser according to USEPA methods.

TOC was determined using a Dorhman DC180 TOC analyser.

Al, B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S & Zn were determined by ICP-OES (Spectro modula Simaltaneous OES)

Arsenic was determined by hydride generation using a GBC Scientific Model 906 Atomic Absorption Spectrometer and Vapour Generation Assembly.

Ferrous iron was determined using a HACH DR2000 spectrometer according to a modified APHA standard method 3500-Fe D .

Soil

Collection

Samples were collected using a gouge auger and transferred to screw top PVC jars filled to the top with sample and sealed. Samples were then cooled in an insulated container and frozen within 6 h of collection.

Preparation

Soil samples were stored frozen until freeze dried. They were then crushed using a mortar and pestle and sieved to pass through a 2mm mesh sieve. Sample for acid digestion were ground to <50µm using a Labtechnics ring and puck mill.

Analysis

Samples for ICP-OES analysis were digested using microwave assisted digestion according to US-EPA method 3051.

Samples for the analysis of total carbon and sulfur were analysed on a LECO CNS2000 Carbon, Nitrogen and Sulfur analyser using standard LECO methods.

Samples for TAA and TPA analysis according to the method of Dent and Bowman, 1996 were titrated using a Radiometer TitraLab 900 titrator.

APPENDIX 4 Soil Data

Table 10 Complete listing of analytical data for soil samples.

Sample	Depth cm BGL			Elevation	Bulk	Total Actual Acidity	Total Potential Acidity	Total	Total	Total Acid Digestable mg kg^{-1}															
	Upper	Lower	Mid	m AHD Mid	Density t m^{-3}	moles H^{+} t^{-1}		C %	S %	Al	As	B	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	Pb	S	Zn
TM1	0	10	5	0.82	0.47	-18	702	8.85	1.90	46100	10	61	3810	1	41	15	23100	7310	6450	154	15800	26	<10	18200	55
TM1	10	20	15	0.72	0.47	-21	929	8.75	1.98	45100	12	63	3870	<1	39	15	22600	7150	6380	134	14700	25	<10	19400	53
TM1	20	30	25	0.62	0.47	-21	929	12.8	1.90	37000	11	79	4030	2	30	12	17600	5820	5800	117	12900	20	<10	17600	42
TM1	30	40	35	0.52	0.47	-23	527	9.15	1.70	21200	8	66	2780	2	22	9	12500	3630	4060	87	9500	15	<10	14600	26
TM1	40	50	45	0.42	0.47	-23	1454	19.1	3.34	18200	17	122	3280	2	22	7	19100	3420	4640	78	13800	17	<10	27200	27
TM1	50	60	55	0.32	0.40	-23	2257	15.7	4.00	21300	26	114	3060	2	24	9	27100	4020	4510	92	11700	21	11	36400	31
TM1	60	70	65	0.22	0.40	-23	2549	15.2	4.76	22100	29	118	3240	<1	24	9	31800	4280	4870	93	13200	19	<10	43100	30
TM1	70	80	75	0.12	0.40	-23	2652	18.9	5.44	22500	29	145	3960	2	26	10	35300	4500	5930	112	18900	22	<10	50800	30
TM1	80	90	85	0.02	0.40	-23	2772	15.3	4.52	22500	22	115	3200	2	25	10	34000	4310	5120	106	15100	20	<10	46000	30
TM1	90	100	95	-0.08	0.40	-23	1939	10.0	4.06	26700	23	74	2820	1	27	11	30800	4760	4730	118	11200	20	<10	37100	33
TM1	100	110	105	-0.18	0.63		2325	10.0	4.48	28100	22	71	2750	<1	29	11	34200	5070	4830	135	11400	21	10	40900	33
TM1	110	120	115	-0.28	0.63		1625	9.00	3.30	32100	22	69	2860	1	33	11	29500	5840	5220	141	11700	23	<10	32700	37
TM1	120	130	125	-0.38	0.63		1547	8.30	3.38	35400	23	65	2880	<1	36	16	30200	6270	5430	164	11500	24	<10	31900	46
TM1	130	140	135	-0.48	0.63		1532	7.70	3.34	38500	25	68	2750	<1	38	48	31200	6770	5650	182	11800	24	10	31000	65
TM1	140	150	145	-0.58	0.63		1427	7.80	3.24	41400	23	73	2820	1	41	14	31000	7330	5890	210	11100	26	<10	29800	47
TM1	150	160	155	-0.68	0.63		1216	6.50	3.38	44800	27	70	2730	2	44	15	35600	7860	6050	267	10400	28	<10	33700	50
TM1	160	170	165	-0.78	0.63		1216	5.65	2.36	40600	21	66	2420	<1	41	15	28000	7040	5520	294	9300	26	21	23700	46
TM1	170	180	175	-0.88	0.63		1216	5.05	2.54	42400	20	62	2190	1	42	15	28000	7140	5410	342	8000	23	14	24500	45
TM1	180	190	185	-0.98	0.63		1216	5.55	2.64	51100	17	74	2520	<1	48	16	31100	8440	6430	310	10500	28	16	25900	53
TM1	190	200	195	-1.08	0.63		1216	5.60	2.98	43400	22	64	2340	<1	42	14	30600	7160	5760	230	10600	27	12	27800	47
TM1	200	230	215	-1.28	0.63		1216	8.65	3.02	34000	23	72	2580	3	35	12	27300	6080	5150	189	11000	22	13	28700	38
TM1	230	260	245	-1.58	0.68		1216	7.05	3.08	41000	21	70	2750	<1	41	14	31000	7210	5860	212	11400	26	10	30100	47
TM1	260	290	275	-1.88	0.68		1229	5.45	2.46	45300	19	66	2170	2	42	15	27100	7480	5560	283	9500	25	<10	22900	45
TM1	290	320	305	-2.18	0.68		1229	5.00	2.54	49500	18	68	1930	<1	44	14	28700	7880	5470	277	9700	26	15	24100	47
TM1	320	350	335	-2.48	0.71		1229	7.35	2.76	50000	16	83	2210	2	44	15	28900	7890	5820	269	11300	26	12	25700	50
TM1	200	240	220	-1.33	0.71	-19	1216																		
TM1	300	400	350	-2.63	0.71	-13	1229																		
TM2	0	10	5	1.08	0.83	-25	-220	3.24	0.20	36200	12	51	3890	1	42	13	20200	6120	4960	191	9100	18	12	2100	48
TM2	10	20	15	0.98	0.80	-15	-20	2.58	0.15	37300	12	49	3670	<1	45	13	20300	6860	4990	191	9900	20	10	1400	45
TM2	20	30	25	0.88	0.80		-7	3.08	0.23	34400	14	50	3630	1	45	12	20500	6750	5170	178	13000	18	<10	2300	43

