SRDC Research Project Final Report

SRDC project number: **UNW003**

Project title: ***Development of a constructed wetland for improving water quality in sugarcane drainage, and ensuring its community acceptance and industry adoption***

Research organisations: Univ. NSW, NSW Sugar Milling Cooperative, Australian National Univ.

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Australian Government

Sugar Research and Development Corporation

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EXECUTIVE SUMMARY:

Canefield drainage water quality is an increasingly important issue for the industry and community because of the potential downstream environmental impacts of contained contaminants. The community is increasingly environmentally conscious, and many perceive agriculture as the main threat to environmental sustainability. Hence, regulators are tightening controls on polluted drainage from agricultural industries. As in other parts of the World, this trend will continue in Australia and agriculture is likely to be required to meet the same standards as other industries. The sugar industry must therefore develop and implement best management to address the issue, and better demonstrate and communicate their environmental stewardship. The means by which the NSW Sugar Industry faced and achieved a win-win outcome with respect to problems with their acid sulfate soil management is discussed in detail by White *et al.* (2007). This provides a model for managing drainage water contaminanation.

PhD research by Green (2005) tested a number of techniques for ameliorating acidy in drainage from Robert Quirk's 100 ha cane farm on the Tweed River. This research showed that most (>70 %) of the acidity in the farm's drain water was in the form of the dissolved metal ions, particularly of iron and aluminium. Many mine sites also have this problem and a commonly used management tool is a constructed and vegetated wetland. Therefore the SRDC-funded project UNW003 constructed an approximately 1.5 ha wetland adjacent to the farm's outflow drain. Natural recruitment, predominantly of Couch grass and Spike rush, established dense vegetation in the wetland. During rain-driven acid discharge events, water from this drain (about 10 % of the discharge) was pumped into the first of six terraced wetland bays and from there it flowed down to outflow into the discharge drain. During 3 years of operation, water quality was measured at the input, throughout, and output of the wetland.

The wetland showed a clear ability to precipitate the important dissolved metals from the drain water and thereby removed nearly all of the contained acidity. Most of this acidity appeared to be deposited in the first two or three bays. However, the amount of acidity that was calculated to have been input over the three years of operation appeared to be only about 10 % of that measured in the soil of the first two bays. Even the total amount of soil acidity was able to be neutralized by lime application at the normal farm rate of about 5 tonne/ha.

Given that that the wetland already occupied about 2 % of the farm but only treated about 10 % of the drainage, the application of such a wetland as a standard management technique to treat all of the acidity discharge is impracticable. Nevertheless, the results might encourage farmers to use their existing drains as extended wetlands rather than seeing any in-drain vegetation as a problem. Also, there are likely to be cane farms located at sufficient elevation above existing wet areas that can manage these as wetlands to remove drainage contaminants.

BACKGROUND:

Beginning about 20 years ago at McLeods Creek on the Tweed River, this team pioneered the research into the existence, distribution, characteristics, and best management of acid sulfate soils (ASS) with respect to the sugar cane industry. Initially, even we academic scientists had some significant misjudgements as to the actual processes involved with the soil's pyrite and its oxidation that has led to these problematic materials and their acidic discharges (e.g. Willett *et al*., 1993) and there were (and in some circles there still are: e.g. Johnston *et al*., 2009) major myths that existed. These misunderstandings have led to conflicts between many groups but fortunately collaboration between we as researchers, the NSW Sugar Industry, Tweed Shire Council, and NSW Government bodies, has provided a win-win outcome with this environmentally important problem. The history of this process is spelled out by White *et al*. (2007) and some aspects discussed in an ABC Landline TV presentation (Courtney, 2007). (Electronic copies of these two works are included as Appendices A and B, respectively).

About 70% of the sugar cane growing areas on coastal lowlands of northeastern NSW are underlain by acid sulfate soils. These materials were deposited naturally but the oxidation of their contained sulfides (mostly pyrite) produces dissolved metals and acidity in their drainage waters. As well, cane drainage can contain sediment, nutrients, and pesticides. These acidic drainage waters cause dramatic environmental damage, particularly fishkills, but may also damage downstream sensitive areas, such as the Great Barrier Reef Marine Park. Much current drainage management focusses on neutralising the immediate acidity but our recent research shows that >70% of the potential acidity in the drainage is from the dissolved metals (Green *et al*., 2006b). (The diagrammatic representation of Ros Green's metal-derived acidity discharge measurements from the Quirk cane farm was used in Quirk *et al.*, 2009 and is shown here as Figure 1). These metals will chemically hydrolyse and produce "acid-at-a-distance". However, they can also be toxic (e.g. Aluminium species) or act as nutrients (e.g. with Iron) for blooms of dangerous phytoplankton (e.g. "red tides" and toxic blue-green algae).

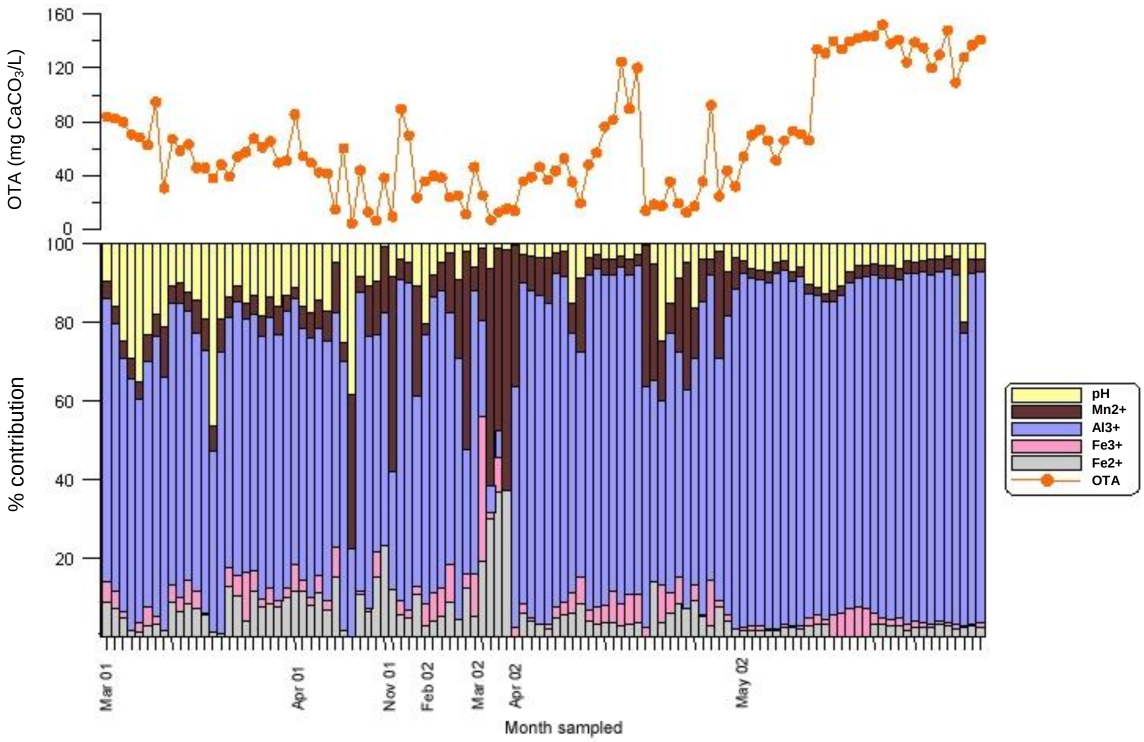

Figure 1- Contribution of dissolved metals and protonic acidity ("pH") to Oxidised Titrable Acidity, OTA (from Green *et al*. 2006b; modified by Annabelle Keene)

The small McLeods Ck catchment (about 450 ha) has been the research study site where much of 12 PhD and about and equal number of Masters and Honours research projects from UNSW and ANU have been completed. Important research outcomes from McLeods Creek include that there is very small lateral hydraulic connectivity between most of the cane field and its field and main drains so that brackish tidal waters can be carefully input to the main drains without causing salinization problems (White *et al*., (1993). Also, on average the existing acidity in ASS profiles under sugar cane is equivalent to about 50 tonne of sulfuric acid per ha (i.e equivalent to about 2.5 L of pure sulfuric acid per square metre) (Smith *et al*., 2003) but much less than 0.5 tonnes per ha of sulfuric acidity equivalence was discharged annually (Wilson *et al*., 1999). The existence of the pyrite and much of the acidification associated with its oxidation are the result of natural geomorphic and pedological processes (Kinsela and Melville, 2004). The latter research also showed that most of the acidity discharged from the cane fields was sourced from very close to the edge of field drains (<3m). This supports the value of laser levelling allowing reduction in the number of field drains (and therefore reduction of acidity discharge), apart from its productivity improvement through allowing more rows of cane where once there were drains. These, and other research outcomes, have been the basis for the management regime adopted by Robert Quirk at his 100ha cane farm on McLeods Ck. Basically, the first element of this regime intends to manage the cane field so as to minimise the discharge of acidity into the drainage waters. The second element intends to minimise the transport and export from the drainage system into the adjacent Tweed River.

Two of the McLeods Ck PhD studies that provided important background for this SRDC project proposal, and where their field research was mainly based in the 100ha cane farm of Robert Quirk, were those of Green (2005) and Smith (2005).

