Cooperative Research Centre for **Contamination Assessment and Remediation of the Environment**

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TECHNICAL REPORT NO. 41

# Remediating and managing coastal acid sulfate soils using Lime Assisted Tidal Exchange (LATE) at East Trinity, Queensland

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CRC for Contamination Assessment and Remediation of the Environment

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# Executive summary

This document is a review of the implementation and associated research activities of a successful coastal acid sulfate soil (CASS) remediation strategy. East Trinity is a case study of how a severely degraded tidal wetland has been returned to a functional estuarine habitat using a cost-effective, low technology method based on the re-introduction of tidal water. The East Trinity experience is a reference point for best-practice remediation and management of broadacre CASS and is an exemplar conversion site linked to the *National Standards for Ecological Restoration* (Luke 2016).

Prior to 1970, East Trinity was a 740 ha tidal wetland draining into Trinity Inlet opposite Cairns in north Queensland, Australia. It is contiguous with important estuarine habitats, and a World Heritage listed wet tropical rainforest. Trinity Inlet borders the Great Barrier Reef Marine Park.

Drained for cane farming in the 1970s, the underlying acid sulfate soils (ASS) oxidised to create a severely acidified and degraded landscape and a major environmental issue. The remediation strategy has dealt with this and provided a platform for a comprehensive, CRC CARE-funded research program. This research has explained why the remediation strategy succeeded in an unprecedented time frame and provided new insights into the underlying interaction of biological and geochemical processes.

It took until the 1990s to fully recognise the impacts of the original disturbance. Fish kills were documented (Russell and McDougall 2003) and soil studies revealed that 3,000 tonnes of sulfuric acid per year had leached from the Firewood Creek catchment alone over a thirty year period (Hicks, Bowman & Fitzpatrick 1999). This information was presented at a public forum, which led to the Queensland Government purchase of the impacted site, and funding of the remediation strategy referred to as lime assisted tidal exchange (LATE).

LATE was implemented in 2001 following a comprehensive site and operational methodology assessment. An initial trial of LATE proved successful in terms of the water quality and soil parameters. The short time period in which these parameters responded was contrary to predictions and prompted the need for a research program aimed at understanding the interaction of daily tidal inundation and an acidified soil landscape. State Government funding was provided for operational aspects and the implementation of LATE, with co-investment from external sources focusing on research to better understand the geochemical drivers of the remediation.

The CRC CARE-funded program led by Southern Cross University researchers has been collaborative and extensive, where new insights have triggered divergent research pursuits capturing the expertise of several national and international research institutions. The research has shown LATE's success can be attributed to the combination of an alkaline input alongside a huge flush of organic matter. This raised the pH above the critical threshold of pH 6, kick-starting the bacterial and ferrous ion catalysed reduction of sulfate and iron minerals. *In situ* bicarbonate production, a by-product of this process, further neutralised soil acidity, promoting the beneficial microbial weathering of acid minerals. This process has become self-propelling toward

a stable and healthy intertidal wetland system, representing a paradigm shift in the understanding of CASS chemistry in an intertidal context.

The East Trinity site now has sufficiently high ecological function to transition from active to passive management. Under passive management, the addition of hydrated lime to the waterways ceases, and regular tidal inundation will remain in place to ensure that ASS remain protected from further oxidation. Real-time water monitoring will confirm that the system is stable under passive management and target interventions if this is not the case. Further research into geochemical pathways that operate over the longer-term is required to verify predictions of future system stability.

# Abbreviations

| | |
|---|---|
| AASS | Actual acid sulfate soil |
| AHD | Australian height datum |
| ASS | Acid sulfate soil |
| CASS | Coastal acid sulfate soils |
| CPUE | Catch per unit effort |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| DES | Department of Environment and Science |
| DO | Dissolved oxygen |
| DTE | Daily tidal exchange |
| EC | Electronic conductivity |
| EIS | Environmental impact statement |
| LATE | Lime assisted tidal exchange |
| MYAC | Mandigalbay Yindinii Aboriginal Corporation |
| PASS | Potential acid sulfate soil |
| SRB | Surface reducing bacteria |
| TAA | Total actual acidity |
| WH&S | Workplace health and safety |

# Key terms

**Actual acid sulfate soil (AASS):** when soils containing metal sulfides are exposed to oxygen, they undergo a chemical reaction known as oxidation which forms acid sulfate soils (ASS) and releases sulfuric acid.

**AHD (Australian height datum):** is a commonly used reference point for altitude measurement in Australia. Mean sea level is zero elevation, based upon average tidal measurements taken between 1966 and 1968.

**Aquifer:** underground rock or sediment with the ability to hold water.

**Ferrous ion:** the reduced form of iron, often present in dissolved form.

**Hydraulic conductivity:** the ability of liquids to move through a soil or rock.

**Hydrology:** water movement, in terms of rainfall, evaporation, outflow, movement on and off site in streams, soil pore water, aquifers, and the tide. Can also indicate how different water bodies are connected.

**In situ**: the production of materials within the environment not exported or imported from elsewhere.

**Ions:** an electrically charged atom or group of atoms that occurs when electrons are lost or gained. Ananion is a negative ion created by an electron gain. Acation is a positive ion created by electron loss.

**pH:** expresses the hydrogen ion concentration in moles per litre on a logarithmic scale from 1–14. Lower values are acidic, pH 7 is neutral and higher values are alkaline.