Sample	Depth cm BGL			Elevation	Bulk	Total Actual Acidity	Total Potential Acidity	Total	Total	Total Acid Digestable mg kg^{-1}															
	Upper	Lower	Mid	m AHD Mid	Density t m^{-3}	moles H$^+$ t^{-1}		C %	S %	Al	As	B	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	Pb	S	Zn
TM2	30	40	35	0.78	0.80		230	3.66	0.95	33600	10	55	3760	<1	45	14	20300	6790	5530	179	15200	22	11	9300	42
TM2	40	50	45	0.68	0.83		565	4.14	1.68	31800	19	58	3990	<1	44	12	23400	6930	5600	173	17000	24	13	15700	42
TM2	50	60	55	0.58	0.83		940	4.18	2.48	35300	24	64	3770	<1	45	10	30300	7530	6130	263	17900	27	11	25100	49
TM2	60	70	65	0.48	0.83		1027	3.78	2.50	37900	22	66	3790	<1	48	10	32400	8070	6480	325	18600	26	<10	26700	52
TM2	70	80	75	0.38	0.83		958	3.42	2.24	37700	19	60	3310	1	46	10	29300	7470	6460	373	18500	26	13	23400	50
TM2	80	90	85	0.28	0.83		882	3.08	2.28	41800	18	62	3540	<1	52	12	31700	8220	6860	409	17900	31	15	24000	58
TM2	90	100	95	0.18	0.83		1029	3.56	2.40	38800	16	67	3540	1	47	10	31400	7960	6890	381	21200	25	12	26000	54
TM2	100	110	105	0.08	0.86		593	2.10	1.86	41600	15	57	5110	<1	50	11	29000	8070	6890	405	17200	26	13	19700	54
TM2	110	120	115	-0.02	0.86	-563	489	2.32	1.74	42000	12	58	10640	<1	52	11	27700	8200	7190	396	18300	26	17	17900	53
TM2	120	130	125	-0.13	0.86	-563	82	2.66	1.78	40700	12	58	21990	<1	48	11	27400	8050	7040	383	18100	25	12	18700	50
TM2	130	140	135	-0.23	0.86	-563	-293	2.64	1.48	32300	10	47	37500	<1	40	9	22700	6450	6120	374	14800	21	11	15500	42
TM2	140	150	145	-0.33	0.86	-563	-6	2.70	1.86	38400	15	56	28450	<1	46	10	27100	7850	7230	370	19100	25	10	19400	49
TM2	150	160	155	-0.43	0.86	-563	-492	2.72	1.64	36500	11	53	37820	<1	44	10	25500	7480	7590	363	18400	23	19	17300	49
TM2	160	170	165	-0.53	0.86	-563	-820	3.26	1.64	31500	14	49	49750	<1	40	9	23800	6590	7180	384	16100	21	12	17500	44
TM2	170	180	175	-0.63	0.86	-563	-458	3.76	2.06	33600	19	56	48630	<1	43	10	26700	6990	7600	392	17400	22	11	21100	45
TM2	180	190	185	-0.73	0.86	-563	-266	3.56	1.90	32900	19	54	51720	<1	41	10	25800	6800	7500	386	18000	22	11	20000	47
TM2	190	200	195	-0.83	0.86	-563	-298	3.36	1.88	35000	16	55	42820	<1	43	10	26300	7080	7930	416	18100	23	10	19400	53
TM2	200	230	215	-1.03	0.86	-563	-480	3.16	1.80	34200	15	54	42220	<1	43	9	25200	7070	7370	389	16500	24	14	18300	45
TM2	230	260	245	-1.33	0.86	-563	-206	2.66	1.38	30100	12	45	35900	<1	35	8	21400	6010	6600	333	14400	21	13	14700	38
TM2	260	290	275	-1.63	0.86	-966	-382	2.36	1.40	38600	10	53	31950	<1	42	10	24900	7610	8530	387	16100	22	9	14500	47
TM2	290	320	305	-1.93	0.86	-966	-488	2.32	1.44	45500	11	59	32050	<1	48	11	28600	9050	10030	420	18200	27	11	15500	54
TM2	320	350	335	-2.23	0.86	-966	-592	2.50	1.32	36700	11	50	37820	<1	41	13	24500	7470	8450	399	14800	23	13	14200	81
TS3	0	10	5	1.18	1.21	-41	-47	0.59	0.15	48500	12	72	2820	1	54	13	29400	10520	12310	585	15600	28	17	1400	59
TS3	10	20	15	1.08	1.18	-30	-15	0.33	0.15	46200	13	65	2740	<1	52	13	30400	10260	10200	935	18300	27	18	1400	62
TS3	20	30	25	0.98	1.18	-51	-41	0.50	0.14	47900	14	72	2900	<1	54	13	30700	10490	11410	503	16900	23	12	1400	100
TS3	30	40	35	0.88	1.04	-28	-24	0.36	0.12	47600	16	69	2610	1	54	13	31000	10490	10550	756	15400	24	12	1300	62
TS3	40	50	45	0.78	1.04	-28	-7	0.58	0.19	46000	16	66	2580	<1	51	13	31300	10080	9370	1061	16500	27	14	2300	71
TS3	50	60	55	0.68	1.04	-28	179	1.18	0.64	41200	26	59	2500	1	47	12	33000	9210	7970	493	20400	22	18	7300	50
TS3	60	70	65	0.58	0.74	-36	440	2.50	1.16	27400	17	46	2720	2	33	10	23300	5930	5910	231	20100	15	<10	13000	35
TS3	70	80	75	0.48	0.74	-36	192	2.58	0.92	26600	12	46	6430	<1	34	10	17500	5710	5750	202	20300	14	<10	10000	32
TS3	80	90	85	0.38	0.74	-36	251	3.22	1.36	19400	14	38	9910	<1	25	8	15600	4370	4880	211	19700	13	<10	14500	26
TS3	90	100	95	0.28	0.74	-36	80	3.36	1.30	17900	13	37	14990	1	24	10	14100	4190	5160	267	22200	11	<10	13300	40
TS3	100	110	105	0.18	0.74	-36		2.78	1.40	18100	15	33	16010	1	25	9	13900	4210	5460	246	25600	11	<10	13700	30
TS3	110	120	115	0.08	0.74	-480	88	2.92	1.22	18700	12	36	17800	<1	26	10	14900	4430	5570	252	25400	14	11	14700	49
TS3	120	130	125	-0.02	0.74	-480	88	3.88	1.72	19800	15	39	15080	1	27	9	17100	4550	6040	250	28700	13	10	18300	43

