Prediction and management of acidity production and export from acid sulphate soils used for sugar production

FINAL REPORT
SRDC PROJECT

DNR 004

June 2001

CRC for Sustainable Sugar Production
CSIRO Land and Water
Department of Natural Resources and Mines

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Project No: DNR004

Title: Prediction and management of acidity production and export from acid sulphate soils used for sugar production

Project Start: 1 July 1997 **Project Completion:** 30 June 2001

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Objectives:

- To measure and predict water table variations and hydrological components of sugar cane growing on acid sulfate soils (ASS) after manipulating surface/subsurface drainage regimes using combinations of laser levelling, drain infilling and irrigation.

- To measure and predict the *in situ* acid production and export flux of acid from canelands on ASS subjected to different drainage and irrigation treatments.

- Transfer knowledge gained on ASS management over a three-year crop cycle to other canegrowers in areas of known risk, using models and other technology transfer tools.

The rationale behind the approach is to demonstrate how different farm scale management techniques can reduce/prevent acid export and/or acid production, accompanied by sufficient process understanding so that the results can be applied to other areas in Queensland and northern New South Wales.

Milestones:

Date	Milestone	Payment	Description
1 July 1997	1	$20,000	Sign project agreement. **Achievement Criteria:** All parties sign project agreement.
1 October 1997	2	$20,000	Appointment of staff.

Date	Milestone	Payment	Description
			Achievement Criteria: Research Scientist and Technician appointed.
31 December 1997	3	$20,000	Install flow sampling equipment, consult local growers/sugar industry personnel **Achievement Criteria:** Flow sampling equipment installed and inspected. Output data checked and operation of equipment verified. Summary of outcome of grower and industry consultations prepared.
31 March 1998	4	$39,992	Install irrigation systems and field monitoring equipment on farm. **Achievement Criteria:** Irrigation systems installed and operational. Field monitoring equipment installed and output data checked to verify operation.
31 December 1998	5	$46,551	Review results from first year of experiment, update milestones. **Achievement Criteria:** Comprehensive report on results from first year of experiment submitted to SRDC.
1 June 1999	6	$46,000	Comparing field results with predictions from ASS hydrology model. **Achievement Criteria:** Acceptable comparison between model output and field results.
31 December 1999	7	$40,586	Review results from year 2. **Achievement Criteria:** Comprehensive report on results from second year of experimentation submitted to SRDC.
31 May 2000	8	$45,000	Major Field Day for coastal cane industry. **Achievement Criteria:** Successful Field Day attended by Qld and NSW cane industry. Media coverage. Fact Sheets distributed.
31 December 2000	9	$40,000	Review results from year 3. **Achievement Criteria:** Comprehensive report on results from third year of experimentation submitted to SRDC.
30 June 2001	10	$36,791	Final Report submitted to SRDC/CRC.

Date	Milestone	Payment	Description
			Achievement Criteria: Final report provides overview of major outcomes of project and analysis of achievement of project objectives.
	TOTAL	**$354,920**	

Harvesting, Mischke site.

Abstract

The experimental design of this project successfully enabled runoff and groundwater drainage flow components to be distinguished in a cane-farming context at Pimpama, southeast Queensland. The majority of acidity exported from the soils of the study area occurred via groundwater flow to drains.

Measurements of water composition showed that iron, aluminium and hydrogen ions are major components of total acidity. Iron will also contribute chemical oxygen demand to the receiving waters. Other heavy metals in drainage water were often in excess of ANZECC (2000) water quality guidelines. Mineralogy of the soils at each site was measured and minor differences were detected.

Evapotranspiration was found to be the major factor controlling the watertable in these soils. For the Pimpama drainage network groundwater flow to the drains is small compared to surface runoff and evapotranspiration. An analytical model of the hydrological system was developed, based on drainage and evaporation components.

A model that included water balance components and an empirical model for acid generation was developed using the Modelmaker software. This was used to show how changing drainage design would affect acid export and periods of waterlogging on soils. A copy of this model is included in this report.

Non-Technical Summary

This project has substantially added to the understanding of the processes of generation and export of acidity by drains from acid sulfate soils. The design of the project meant that water that ran over the soil surface (runoff) before entering drains could be measured separately from water that flowed through the ground (groundwater) to the drain. This allowed us to determine that the major route for acid discharge into drains was via the groundwater.

This project showed that drains only lowered the watertable of the soil within 10 m of the drain for these particular soils. The major function of the drains was removing surface runoff. It was evaporation from the soil surface and transpiration by the cane (termed evapotranspiration) that actually lowered the watertable for most of the site. Hence drains need to be designed specifically to get rid of surface water. Drains do not need to be deep in order to do this. Having shallow drains will also reduce the amount of groundwater and acid reaching the drains. Making shallower drains may result in the soil being waterlogged for longer. A model that predicts the affects of changing drainage depth and spacing on both acid export and waterlogging was developed.

Measurements of the composition of the water in the drains showed that it contained a lot of sulphate, iron and aluminium and generally had low pH values (acidic). The amount of acid the water contained (measured by pH) is related to how much neutralising chemical (lime, etc) is needed to bring the pH of the water back to acceptable limits. The high iron and aluminium concentrations in the water mean that

much more of the neutralising agent is required to correct the acidity than indicated by pH alone. This is because the iron reacts with oxygen in the receiving water to produce 2 moles of acid per mole of iron. The aluminium acts as a buffering reagent reacting by hydrolysis to product aluminium hydroxides and acid as neutralising agents try to raise the pH of the water. The acid nature of the water means that it also contains other metals such as copper, zinc and manganese, which can have adverse environmental effects.

Measurements of the amount of minerals with the potential to generate acid in the soil showed that the potential was thousands of times greater than the amount of acid coming out annually in the drainage water. The estimated rate at which new acid was being formed was found to be greater than that being lost via drainage. Therefore the hope that acid drainage will go away with time is a false hope, and acid will continue to be lost in drainage water from these soils for many decades, even centuries to come. It is thus necessary to reduce the amount of acid lost in drainage water. Changing the drainage design by laser levelling and shallow drains can do this.

In light of these results, drainage design needs to be reassessed at the farm, catchment and district levels. Drains need to be designed to cope with surface runoff, and deeper drains are not the answer. Laser levelling of fields can reduce waterlogging due to inadequate surface drainage, and planting on raised beds may allow oxygen to the root zone sooner after localised flooding, therefore lowering the watertable more quickly. These techniques combined with shallow drains could produce a win-win situation with more cane production and less environmental impact.

Report

This project has fulfilled its objectives and delivered some high quality science. The extent of the science delivery can be seen in the publications arising from the project. A selection of these is collated as part of this final report. This report provides an overview of the outcomes and how they have met specific project objectives. The attached papers contain additional detail.

1. **To measure and predict water table variations and hydrological components of sugar cane growing on acid sulfate soils (ASS) after manipulating surface/subsurface drainage regimes using combinations of laser levelling, drain infilling and irrigation.**

The project was designed to use existing knowledge of drainage behaviour and uses the symmetry of the watertable shape to define the catchment area. Figure 1 shows the ideal shape for three parallel drains and compares this with the measured watertable at one point in time. The measured watertable shape is similar to the idealised conceptual shape thus showing that the water collected by the central drain will come from a defined catchment area.