**Oxide minerals:** minerals containing oxygen, with iron and sometimes sulfur in the oxidised form, typically forming in oxidising conditions.

**Oxidation:** the loss of electrons from, or an increase in oxidation state of a molecule, atom, or ion.

**Potential acid sulfate soil (PASS):** soils that contain metal sulfides. In an undisturbed and waterlogged state, these soils may pose no or low risk.

**Redox:** the term arises from the two processes of electron transfer between molecules, called reduction and oxidation.

**Reduction:** the gain of electrons by, or a decrease in oxidation state of a molecule, atom, or ion.

**Soil pore water:** the water that is held in between the sediments.

**Sulfide minerals:** a class of minerals containing reduced sulfur (sulfide, $S^{2-}$) as the major anion. Most sulfide minerals are inorganic metal compounds.

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# 1. Introduction

## 1.1 Introduction

The East Trinity acid sulfate soil (ASS) remediation project is a case study of how a severely degraded tidal wetland has been returned to a functional estuarine habitat using a cost-effective, low technology method based on the re-introduction of tidal water. Lime assisted tidal exchange (LATE) is a highly successful remediation strategy that has addressed a major environmental issue and facilitated groundbreaking research outcomes. The East Trinity case study is a reference point for best-practice large-scale remediation and management of coastal acid sulfate soil (CASS). Figures 1 and 2 show some of the key parameters improved by the LATE remediation strategy and some visible landscape changes because of this strategy, respectively.

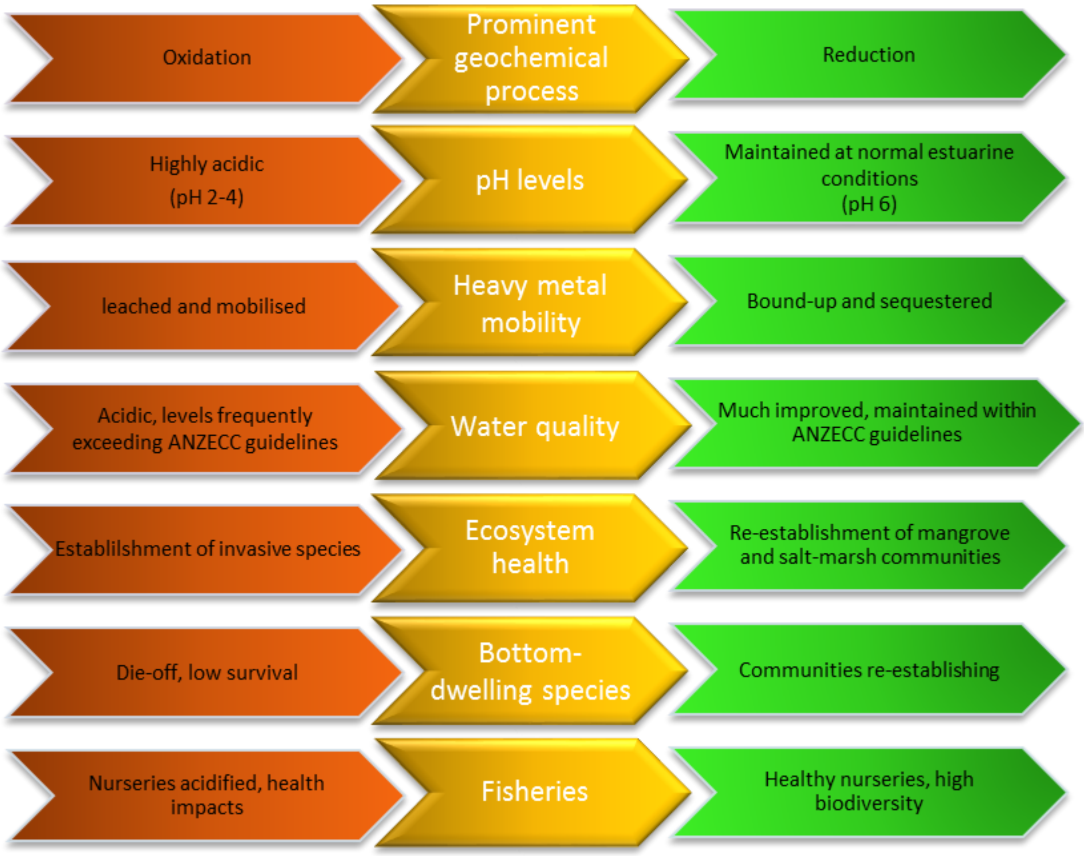


**Figure 1. Some of the key parameters that have been improved by LATE.**


**Figure 2. Changes to the Upper Firewood area as a result of LATE.** A highly acidified environment in 2001 with Melaleuca spp. and iron staining; and the same area in 2016 showing mangrove recolonisation after >10 years of active LATE.

# 2. Coastal acid sulfate soils (CASS)

## 2.1 Formation and geomorphology of CASS

Coastal ASS are formed when microbial bacteria derive energy from organic matter in waterlogged, anoxic coastal sediments and use soluble sulfate ions in sea water to produce hydrogen sulfide (rotten egg gas, $H_2S$) as a waste by-product. The $H_2S$ reacts with soluble iron, first precipitating amorphous FeS (iron monosulfide). With continued bacterial production of $H_2S$, FeS is converted to $FeS_2$ (iron disulfide; pyrite or marcasite). The sulfide combines with metals to create metal sulfides such as pyrite, an iron sulfide mineral (Dent 1986). Coastal ASS are forming along most tidal wetlands today, but the main body of CASS was deposited in the period between 7,000 and 5,000 years ago.