Sample	Depth cm BGL			Elevation	Bulk	Total Actual Acidity	Total Potential Acidity	Total	Total	Total Acid Digestable mg kg^{-1}															
	Upper	Lower	Mid	m AHD Mid	Density t m^{-3}	moles H^{+} t^{-1}		C %	S %	Al	As	B	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	Pb	S	Zn
TS3	130	140	135	-0.12	0.74	-480	88	2.64	1.34	19500	14	34	20450	<1	28	8	15600	4380	5380	285	23100	14	<10	14500	26
TS3	140	150	145	-0.22	0.74	-480	88	2.22	1.02	15200	11	27	25070	1	20	7	12200	3450	4700	236	21100	12	<10	10700	29
TS3	150	160	155	-0.32	1.19	-480	88	3.04	1.44	24200	15	42	26890	<1	30	10	18000	5250	6600	339	27200	15	<10	15700	32
TS3	160	170	165	-0.42	1.19	-480	88	2.68	1.22	20300	11	34	31440	<1	26	8	15900	4440	5860	319	22500	13	11	12600	31
TS3	170	180	175	-0.52	1.19	-480	88	3.54	1.36	21900	12	39	42190	<1	30	10	17400	4860	6180	325	22200	14	11	14600	65
TS3	180	200	190	-0.67	1.19	-480	88	3.08	1.36	22100	14	39	34700	<1	28	8	17000	4880	6000	307	22600	14	<10	14300	34
TS3	200	230	215	-0.92	1.19	-746	-24	3.08	1.60	27700	14	40	30860	<1	35	9	20600	5650	6610	369	22400	19	<10	16700	51
TS3	230	260	245	-1.22	1.19	-746	-24	2.84	1.32	24600	13	37	35180	1	31	9	18500	5020	6140	356	18200	17	11	13900	32
TS3	260	290	275	-1.52	1.19	-746	-24	2.54	1.32	29600	11	40	35630	<1	34	9	21100	5910	7180	353	17700	18	<10	13300	37
TS3	290	320	305	-1.82	1.19	-746	-24	2.40	1.20	23900	12	35	34340	<1	27	8	18700	4680	6070	332	15300	16	<10	12400	40
TS3	320	350	335	-2.12	0.99			2.22	1.20	24900	12	35	32880	<1	29	8	19900	4730	6260	404	13500	15	10	12700	45
TS3	60	100	80	0.43	0.74	-36	852																		
TS3	100	180	140	-0.17	1.19	-480	88																		
TS3	180	200	190	-0.67	1.19	-263	-11																		
TS3	200	300	250	-1.27	1.19	-746	-24																		
TS3	300	400	350	-2.27	0.99	-846	-31																		
TC1	0	10	5	-0.44	0.89	134	164	7.50	0.53	49800	39	42	970	<0.5	51	15	75500	7630	3420	117	700	19	16	5700	105
TC1	10	20	15	-0.54	0.89	140	181	4.94	0.55	56400	33	43	940	<0.5	59	15	65600	9380	3870	131	800	25	21	6000	45
TC1	20	30	25	-0.64	0.94	142	165	4.72	0.48	59600	36	43	1050	<1	64	14	53100	9820	4010	135	1000	27	19	5300	49
TC1	30	40	35	-0.74	1.01	111	163	4.08	0.46	56800	33	41	1090	1	60	11	42900	9560	3730	131	1000	28	13	5300	46
TC1	40	50	45	-0.84	0.54	146	291	4.62	0.37	49200	23	35	990	1	56	12	28500	7720	2940	105	1000	22	<10	4200	36
TC1	50	60	55	-0.94	0.82	109	365	4.80	0.38	49600	22	35	1050	<1	53	11	25000	7300	2990	107	1200	22	14	4400	36
TC1	60	70	65	-1.04	0.80	118	473	4.16	0.52	47100	20	36	1030	<1	51	11	21900	6900	2850	117	1400	23	14	6100	35
TC1	70	80	75	-1.14	0.79	146	627	5.00	0.83	44400	20	41	1030	<1	43	9	19900	6360	2800	118	2700	19	10	9200	33
TC1	80	90	85	-1.24	0.95	151	597	4.56	1.70	44200	31	44	1060	1	42	19	31000	8250	3020	206	3500	25	16	17500	95
TC1	90	100	95	-1.34	0.95		597	4.38	2.02	48700	22	48	1190	<1	46	9	29400	7190	3620	235	3700	29	13	21100	43
TC1	100	110	105	-1.44	0.83	33	1007	4.98	1.08	54000	23	42	1210	1	54	10	27700	7830	3740	173	2700	26	10	12100	120
TC1	110	120	115	-1.54	0.83	33	1007	4.86	1.98	56900	19	50	1430	1	52	9	34400	8100	4640	259	4700	32	13	20700	65
TC1	120	130	125	-1.64	0.83	33	1348	4.74	2.62	54300	19	52	1550	<1	47	9	31300	7490	4830	283	5800	31	14	25300	70
TC1	130	140	135	-1.74	0.83	33	1313	5.40	2.90	55800	18	69	2360	<1	49	10	34700	8340	5850	383	7600	28	11	29600	53
TC1	140	150	145	-1.84	0.83	33	1204	5.50	2.58	49200	13	70	2330	3	43	8	30100	7290	5480	351	7900	24	11	27300	45
TC1	150	160	155	-1.94	0.83	33	1204	5.50	2.46	50600	15	69	2220	<1	44	9	28500	7480	5550	357	7900	25	10	24500	48
TC1	160	170	165	-2.04	0.83	33	1223	5.80	2.80	58700	16	90	2440	1	50	10	33100	9190	6430	392	10200	30	20	28500	52
TC1	170	180	175	-2.14	0.83	33	947	5.25	2.20	52100	12	73	2190	1	45	9	28200	7960	5760	307	9400	26	11	23600	56
TC1	180	190	185	-2.24	0.83	33	1191	7.45	2.66	54000	15	82	2570	1	48	9	29400	8830	6270	276	11800	25	17	27000	59