Pressure transducers were installed in one transect of the dipwells at Mischke's site to give a continuous record of watertable behaviour. From these results it was noted that reduction in the watertable height, due to water flow to the drains, only occurred for a short distance (10 m) from the drain. It was noted that evapotranspiration was the main component for water loss from these soils. This led to the derivation of an analytical mathematical expression that coupled evaporation and drainage together to predict the watertable behaviour for a single drainage event. This was shown to describe the watertable fall during drainage well in these soils (Cook *et al*., 2000e,f).

Downloading data at Holm dryland site.

Installing the dipwells at Holm irrigated site

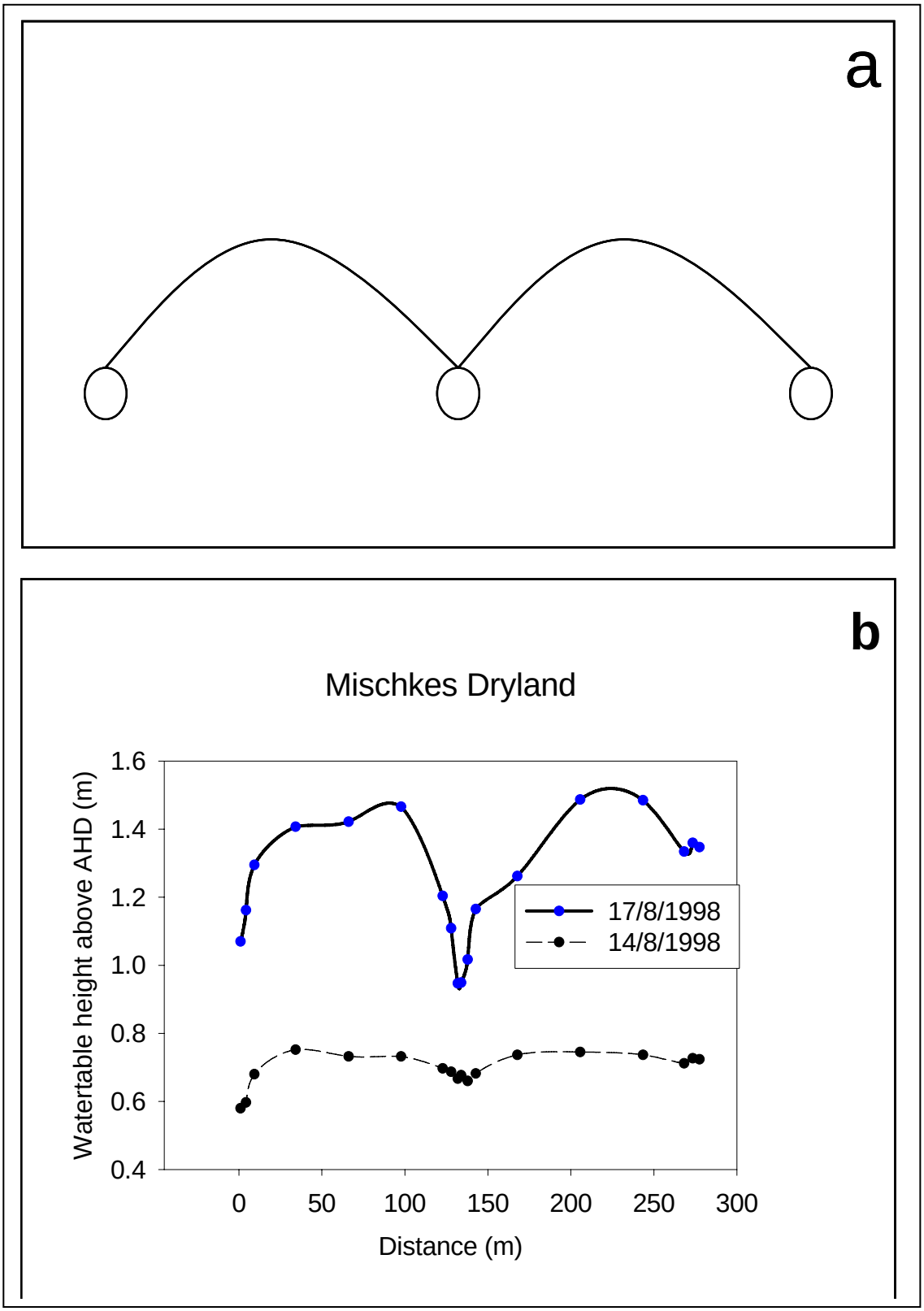

Figure 1. a) Hypothetical watertable shape and b) measured watertable shape at Mischke's site on two dates.

Subsequently a numerical model (FLASSH – flow in acid sulfate soils and hydrology) was developed using the concepts of the analytical watertable model (Cook *et al*., 2001a). The FLASSH model can calculate the runoff, and the number of days when the watertable is above a given height, as well as the individual components of the water balance. The model can be used to solve both inverse and forward problems. The inverse problem is solved when we obtain soil properties from the measured flow and watertable data, while the forward problem uses known soil property data to predict the flow rate and watertable heights.

The FLASSH model was firstly used inversely to derive the hydraulic conductivity and specific yield from measured flow and watertable height data. Subsequently, the effects on the components of the water balance were predicted for changes in the drainage depth and/or spacing. An example using FLASSH for Mischke's site shows that changing the drainage depth is likely to be more effective in reducing acid discharges than reducing the drain spacing (Fig 2a,b). The number of days the watertable is predicted to be above 0.5 m and hence causing reduced yields is calculated with FLASSH (Fig. 2c). This will allow the model to be used along with economic models to estimate the economic benefits/costs of changing drainage design and work in this direction has started (Mallawaarachchi *et al*., 2001) An executable version of FLASSH is attached on a CD.

Inside a sump.

Cleaning out iron build up in pipe.

Normal drainage water discharge – water is clear until oxidation of the iron occurs.

Runoff occurring at Holm dryland site.