In response to the end of the last ice age 19,000 years ago, the shorelines of global seas commenced their advance from 130 metres below the present level. Sea levels reached their present level approximately 7,000 years ago (Grindrod & Rhodes 1984). Sea levels then rose to approximately 1 m higher. This shoreline advance ceased approximately 6,000 years ago (Chappell 1983; Thom & Roy 1985). This advance and subsequent retreat to the present level was the mechanism for the main body of ASS deposition. The geomorphology of the East Trinity site has been investigated by Graham and Larsen (2003) in Smith *et al* (2003b), resulting in a stratigraphic model which explains current landscape features (see Appendix 1).

## 2.2 Global occurrence

Andriesse and Van Mensvoort (2006) estimated that there are 170,000 km$^2$ of ASS in wetlands across the globe. This was based on a 1997 estimate of Australian ASS of 30,000 km$^2$. The Atlas of Australian Acid Sulfate Soils 2006 estimate is 74,000 km$^2$ of CASS above the low tide level (CSIRO 2012) –this approximates the area of tidal wetlands, which in the undisturbed state, support a wide range of mangrove and samphire species.

ASS contain iron sulfides, which generate sulfuric acid when exposed to air. A conservative estimate of disturbed CASS is 7,400 km$^2$ or 10% of the total. This is likely to have produced 230,000 tonnes of sulfuric acid (CSIRO 2012). In Queensland, more than 25% of CASS are in the Great Barrier Reef catchments (Powell & Martens 2005) which, if not properly managed, may present a threat to water quality for the reef, estuarine and other associated ecosystems.

## 2.3 The importance of tidal wetlands

The mangroves and salt marshes in tidal wetlands play an important part in linking the land to the ocean, having high ecological value for both marine and terrestrial species. Tidal wetlands act as a buffer between land and sea protecting the latter from excess sediment. They act as a nursery and habitat for commercially important fish, crab, prawn and oyster species (Manson *et al* 2005). Fringing reefs can have double the amount of fish when associated with healthy mangrove systems (Mumby 2006). Coastal waters are the nurseries that support about 90% of the global fish catch (Wolanski *et al* 2004).

Mangroves sequester up to 25.5 million tonnes of carbon per year (Ong 1993), and provide more than 10% of essential organic carbon to the global oceans (Dittmar *et al* 2006).

## 2.4 Consequences of ASS disturbance

Left undisturbed and permanently wet, ASS are benign and referred to as potential acid sulfate soils (PASS). Any drying will oxidise the pyrite and produce acid when re-wet, thus forming actual acid sulfate soil (AASS). Short-term wetting and drying cycles often occur naturally at the upper limits of the tidal range. The acid produced is limited, buffered by seawater and rarely causes environmental harm.

The environmental hazard associated with ASS arises from artificial drainage and other forms of disturbance, which expose the pyrite to air. The sulfuric acid produced creates conditions for the release of toxic metals and gases. The consequences of soil acidification and the release of acid and potentially harmful metals into ground and surface waters are wide ranging, encompassing the natural and built environment, and human health (Sullivan *et al* 2012; Powell & Martens 2005).

Acidification of coastal wetlands results in the partial or total collapse of the aquatic ecosystem. Mangrove and salt marsh species do not survive. Aquatic biota move away, die or become unhealthy through contamination. The association of ASS disturbance and fish kills is well-documented (Sammut *et al* 1995; Russell *et al* 2011).

Until recently, acid damage to concrete and steel infrastructure over decades has created a major impost on the public and private funds. Specialised concrete and other measures are now employed to mitigate the problem. Premature ageing and other human health problems have been related to elevated aluminium levels in water where ASS has been disturbed. Hydrogen sulfide levels emitted from ASS in confined situations can be lethal.

In their undisturbed state ASS contains 15 to 25% carbon as organic matter and represent a major global sink of organic carbon (Wollast 1991). When disturbed, accelerated decomposition of organic matter occurs, resulting in the production of the greenhouse gas carbon dioxide. More carbon dioxide is produced by the reaction of acid with soil carbonates and seawater bicarbonate. Hicks, Bowman and Fitzpatrick (1999) estimated that the annual release of carbon from drained soils at East Trinity was as high as 33 tonnes per hectare from organic matter decomposition and soil carbonate. A further 8 tonnes is released when escaping acid is neutralised by seawater bicarbonate. This equates to 150 tonnes carbon dioxide equivalent ($CO_2$-e) per hectare per year (CSIRO 2012). Representing a loss of 111 Mt $CO_2$-e from the estimated 7,400 $km^2$ of disturbed ASS.

## 2.5 Conventional ASS management

The first principle of ASS management is to avoid the disturbance of ASS wherever possible (Dear *et al* 2014). A thorough assessment and understanding of the site is required in order to do this. However, in situations where disturbance may be unavoidable, the *Queensland Acid Sulfate Soil Management Guidelines* recommend the minimisation of disturbance, with the use of site-appropriate risk-based management strategies: neutralisation of acidity through addition of alkalinity; hydraulic separation; and/or strategic reburial of potential ASS below permanent standing water (Dear *et al* 2014).