Dr Jodie Smith's study concerned the formation and oxidation of black iron monosulfides in canefield drain-bottom sediments (see Smith and Melville, 2004; Smith, 2004). The oxidation and acidification of these materials is the basis of management needed during drain cleaning, as detailed in the NSW Sugar Industry's Code of Best Management Practices (NSW, 2005). An additional component of her work tested the feasibility of desulfurization catalysts for use in manufacturing and refining industries. At present Australia imports $M's of these valuable materials. As explained in earlier SRDC Milestone Reports, while Jodie's preliminary testing had shown that very efficient catalysts could be manufactured from these otherwise problematic materials, much more research was needed to take this further than her thesis scholarship allowed. We therefore requested that this desulfurization catalyst manufacture component be removed from our initially proposed Project outcomes.

Dr Ros Green's thesis research installed and tested a number of techniques for treating acidity in the Quirk farm drain discharge. These were reported in her thesis (Green, 2005) and published journal papers (Green *et al*., 2006a; 2006b; 2006c; 2008a; 2008b). One of the techniques to which Ros (with her environmental engineering background) gave some thesis review was the use of constructed wetlands, such as are used for treating acid rock drainage in the mining and construction industries. However, this option was beyond the scope of implementation in her thesis research. Constructed wetlands can trap and store the problematic pollutants contained in ASS drainage from canefields. We therefore proposed UNW003 and this was funded by SRDC.

OBJECTIVES:

(i) construct a wetland to reduce drainage discharges of sediment, nutrients, acidity, dissolved metals and pesticides;

(ii) utilise and enhance vegetation and natural formation of drain sludges to concentrate acidity and precipitate metals from drainage waters with potential use as a soil amendment or as desulfurization catalysts; and

(iii) ensure wide adoption of the technology and best practice guidelines for discharge water quality.

METHODOLOGY:

Preliminary Hypotheses on the Operation of the Wetland

The preliminary hypotheses underpinning the operation of the wetland were that generally oxic conditions were expected to prevail close to the inlet of the wetland due to pumping from the main drain which would favour the precipitation of iron oxyhydroxides and the release of additional protons, so called "ferrolysis" (Mann, 1983).

$$Fe^{2+} + 1.5H_2O + ¼O_2 \rightarrow FeOOH\ (s) + 2H^+ \quad [1]$$

While this removes much of the dissolved iron it generates more protonic acidity. The key to removing the dissolved metals and particularly aluminium from the drainage system is to decrease the protonic acidity. One way of doing this efficiently is to ensure that reducing conditions exist so that eventually dissolved sulfate is reduced to iron sulfide precipitates. For every mole of sulfate reduced, 2 moles of acidity are consumed. Before this can happen a number of overlapping sequential reactions need to occur. As water proceeds through the wetland it is expected that the wetland is essentially titrating the discharge with organic matter, so that redox potentials and DO levels should fall as organic matter and protonic acidity is consumed. Writing CH_2O for organic matter, the sequence of progressive reduction of redox potential can be written as:

Denitrification:

$$NO_3^- + 5/4\,CH_2O + H^+ \rightarrow 1/2\,N_2 + 7/4\,H_2O + 5/4\,CO_2$$
$$NO_3^- + 3/4\,CH_2O + H^+ \rightarrow NO + 5/4\,H_2O + 3/4\,CO_2 \quad [2]$$
$$NO_3^- + CH_2O + H^+ \rightarrow 1/2\,N_2O + 3/3\,H_2O + CO_2$$

Nitrate reduction: $NO_3^- + 2CH_2O + 2H^+ \rightarrow NH_4^+ + H_2O + 2CO_2$ [3]

Dissolution of precipitated Mn:

$$MnO_2 + 1/2CH_2O + 2H^+ \rightarrow Mn^{2+} + 3/2H_2O + 1/2CO_2 \quad [4]$$

Dissolution of precipitated iron:

$$FeOOH + 1/4CH_2O + 2H^+ \rightarrow Fe^{2+} + 7/4H_2O + 1/4CO_2 \quad [5]$$

Fermentation:

$$CH_2O + 1/3H_2O \rightarrow 2/3CH_3OH + 1/3CO_2 \quad [6]$$

Sulfate reduction $SO_4^{2-} + 2CH_2O + H^+ \rightarrow HS^- + 2H_2O + 2CO_2$ [7]

And finally methanogenesis: $CH_2O \rightarrow 1/2CH_4 + 1/2CO_2$ [8]

Combining reactions [5] and [7] shows the reduction of sulfate to sulfide, the reduction of FeOOH to Fe^{2+}, the consumption of protonic acidity and the precipitation of iron sulfides.

$$4\ FeOOH\ (s) + 4\ SO_4^{2-} + 9CH_2O + 8H^+ \rightarrow 4FeS\ (s) + 9CO_2 + 15H_2O \quad [9]$$

Apart from reactions [6] and [8] all the others consume protonic acidity. The rise in pH following the consumption of protonic acidity leads to the precipitation of aluminium and other dissolved metals. As well, it implies that the large amount of carbon dioxide produced by the oxidation of organic matter should be present at higher pHs as bicarbonate.

It is not clear if the shallow depth of the wetland (approximately 0.1m) will allow full reducing conditions to exist and there may be patches of reducing and oxidizing conditions. If that is the case methanogenesis may not occur. If purple and green sulfur bacteria and cyano-bacteria are present in the wetland, even in the absence of oxygen, hydrogen sulfide may be used as an energy source for growth, converting CO_2 back to biomass.

$$CO_2 + 2H_2S \rightarrow CH_2O + H_2O + 2S \qquad [10]$$

It would seem from above that what should be aimed for in the operation of the wetland is encouraging the precipitation of iron oxy-hydroxides in the first bay with the corresponding increase in protonic acidity and then trying to ensure that sufficient organic matter and nitrate are present in the other bays to foster the oxidation of organic matter, the reduction of dissolved sulfate, the precipitation of iron sulfides, and the reduction in protonic acidity.

Subsequent to the above hypotheses for our wetland operation, our colleague, Prof David Waite and his team (Richard Collins, Andrew Kinsela, and Adele Jones) at UNSW Water Research Centre (UNSW.WRC) have studied the chemical/physical processes involved with contaminant transport from drainage of acid sulfate soils, through drains and into the Tweed Estuary. This research was completed along Blacks Drain through the cane fields of the late Bill Stainlay, and the pasture areas of other landholders upstream. While this research focussed more on the drain and estuary waters interactions, the work has direct relevance to the sugar industry and our wetland.

While we have identified Al and Fe as the primary contaminants being discharged from coastal acid sulfate soils on the Tweed River floodplain (see Figure 1), there is no comprehensive knowledge on the transport, transformation and fate of these elements once they have entered the estuary. UNSW.WRC identified that natural organic matter (NOM) from coastal acid sulfate soils affects the ability of Fe (but not Al) metal species to remain in solution and be transported within estuarine systems (Jones *et al*. 2009a). More specifically, Al complexes with acid sulfate soil NOM are labile in comparison to the more stable complexes formed between Fe(III) and NOM. As such, Al will be removed rapidly from the dissolved phase, via hydrolysis and precipitation, upon entering buffered estuarine tidal waters (pH 6-8) whereas Fe(III)-NOM complexes will be transported further within estuarine systems.

Therefore, processes such as drainwater suspension particle growth and aggregation, settling rates, etc., and the forces which influence these processes (shearing, turbulence, flow, etc.), will also significantly contribute to the spatial variation in transport and deposition of these metals within the Tweed River estuary and our wetland. The Tweed River estuary is a wave-dominated estuary outlet that has a high sediment trapping efficiency, so too does our wetland. Therefore, the deposition of Al and Fe particles are likely to be spatially limited to within the estuary, depending highly on the tidal cycle at the moment of contaminant discharge, and for constructed wetlands, close to the inlet, depending upon the through-flow volume and velocities.

The initial stages of Al and Fe precipitation typically results in the formation of amorphous particles (e.g. ferrihydrite) that have a high surface area and are, therefore, likely to be chemically/biologically very reactive. In our preliminary hypotheses we used the very general terms of “iron oxy-hydroxides” and “goethite” for the Fe_{III} precipitates but Collins *et al.* (2009) and Sullivan *et al.* (2006) have shown that most of the orange/red precipitates seen in ASS and their drainage waters is an iron oxy-hydroxide sulfate complex, “Schwertmannite” $\{Fe^{3+}{}_{16}O_{16}(OH)_{12}(SO_4)_2.nH_2O$, where n=10 to 12}. However, these particles are also known to undergo structural transformations (aging reactions) which render the particles more crystalline and, hence, less biologically active. The kinetics of these structural transformations in relevant environmental conditions have not been well researched. For example, the monomeric silica oxyanion (SiO_4^{2-}) and NOM are known to inhibit or retard these crystallization processes (Jones *et al.,* 2009b) and, hence, promote the reactivity of Al and Fe for an extended period of time. While Jones *et al.* (2009b) measured both SiO_4^{2-} and NOM in significant concentrations in waters discharged from acid sulfate soils, their influence on crystallization reactions in the natural environment has not been quantified. Essentially, it is unclear if Al and Fe no longer represent a threat to the health of estuaries once they have been deposited in the river sediments. For constructed wetlands, it is essential that management take cognizance of the drainwater contaminants that have been deposited, and appropriate disposal regimes be in place during periodic cleaning. The NSW Sugar Industry’s CBMP (NSW Sugar Industry, 2005) for drain cleaning therefore is appropriate here.