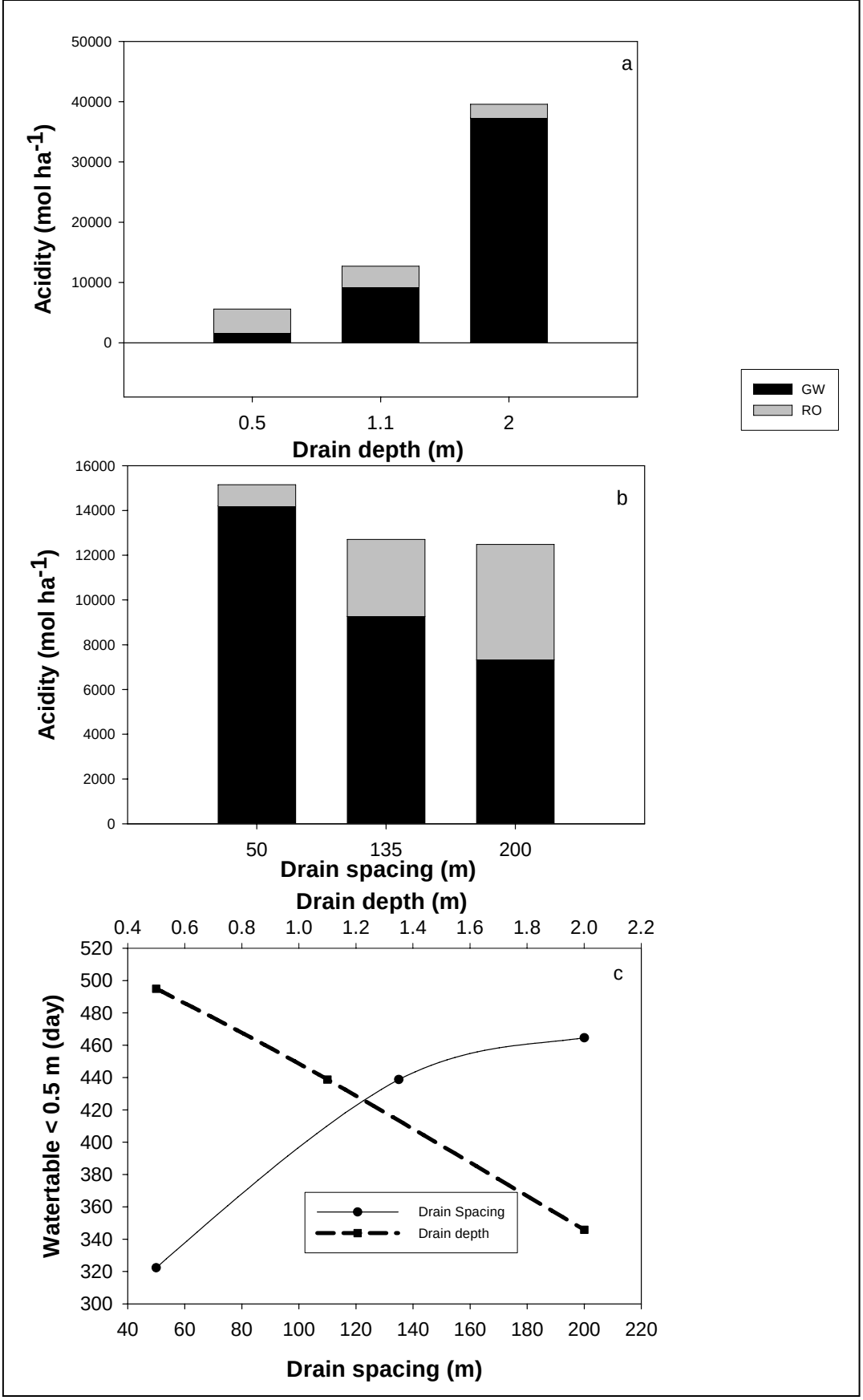

Figure 2. Predictions of the acidity discharged during the time of the experiment (August 1998 to December 2000) via runoff (RO) and groundwater (GW) flow to drains with; a**)** drain spacing of 135 m and various drain depths, b**)** drain depth of 1.1 m and various drain spacings and c**)** the time that the water table is predicted to be less than 0.5 m from the soil surface. Note the middle bar in graphs a and **b** is based on measured data.

Holm's property had two sites both of, which allowed the second part of the objectives (manipulating surface/subsurface drainage regimes using combinations of laser levelling, drain infilling and irrigation**)** to be evaluated. At the dryland site, 5 parallel drains were installed. In the first 18 months of operation only 3 of these drains were pumped giving an effective drain spacing of 90 m. In the last 5 months of operation all 5 drains were pumped giving a drain spacing of 45 m. Unfortunately the climatic conditions were very different in these two periods, as was the composition of the drainage water discharge (Table 1). This means that this experiment did not deliver results, which are easily interpreted. However, as the processes involved in the hydrology of these soils has been elucidated and synthesised into FLASSH this objective has still been met. This is seen in figure 3 where estimates using FLASSH are compared with the measured data. There is some under- and over-estimation by the model, but given the assumptions in the model, it does a reasonable job. More sophisticated modelling was attempted using HYDRUS2D (Simunek *et al.* 1999), but this model was difficult to parameterise and consistent results were not produced. This is due to highly non-linear nature of the physics involved in the behaviour of acid sulphate soils (see Rassam *et al*., 2001a – f).

Table 1. Mean composition of drainage water at Holm's dryland site when 3 or 5 drains were operating.

	EC ($dS\ m^{-1}$)	pH	Fe ($mg\ l^{-1}$)	SO_4 ($mg\ l^{-1}$)	Cl ($mg\ l^{-1}$)	Al ($mg\ l^{-1}$)	Cu ($\mu g\ l^{-1}$)	Mn ($mg\ l^{-1}$)	Zn ($\mu g\ l^{-1}$)
3 drains	11	6.5	4.4	1184	3181	10.6	123	1.2	151
5 drains	14	4.3	122.4	3614	3346	201.0	485	5.9	336

The second site at Holm's property was irrigated using trickle irrigation. There are some difficulties with interpreting the effectiveness of irrigation in reducing acid discharge from this site. Firstly this site had been drained for a longer period of time than the dryland site. This means there is likely to be more actual acidity in the soil at this site compared with the dryland site. Secondly the soil is sandier at this site, which means there is probably less neutralising capacity. Also the site was irrigated infrequently due to the wet conditions in the first 18 months. Lastly, in the latter period of the study, there was a need to let the site dry out prior to harvesting. However, this site was successfully used to determine field scale solute transport parameters (Rassam *et al*., 2001d,e) and demonstrate some of the difficulties with predicting instantaneous flow rates and solute fluxes.

Iron floc on pump filter!

Iron sludge in base of sump.