Higher-risk management strategies include stockpiling ASS, strategic reburial of soils with existing acidity, large-scale dewatering or drainage, and vertical mixing (Dear *et al* 2014). Above ground capping, hastened oxidation, and seawater neutralisation are generally regarded as unacceptable management strategies. Similarly, offshore disposal of ASS is considered unacceptable unless specific approval has been granted.

The *Queensland Acid Sulfate Soil Management Guidelines* state that the receiving environment should not be relied on as a primary means of treatment (Dear *et al* 2014). A possible exception is given to legacy ASS disturbances where a site was disturbed before the environmental impacts of ASS were recognised,where there is an acid and/or metal load impacting the downstream environment, and there are no other reasonable management options (e.g. broadscale disturbance associated with agricultural production). In such situations, some of the higher risk strategies may be considered if there is no practical alternative and it can be scientifically shown through a pilot trial that the existing risk to the environment can be lowered.

Johnston *et al* (2003) provide guidelines for improving the environmental performance of coastal floodplains which have an extensive network of constructed drains, floodgates and altered water courses as a result of historic farming practices. These guidelines rely on an assessment of key features of the altered landscape in order to integrate three strategies for improving management:

- modifying floodgates to enable controlled tidal exchange of drain water;
- installing water retention structures to reduce seepage of acidic groundwater, control unwanted saline water entry and raise the water table to keep ASS wet; and
- preventing further oxidation and redesign drains to remove surface water without intercepting groundwater.

# 3. Background and history of the East Trinity site

Prior to 1970, East Trinity was a 740 ha tidal wetland draining into Trinity Inlet opposite Cairns in north Queensland, Australia (Figure 3). Contiguous with important estuarine habitats and a World Heritage listed wet tropical rainforest, Trinity Inlet borders the Great Barrier Reef Marine Park. Two major streams, Hills Creek and Firewood Creek, received water from off site and flowed into Trinity Inlet.

The East Trinity ASS issue had its origins in the early 1970s when the site was excluded from tidal influence in a failed attempt to grow sugarcane. Tidal exclusion and drainage of ASS created an environmental issue that was eventually recognised publicly in late 1999 leading to the funding of a remediation strategy, which commenced in 2001. The need to understand the success of this strategy resulted in ground breaking research which has provided an understanding of the hydrological, chemical and biological interactions at play – thereby enabling reliable knowledge transfer. Table 1 outlines the major events in this history.