Recent monitoring in nearby Blacks Drain by the UNSW.WRC group, of the dissolved ferrous iron (rather than total iron) concentration over 3 consecutive daytime hours showed a more than fifty-fold increase from the negligible concentrations at midnight. The importance here is that ferrous iron is a much more mobile transporter of acidity than is the ferric species. The hourly swings in ferrous iron concentrations, matches approximately the diurnal swings of solar radiation. Clearly, there is a marked (possibly biochemical) reduction of the ferric iron sourced mainly from the dissolved iron but also possibly from ferric oxy-hydroxides in the drain sediment below clear water. These results show one of the possible mechanisms by which wetland vegetation can reduce acidity transport where shading assists the precipitation/ retention of iron and it also suggests a possible drain management option. It also means that we need to measure ferrous as well as total iron in our wetland water sampling and be cognizant of the sampling-day time and solar radiation conditions

Background to Construction of the Wetland

As seen in Figure 2, Robert Quirk’s 100 ha cane farm is bordered in the East by McLeods Ck, in the West by Leddays Ck, and to the North by Stotts Channel (a right-bank anabranch of the Tweed River). Apart from times of Tweed River flooding, the farm is hydrologically isolated by constructed roadways on the Eastern and Southern boundaries and by natural sedimentary levees and constructed bund walls/roadways on the Western and Northern boundaries. Drainage egress from the farm is through the north flowing Discharge Drain with an electrical pump located on a barrier wall in about the middle of the Discharge Drain (see Figure 2). The natural fall of the land is generally from South to North until about the East/West drain at the start of the Discharge Drain. The land along the northern farm boundary falls southwards from the Stotts Channel levee to this East/West drain.

The wetland was constructed on the 2ha cane block immediately East of the Discharge Drain (see Figure 2). Because of the generally raised elevation of this cane block it was necessary to use an electric pump to provide ingress of drain water to the wetland, and for this inlet to be placed at the northern end with gravity flow back towards the South. So as to provide appropriate falls and length of flow through the wetland, the wetland was constructed as 6 bays separated by bund walls after laser levelling each bay with a series of hinge-points. The bund walls of each bay were excavated from the immediately adjacent downstream bay, thus providing a deeper "borrow-pit" that can be seen in Figure 4. Water depth within each bay and over-flow from each bay to the next was controlled by small weirs in the intervening bund walls. A schematic diagram of the wetland showing the inlet, outlet, and bay over-flow points is shown in Figure 3.

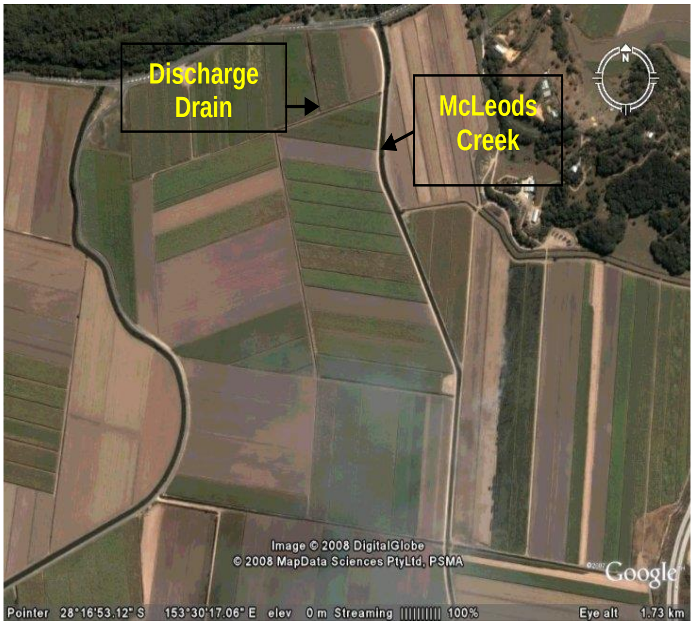

Figure 2. Aerial view of the 100 ha drained floodplain site chosen for the constructed wetland.

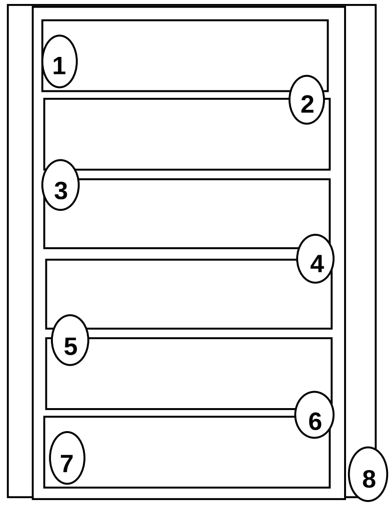

Figure 3. Schematic of the 6 bays in the wetland showing inlet, 1, outlet, 7, and overflow weirs, 2 to 6.

Details of Wetland Construction

Because of the wetland's proximity to the environmentally sensitive Stotts Island Nature Reserve (part of the World Heritage-listed Subtropical Rainforest Preserve), initially we anticipated the need to prepare an environmental impact study. After detailed discussions with officers of NSW National Parks and Wildlife Service and Tweed Shire Council, it was deemed that the construction and management of the wetland was within the provisions of TSC's Local Environment Plan for agriculture and could be handled by adherence to the NSW Sugar Industry's CBMP for managing acid sulfate soils (ASS). This was an important saving in time and cost and again illustrates the value to the NSW Sugar Industry of its agreement with the NSW Government allowing self-regulation (with annual external auditing) in management of ASS. This industry is the only body to date in NSW given such self-regulation, otherwise disturbance of >1 m^3 of ASS requires provision of an EIS and specific acidity management plan. With the extent and number of cane farms (>70%??) on ASS in NSW, such a planning requirement would be ruinous for the industry.

Weather, in terms of its timing and too little or too much rain with flooding, has greatly dogged the construction and management of the wetland and its monitoring. Once banks and temporary sills between bays were completed in early 2006, rainfall filled the wetland before any planting could be undertaken and volunteer plants (a mix of grasses and herbs) rapidly established themselves. We then decided to complete a trial run of the wetland by pumping water into the top bay and test whether the system would hold water. (There is a strong belief among many government personnel, in NSW at least, that acid sulfate soils have very large lateral hydraulic conductivity and therefore if this were true, our wetland might not hold ponded water. Our experience and measurements on canefields at McLeods Creek is contrary to this and it is on this basis that we have supported careful management by farmers of brackish water input into drains as a means of improving water quality, controlling weeds, and improving fish habitat.)

Nevertheless, once the wetland filled, several mole drains that we believed would have been destroyed under the tractor wheel loading during construction, leaked significantly. We continued to pump water through the wetland to provide an initial indication of any improvement in water quality between input and output (the results here will be presented later).

The final cost of construction using various local contractors and material supplies (e.g. agricultural lime and limestone aggregate) was about $12,000. Such a cost for the < 2ha wetland is only indicative for other sites, depending on specific site characteristics such as slope and the amount of laser levelling needed.

It became clear that the electric pump we were using was barely coping and could not supply sufficient water later in the year when evapotranspiration increased. Since we wanted to increase the ponding depth in the wetland, we also needed to stop pumping and allow the wetland to dry sufficiently to put a tractor along the perimeter banks to squash the leaky mole drains. Unfortunately, the region continued to experience well above average rainfall, having already received its annual average and we were frustrated in our efforts to make the facility fully operational. A new much larger capacity electric pump was purchased and installed.

Rather than selecting and planting vegetation in the wetland, we decided to use volunteer plant species in the wetland because they showed themselves to establish easily and provide the large amount of organic matter that was the initial intention. To that end, a program of seasonally quantifying the amounts and species of vegetation in the wetland has commenced and an initial survey and report was completed. As well, any problem weeds [e.g. crowfoot grass (*Eleusine indica*), Johnson grass (*Sorghum halepense*), and giant paspalum (*Paspalum urvillei*)] that established were mowed or spot and wick-sprayed with glyphosate, and the perimeter banks mowed and a grass sward established there. We wanted the site to have a reasonably tidy appearance whilst being functional (see Figure 4).

Figure 4. Panoramic eastward view of wetland middle bays 3, 4, and 5 (from left). Bays 1 and 2 cannot be identified at the extreme left, on this side of the highway. In the foreground is the overflow weir (# 4) through the bund wall between Bays 4 and 5 along with its "borrow-pit" vegetated with *Eleocharis* reeds.

The construction of weirs is illustrated in Figure 5. Addition of extra drop-boards to this construction allowed variation in the depth of ponding in any bay, depending on the elevation of the eastern perimeter bund wall. Further details of the wetland construction follow here.

Figure 5. Detail of overflow weir # 4 between Bays 4 and 5.