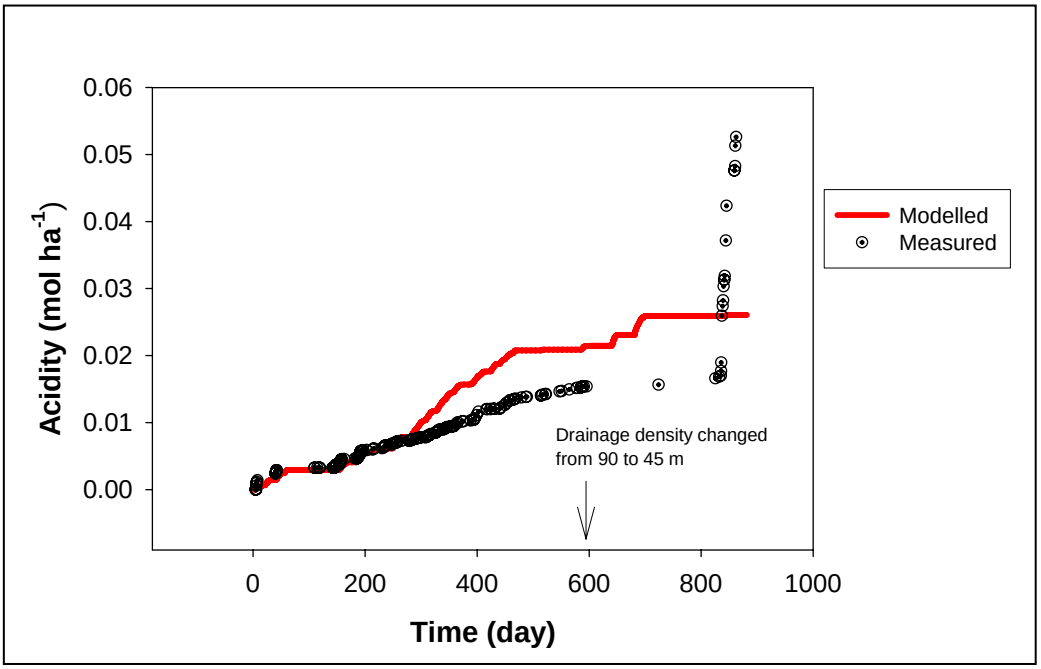

Figure 3. Comparison of modelled and measured cumulative acidity discharge at Holm's dryland site. The measurements and modelling incorporated a period when the drainage density changed.

2. **To measure and predict the *in situ* acid production and export flux of acid from canelands on ASS subjected to different drainage and irrigation treatments.**

The acid export from all sites via groundwater flow to the drains was monitored by measuring the volume discharged, pH and EC, and taking samples at prescribed drainage volumes with a pumping sampler. The samples were split into two with one sample acidified to < pH 2 by the addition of 4M nitric acid and filtered before storage in a cold room at 4°C. The samples were analysed by standard chemical methods for a range of cations and anions (Table 2). In terms of the actual and potential acidity in the water the important ions are H^+, Al^{3+} and Fe^{2+} (Cook, *et al.* 2000a). The amount of acidity from the 3 sites shows that the potential acidity associated with the metal ions is the dominant source of acidity in the drainage water (Fig 4). It also shows that, Al at Holm's dryland site, Fe at Mischke's site and a combination of both metal ions at Holm's irrigated site dominate the acidity. The average rate of acidity exported via the groundwater flow to the drains is 3400, 5200 and 7900 mol ha^{-1} y^{-1} for Holm's dryland, Holm's irrigated and Mischke's sites respectively. The increasing trend in acidity is associated with an increasing age since drained and possibly an accumulation of acidity in the soil. This trend of increasing acidity discharge with increasing age since drained is complicated by the difference in the soil elevation at each of the sites but is something that should be further investigated.

The composition of the drainage water contained levels of metals that exceed fresh water guidelines by many fold for some of the metals (Table 2). Aluminium and iron grossly exceed the guideline level. Dilution by surface runoff will reduce the concentrations in farm drains during flood conditions. However, during flood recession when groundwater flow will be a major proportion of the water in the drains, values as high as those in Table 2 may occur.

Table 2. Comparisons of drainage water concentrations of aluminium, iron, copper zinc and manganese with ANZECC guidelines for freshwater (ANZECC, 2000[1]) during the study. The average is a flow-weighted average.

Element	Mischke's		Holm's Dryland		Holm's Irrigated		Guideline
	Peak (µg/L)	Average (µg/L)	Peak (µg/L)	Average (µg/L)	Peak (µg/L)	Average (µg/L)	(µg/L)
Al	30,000	7,000	444,000	18,000	309,000	11,000	55 if pH < 6.5
Fe	229,000	61,500	337,000	9,000	352,000	18,000	300
Cu	180	17	240	19	1,100	17	1.4
Zn	1,230	290	540	220	3,600	170	15
Mn	2,400	1,140	9,800	1,200	12,000	840	1700

The mineralogy and electro-chemistry of the soils was studied in a joint project with Assoc. Prof Maria Elektorowicz (Concordia University, Montreal, Canada). This showed that different mineralogy's occurred at Mischke's and Holm's dryland sites. Aluminium minerals such as Albite were present at both sites but were more abundant at Holm's site. Iron rich minerals such as jarosite, siderite and goethite were more abundant at Mischke's site. Further results from this work will be published in the future as the data is processed.

Electro-chemistry with Assoc. Prof Maria Elektorowicz, assisted by Freeman cook and David Rassam.

[1] ANZECC, 2000. Australian and Newzealand guidelines for fresh and marine water quality. Volume 2, Aquatic ecosystems.