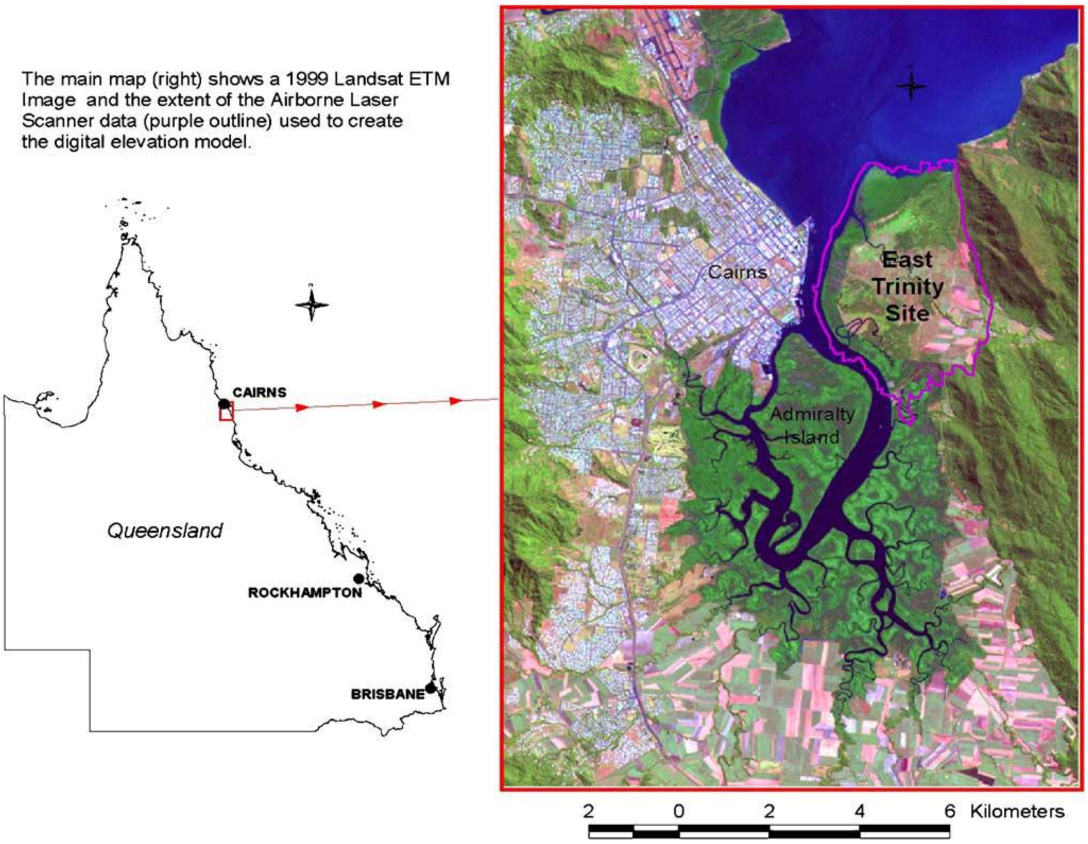


**Figure 3. Location of the East Trinity site** (Powell & Martens 2005).

**Table 1. Milestones in the land management history of the East Trinity site.**

| Date | Event | Highlight |
| --- | --- | --- |
| Pre 1970 | East Trinity is a functioning tidal wetland comprising 7 mangrove communities, supra-tidal samphire flats and chenier ridges. | |
| 1970 | Tidal exclusion commenced through bund and tide gate construction and surface drainage for the purpose of growing sugarcane. | Mangroves died, sugarcane growing proved unviable; anecdotal accounts of major fish kills. |
| 1992–96 | Several unsuccessful development proposals involving canal estates, marinas and tourist resorts. | These proposals included limited documentation of ASS. |
| 1995–98 | CSIRO documented the environmental hazard created by the export of acid and toxic metals from the drained landscape | 3,000 tonnes of sulfuric acid exported per annum for 30 years from Firewood Creek alone. |
| 1999 | CSIRO presented their findings to a public forum in Cairns organised by the State government. This included the results of a freshwater re-flooding trial. The then Department of Primary Industries presented evidence of major fish kills. | |
| May 2000 | Queensland State government purchased the property and requested relevant government scientists to propose a remediation strategy for funding by the State | LATE proposed |
| Dec. 2000 | The East Trinity Property ASS Remediation Action Plan released for public comment and accepted. | Hills Creek to be treated and the effectiveness of LATE assessed |
| 2001 | Preliminary site assessment and planning carried out to guide the remediation strategy. | Soil, stratigraphy, hydrology, topography, tide control, water treatment, monitoring. |
| Jul. 2001 | LATE trial commenced on Hills Creek. | The Coastal Acid Sulfate Soils Program (CASSP) of the Natural Heritage Trust brought external scientists and additional funding to study the trial on Hills Creek. |
| Dec. 2002 | CASSP report finalised documenting the success of LATE | |
| 2004 | *Environmental Protection Biodiversity and Conservation Act* (1999) referral and decision that remediation of Firewood and Magazine Creeks using LATE is not a controlled action under the Act. | LATE can be used to treat Firewood and Magazine catchments, without conditions or concerns about the receiving environment of Trinity Inlet and the GBR. |
| 2004–16 | Maintenance of LATE and associated soil, water, vegetation and aquatic biota monitoring activities. | |

| | | |
|---|---|---|
| 2006 | Active LATE ends in Hills Creek catchment and commences in Firewood Creek catchment. The Hills Creek system is now under passive LATE. | |
| 2007 | Commencement of CRC CARE-funded research to understand how the LATE process works. | This provided a paradigm shift in the understanding of the hydrological, chemical and biological processes that are brought into play under a lime assisted, controlled return of tidal water to a highly acidified landscape. |
| 2009 | Additional floodgates installed through the bundwall to reconnect Georges Creek and upper Firewood Creek with Trinity Inlet. | This has resulted in increased tidal exchange and enhanced remediation. |
| Nov. 2016 | Active treatment ceased in Firewood Creek catchment. | The East Trinity site is now managed by passive LATE. |

## 3.1 Pre-development

Prior to drainage, the 740 hectare East Trinity site was a tidal wetland site comprised seven distinct mangrove communities, expansive samphire (supratidal) flats, chenier (sand) ridges and an area of coastal lowland forest above the former tidal limit (figure 4). East Trinity was also part of the land traditionally occupied by the Mandingalbay Yidinji people.

**Figure 4. 1952 aerial photo showing the East Trinity site prior to development for sugarcane.** The dark areas adjacent to creeks are mangroves; the pale areas are supra tidal samphire flats (salt pans).

## 3.2 Reclamation for agriculture and ASS disturbance

CSR Hambledon Mill acquired the property in the early 1970s and carried out a large-scale drainage program in an attempt to grow sugarcane. A 7 km long bundwall was constructed incorporating large tide gates where it intercepted two major streams. Tidal waters were effectively prevented from entering an area, which previously experienced tidal movement up to 3 km inland from the shoreline. This resulted in severe soil acidification as a consequence of the oxidation of the underlying iron sulfide (pyrite) rich marine sediments, and the formation of AASS. Figure 5 represents a conceptual for development of AASS.

The site became severely degraded and no longer functioned as a coastal marine habitat and breeding zone for aquatic biota. All mangrove and samphire species died except for one small black mangrove community. *Melaleuca spp*. were able to tolerate soil acidity as low as pH 2.5 and subsequently colonised the former mangrove areas (figure 6).