Table 1. Hydraulic characteristics of the wetland

Width	80 m
Length	190 m
Area	1.44 ha
Average water depth	=0.1 m
Wetland water volume	1440 m^3
Pumping Rate	162 ± 4 m^3/day
Number of Bays	6
Flow path length	494 ± 1 m
Hydraulic Gradient	0.13%
Water residence time with evaporation 6 mm/day	19 days
Water residence time with evaporation 10 mm/day	82 days

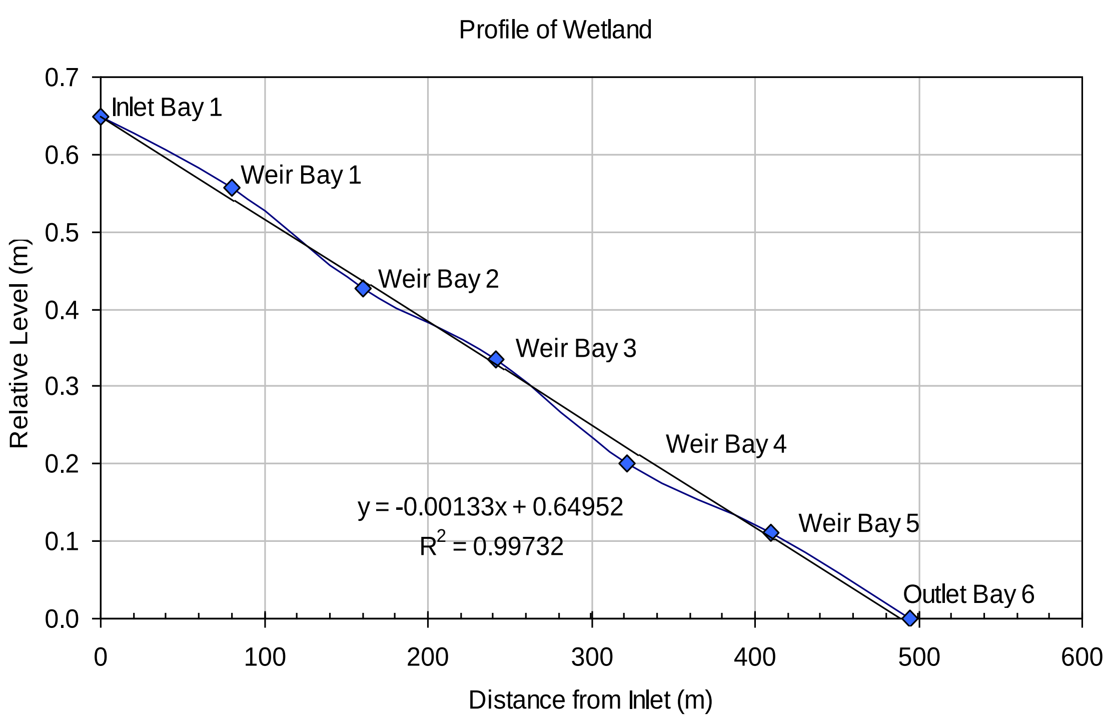

Figure 6. Slope profile of constructed wetland

Figure 7. Upstream southward view of farm's Discharge Drain from which water is pumped into the wetland. The monitoring unit at the wetland outlet well is in the distant LHS.

Figure 8. Small yellow electric pump supplying input to wetland. Main farm drainage export by PTO pump while large electrical pump temporarily under repair.

Figure 9. Northward view of Discharge Drain, downstream of the farm's electric discharge pump. The wetland is to the RHS.

Figure 10. Overflow well into which the wetland Bay 6 discharges. A pipe under the western bund wall connects this flow back into the North/South farm Discharge Drain. White PVC pipe is access for water quality monitors.

Figure 11. Bay 6 overflow well with water quality monitoring unit.

Figure 12. Wetland overflowing into farm's Discharge Drain. Black flocs forming (probably iron monosulfide) as high pH wetland water meets more acidic farm drainage.

Project Reference Panel
A panel of Condong Mill cane growers (Messers Robert Hawken, Alan Quirk, and Bill Stainlay) and staff (Peter McGuire) and the Tweed Shire Council Floodplain Officer, Dr Marty Hancock, agreed to serve as a reference panel to receive progress reports and advise on management of this project. Given their other time commitments and the episodic nature of the project's progress, few formal meetings were held.

Initial Survey of Cane Farmers Concerning the Wetland
A questionnaire was drawn up after consultation with members of the reference panel and others in the cane industry. This document was then submitted for approval to the ANU Privacy and Ethics Committee. After advice from the local industry as to timing, Dr Ben Macdonald undertook this questionnaire assessment in mid-January 2007 by mail and follow-up detailed interview for a random sample of cane farmers using the list from the Condong Mill. The provision of this list was approved by NSW COOP technical director, Mr Rick Beattie, and the ANU Privacy and Ethics Committee on the proviso of complete anonymity for participants. Because of the need for the follow-up interview and its time-constraints, only 20 farmers from the Condong Mill were included in the original mailing. Somewhat disappointingly, only nine responded and agreed to be involved, mainly because of other time commitments. However, those who did agree were enthusiastic and fully involved.

While only 9 growers responded to the survey, and not all of those provided accurate areas of their cane land, it appears likely that they represent > 10% of the land supplying the Condong Mill. Most (8/9) growers had some acid sulfate soil (ASS) as their cane land, some (3/9) reported that theirs was nearly all ASS.

All respondents provided very detailed information on the wide range of their fertilizer management regimes. Many of these fertilizer applications were based upon soil testing and some foliar analyses, with particular credit being given to the local BSES officer, Peter McGuire, for his assistance and knowledge. Approximately half of the growers appeared also to rely to some extent on their personal knowledge and observation from year to year. Three growers saw an environmental benefit from their ability to reduce fertilizer inputs.

To a large extent, and in line with the amount of ASS they managed, most growers had undertaken laser levelling or were completing laser levelling as a means of improving surface water run-off. This was seen as primarily of productivity benefit; one grower reporting an improvement of harvesting cost from $1.56/tonne before levelling, to $0.98/tonne afterwards. There was also believed to be an environmental benefit from laser levelling but this was secondary to that of increased productivity.

To assess farm's drain management regime, the question was asked: ***"Is your farm drained? What floodgate management strategies do you use?".*** All farms were in some way involved with tidal floodgates and their management. This is not surprising given that much of the back-swamp part of the Tweed River floodplain would be subject to high tide inundation without the existence of the river levees and the floodgates. These provide a means of draining to the river, hillslope runoff and rain falling on the floodplain cane fields, when tidal conditions are sufficiently low. The beneficial role of the Tweed Shire Council Floodplain Officer, Marty

Hancock, was particularly acknowledged for demonstrating the value and arranging the gradual installation of improved floodgates that enable some tidal exchange and fish passage. These new types of floodgates and their management were seen to have environmental benefit but also to provide valuable assistance in drain weed control.

To the question: ***"In your opinion, are drain and water quality management important issues for the Australian Sugarcane Industry?";*** **5/9** responded **'important'**,
4/9 responded **'very important'**.

To the question: ***"Is water quality of the water discharging from your farm important to you?" ;*** **1/9** responded **'important'**, **7/9** responded **'very important'**, one grower responded that nothing but rain water drained from the farm. Of two who responded 'very important' was added the rider of wanting a 'clean, green image'.

To the question: ***"What are your main sources of information for farm management?";*** a wide range of sources were quoted mainly from industry publications but a couple cited more technical 'books'. However, nearly all growers used their own experience and that of neighbours, but many also specifically acknowledged the important role of the particular local BSES officer from the Condong Mill. Only 2/9 growers cited the internet as an information source.

It was clear that the respondents believed water quality was an important issue for the Australian sugar industry and at least in NSW, acid sulfate soils (ASS) were an issue that needed to be addressed. However, at least one respondent felt that the emergence of ASS problems and the research involving collaboration with farmers, local government, and academics had beneficial spin-offs in other ways, with the NSW industry being willing to undertake important other initiatives in natural resource management.

Respondents were generally aware of this wetland's existence on Robert Quirk's property but several expressed concern that such wetlands might be misconstrued by regulators as a standard practice to be foisted on the industry. This is a very important issue that needs careful further review.

Water Quality Monitoring

Three water quality (WQ) monitoring units were installed and intended to give continuous measures of pH, Electrical Conductivity (EC), and temperature. These units were located above anticipated flood heights (>2 m; e.g. see Figure 11). A measure of the wetland's input WQ was from a unit located in the main East/West drain, immediately upstream of the farm's Discharge Drain. The wetland's output WQ was from a unit located in the outlet well of Bay 6 (see Figure 9). The overall farm's discharge WQ was from a unit located in the farm's Discharge Drain, downstream of the main pump. This section of the Discharge Drain is subject to diurnal tidal exchange from Stotts Channel.

Despite our own best efforts and assistance from the floodplain officers of Tweed Shire Council, because of malfunctions, lightning strikes, and unknown causes, the amount and quality of data provided from these continuous monitoring units proved practically useless. This has probably been the most disappointing outcome of the wetland's research because we have previously used similar units to these and they proved fairly reliable. One possible reason is an inability to provide a suitably constant inspection and maintenance regime. Unfortunately there were insufficient funds available to replace the equipment with other units or employ better maintenance. Nevertheless, our WQ measurements and sampling during several periods of intensive study have provided sufficient data upon which the wetland performance can be judged. The outcome of four of these measurement periods will now be described. Also, the doppler-flowmeter units that we were to use for this project to monitor input/output water volumes, proved useless despite many attempts to rectify them. Therefore we have relied upon the duration and measured flow from the pump to determine the input volume (approx 500L/h).

1. Initial Input/Output Water Quality. Three water samples were collected from the wetland in June 2006 after the initial filling and period of operation. These samples were submitted to TSC Water Laboratory for analysis. One sample was of the input water quality (Figure 3 sample point #1); the second is the output water quality (Figure 3 sample point #7)); the third was of water leaking through mole drains into the eastern perimeter field drain (Figure 3 sample point #8).

The pH improved from 2.8 to 4.0 between wetland input and output.
Total Acidity improved from being 110 to being 60 mmol/L
Dissolved Fe improved from 51 down to 0.8 mg/L
Dissolved Al improved from 13 down to 9 mg/L
Mn actually increased but Figure 1 shows that Mn generally provides a relatively small contributor to acidity and varies greatly, depending on the nature of antecedent hydrological events.
Salinity as measured by EC decreased somewhat in the wetland flow and this decrease is also reflected in that of dissolved metals and anions Cl and S (existing as SO_4).