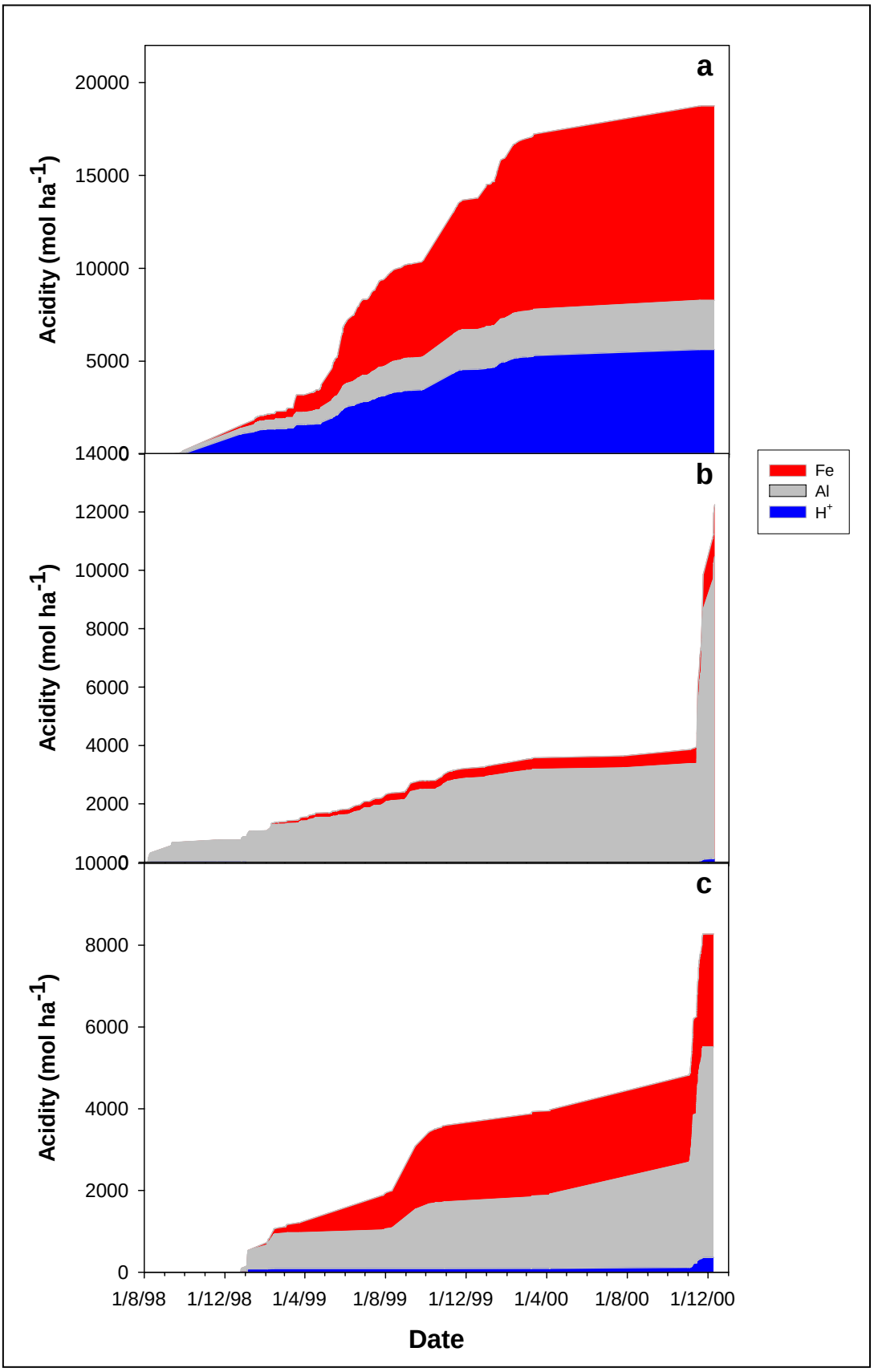

Figure 4. Amount of acidity with time for a) Mischke's, b) Holm's dryland and c) Holm's irrigated sites. Note Acidity scale is different for the other sites.

V-notch weirs were installed at Mischke,s and Holm's dryland sites to measure runoff. The lack of fall, at both sites, through the weir means that the runoff volume cannot be measured using these weirs. Runoff samples were collected when the water level was rising but had not reached the point where water from offsite would have contaminated the flow. The runoff structure at Holm's dryland site was only installed in 2000 and due to the dry year, failure of equipment and vandalism only two samples were collected. However, a water quality sampling site existed only 20 m from the corner of the block on Hotham creek and this data, supplied from an associated NHT project (Gardner & Ray) was used as an indication of the acidity of the water.

One option for managing ASS would be to allow leaching of the acidity, on the assumption that this would only take a short amount of time. To determine the whether this option would be possible, soil core samples were taken and measurements of the total oxidisable sulphur (TOS) and sulphur extracted by 4M HCl at Mischke's and Holm's dryland site were made. This showed that the amount of actual acidity and potential acidity in these soils is millions of moles (H^+) per hectare. The rate at which the acid is being discharged from these soils is tens of thousands of moles per hectare per year. From these data it can be seen that it will take many hundreds to thousands of years to exhaust the supply of acidity in these soils. Thus management options that minimised the release of acid will have to be devised.

A method was developed that directly measured the rate of pyrite oxidation by estimating the difference in the flux of oxygen into the soil profile and carbon dioxide out from their concentration profiles (Cook, *et al.*, 2001(Poster paper 5)). The method was only tried at Mischke's site. An estimate of an average oxidation rate of 220,000 mol ha^{-1} yr^{-1} of H^+ ions was obtained. This suggests that the rate of production of acidity at Mischke's site is about 20 times the rate of export. This implies that acidity is still accumulating in the soils at this site. The method developed appears promising and should be used to further investigate the rate of oxidation at other sites and over longer time periods.

3. **Transfer knowledge gained on ASS management over a three-year crop cycle to other canegrowers in areas of known risk, using models and other technology transfer tools.**

In this project knowledge has been transferred to canegrowers through a number of routes: papers at ASSCT conferences, CRC Sugar annual meetings, CRC environment workshops, QASSIT acid sulfate soil workshops, grower meetings, and field days (see the list attached). The FLASSH model has only recently been finished and will be used in further demonstrating the effect of changing drainage systems to growers and in particular evaluating the economic consequences of changing drainage systems.

Knowledge gained in this project has been transferred the to the scientific community through a number of publications at conferences and in journals listed below. This process will continue for sometime to come as the papers make their way through the scientific refereeing and publishing process.

Field day - showing air forced pump.

Conclusions

This project has substantially added to the understanding of the processes of generation and export of acidity from acid sulfate soils. In particular it has shown:

1. the role of the metal ions Al and Fe in the acidity of the drainage waters
2. the role of Fe as a contributor to the low dissolved oxygen in drainage water
3. metal concentrations in the groundwater exceed fresh water guidelines particularly for iron and aluminium
4. that drains do not contribute greatly to lowering of water tables by loss of groundwater
5. evapotranspiration is the major controller of the water table
6. that the groundwater pathway is the major export route for acidity
7. that the amount of acidity in these soils is vast compared to the export rate
8. that the oxidation rate of pyrite is about 20 times the discharge rate, so acidity is still accumulating in these soils
9. that acid loss from these soils will continue for centuries
10. that modelling of the two dimensional solute transport process is a complex problem
11. that a simplified empirical model can predict acidity export from soil and climate data.

This project has also raised further questions that need to be answered that are listed below:

1. Does Fe cycling in the soil profile occur and add to the oxidation of the pyrite?
2. What is the role of secondary sulfides (jarosite etc) in the acid storage and release from soils?
3. Would raised beds and reduce drainage benefit cane yield and reduce acid export?
4. What is the long-term effect of acidity from these drainage systems on aquatic biota?
5. Would treatment of drainage water directly improve water quality for biota?
6. What greenhouse gas implications arise from oxidation of organic matter and release of sulfate from acid sulfate soils?
7. Would reducing drainage intensity increase denitrification and release of nitrous oxide, a greenhouse gas?

Recommendations For Cane Production on Acid Sulfate Soils

The major finding from this study is that the main acid export pathway from ASS is via groundwater flow to the drains and that this flow has a minor effect in lowering the watertable. The drainage system in cane growing areas on acid sulfate soils should be designed to remove the surface water efficiently but remove only minor amounts of the groundwater. The drainage system for cane production in acid sulfate soil areas should have the following features:

1. Laser levelling to eliminate low features that cause localised ponding and facilitate runoff to spoon drains
2. Shallow spoon drains to receive runoff and reduce groundwater flow
3. Cane planted on raised beds to allow transpiration to occur quickly after surface water has gone
4. Regional drainage systems designed to remove surface runoff but to not lower the regional watertable below AHD

Such a drainage system may involve the removal of drains or reduction of depth of drains in the present drainage systems. Knowledge of the soil properties should be sought before making changes. This process should be planned both at regional and farm scales.

The FLASSH model should be helpful in developing the farm scale drains.

Point 3 above will require further research to determine the usefulness of raised beds planting.

Acknowledgement
We would like to acknowledge the enthusiastic cooperation and assistance of the growers Lindsay and Kev Mischke and Ian Holm on whose properties these trials were carried out. We would like to thank the people without whose efforts and enthusiasm this project would not have been as successful: the setting up, data collection technical input were provided by; Geoff Carlin, Dan Morton, Tom McShane, Grant Millar, David Froggatt, Jeremy Claridge, David Hunt, James Ray,

Anita Petzler, Fiona Gavin, and Celia Mackie; scientific and modelling; Drs David Rassam, Mabo Suzuki, Maria Elektorowicz; water chemical measurements Rob de Hayr, Colleen Watson and Matthew Detering. Geoff Carlin's efforts are especially noteworthy in his dedication to this project. Dr David Rassam is thanked for his resourcefulness, persistence, patience and rigour in experimentation and modelling.