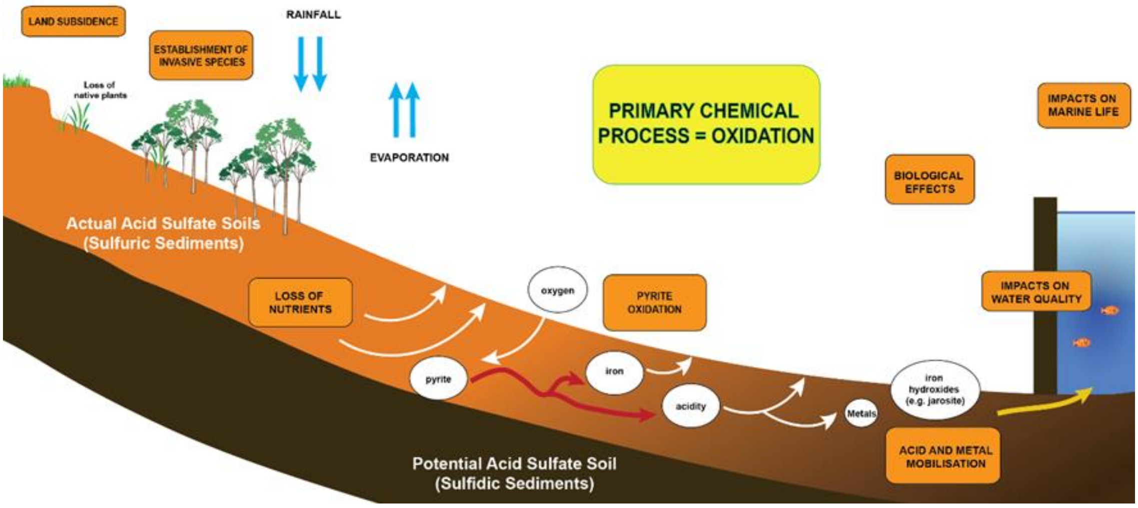


**Figure 5. A conceptual model showing oxidisation of the East Trinity sediments following drainage** (Adapted from Ward, Sullivan & Bush 2013).

**Figure 6. The East Trinity site circa 1980** (Powell & Martens 2005). Note the Bundwall zig zagging from top to bottom. To the right is the mangrove fringe of Trinity Inlet with obvious mangrove deaths in the vicinity of the Firewood Creek outlet. To the left is the iron-stained, and in many areas bare, acidified soil of the East Trinity site.

Additionally, sulfuric acid and toxic metals regularly impacted the receiving waters in Trinity Inlet over a period of thirty years. Hicks, Bowman and Fitzpatrick (1999) found that 3,000 tonnes of sulfuric acid exited the Firewood Creek catchment alone annually over a period of approximately thirty years. Russell and McDougall (2003) documented fish kills associated with this acid release. CSR documents record fish kills within the bunded area during the sugarcane development period.

## 3.3 Urban development proposals

Following the failure of the sugarcane cultivation, the site became the focus of several development proposals involving tourist resorts, canal estates and marinas (Brannock Humphreys 1992; Hollingsworth, Dames & Moore 1993; Golder Associates 1996). None of these proceeded and the area continued to degrade.

## 3.4 Recognition of the environmental hazard

A Queensland Government organised public forum was held in 1999 in Cairns at the instigation of the East Trinity Ratepayers' Association, at which investigations by CSIRO, Department of Primary Industries (DPI)-Fisheries and Department of Natural Resources (DNR) were presented. In the report of that workshop (Fitzpatrick, Fox & Hicks 1999) concluded that:

> 'the site cannot be left in its present state. It is imperative that the scientific assessments of remediation options are tightly coupled with other, non-scientific considerations so that neither becomes the sole basis for selecting the ultimate management strategy.'

In May 2000, the Queensland Government purchased the East Trinity property with the aim of addressing the extreme ASS problem on the site and maintaining the green tropical backdrop to Cairns. Queensland Government scientists were then requested to propose a solution to the problem.

## 3.5 Choosing a remediation strategy

At this time, CSIRO researchers had not only documented the extent of the problem, but had conducted a trial on the effect of re-flooding as a remediation technique (Hicks, Bowman & Fitzpatrick 1999). This led to the conclusion that re-flooding would not stop pyrite production or decrease acidity. This trial involved inundation with freshwater for 100 days. In the document presented by CSIRO at the public forum in May 1999, the same researchers stated that it would take 540 recharges of one-metre deep seawater to neutralise the acidity present on the site.

The CSIRO conclusions were very much part of the decision process when the Queensland Government scientists took on the challenge of dealing with ASS hazard at East Trinity. CSIRO calculations of seawater recharge led to the consideration of daily tidal exchange (DTE) as a potential methodology. DTE differs from re-flooding with freshwater for an extended period as occurred in the CSIRO trial. Unlike freshwater, seawater has a buffering capacity to counter acidity, and if this could be enhanced by the addition of a soluble neutralising agent then incoming tides could push the neutralising agents up and across acidified soils and then more neutralising agent could be added on the outgoing tide to add a significant measure of protection to the receiving environment.

Queensland Government scientists discussed the concept with an ASS expert with global experience. It was his view that twice daily seawater flushing enhanced by soluble lime would be an effective way to treat acidity and suppress further pyrite oxidation, but keeping the treated soils in a wet condition was imperative. It was then a matter of devising a reliable way of adding a requisite amount of lime to both incoming and outgoing tides, a means of controlling tidal volumes, and, if necessary, shutting off tidal flow in an emergency situation. With these and other key issues addressed, LATE was proposed to the Queensland government for funding.

The Queensland Government subsequently released the *East Trinity Property Remediation and Management Project Plan* (Queensland Government 2000) and *East Trinity Property Acid Sulfate Soils Remediation Action Plan* (ASSRAP) (Queensland Department of Natural Resources 2000) for public comment in December 2000. Under these plans, Hills Creek catchment would be scientifically assessed and then changes induced by the treatment strategy would be evaluated. The *Demonstration of Management and Rehabilitation of Acid Sulfate Soils at East Trinity, Queensland* (2003) project involved additional scientific researchers and funding under the auspices of the Natural Heritage Trust's Coastal Acid Sulfate Soils Program to assess and demonstrate the Hills Creek LATE trial (Smith *et al* 2003a).