Sample	Depth cm BGL			Elevation	Bulk	Total Actual Acidity	Total Potential Acidity	Total	Total	Total Acid Digestable mg kg^{-1}															
	Upper	Lower	Mid	m AHD Mid	Density t m^{-3}	$\text{moles H}^{+}\text{ t}^{-1}$		C %	S %	Al	As	B	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	Pb	S	Zn
TC1	190	200	195	-2.34	0.83	33	1060	5.35	2.58	64200	17	79	2340	2	56	12	33400	10320	6810	347	11800	32	17	26100	58
TC2	0	5	2.5	0.81	0.96	1	142	3.94	<0.01	30800	13	21	5130	1	40	9	21300	5640	3580	444	600	19	12	400	60
TC2	5	10	7.5	0.76	0.94	14	142	2.82	0.01	35500	13	24	4040	1	44	11	24800	5870	3800	251	600	18	10	400	47
TC2	10	30	20	0.64	1.09	64	136	1.98	0.03	38200	15	28	3010	1	47	9	24600	6160	3570	183	600	17	<10	500	65
TC2	30	100	65	0.19	0.75	109	241	1.96	0.54	42600	21	34	2320	1	52	12	28000	8750	3390	141	2100	18	17	6200	37
TC2	100	170	135	-0.52	0.73	-508	18	2.66	1.70	41800	15	53	28480	1	48	13	29600	7720	6890	444	11200	26	15	17900	56
TC2	170	230	200	-1.17	0.73	-750	-7	2.74	1.32	31400	12	46	37570	<1	38	10	22400	6260	6480	346	12700	20	12	14300	42
TC2	230	400	315	-2.32	0.80	-678	3	2.62	1.54	49900	11	64	36500	<1	53	13	31100	10030	10980	474	19600	30	10	16300	58
TC3	0	5	2.5	1.18	1.04	-31	-88	4.44	0.03	55000	10	60	2970	1	59	14	32400	11260	12540	488	2300	30	18	1000	70
TC3	5	10	7.5	1.13	1.27	-24	-69	0.57	0.02	54500	11	66	2400	1	59	13	33400	10660	15640	553	2300	31	14	400	69
TC3	10	35	23	0.98	1.01	-34	-56	0.44	0.05	54700	14	65	2430	<1	59	12	34600	10480	14670	975	4800	32	17	700	78
TC3	35	57	46	0.75	1.01	3	94	0.49	0.14	47300	29	56	2370	1	53	12	40900	9040	8020	484	10100	29	25	1700	68
TC3	57	75	66	0.55	1.01	63	713																		
TC3	75	150	113	0.08	0.66	-184	82	3.34	1.44	19600	10	38	20650	3	26	10	15500	4160	5510	242	20700	18	<10	15100	32
TC3	150	300	225	-1.04	1.01	-414	33	3.22	1.62	23200	24	36	39590	1	30	13	20200	4800	6410	329	20000	19	12	17100	45
TC3	300	400	350	-2.29	1.06	-395	5	3.18	1.40	25500	19	41	41430	<1	32	14	20500	5300	7140	396	19900	20	<10	15000	48

APPENDIX 5 WATER DATA

Table 11 Complete listing of analytical data for surface waters.