George Rayment, for providing assistance, friendship, learned council and critical review throughout this project, which was greatly appreciated. The CRC Sugar staff especially Patricia Kennedy who were always helpful and cheerful.

Extension

Selected papers are attached as a compendium of the outputs from this project in the appendix. These papers are indicated by an * in the list below.

Field Days

1. Gold Coast City Council and Northern Waste Water Strategy Group visit, 20 January 1998.
2. Cook, F. 'Acid sulfate soils management study'. National Soil Science Conference field trip, 27 April 1998.
3. Sugar CRC Programme 1 field trip 13 May 1998.
4. Cook, F. 'Acid flow to drains in ASS: Some research results'. BSES extension day, 20 May 1998.
5. Cook, FJ and Gardner, EA (2000). 'Acid sulphate soils drainage, composition and water quality'. CRC Environment Short Course Field Trip, 9 February 2000.
6. Cook, FJ, Rassam, DW, Gardner, EA and Carlin, GD (2000). 'Acid flow to drains in ASS: Some research results'. Morton field day, 11 May 2000.
7. Field Day, Rocky Point. 19 May, 2000. International Standards Organisation Field trip. 8 November 2000.

Presentations and Workshops

1. Cook, F (1998).'Presentation on ASS experimental work'. *CRC Program 1 Review and Planning Workshop*, 12-14 May 1998.
2. Cook, FJ (1998). 'Waterlogging: An issue for cane production', CRC for Sustainable sugar production meeting on Soil measurements, 6-7 August 1998.
3. Cook, FJ (2000). 'Acid sulphate soils: Towards an understanding of the acid export processes'. Seminar at QDNR, Brisbane, 9 August 2000.
4. Cook, F and Gardner, E (1998). 'Water management and drainage of acid sulfate soils'. *Workshop 6, Managing Potential Acid Sulfate Soils. Canegrowers Environmental Forum*, 24-25 March 1998.
5. Cook, FJ and Gardner, EA (1999). 'Acid production and export from canelands on acid sulfate soils'. *CRC for Sustainable Sugar Production Annual meeting*, Townsville, 23-25 February 1999.
6. Cook, FJ**,** Gardiner, EA and Carlin, G (1999). 'Research results - Acid production and export from canelands case study'. *Acid sulfate soils: Short course and North Queensland Issues, Abstracts*. Townsville, 1-2 February 1999.
7. Cook, FJ and Gardner, EA (1999). 'Acid production and export from canelands on acid sulfate soils'. *CRC Sugar Annual Meeting*, Townsville, 23-25 February 1999.
8. Cook, FJ, Gardner, EA and Carlin, GD (1999). 'ASS impacts in canelands - Preliminary results from Pimpama research'. *Acid Sulfate Soils and Their*

9. *Management in Coastal Queensland, Forum and Technical Course*, Brisbane 21-23 April 1999.
10. Cook, FJ, Hicks, W, Gardner, EA, Carlin, GD and Froggatt, DW (1999). 'Export of acidity in drainage water from acid sulfate soils'. *Sources. Fates and Consequences of Pollutants in the Great Barrier Reef and Torres Strait Environments Workshop, GRMPA*, Townsville, 30 June 1999.
11. Cook, FJ, Rassam, DW, Blunden, B, Gardner, EA and Carlin, GD (1999). 'Irrigation and drainage: Effects on acidity exported from acid sulfate soils'. *ASSMAC Workshop*, Lismore, 1 September 1999.
12. Cook, FJ, Rassam, DW, Gardner, EA and Carlin, GD, (1999). 'The flow of acid to drains from ASS: Some research results'. *Acid Sulfate Soils - Short Course and Central Queensland Issues, Short Papers.* Mackay, 3-4 November 1999.
13. Cook, FJ (2000) 'Soil Issues — Outcomes and future directions'. *CRC Annual Meeting*, Townsville, 6-9 March 2000.
14. Cook, FJ (2000). 'Examples of Acid Sulphate Runoff Chemistry'. *AIMS-CSIRO Workshop on Bowling Green Bay Wetlands*, Aust. Institute of Marine Sciences, Townsville, 15 March 2000.
15. Cook, FJ (2000). 'Large Scale Field Experiments and Modelling to Determine the Processes Involved in Acid Export from Acid Sulphate Soils'. Seminar, CSIRO Davies Laboratory, Townsville, 17 March 2000.
16. Cook, FJ, Rassam, DW, Gardner, EA and Carlin, GD (2000). 'Acid flow to drains in ASS: Some research results'. *Acid Sulfate Soils Technical Course and Regional Issues* – Townsville, 6-7 March 2000.
17. Cook, FJ, Rassam, DW, Gardner, EA, Carlin, GD and Millar, GE (2000). 'Drained acid sulphate soils: Pathways of acid export'. *Acid Sulfate Soils: Environmental Issues, Assessment and Management.* Brisbane, 20-22 June 2000.
18. Cook, FJ, Gardner, EA, Rassam, DW, Carlin, GD, Millar, GE (2000). 'Acid sulphate soil research: A review'. *CRC Sugar, Technology Transfer Program Consultative Group*. Canegrowers, Brisbane, 21 November 2000.
19. Cook, F.J., Rassam, D.W., Carlin, G. D., Gardner, E.A. and Millar, G. (2001). Modelling and measuring water and acid fluxes in an acid sulphate soil. *4th International Conference on Environmental Chemistry and Geochemistry in the Tropics*, Townsville, Australia, 7-11 May 2001.
20. CRC Reef/CRC Sugar Water Quality Workshop. 14-15 June 2000.
21. Gardner, EA, Rayment, GE Powell, B, Cook, FJ, Smith, CD and Hey, KM (1999). 'Distribution, behaviour and management of acid sulfate soils'. *CRC Sugar Environmental Short Course for Sustainable Sugar Production*. Townsville, 26-27 October 1999.
22. Gardner, EA, Rayment, GE, Powell, B, Cook, FJ, Smith, CD and Hey, KM (2000). 'Distribution, behaviour and management of acid sulphate soils'. *CRC Sugar Environmental Short Course for Sustainable Sugar Production*. Brisbane, 12-13 May 2000.
23. Mallawaarachchi, T., Rayment, G., Cook, F. and Grundy, M. 2001, 'Externalities in cane production and environmental best practice', Paper presented *to AARES2001 45th Annual Conference of the Australian Agricultural and Resource Economics Society*, Stamford Plaza, Adelaide, 23 - 25 January 2001.

24. Mitchell, DC, Roth, CH, Bohl, HP, Cook, F, Raine ,S (2000). 'Surface drainage for sugarcane'. *CRC Sugar Annual meeting*, Townsville, 4-10 March 2000.
25. Rassam, D.W., Cook, F.J., and Gardner, E.A. (2000). 'Managing acid sulphate soils with the aid of numerical modelling'. *CRC Sugar Annual Meeting*, Townsville, 4-10 March 2000.
26. Freeman Cook attended: "Technical review of the impacts of February 2001 Richmond River floods on water quality and fish kill". Alstonville NSW, 15 May 2001.