The eastern perimeter water (Figure 3 sample point #8), leaking into the drain through mole drains at the eastern end of Bays 1 and 2, tended to be similar to the wetland input water quality, probably because in part it had insufficient time for reaction with wetland vegetation and partly because it was leaching metals, particularly Fe, from the soil surface layers into the mole drain prior to discharge into the field drain. Much of the very large Fe discharge precipitated in the drain as very noticeable iron oxy-hydroxides (probably Schwertmannite). This water is returned to the main drain system to become part of the wetland input. Even at this preliminary stage it was apparent that the wetland was able to reduce acidity in the input water.

The operation of the wetland after the initial filling and measurement continued for only a brief period when a prolonged dry period required pumping of water to cease. In fact, only during several weeks in October/November 2006 was there sufficient rain and drainage discharge available so that the wetland could be operated for any meaningful time period. This is despite the rainfall record that shows about 500 mm of rain fell for the Tweed from Aug 1 to Jan 31, although this is still below "normal" rainfall.

The prolonged dry periods in 2006 and 2007 meant that drains of the cane farm were too saline and had too little water for regular introduction to the freshwater wetland. This meant the wetland dried out, re-oxidising deposited sediments/precipitates. The problem arises because of the increased salinity in the farm's main drain system during dry periods and this drain system provides the ingress water to the wetland. As part of his overall farm drain management regime, Robert Quirk controllably allows water from McLeods Creek to enter the most upstream point of his main drain (using his "salt-shaker" flap-gate device) so as to stop the main North/South drain sludge from drying, oxidising, and thereby releasing its stored acidity. In turn, the farmers allow controlled ingress of tidal water into McLeods Creek from Stotts Channel/Tweed River. This gives a tidal range in McLeods Creek of about 0.5 m with a salinity level up to about 20 to 30 dS/m during dry time (about half seawater concentration). Robert's long-term plan for the land on which the wetland has been constructed (part of his best caneland) is to return to cane production. He does not want to salinize this land such that it may take many years of rainfall leaching to bring it back to production. Therefore he has set an upper salinity limit of about 5 to 8 dS/m for allowing drain water into the wetland.

In late 2007 and early 2008 excessively heavy rainfall led to widespread flooding in the Tweed river floodplain, inundating the wetland and upstream catchment and depositing fresh alluvial sediments in the wetland, blanketing or removing any wetland sediments deposited during earlier treatment of drainage water.

2. Water Quality Measurements in February 2008.

Heavy rainfall in January 2008 led to widespread flooding on the Tweed, including the wetland site. After surface water had drained away, highly acidic groundwater commenced discharging and was pumped into the wetland. After the wetland had been operating for about 3 weeks, water quality transects were carried out and filtered water samples were taken for analysis. Figures 13 to 16 show the results for pH, EC, TPA (Total Potential Acidity) and TAA (Total Actual Acidity) of the water, and dissolved sulfate. During operation of the wetland it can be seen in Figure 14 that pH increases to near neutral conditions at the wetland outlet, an over 1000-fold decrease in H^+ concentration, while EC decreased 8-fold. TPA and TAA drop by almost 10-fold and SO_4 by over 20-fold. These suggest dramatic declines in ions that contribute to TPA namely Fe, Al and possibly Mn. These changes are consistent with the hypothesis on the operation of the wetland which underpinned the original proposal and design.

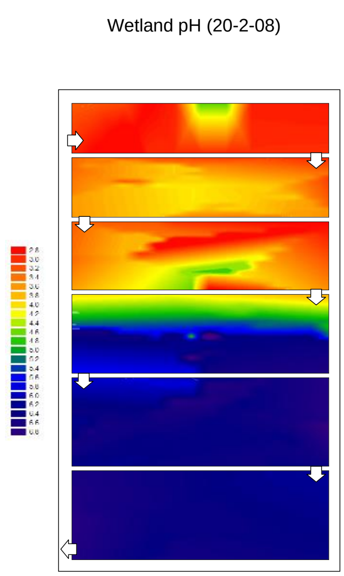

Figure 13. Spatial variation of pH throughout the 6 bays of the operating wetland in Feb 08.

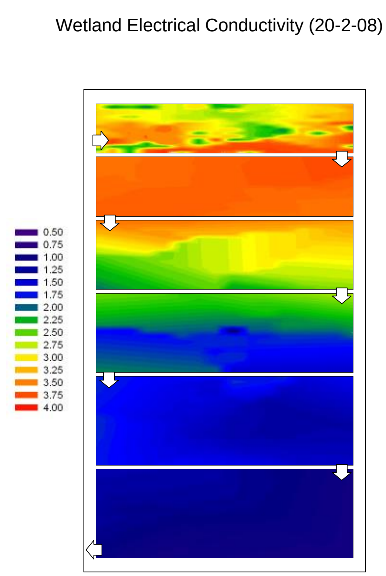

Figure 14. Spatial variation of EC (mS/cm) throughout the 6 bays of the operating wetland.

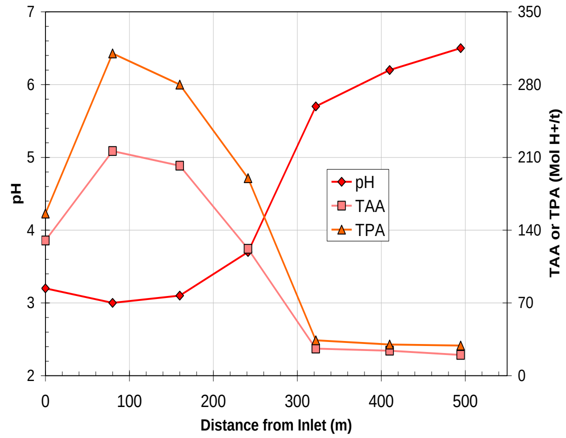

Figure 15. Transects of pH, TPA and TAA through the operating wetland in February 2008.

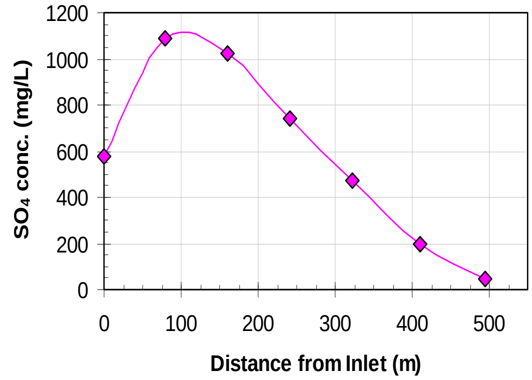

Figure 16. Transects of dissolved sulfate through the operating wetland in February 2008.

Figure 17. Orange oxyhydroxide precipitates at the wetland inlet.

The precipitation of orange Fe oxy-hydroxides (probably Schwertmannite) around the wetland inlet is illustrated in Figure 17. Another illustration of these precipitates in the wetland is shown in Figure 18. This iron precipitation, particularly in the first two bays is as predicted in our original hypotheses.

Figure 18. Oxyhydroxide precipitates on the Couch vegetation in Bay #1 of the wetland.

The measurement throughout the wetland used in Figure 14 and 15 were made along about 6 transects across each Bay using hand-held meters (see Figure 21 and 22).

Figure 19. Mike Melville measuring WQ in *Eleocharis*-vegetated "borrow-pit" (water depth about 0.3m).

Figure 20. WQ measurement in Couch vegetation (water depth about 0.1m).

3. Water Quality Measurements in April 2008

Water quality transects of field and laboratory measured water quality parameters have been measured both during wetland filling and during complete operation of the wetland. Figure 21 shows the decreasing ratio of EC to pH, reflecting decreases in salinity and increasing pH through the wetland during filling of the wetland. The decrease in DO and redox potential through the first 3 bays of the wetland during filling is also shown in Figure 21.

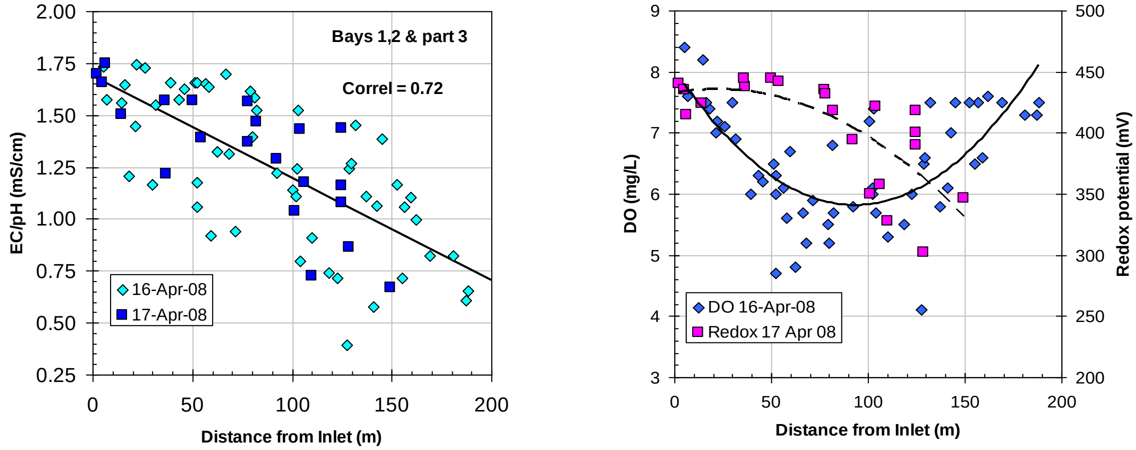

Figure 21. Transects of the ratio EC/pH and DO and redox potential in Bays 1, 2 and part of 3 during wetland filling.