# 4. Lime assisted tidal exchange (LATE) and East Trinity

## 4.1 Rationale

The conventional method of treating ASS is to incorporate agricultural lime into the soil. The depth of oxidation at East Trinity ranges from 1–2 m below the soil surface. Lime incorporation to this depth would therefore be required at rates of up to 600 tonnes of lime per hectare. The cost of conventional agricultural lime-treatment of the affected soils at East Trinity was estimated to be of the order of $60–80 million. Much of the site is heavily vegetated and therefore would need to be cleared. An alternative to just treat the acidity in the watercourses with hydrated lime was estimated to cost $55–70 million and would take at least 25 years.

Rehabilitation of the area by conventional means was judged prohibitively costly, impractical and would not guarantee that the area could be brought to a stabilised condition. An alternative wet option was therefore evaluated. However, controlled, daily tidal flushing augmented by the addition of hydrated lime had not been previously undertaken on the scale proposed at East Trinity, and was not recommended as a primary treatment method in Queensland. Liming directly into streams had been proposed to address acid discharge (Bowman *et al* 2000), but not as a soil remediation technique. Cook *et al* (2000a) argued that the low conductivity of soils would inhibit seawater penetration.

As discussed in the previous section, the decision to consider daily tidal flushing as remediation method was arrived in conceptual terms based on the buffering capacity of seawater enhanced with soluble lime in the light of the known acidity load of the site. Additionally, there were established scientific principles, which supported the decision, namely:

- tidal exchange was expected to hydraulically suppress acid export from the soil and buffer existing water acidity;
- maintenance of daily tidal exchange will raise the level of the permanent water table and hence ultimately halt the process of oxidation of the pyritic layers, thereby preventing the generation of more acid from these areas;
- the addition of hydrated lime ($Ca(OH)_2$) to the waterways will not only enhance the buffering capacity of tidal waters but will counteract the acidity being transported off-site if or when an adverse event is detected; and
- agricultural lime would be incorporated into the surface soil of some areas (where practical) to assist with reducing acid export.

Given an environment of both certain and uncertain knowledge regarding re-introduction of tidal exchange, it was imperative that a comprehensive site assessment was carried out and that practical methodologies with respect to water quality monitoring, water treatment and tide control be in readiness for the commencement of LATE. Figure 7 summarises the implementation steps undertaken at East Trinity, with details following.