Industry Journals and Newsletters

1. Measuring acid drainage from acid sulfate soils. Australian Sugarcane 1, 1998, 13-15.
2. Rocky Point – Southern Queensland. Assay, 22:5, June 1999.
3. Drainage role in Acid management. Assay, 25:6, May 2000.
4. Gas measure of oxidation rate. Assay, 26:6, July 2000.
5. Acid sulphate soil mapping progress. Acres, 8:4, May 2000.
6. Electrical currents aid acid sulfate soils runoff. North Queensland Register, 17 August 2000.
7. Drain water and iron. Assay, 28:13, March 2001.

Posters

1. Cook, FJ, Suzuki, MM, Gardner, EA and Rayment, GE (1998). Measurement and modeling of acid export from acid sulfate soils used for sugar production. *Aust. Soc. Sugarcane Technologists Conference*, Balina, 28 April to 1 May 1998.
2. Rassam, David, Cook, Freeman and Gardner, Ted (1999). How numerical models can help manage acid sulphate soils. *CRC Sugar Annual Meeting*, Townsville, 23-25 February 1999.
3. Rassam, D, Cook, F and Gardner, E (2000). Managing acid sulfate soils with the aid of numerical modeling. Posters 2000, *CRC Sugar Ocassional Publication*, June 2000.
4. Cook, FJ**,** Gardner, EA, Carlin, G and Rassam, D (1999). Production and export of acidity from acid sulfate soils. *CRC Sugar Annual Meeting*, Townsville, 23-25 February 1999.
5. Cook, F, Carlin G, Orr, P, Millar, G. and MacDonald, C. (2001). Direct In situ measurement of the oxidation rate of pyrite in acid sulfate soil. *CRC Sugar Annual Meeting*, Townsville, 12-15 March, 2001.
6. Mallawaarachchi, T, Qureshi, E, Grundy, M, Cook, F, Rayment, G, Beattie, R, Bohl, H, Hunt, R, Kingston, G and Nelson, P. (2000). Managing economic Environmental Trade-offs in the sugar industry: Maximising net farm income

under environmental compliance. *CRC Review Meeting*, Mercure Inn, Townsville, 6-8 March 2001.
7. Rassam D, Cook, F and Gardner, T (2001). 'An irrigation trial in an acid sulfate soils cane field. *CRC Sugar Annual Meeting*, Townsville, 12-15 March 2000.
8. Cook, F.J., Rassam, D.W. Gardner, E.A. and Carlin G.D. (2000) What controls water tables in low permeability acid sulfate soils *Australian Society of Sugar Cane Technologists Conference*, Bundaberg, 2-5 May 2000.

Refereed Scientific Papers

1. Cook, FJ (1999). Water Logging. In: *Soil Characterisation*. CRC Sugar Workshop Report 6-7 August 1998, Townsville. CRC Sugar Occasional Publication. p11-12.
2. Cook, FJ, Suzuki, MM Gardner, EA and Rayment, GE (1998). Measurement and modeling of acid export from acid sulphate soils used for sugar production. *Proceedings of the Aust. Soc. Sugarcane Technologists*, **20**:555.
3. Cook, F and Gardner, E (1998). Paper 5. Water management and drainage of acid sulfate soils. In *Workshop 6, Managing Potential Acid Sulfate Soils*, Canegrowers Environmental Forum, Brisbane, 24-25 March 1998, CANEGROWERS, QDNR, and CRC for Sustainable Sugar Production, 5-1 to 5-6.
4. Cook, FJ**,** Gardiner, EA and Carlin, G (1999a). Research results - Acid production and export from canelands case study. In Ahern, CR, Eldershaw, V, Hey, KM and Anorov, J (eds). In *Acid sulfate soils: Short course and North Queensland Issues, Abstracts*. Townsville, 1-2 February 1999. Queensland Dept. of Natural Resources, Indooroopilly, Brisbane. 8-1 to 8-2.
5. Cook, FJ, Gardner, EA and Carlin, GD (1999b). ASS impacts in canelands - Preliminary results from Pimpama research. *Proc. Acid Sulfate Soils and Their Management in Coastal Queensland, Forum and Technical Course*, 21-23 April 1999, Brisbane, 21-1 to 21-9.
6. Cook, FJ, Rassam, DW, Gardner, EA and Carlin, GD (1999c). The flow of acid to drains from ASS: Some research results. In Hey, KM, Watling, KM, Ahern CR and Anorov, JM (eds) *Acid Sulfate Soils - Short Course and Central Queensland Issues, Short Papers.* Mackay, 3-4 November 1999. Department of Natural Resources, Indooroopilly, Queensland, Australia. 9-1 to 9-2.
7. Cook, FJ, Gardner, EA and Carlin, GD (1999d). Acid drainage from canelands: Quantities exported and mechanisms of production. *Proc. Aust. Soc. Sugar Cane Technologist*, **21**: 246-258.
8. *Cook, FJ, Hicks, W, Gardner, EA, Carlin, GD and Froggatt, DW (2000a). Export of acidity in drainage water from acid sulfate soils. *Marine Pollution Bulletin*, **41**:319-326.
9. Cook FJ, Rassam DW, Gardner EA, and Carlin GD (2000b). Acid flux to drains in acid sulfate soils: Some research results. In *Acid Sulfate Soils - Short*

Course and Central Queensland Issues, Short Papers. Watling KM, Hey KM, Eldershaw, VJ, Ahern CR and Anorov JM (eds), Cairns 10-11 April 2000. Department of Natural Resources, Indooroopilly, Queensland, Australia. 9-1 to 9-3.