Date	EC dS/m	pH	Eh V	As ug/L	TOC	Cl	NH_4 N	NO_3 N	Si	Al	B	Ca	Cu	Fe	K	Mg	Mn	Na	P	S	Zn	Acidity mmoles $H^+ L^{-1}$	Alkal mmoles $HCO_3^- L^{-1}$
													mg/L										
Firewood Ck Bunded																							
19/01/97	2.1	3.7	nd	nd	nd	436	nd	nd	12	6.2	0.3	62	<0.02	2.6	17	46	0.84	280	0.20	120	0.10	nd	nd
2/02/97	2.9	2.4	nd	nd	nd	630	nd	nd	18	6.5	0.4	67	0.02	5.4	24	61	1.1	430	0.28	150	0.18	nd	nd
17/02/97	1.4	3.6	nd	nd	nd	240	nd	nd	12	1.9	<0.1	31	0.05	1.6	9	25	0.48	180	<0.1	69	0.64	0.50	0.00
8/03/97		3.5	nd	nd	nd	630	nd	nd	24	4.0	0.3	52	0.08	20	20	53	1.2	410	0.22	150	0.66	nd	0.00
6/04/97	1.6	3.5	nd	nd	nd	371	nd	nd	14	1.0	0.2	27	<0.02	7.2	12	30	0.40	240	0.10	66	0.08	0.66	0.00
20/04/97	1.9	3.4	nd	nd	nd	426	nd	nd	13	1.0	0.2	32	<0.02	5.2	13	32	0.40	260	0.14	68	0.07	0.79	0.00
13/05/97	1.4	3.4	nd	nd	nd	315	nd	nd	12	<0.1	0.2	28	<0.05	0.8	11	24	0.30	210	0.03	61	0.07	0.61	0.00
25/05/97	2.7	3.6	nd	nd	nd	704	nd	nd	14	11.6	0.3	36	<0.02	3.4	20	54	0.50	480	0.19	86	0.09	0.93	0.00
8/06/97	32.8	6.2	nd	nd	nd	14800	nd	nd	3.2	<0.1	3.6	350	<0.02	0.3	320	980	0.15	8450	1.3	710	0.09	0.00	1.73
23/06/97	15.6	3.7	nd	nd	nd	14800	nd	nd	3.2	<0.1	3.6	350	<0.02	0.3	320	980	0.15	8450	1.3	710	0.09	0.00	0.00
7/07/97	32.5	6.9	nd	nd	nd	18200	nd	nd	0.9	<1	4.1	402	<0.5	<1	456	1189	<0.5	10580	<1	810	0.50	0.00	0.00
21/07/97	43.0	7.3	nd	nd	nd	19300	nd	nd	16	<1	4.1	412	<0.5	<1	432	1212	<0.5	10650	<1	825	0.50	0.00	2.35
9/08/97	25.6	6.2	nd	nd	nd	10000	nd	nd	4.8	<0.1	2.4	210	<0.02	0.1	200	620	0.36	5400	0.30	480	0.08	0.00	0.39
24/08/97	29.6	6.7	nd	nd	nd	12000	nd	nd	1.8	<0.1	2.7	240	<0.02	<0.1	250	740	0.13	6600	1.1	540	0.02	0.00	0.58
7/09/97	12.1	5.9	nd	nd	nd	4200	nd	nd	7.3	<0.1	1.0	96	<0.05	0.2	110	260	0.27	2400	0.31	220	0.11	0.00	0.31
13/10/97	nd	6.5	nd	nd	nd	10400	nd	nd	5.0	<0.1	2.4	220	<0.05	<0.1	210	630	0.33	5600	0.37	480	0.08	0.00	0.00
17/11/97	nd	6.8	nd	nd	nd	14300	nd	nd	0.4	<0.1	3.4	320	<0.05	<0.1	340	900	<0.1	7800	0.50	670	0.12	nd	nd
1/12/97	6.6	3.4	nd	nd	nd	2000	nd	nd	24	15	0.6	120	<0.05	2.6	53	150	1.8	1200	0.10	240	0.19	nd	nd
15/12/97	nd	3.9	nd	nd	nd	6300	nd	nd	22	11	1.5	200	<0.05	1.5	140	390	1.8	3200	<0.1	390	0.20	nd	nd
7/01/98	nd	4.0	nd	2	7	330	0.17	0.15	11	1.2	<0.5	40	<0.2	<0.5	12	28	<0.5	190	<0.5	63	0.20	nd	nd
26/01/98	1.3	3.2	nd	<2	13	490	nd	nd	16	2.4	<0.5	48	<0.2	14.0	17	41	0.70	290	<0.5	100	0.20	0.85	0.00
9/02/98	1.3	3.0	0.66	<2	8	540	nd	nd	15	1.2	<0.5	38	<0.2	3.2	19	45	<0.5	320	<0.5	78	0.20	0.59	0.00
23/02/98	0.8	3.4	0.35	<2	6	440	0.17	0.05	10	0.9	<0.5	24	<0.2	2.8	11	32	<0.5	250	<0.5	54	0.20	0.29	0.00
9/03/98	0.4	3.5	0.61	2	8	350	0.10	0.06	12	1.3	<0.5	33	<0.2	2.6	9	30	<0.5	210	<0.5	66	0.20	0.16	0.00
23/03/98	nd	3.3	0.63	<2	7	310	0.08	0.07	9.8	<0.5	<0.5	23	<0.2	1.6	10	24	<0.5	180	<0.5	48	0.20	nd	nd
8/04/98	2.3	3.3	0.41	<2	6	500	0.17	0.06	12	1.0	<0.5	36	<0.2	2.8	16	40	<0.5	290	<0.5	72	0.20	0.88	nd
19/04/98	1.7	3.3	0.40	<2	3	340	0.25	0.1	12	0.6	<0.5	28	<0.2	2.6	12	28	<0.5	200	<0.5	58	0.20	0.70	0.00