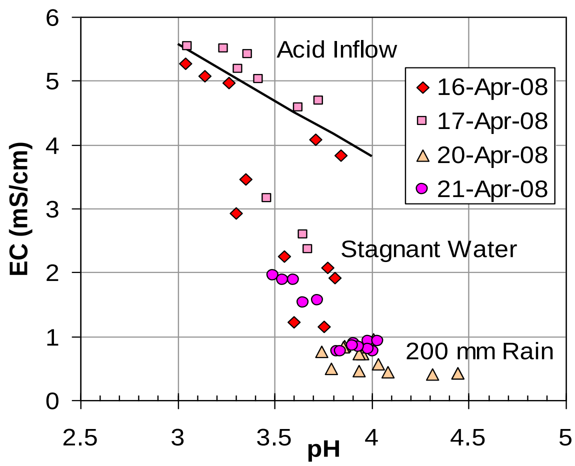

Figure 22. Relation between EC and pH during wetland filling and following 200 mm of rain which commenced on 18 April 08.

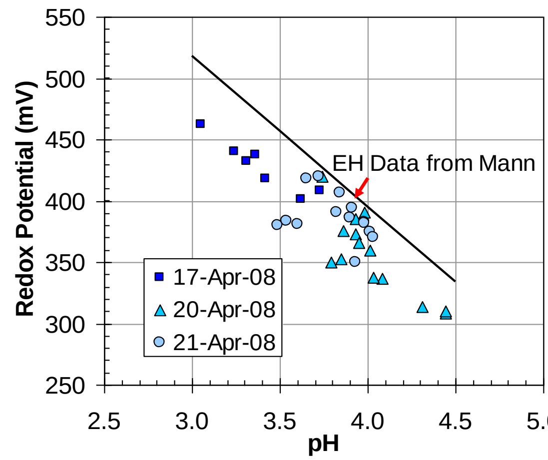

Figure 23. Relation between redox potential and pH during wetland filling and following 200 mm rain compared with the EH data of Mann (1991) for ferrolysis (eqn [1]).

After the initial transects (April 16 & 17, 2008), 200 mm fell over 36 hours, filling the wetland and causing flow over all weirs and the wetland outlet. Transects after rain show a complex relationship between EC and pH (Figure 22) although a simpler relationship between redox potential and pH (Figure 23) appears consistent with the ferrolysis reaction causing the deposition of iron flocs in the wetland.

The results of the two detailed studies in 2008 were presented later that year at conferences; firstly by Robert Quirk in Egypt and secondly by Ian White in China. This work is now published in *Sugar Technology* (see Quirk *et al.* 2009).

4. April 2009 Wetland Operation and Modifications

A major problem with operation and monitoring of water quality performance in the wetland has been the need to pump water into it from the farm's outlet drain after an appropriate amount of rain that promoted an acidity discharge event. Rainfall was often insufficient to retain water over the wetland surface, with sediments and any precipitated metals frequently drying out. At other times flooding from the adjacent Tweed River inundated the area under more than 1 m of floodwater. During periods of low rainfall the farm's drain water was both too little and became too saline (electrical conductivity, EC > 5 dS/m) to allow pumping into the wetland. Controlled leakage into the farm's drain system is enabled from the adjacent semi-tidal McLeods Creek (EC up to 20 dS/m) so that drain-bottom sediments do not dry out and oxidise. A large capacity electrical pump at the farm drain's outlet maintains the drain system water level sufficiently low to provide small rain event runoff storage but below that which would cause any lateral transfer of saline water under the cane crop. Generally, a rain event of about 35 mm is sufficient to fill the farm's drain system and initiate the automatic pump.

At the end of March 2009 about 120 mm of rain occurred followed by a further 300 mm during the first week of April (see Figure 24). An intensive final monitoring program between April 7 and 24 was therefore undertaken that included shifting the wetland inlet position from Bay #1 to Bay #3. Bays #1 and #2 were then allowed to commence drying and enable vegetation and sediment sampling as a prelude to trialling acidity neutralisation and wetland rehabilitation for cane production.

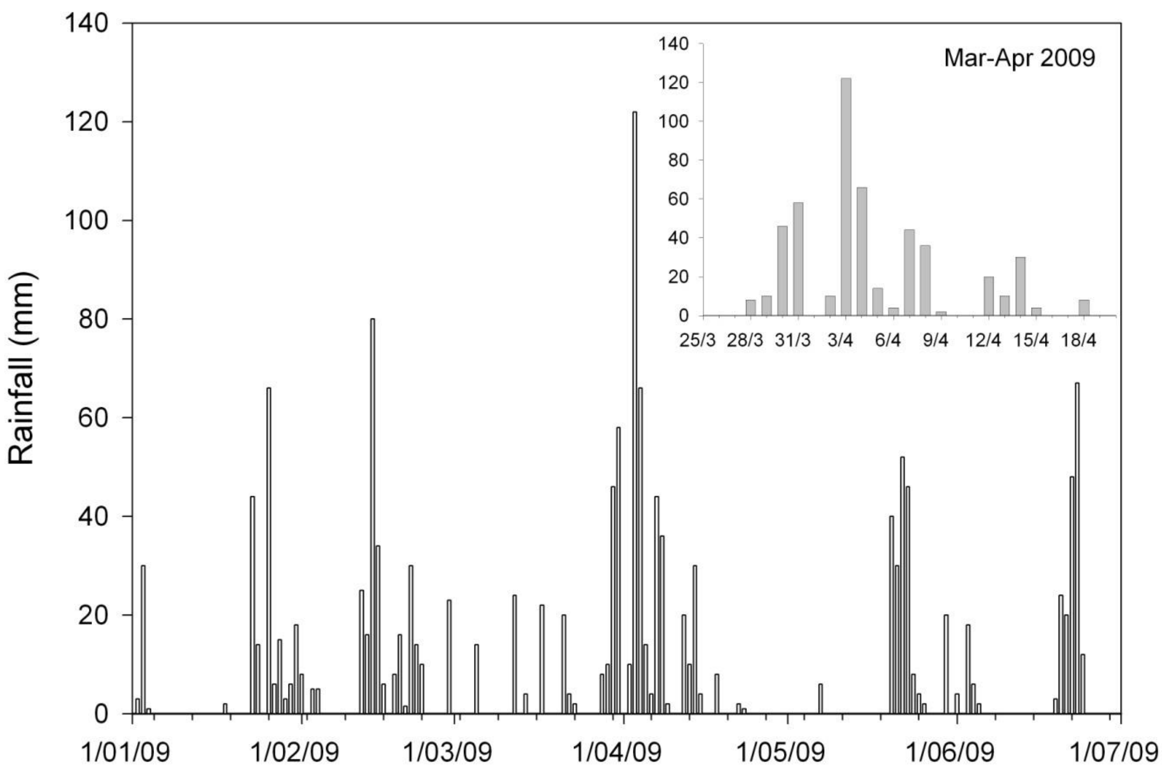

Figure 24. Daily rainfall at site during 2009 with late March and April inset

Water quality monitoring was completed across the wetland during the April study period. Initially, water quality in all wetland bays was measured (pH, EC, dissolved oxygen-DO or redox potential) but on April 10th the water inlet was transferred from Bay #1 into Bay #3 as mentioned above (see Fig. 3 & 4). The effect of the initial large rainfall event is seen with the input water and down through the wetland, in values of high pH and low EC. The initiation and progress of acidic inputs through the wetland is seen in Figure 25.