10. *Cook FJ, Rassam DW, Gardner EA, and Carlin GD (2000c). Drained acid sulfate soils: Pathways of acid export. In *Acid Sulfate Soils: Environmental Issues, Assessment and Management*. Ahern CR, Hey KM, Watling KM and Eldershaw, VJ (eds), Brisbane 20-22 June 2000. Department of Natural Resources, Indooroopilly, Queensland, Australia. 38-1to 38-11.
11. Cook, FJ, Rassam, DW, Gardner, EA and Carlin, GD (2000d). What do drains do in low permeability acid sulphate soils*? Proceedings of the Aust. Soc. Sugarcane Technologists*, **22**:507-508.
12. *Cook, FJ, Rassam, DW, Carlin, GD and Gardner, EA (2000e). Acid flow from acid sulphate soils: Measurements and modelling of flow to drains. *Proceedings 3rd Environmental Conference*, 26-25 May 2000, Brisbane, Australia. 195-199.
13. *Cook, FJ, Rassam, D, Blunden, B, Gardner, EA and Carlin, GD (2000f). Irrigation and drainage: Effects on acidity export from acid sulfate soils. In Slavich, PG (ed) *Proceedings of Workshop on Remediation & Assessment of Broadacre Acid Sulfate Soils*, 31 August - 2 September 1999. Southern Cross University. 78-87p.
14. Cook, FJ, Rassam, DW, Carlin, GD, Gardner, EA and Millar, G (2001a). Modelling and measuring water and acid fluxes in an acid sulphate soil. *Proceedings, 4th International Conference on Environmental Chemistry and Geochemistry in the Tropics*, Townsville, Australia, 7-11 May 2001. p7.
15. *Cook, FJ, and Rassam, DW (2002). An analytical model for water table dynamics during drainage and evaporation. *Journal of Hydrology*, (In Press).
16. Gardner, EA, Rayment, GE, and Cook, FJ (2000). Distribution, behaviour and management of acid sulphate soils. In Bruce, RC, Johnston, M and Rayment, GE (eds). *Environmental Short Course for Sustainable Sugar Production, Course Manual*. CRC Sugar, 91-108.
17. *Gardner, EA, Rayment, GE, Powell, B, Cook, FJ, Smith CD and Hey, KM (2000). Distribution, behaviour and management of acid sulphate soils. In Bruce, RC, Johnston, M and Rayment, GE (eds). *Working Papers, Environmental Short Course for Sustainable Sugar Production, Course Manual*. CRC Sugar, 118-139.
18. Mallawaarachchi, T, Rayment, G, Cook, F and Grundy, M (2001). Externalities in cane production and environmental best practice. Paper presented *to AARES2001 45th Annual Conference of the Australian Agricultural and Resource Economics Society,* Stamford Plaza, Adelaide, 23 - 25 January.
19. *Rassam, DW, Cook, FJ, and Gardner, EA (2001a). 1. Field and laboratory studies of drained acid sulphate soils. Accepted for publication in the Journal of *Irrigation and Drainage Engineering, ASCE* (Accepted)
20. *Rassam, DW, and Cook, FJ (2001b). 2. Numerical simulations of water and solute transport applied to drained acid sulphate soils. *Journal of Irrigation and Drainage Engineering, ASCE* (Accepted).

21. *Rassam, DW, and Cook, FJ (2001c). Solute transport parameters from experimental solute break-through curves. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE (Submitted).
22. *Rassam, DW, Cook, FJ, and Gardner, EA (2001d). Export of aluminium from drained acid sulphate soils. *Journal of Contaminant Hydrology*, Submitted).
23. *Rassam, DW, and Cook, FJ (2001e). Interaction of hydraulic conductivity, solute transport, and preferential paths on field and laboratory scales. *Canadian Geotechnical Journal* (Submitted).
24. *Rassam, D.W., Cook, F.J., and Gardner, E.A. (2001f). Acid sulphate soils: 1. A field investigation. In the *2nd Australia-New Zealand Conference on Environmental Geotechnics*, Newcastle (Abstract accepted).
25. *Rassam, D.W., Cook, F.J., and Williams, D.J. (2001g). Acid sulphate soils: 2. A leaching-column experiment. *2nd Australia-New Zealand Conference on Environmental Geotechnics*, Newcastle (Abstract accepted).
26. Rassam, D.W., and Cook, F.J. (2001h). 1. Inverse modelling for estimating SO4- ion-transport parameters in acid sulphate soils. *International Congress on Modelling and Simulation*, Canberra (Accepted).
27. Rassam, D.W., and Cook, F.J. (2001i). 2. Modelling the transport of SO4- ions in an acid sulphate soils cane field. . *International Congress on Modelling and Simulation*, Canberra (Accepted).

Electronic Media

1. Radio interview with Freeman Cook, ABC, Townsville 2 February, 1999.
2. Managing acid sulphate soils Video featured the experimental sites and interviews with Ted Gardner and Freeman Cook and was released at the ASSCT conference at Townsville 1999.
3. Aussie Estuaries Solving Acidity, a Video By Out of The Blue Ocean and Earth Films, features the site and Ted Gardner. This was shot in 1999.

Appendix: Copies of Key Publications

The following manuscripts are included in this report.

1. Cook FJ, Rassam DW, Gardner EA, and Carlin GD (2000). Drained acid sulfate soils: Pathways of acid export. In *Acid Sulfate Soils: Environmental Issues, Assessment and Management*. Ahern CR, Hey KM, Watling KM and Eldershaw, VJ (eds), Brisbane 20-22 June 2000. Department of Natural Resources, Indooroopilly, Queensland, Australia. 38-1to 38-11.
2. Cook, FJ, Rassam, DW, Carlin, GD and Gardner, EA (2000). Acid flow from acid sulphate soils: Measurements and modelling of flow to drains. *Proceedings 3rd Environmental Conference*, 26-25 May 2000, Brisbane, Australia. 195-199.
3. Cook, FJ, and Rassam, DW (2001b). An analytical model for water table dynamics during drainage and evaporation. *Journal of Hydrology*, (submitted).
4. Cook, FJ, Rassam, D, Blunden, B, Gardner, EA and Carlin, GD (2000f). Irrigation and drainage: Effects on acidity export from acid sulfate soils. In Slavich, PG (ed) *Proceedings of Workshop on Remediation & Assessment of Broadacre Acid Sulfate Soils*, 31 August - 2 September 1999. Southern Cross University. 78-87p.
5. Rassam, DW, Cook, FJ, and Gardner, EA (2001). 1. Field and laboratory studies of drained acid sulphate soils. Accepted for publication in the Journal of *Irrigation and Drainage Engineering, ASCE* (Accepted)
6. Rassam, DW, and Cook, FJ (2001). 2. Numerical simulations of water and solute transport applied to drained acid sulphate soils. *Journal of Irrigation and Drainage Engineering, ASCE* (Accepted).
7. Rassam, DW, Cook, FJ, and Gardner, EA (2001). Export of aluminium from drained acid sulphate soils. *Journal of Contaminant Hydrology*, Submitted).
8. Rassam, DW, and Cook, FJ (2001). Solute transport parameters from experimental solute break-through curves. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE (Submitted).
9. Rassam, DW, and Cook, FJ (2001). Interaction of hydraulic conductivity, solute transport, and preferential paths on field and laboratory scales. *Canadian Geotechnical Journal* (Submitted).
10. Gardner, EA, Rayment, GE, Powell, B, Cook, FJ, Smith CD and Hey, KM (2000). Distribution, behaviour and management of acid sulphate soils. In Bruce, RC, Johnston, M and Rayment, GE (eds). *Working Papers, Environmental Short Course for Sustainable Sugar Production, Course Manual*. CRC Sugar, 118-139.
11. Rassam, D.W., Cook, F.J., and Gardner, E.A. (2001). Acid sulphate soils: 1. A field investigation. In the *2nd Australia-New Zealand Conference on Environmental Geotechnics*, Newcastle (Abstract accepted).
12. Rassam, D.W., Cook, F.J., and Williams, D.J. (2001). Acid sulphate soils: 2. A leaching-column experiment. *2nd Australia-New Zealand Conference on Environmental Geotechnics*, Newcastle (Abstract accepted).
13. Cook, FJ, Hicks, W, Gardner, EA, Carlin, GD and Froggatt, DW (2000). Export of acidity in drainage water from acid sulfate soils. *Marine Pollution Bulletin*, **41**:319-326.