Date	EC dS/m	pH	Eh V	As ug/L	TOC	Cl	NH_4 N	NO_3 N	Si	Al	B	Ca	Cu	Fe	K	Mg	Mn	Na	P	S	Zn	Acidity mmoles $H^+ L^{-1}$	Alkal mmoles $HCO_3^- L^{-1}$
					mg/L																		
Firewood Ck Marine																							
19/01/97	6.6	3.8	nd	nd	nd	1640	nd	nd	13	5.5	0.6	87	<0.02	1.5	47	123	0.87	950	0.30	178	0.14	nd	nd
2/02/97	30.3	6.0	nd	nd	nd	13200	nd	nd	2.8	<0.1	2.8	280	<0.02	<0.1	300	890	0.14	7300	1.1	670	0.09	nd	nd
17/02/97	5.5	4.7	nd	nd	nd	1500	nd	nd	9.9	0.8	0.3	51	0.07	0.9	35	100	0.38	920	0.29	110	0.62	0.20	0.00
8/03/97	3.0	3.1	nd	nd	nd	8040	nd	nd	12	<0.1	1.9	170	0.07	6.4	170	480	0.61	4510	0.75	410	0.56	0.00	0.51
6/04/97	32.5	6.8	nd	nd	nd	14000	nd	nd	2.6	<0.1	3.0	310	<0.02	<0.1	330	890	0.05	8400	1.3	650	0.08	0.00	2.1
20/04/97	13.8	5.5	nd	nd	nd	5100	nd	nd	9.5	<0.1	1.0	110	<0.02	0.8	91	275	0.14	2640	0.43	240	0.08	0.00	0.42
13/05/97	38.6	6.9	nd	nd	nd	18700	nd	nd	1.2	<0.1	3.6	395	<0.05	<0.1	399	1065	<0.1	9510	1.4	776	0.14	0.00	2.3
25/05/97	38.1	6.3	nd	nd	nd	16200	nd	nd	2.0	<0.1	3.6	390	<0.02	<0.1	420	970	0.05	9100	1.4	720	0.08	0.00	2.3
8/06/97	35.4	6.4	nd	nd	nd	17100	nd	nd	1.2	<0.1	4.0	400	<0.02	<0.1	370	1100	0.05	9680	1.5	810	0.08	0.00	2.4
23/06/97	35.5	6.2	nd	nd	nd	17100	nd	nd	1.2	<0.1	4.0	400	<0.02	<0.1	370	1100	0.05	9680	1.5	810	0.08	0.00	2.2
7/07/97	30.7	6.3	nd	nd	nd	18500	nd	nd	1.6	<1	3.9	400	<0.5	2.1	435	1177	<0.5	10350	<1	800	0.50	0.00	0.00
21/07/97	42.7	6.4	nd	nd	nd	18900	nd	nd	4.9	<1	3.9	410	<0.5	4.1	412	1207	<0.5	10470	<1	827	0.50	0.00	2.2
9/08/97	44.0	6.5	nd	nd	nd	18900	nd	nd	0.7	<0.1	4.3	350	<0.02	<0.1	370	1200	<0.1	10400	0.89	840	0.07	0.00	2.4
24/08/97	42.9	6.7	nd	nd	nd	18500	nd	nd	0.7	<0.1	4.2	360	<0.02	<0.1	410	1200	<0.1	10700	1.6	810	0.02	0.00	2.3
7/09/97	38.7	6.3	nd	nd	nd	22500	nd	nd	0.9	<0.1	3.4	360	<0.05	<0.1	440	1200	<0.1	9800	1.1	820	0.09	0.00	2.3
13/10/97	nd	6.7	nd	nd	nd	19100	nd	nd	1.3	<0.1	4.5	380	<0.05	<0.1	410	1200	<0.1	10700	0.85	850	0.09	0.00	0.00
17/11/97	nd	6.6	nd	nd	nd	19600	nd	nd	1.1	<0.1	4.7	420	<0.05	<0.1	490	1200	<0.1	10800	0.80	880	0.15	nd	nd
1/12/97	nd	6.6	nd	nd	nd	15500	nd	nd	4.1	<0.1	3.9	360	<0.05	<0.1	350	1000	0.1	8600	0.10	710	0.13	nd	nd
15/12/97	nd	6.5	nd	nd	nd	18900	nd	nd	3.0	<0.1	4.4	410	<0.05	0.1	410	1200	<0.1	10500	0.10	810	0.13	nd	nd
7/01/98	31.4	5.9		3	10	11300	0.08	0.1	3.8	<0.5	2.7	240	<0.2	<0.5	240	710	<0.5	6200	<0.5	490	0.20	nd	1.7
26/01/98	37.2	6.6		<2	14	13300	nd	nd	3.5	<0.5	3.2	290	<0.2	<0.5	280	850	<0.5	7300	<0.5	600	0.20	0.00	1.7
9/02/98	27.7	6.5	0.41	<2	10	14400	nd	nd	3.6	<0.5	3.4	300	<0.2	<0.5	270	860	<0.5	7700	<0.5	630	0.20	0.00	1.2
23/02/98	26.9	6.8	0.16	<2	10	10400	<0.05	<0.05	2.4	<0.5	2.6	200	<0.2	<0.5	190	600	<0.5	5600	<0.5	430	0.20	0.00	1.3
9/03/98	33.2	6.8	0.32	<2	12	12500	0.19	<0.5	3.2	<0.5	2.9	260	<0.2	<0.5	260	800	<0.5	6900	<0.5	540	0.20	0.00	0.92
23/03/98	11.0	5.3	0.34	<2	8	3400	0.08	0.05	8.2	<0.5	0.9	76	<0.2	<0.5	78	210	<0.5	1800	<0.5	160	0.20	0.00	0.17
8/04/98		6.7	0.08	<2	12	11200	<0.05	<0.05	2.6	<0.5	2.6	220	<0.2	<0.5	230	670	<0.5	6100	<0.5	460	0.20	nd	nd
19/04/98	12.2	5.9	0.14	<2	5	3700	0.13	0.05	9.1	<0.5	1.0	95	<0.2	0.8	85	230	<0.5	2100	<0.5	200	0.20	0.00	0.15