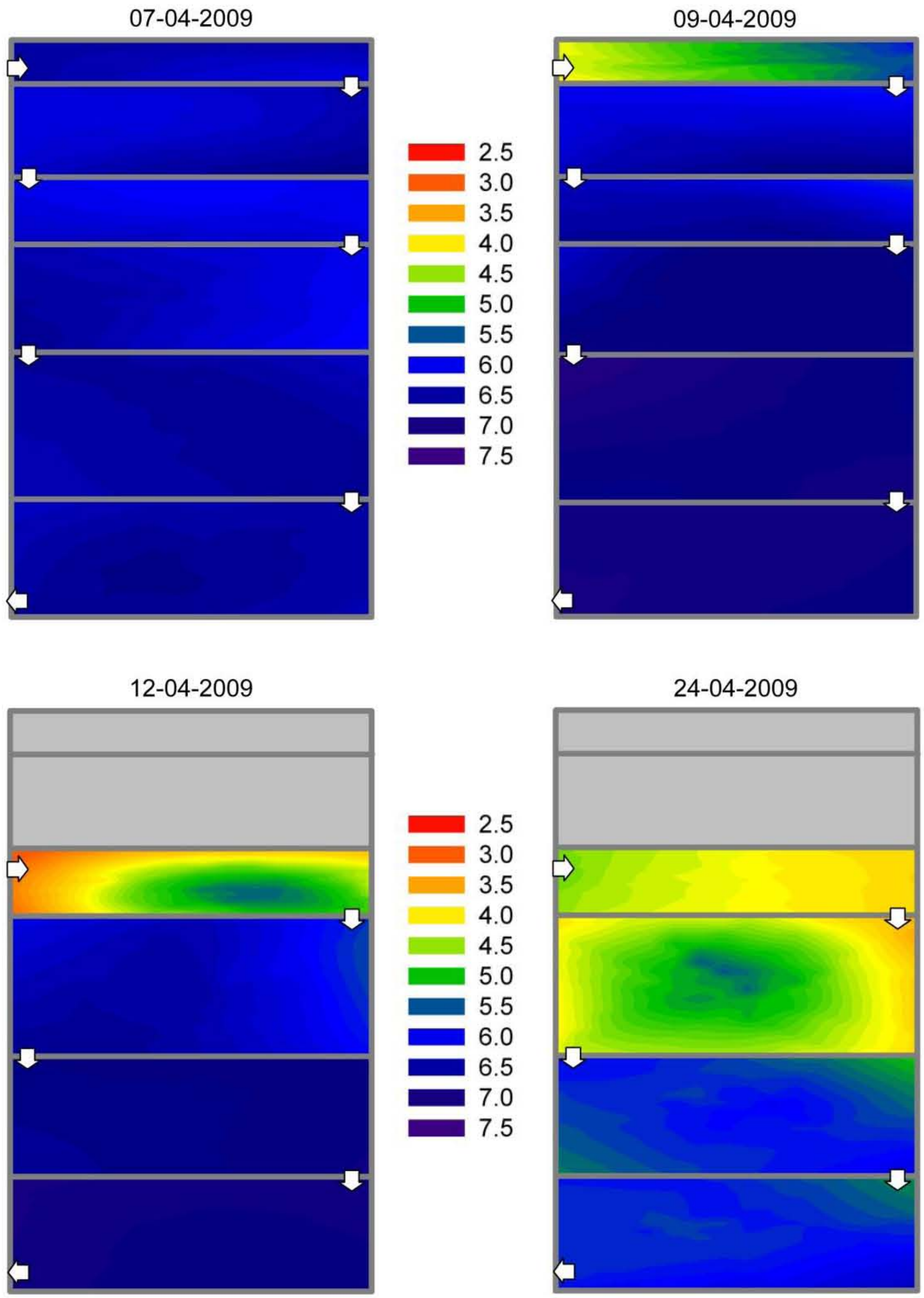

Figure 25. Wetland water quality pH during April 2009 study period

Towards the end of the study period the input of less acidic (higher pH) and more brackish drain water (higher EC) can be seen. Clearly, although acidic water was input continuously at about 100 L/min (there were some brief occasions when the pump stopped), as previously shown in Quirk *et al.* (2009), the wetland neutralised this acidity in the first one or two bays so that little of this acidity load exited from the wetland. Red-brown iron precipitates on the wetland vegetation were obvious, particularly nearer the inlet points where initially reduced ferrous iron oxidised to ferric oxy-hydroxides (see Equ. 2 and Figures 17 and 18). The reduction of incoming dissolved sulfate to metal sulfide was seen in formation of black precipitates and objectionable odours, particularly after rain ceased and DO decreased over time.

These preceding illustrations of WQ variations across and through each wetland bay to some extent mask some of the great variability that may occur because of preferential flow paths throughout the wetland. Some of these preferential flow paths are due to the initial construction such as the presence of the deeper "borrow-pits", or the presence of particular vegetation clumps and concentrations, or of wetland edge effects. One such edge effect is shown in Figure 27, just above the overflow weir (Figure 3 sample point #4) in Bay 3. The precipitation of dark brown iron oxy-hydroxides or monosulfides against the shallow water's edge sharply contrasts with the very clear, deeper and somewhat faster flowing water, possibly with some precipitated light coloured aluminium flocs, and a surface scum of some sort of iron oxides.

Figure 26. Spatial variation in water quality and precipitation above overflow weir #3.

Such localised variation in water quality will depend upon the flow velocity and depth, particularly as they affect the dissolved oxygen status that in turn affects the metal precipitation processes.

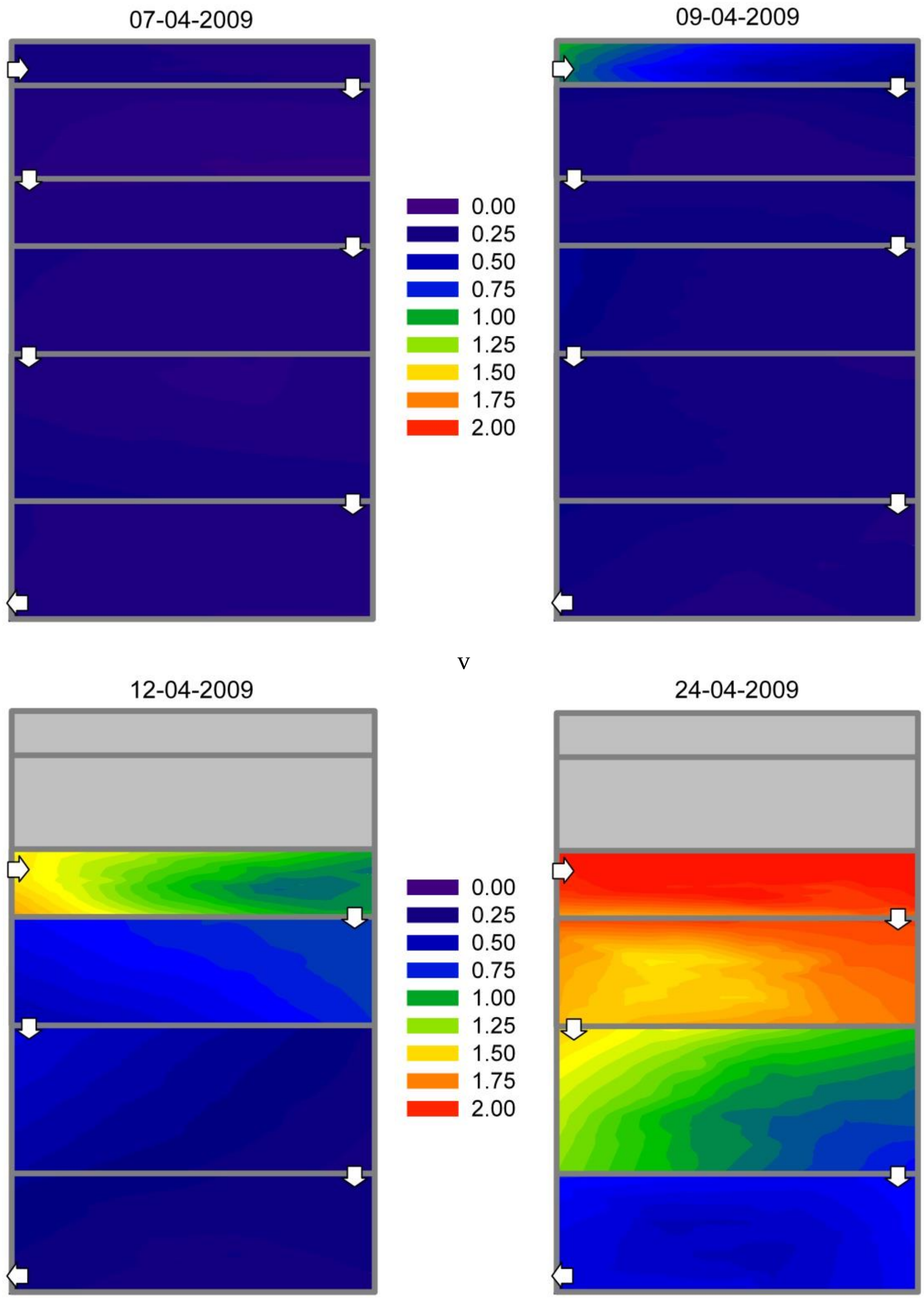

Figure 27. Wetland water quality electrical conductivity (dS/m) during April 2009 study period

The progress through the wetland of the increasingly acidic (see Figure 25) and brackish water (see Figure 27) can be seen following the switching of input location to Bay #3. This change in WQ and the lack of predicted rain drove the decision to stop all further inputs from the pump and to initiate the decommissioning and rehabilitation of the wetland.

Wetland Vegetation Sampling

Wetland vegetation was established by natural recruitment from apparently waterborne seeds. The main two species were couch grass (*Cynodon dactylon*) and common spike rush (probably *Eleocharis palustris*). Both of these perennial, strongly rhizomatous species are native to Australia, although widespread elsewhere in the tropics and sub-tropics. A number of larger and woodier weed species established in the wetland over time, particularly on the wetland bay and perimeter banks. However, these weeds were controlled by weedicide wicking and spot spraying. The couch grass established best on the flat area of each bay while the *Eleocharis* tended to establish in the deeper water of the borrow-pits formed during bank construction (see Figure 28).

Figure 28. Dr Kinsela standing amongst: (A) Couch Grass (*Cynodon dactylon*); (B) Common Spike Rush (*Eleocharis palustris*)

Total plant dry biomass samples of each of the two main species were taken from Bays #1 and #2. Three samples of each species were extracted using a spade, separating the root and shoot portions, bulking the sub-samples together, and oven-drying (85^{o}C) and weighing. The total biomass of Couch was 3.17 kg/m^2 (about 32 t/ha, with approx. 60% shoot and 40% root): *Eleocharis* was 2.55 kg/m^2 (about 25 t/ha, with approx. 50% shoot and 50% root). These biomass yields are after more than 3 years growth; small by comparison to sugar cane and rather small by comparison to one-year irrigated pasture yields in Victoria, Australia (19-31 t/ha, shoot only; from Blaikie *et al*. 2002).