Date	EC dS/m	pH	Eh V	As ug/L	TOC	Cl	NH_4 N	NO_3 N	Si	Al	B	Ca	Cu	Fe	K	Mg	Mn	Na	P	S	Zn	Acidity mmoles $H^+ L^{-1}$	Alkal mmoles $HCO_3^- L^{-1}$
					mg/L																		
Drainage water site 1																							
19/01/97	2.7	3.3	nd	nd	nd	570	nd	nd	19	11	0.4	67	<0.02	8.4	21	60	1.4	360	0.30	156	0.16	nd	nd
2/02/97	3.1	2.8	nd	nd	nd	560	nd	nd	29	15	0.5	61	<0.02	42	23	64	1.7	420	0.40	210	0.20	nd	nd
17/02/97	3.7	2.9	nd	nd	nd	710	nd	nd	38	17	0.4	74	0.09	47	22	69	2.6	500	0.34	230	0.79	5.1	0.00
8/03/97	6.6	3.6	nd	nd	nd	1600	nd	nd	64	16	1.1	110	0.07	203	49	130	2.8	1060	0.76	390	0.74	nd	0.00
6/04/97	6.6	3.5	nd	nd	nd	1710	nd	nd	61	10	1.0	110	<0.02	200	51	130	1.9	1200	0.80	360	0.22	2.6	0.00
20/04/97	5.7	3.5	nd	nd	nd	1390	nd	nd	51	8.2	0.9	91	<0.02	180	44	110	1.6	900	0.62	320	0.20	2.3	0.00
13/05/97	1.3	3.3	nd	nd	nd	234	nd	nd	15	<0.1	0.2	30	<0.05	2.5	11	22	0.44	174	0.04	73	0.05	1.2	0.00
25/05/97	4.5	3.3	nd	nd	nd	1100	nd	nd	49	12	0.9	120	<0.02	155	45	95	1.9	720	0.68	330	0.21	3.1	0.00
8/06/97	6.1	5.1	nd	nd	nd	1560	nd	nd	47	1.7	1.0	50	<0.02	310	67	110	0.90	960	0.64	330	0.13	9.7	0.00
23/06/97	6.4	4.4	nd	nd	nd	1560	nd	nd	47	1.7	1.0	50	<0.02	310	67	110	0.90	960	0.64	330	0.13	10	0.00
7/07/97	7.1	4.4	nd	nd	nd	2190	nd	nd	51	9.1	1.2	98	<0.1	212	79	161	2.0	1270	<0.5	340	0.28	0.00	0.00
21/07/97	10.0	3.7	nd	nd	nd	2650	nd	nd	4.0	15	1.4	114	<0.1	329	72	194	3.0	1440	0.50	442	0.35	13	0.00
7/09/97	1.3	3.5	nd	nd	nd	410	nd	nd	12	2.0	0.2	17	<0.05	0.9	20	23	0.36	200	<0.1	43	0.08	0.50	0.00
1/12/97	3.5	3.2	nd	nd	nd	970	nd	nd	43	23	0.5	72	<0.05	47	33	89	1.7	520	<0.1	230	0.24	nd	nd
15/12/97	nd	3.0	nd	nd	nd	2700	nd	nd	60	30	1.2	97	<0.05	190	81	210	2.9	1600	<0.1	420	0.37	nd	nd
7/01/98	nd	3.0	nd	2	7	410	0.15	0.09	21	6.8	<0.5	41	<0.2	4.5	16	34	0.80	230	<0.5	89	0.20	nd	nd
26/01/98	6.2	3.0	nd	20	29	1200	nd	nd	61	38	1.1	97	<0.2	260	43	140	4.9	790	<0.5	470	0.50	14.7	0.00
9/02/98	4.5	3.0	0.61	130	39	1700	nd	nd	63	17	1.0	100	<0.2	210	53	130	2.7	980	<0.5	370	0.30	5.8	0.00
23/02/98	1.1	3.2	0.39	4	9	140	0.44	<0.05	23	1.7	<0.5	14	<0.2	12	8	16	<0.5	110	<0.5	55	0.20	1.3	0.00
9/03/98	3.1	3.0	0.65	<2	14	470	0.33	<0.5	27	6.8	<0.5	40	<0.2	37	15	41	1.1	300	<0.5	110	0.20	2.6	0.00
23/03/98		3.2	0.69	<2	9	110	0.07	0.24	14	1.0	<0.5	12	<0.2	4.9	8	11	<0.5	85	<0.5	42	0.20	nd	nd
8/04/98	1.0	3.0	0.43	<2	7	130	0.19	0.10	17	1.0	<0.5	9	<0.2	3.9	11	11	<0.5	84	<0.5	34	0.20	1.1	0.00
19/04/98	1.1	2.9	0.44	<2	4	140	0.07	<0.05	15	1.3	<0.5	17	<0.2	5.9	10	15	<0.5	110	<0.5	53	0.20	1.2	0.00

Date	EC dS/m	pH	Eh V	As ug/L	TOC	Cl	NH_4 N	NO_3 N	Si	Al	B	Ca	Cu	Fe	K	Mg	Mn	Na	P	S	Zn	Acidity mmoles $H^+ L^{-1}$	Alkal mmoles $HCO_3^- L^{-1}$
					mg/L																		
Magazine Ck Bunded																							
13/10/97	19.8	2.9	nd	nd	nd	6600	nd	nd	13	5.7	2.1	450	<0.05	22	220	500	3.3	3800	1.1	830	0.16	3.5	0.00
17/11/97	22.2	2.9	nd	nd	nd	8000	nd	nd	14	9.4	2.6	550	<0.05	18	250	600	3.8	4400	1.2	980	0.27	nd	nd
1/12/97	15.1	3.2	nd	nd	nd	5300	nd	nd	25	31	1.3	420	<0.05	6.8	160	410	3.6	2900	0.10	780	0.35	nd	nd
15/12/97	nd	3.0	nd	nd	nd	7700	nd	nd	27	25	2.0	530	<0.05	13	210	570	4.3	4000	0.20	940	0.33	nd	nd
7/01/98	4.4	6.2	nd	2	19	1100	0.37	0.09	8.0	<0.5	<0.5	190	<0.2	<0.5	36	93	1.0	600	<0.5	220	0.20	nd	12
26/01/98	13.3	3.7	nd	<2	20	3300	nd	nd	17	3.2	1.3	430	<0.2	4.7	100	300	3.6	1900	<0.5	630	0.30	0.63	0.00
9/02/98	7.4	2.9	0.68	<2	14	4800	nd	nd	26	12	1.8	470	<0.2	20	150	420	4.7	2800	<0.5	820	0.20	1.2	0.00
23/02/98	15.6	2.8	0.43	<2	14	4500	2.7	<0.05	20	11	1.5	430	<0.2	21	120	370	4.6	2600	<0.5	760	0.30	3.8	0.00
9/03/98	12.1	4.4	0.31	3	23	2600	0.68	<0.5	16	2.4	1.1	340	<0.2	4.1	87	230	2.8	1600	<0.5	500	0.20	0.17	0.00
23/03/98	nd	2.9	0.67	<2	15	3000	0.71	<0.05	20	4.5	1.4	350	<0.2	11	92	260	3.4	1700	<0.5	580	0.20	nd	nd
8/04/98	10.7	2.9	0.45	<2	15	2800	0.64	<0.05	20	4.3	1.3	330	<0.2	18	88	240	3.0	1700	<0.5	560	0.20	2.9	nd
19/04/98	10.9	2.6	0.45	<2	10	2800	0.65	<0.05	18	2.8	1.3	340	<0.2	25	87	240	3.3	1700	<0.5	570	0.20	3.1	0.00

Date	EC dS/m	pH	Eh V	As ug/L	TOC	Cl	NH_4 N	NO_3 N	Si	Al	B	Ca	Cu	Fe	K	Mg	Mn	Na	P	S	Zn	Acidity mmoles $H^+ L^{-1}$	Alkal mmoles $HCO_3^- L^{-1}$
					mg/L																		
Tidal Pools Site 1																							
19/01/97	17.7	6.4	nd	nd	nd	6990	nd	nd	2.2	<0.1	1.9	120	<0.02	<0.1	159	380	0.11	3960	0.60	295	0.08	nd	nd
2/02/97	25.0	5.9	nd	nd	nd	10900	nd	nd	2.2	<0.1	2.8	220	<0.02	0.2	260	700	0.15	6100	0.86	530	0.08	nd	nd
17/02/97	14.2	6.7	nd	nd	nd	5150	nd	nd	1.7	<0.1	1.4	81	0.06	<0.1	110	260	0.08	2790	0.26	190	0.47	0.00	1.8
8/03/97	31.6	6.8	nd	nd	nd	11800	nd	nd	2.2	<0.1	2.8	250	0.05	<0.1	280	790	0.06	7320	1.1	580	0.43	0.00	2.1
6/04/97	32.5	6.5	nd	nd	nd	12900	nd	nd	2.6	<0.1	2.8	310	<0.02	<0.1	300	830	0.10	7700	1.2	600	0.08	0.00	1.9
20/04/97	28.2	6.5	nd	nd	nd	11400	nd	nd	2.3	<0.1	2.3	230	<0.02	<0.1	210	640	0.15	6300	1.0	470	0.06	0.00	3.0
13/05/97	32.8	6.6	nd	nd	nd	13500	nd	nd	2.7	<0.1	2.8	328	<0.05	2.7	315	874	0.13	7450	1.1	625	0.12	0.00	3.5
25/05/97	34.3	6.8	nd	nd	nd	14500	nd	nd	2.1	<0.1	3.2	300	<0.02	<0.1	360	910	0.15	8300	1.3	660	0.08	0.00	2.8
8/06/97	32.9	6.5	nd	nd	nd	15300	nd	nd	1.6	<0.1	3.4	370	<0.02	1.0	330	1100	0.15	8770	1.4	750	0.09	0.00	2.6
23/06/97	33.5	6.6	nd	nd	nd	15300	nd	nd	1.6	<0.1	3.4	370	<0.02	1.0	330	1100	0.15	8770	1.4	750	0.09	0.00	2.3
7/07/97	28.2	6.6	nd	nd	nd	16800	nd	nd	2.0	<1	3.3	380	<0.5	<1	404	1118	<0.5	9590	<1	754	0.50	0.00	0.00
21/07/97	40.8	6.3	nd	nd	nd	18100	nd	nd	0.9	<1	3.5	404	<0.5	1.8	382	1185	<0.5	10040	<1	810	0.50	0.00	2.1
24/08/97	41.0	6.4	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.00	2.5
7/09/97	38.2	6.7	nd	nd	nd	21700	nd	nd	2.1	<0.1	3.1	370	<0.05	0.2	420	1200	0.17	9600	1.1	780	0.08	0.00	3.4
13/10/97	nd	6.5	nd	nd	nd	19300	nd	nd	1.9	<0.1	4.3	390	<0.05	<0.1	400	1200	0.13	10600	0.91	870	0.11	0.00	21
17/11/97	nd	6.3	nd	nd	nd	19700	nd	nd	2.4	<0.1	4.7	450	<0.05	0.9	500	1300	0.20	11000	0.80	930	0.14	nd	nd
1/12/97	nd	6.4	nd	nd	nd	15600	nd	nd	4.0	<0.1	2.9	370	<0.05	0.2	350	1000	0.10	8600	0.10	710	0.13	nd	nd
15/12/97	nd	6.5	nd	nd	nd	18600	nd	nd	3.6	<0.1	4.4	420	<0.05	0.2	400	1200	0.20	10300	<0.1	830	0.14	nd	nd
7/01/98	27.1	6.5	nd	4	14	9400	0.19	0.06	3.4	<0.5	2.6	210	<0.2	1.1	210	570	<0.5	5300	<0.5	380	0.20	nd	2.4
26/01/98	32.2	6.7	nd	<2	12	11500	nd	nd	3.9	<0.5	2.8	240	<0.2	<0.5	230	730	<0.5	6200	<0.5	520	0.20	0.00	1.7
9/02/98	25.5	6.5	0.38	<2	11	13200	nd	nd	3.6	<0.5	3.2	280	<0.2	<0.5	250	790	<0.5	7000	<0.5	580	0.20	0.00	1.2
23/02/98	14.9	6.6	0.08	<2	11	5700	<0.05	<0.05	2.3	<0.5	1.7	100	<0.2	<0.5	100	300	<0.5	3100	<0.5	220	0.20	0.00	1.0
9/03/98	33.5	6.8	0.33	<2	11	10400	0.15	<0.5	3.6	<0.5	2.6	220	<0.2	<0.5	220	670	<0.5	5700	<0.5	460	0.20	0.00	1.0
23/03/98	27.6	6.4	0.30	<2	14	9700	<0.05	<0.05	3.6	<0.5	2.6	200	<0.2	<0.5	200	600	<0.5	5300	<0.5	410	0.20	0.00	2.1
8/04/98	nd	6.6	0.06	<2	14	6300	<0.05	<0.05	2.3	<0.5	1.7	110	<0.2	<0.5	140	360	<0.5	3500	<0.5	240	0.20	nd	nd
19/04/98	24.0	6.9	0.08	<2	15	8100	0.07	<0.05	2.8	<0.5	2.2	150	<0.2	<0.5	170	460	<0.5	4500	<0.5	310	0.20	0.00	1.9

List of Figures and Tables

List of Figures

List of Tables