Wetland soil samples and contained acidity measurement

Three surface soil samples (0-50 mm) were taken by core (see Figure 29) from each of Bays #1 and #2 after diversion of the water flow. Each sample was bulked from 3 sub-samples. The samples were dried, sieved and analysed at the Tweed Laboratory (Tweed Shire Council) using the standard acid sulfide soil analytical methods of Ahern *et al*. (2004). The measured pH (pH_{KCl}) and total existing acidity measured by titrating to end-point pH 5.5 in a 1M KCl soil extract ("TAA"), and the existing plus potential acidity with another such titrated extract, but additionally after oxidation with 30% hydrogen peroxide ("TPA"), are shown in Table 1. The peroxide treatment in TPA is intended to oxidise any sulfide minerals in the sample.

Figure 29. Core sample of wetland surface soil.

Table 1 – Wetland surface soil (0-50 mm) acidity analyses. Values of TAA and TPA in mol H^+/t dry soil

	Bay #1				Bay #2			
Sample #	1	2	3	Mean (s.e.)	1	2	3	Mean (s.e.)
pH KCl	4.2	4.1	4.1	**4.1**	5.6	4.2	4.0	**4.3**
TAA	85	130	120	**112 (16)**	15	108	102	**75 (35)**
TPA	110	193	140	**148 (30)**	65	183	145	**131 (47)**

The overall mean TPA of 139 mol H^+/t across Bays #1 and #2 equates to approx. 7 kg H_2SO_4/t soil. Assuming this represents the surface 0-50mm of the total 1.6 ha of the wetland surface, and further that this soil bulk density is 1 t/m^3, the measured acidity is the equivalent of approx. 5.6 tonnes of H_2SO_4 in the 1.6 ha. Each tonne of H_2SO_4 requires approx. 1 tonne of lime ($CaCO_3$) for acidity neutralisation. Using the common factor of safety of 1.5, neutralisation of the surface soil acidity, mostly sourced from inputs to the wetland, therefore would require about 8.5 tonnes of lime (about 5.3 t/ha). This approximates the rate of lime normally applied by Robert Quirk (5 t/ha) with a plant cane crop to satisfy the NSW cane industry's Code of Best Management Practices (CBMP) for managing acid sulfate soils. Of course the measured surface soil acidity was from those bays where most metal-sourced acidity would have been precipitated.

Calculated Acidity Loading by Pumping into Wetland

The measured input pump rate was approximately 100 L/min. From Figure 1 we could presume initially that the high concentration acidity load was approximately 150 mg/L acidity (presuming H_2SO_4 = $CaCO_3$), therefore the input of this level of acidity is about 21.6 kg H_2SO_4/day. If we assumed that such a high concentration of acidity was pumped into the wetland for 100 days during its 3 years of operation, the acidity load would be 2.16 tonne. Figure 1 shows that a more probable acidity concentration is only about 50 mg/L and it is very unlikely that there would be a need to pump continuously for about 30 days per year. Thus the likely acidity load into the wetland over the past 3 years would only have been less than 0.5 tonne of H_2SO_4. Comparing this with the measured soil acidity (5.6 tonne H_2SO_4 in the 1.6 ha of wetland) it appears that much of the measured soil acidity is from that present initially rather than from the acid drain water input.

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OUTPUTS:

The operation of this wetland is only one part of the management initiatives being undertaken by Robert Quirk to improve the quality of drainage water discharged from his farm. Recognition of his environmental stewardship was shown by his award of the 2006 McKell Medal. He therefore made a presentation on his NRM initiatives, in Canberra to DAFF staff and also a community audience at ANU. We have acknowledged this NRM initiative in a general paper presented as a poster at the ISSCT in Durban, 2007. A poster/oral presentation in Dec 2006 was made by Mike Melville at the Australian National Soil Science Conference in Adelaide. Papers were also presented at 2008 conferences in Egypt (Quirk) and China (White). An article on the wetland is to appear shortly in the *Australian Canegrower* magazine.

On-site visitations have been an on-going element of the project has since August ’06. In mid-August 2007 delegates from the Brisbane International Conference of Agricultural Economists visited the wetland and were addressed by Robert Quirk and Mike Melville. In September 07, delegates from the International River Symposium visited the field site. In November the Federal Minister for Agriculture Forests and Fisheries made a visit and met with Quirk and Melville. In December 2007 the NSW Minister of Agriculture and later, the Northern Rivers CMA Board, visited the site and Robert Quirk addressed them on the wetland and how the cane industry was addressing improved natural resource management. In early 2008, 34 SRDC PhD students visited the wetland site and where shown its operation as was the SRDC Board in March 2008. Many other local and international sugar industry representatives have also visited the wetland site (e.g. see Figure 30).

Figure 30. Visit to the wetland by Professor Peter Lyne (left) South African Sugar Research Institute, April 2008 with canefarmer Robert Quirk (centre) and researcher Mike Melville (right).

INTELLECTUAL PROPERTY AND CONFIDENTIALLITY:

There are no issues concerning Intellectual Property and Confidentiality with this Project.

ENVIRONMENTAL AND SOCIAL IMPACTS:

Attempting to reduce the discharge of contaminants in drainage from sugar cane lands can only have positive social or environmental impacts. Many in the public see agricultural industries as important contributors to the degradation of the environment. Given that most farmers see themselves as the best managers of their land for themselves and future generations, they need to demonstrate this stewardship. Increasingly it is likely that all Australian agricultural industries will be required to meet the same environmental standards as other industries. Such is already the case in many other developed economies around the World.

EXPECTED OUTCOMES:

We believe that the outcomes of greatly improved water quality shown here with this constructed wetland have important possible application in the Australian Sugar Industry. In retrospect, the location of the wetland on Robert Quirk's low elevation cane farm, adjacent to the Discharge Drain that cuts through the natural Tweed levee imposed the severe limitation of needing to have a pumping input. This limitation would not exist with sufficiently elevated cane land so that gravity feed into the wetland could be used. Caution needs to be practiced here though so that the maintenance of important riparian vegetation corridors is not compromised.

FUTURE RESEARCH NEEDS:

We believe that this wetland has proved a very valuable research tool for understanding the principles involved with using wetland vegetation as a means of improving drainage water quality. Nevertheless, one of the possibilities (again raised by farmer respondents in our January survey) is to use existing main drains as extended vegetated wetlands. It is already clear that because of the small lateral hydraulic conductivity in most estuary floodplain cane soils, that quite high salinity waters from tidal flushing can beneficially be allowed into main drain systems, although in some locations there seems to be some problem with increased slumping of such drain batters after the flushing is undertaken. We need to see the extent to which we can maintain such wetland vegetation to perform this water quality improvement function and yet still provide adequate drain flows during prolonged wet and flood periods. To some extent the problem of channel wetland vegetation management is well-established in engineering hydraulics where vegetation is designed and managed in channels to provide protection from erosion but not excessively impede flood flows. We suggest this use of in-drain wetland vegetation management but it will require some shifts in understanding by many cane farmers who see only the existence of vegetation-free drains as acceptable. There is also an important knowledge-gap concerning suitable wetland plant species here.

Other key questions are what plant species maximise the production of readily oxidised organic matter? How do we foster the growth of the required microorganisms and algae (addition of nitrate?)? Do any of the plant species take up metals? How much organic matter is needed?

The further development and application of wetland technology for the cane industry requires site-specific study and engineering of the hydrological regime and contaminant loadings. Probably most cane farm drain systems were designed, installed, and managed with the best intentions and knowledge available to farmers at the time but more recent understanding suggests that major changes could be beneficial.

RECOMMENDATIONS:

Application of constructed wetlands for acidity amelioration in sugar cane

It is clear that acid water passing through vegetation stands has some of its acidity removed. Most drains in NSW cane lands have various vegetation growth, often including the main species (Couch and *Eleocharis*) identified in this wetland. In some instances the water depth in the drain is too great for these species but there is a move being encouraged for farmers to use shallower drains. On many occasions farmers see the presence of any in-drain plant growth as deleterious to the passage of drainage water. Nevertheless, the drains are mostly required to remove water quickly under fairly high flow conditions. At these times the useful plant species we have identified are drowned-out and would cause little obstruction to flow. In the latter phase of a flood hydrograph the flow rates are less and it is at this time that acidity discharge is greatest so the presence of in-drain plants would reduce acidity discharge. Any metal-sourced acidity precipitates would periodically be neutralised by liming during drain cleaning in accordance with industry's CBMP.

It is clear from these results that, having limited the input of salt to the wetland, the inputs of acidity from the farm's drain water has not permanently damaged the soil and the land can easily be rehabilitated for cane production after adequate lime application, removal of terrace and perimeter bank by in-filling their adjacent borrow-pits, and re-establishing the laser-levelled drainage regime. The amount of acidity accumulated in the wetland over the 3 to 4 years of its intermittent operation probably had a significantly smaller effect than that of the land adjacent to cane field drains when they are cleaned and the drain sediments limed, spread, and incorporated into the cane field, as per the NSW industry's CBMP.

This wetland already occupied about 2% of the farm's land area and only treated about 10% of the acid water discharge. On this basis it might require a constructed wetland occupying up to 20% of a cane farm to treat all of the acidity discharge. Such a possible management tool is completely impracticable. However, there are still useful lessons that can be gained from this experiment, but these would require some shift in understanding and operation by cane farmers.

LIST OF PUBLICATIONS DIRECTLY RELEVANT TO THE PROJECT:

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Macdonald, B.C.T**.**, White, I., Astrom, M.E., Keene, A.F., Melville, M.D., Reynolds, J.K. (2007). Discharge of weathering products from acid sulfate soils after a rainfall event, Tweed River, eastern Australia. *Applied Geochemistry*. **22**(12): 2695-2705.

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