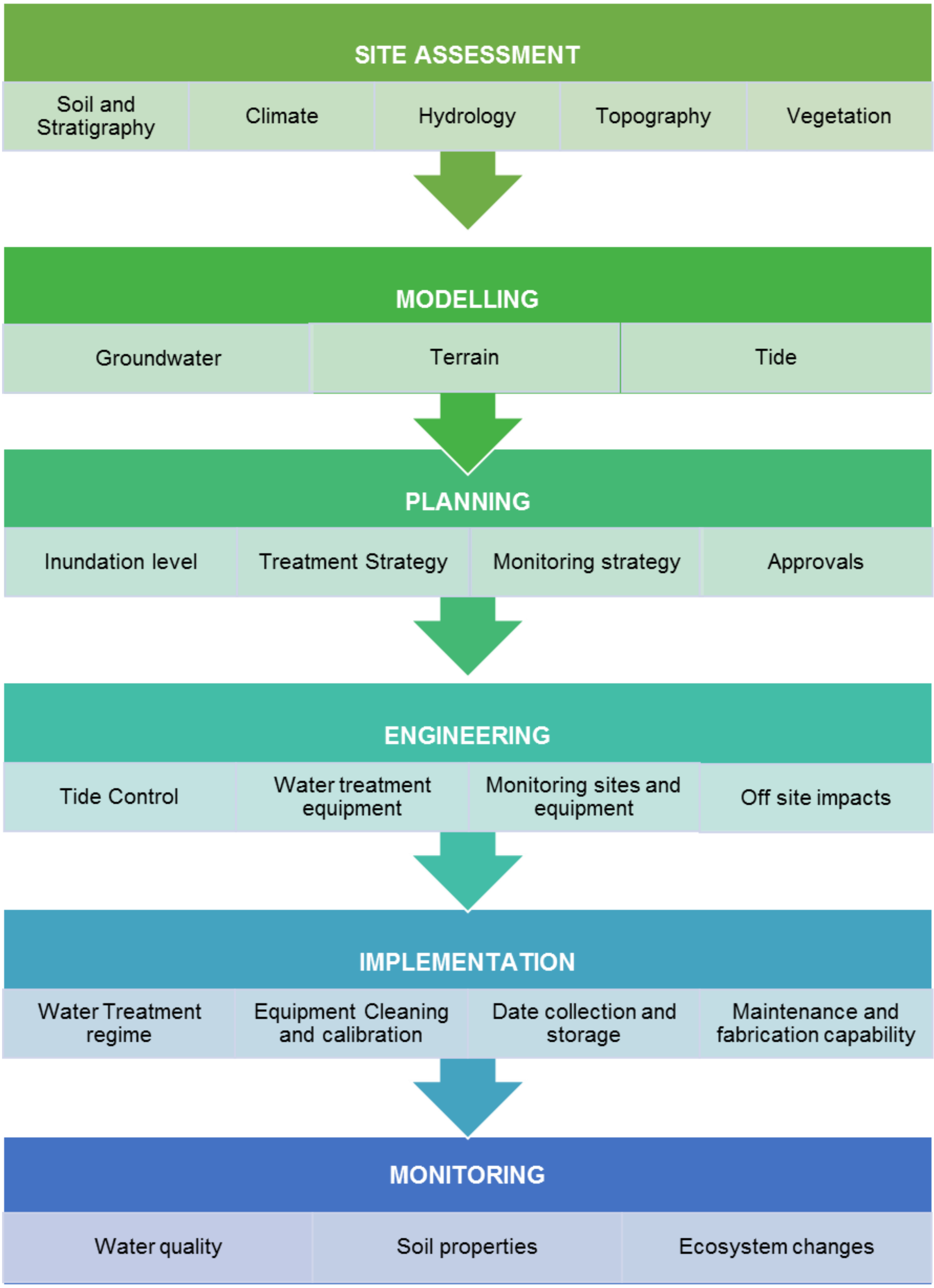


**Figure 7. Sequence of steps required for the application of LATE.**

## 4.2 Planning

### *4.2.1 Understanding the site*

***Soil and stratigraphy***: A comprehensive drilling, sampling and laboratory analysis program was carried out to provide an understanding of surficial soils and underlying stratigraphy (figure 8). The soil assessment determined the extent and degree of acidification of ASS on the site as well as soils of non-marine origin. Cores up to 23 metres were taken down to just into the pre-Holocene layer to establish the sequence and nature of the marine strata. One important conclusion from this work was that the acidified layer did not have low permeability. A stratigraphic/geomorphic model constructed from the deep drilling survey is shown in Appendix 1.

**Figure 8. Deep drilling at East Trinity for ASS and stratigraphic assessment in June 2001.**

***Groundwater*:** Additional deep drilling was carried out well into the pre-Holocene sediments to understand the sequence of aquifers and aquacludes and whether tidal re-flooding will impact important aquifers. Included in this work was an assessment of likely shallow groundwater transmissivity from the site to neighbouring lands.

***Topography*:** Laser altimetry and detailed bathymetry was used to provide an accurate digital elevation model.

***Climate:*** Standard climatic data was compiled, from both the Bureau of Meteorology and neighbours who shared 30 years of rainfall records.

***Vegetation and aquatic fauna**:* While not carried out as preliminary tasks, a commitment was made to carry out base line vegetation and fauna surveys as soon as feasible.

### *4.2.2 Other preparatory issues*

***Tide control**:* The existing tide control gates at East Trinity were top hinged flapgates which prevented tidal entry but allowed freshwater exit and they were in poor condition. In renewing the gates, a design was required that facilitated control over the volume of water entering the site on a daily basis (figure 9).

**Figure 9. Removing the old and installing the new sliding flap gates on Hills Creek to allow better control over tidal exchange.**

***Level of inundation:*** In light of the initial understanding of various site characteristics, it was decided not to allow full tidal re-entry to the site.

Two important issues interacted to determine that a 0.5 m Australian height Datum (AHD) upper inundation level was appropriate. Firstly, the most concentrated area of acidity occurred below this level. Secondly, a study of tidal patterns showed that most tides would reach this level and hence keep soils wet. Land above the 0.5 m level would be wet on fewer tides and would be subject to drying and wetting cycles. Such cycles would continue to produce soil acidity and increase the amount of acidity requiring treatment in outgoing tides.

An additional matter was that saline encroachment into neighbouring banana and sugarcane land would be more likely if higher inundation levels were to occur.

***Tide modelling:*** Tidal modelling was used to determine the setting or aperture of the tide control gates to achieve the desired level of inundation. It was also used to predict inundation levels during times of freshwater flooding.

***Tide prediction and gauge board network:*** Tables of predicted tide heights based on the AHD were compiled from Cairns tide gauging station data and adjusted for time delays relevant to the East Trinity site. Gauge boards to read AHD water heights were placed at strategic locations.

***Water treatment:*** The tide model indicated that large and rapid tidal flows occur at the site. An efficient means of delivering large quantities of hydrated (soluble) lime into incoming and outgoing tidal water was therefore required before re-flooding commenced.

***Surface water monitoring*****:** Water quality monitoring stations were needed at all tidal exit points and at strategic locations across the site. Real time short interval data was required that could be relayed telemetrically to a central database.

***Ground water monitoring:*** To ensure that re-introduced tidal water was not encroaching on deep aquifers, a series of deep monitoring wells were established. Shallow wells were installed near to neighbouring properties to monitor possible encroachment of saline water.

***Neighbour protection:*** Control structures were constructed on drains to prevent the entry of tidal water into adjacent farming land.

***Approvals:*** Approvals required before implementing LATE will vary between jurisdictions and locations, and also with time. Recently, the legislative environment has changed quite quickly.

At East Trinity, we needed several Queensland Government approvals including:

- a dredging approval in order to clear drains and creeks of sand that washed in during the wet season;
- a marine plant permit to remove mangroves to keep visibility around water monitoring stations;
- a general fisheries permit for placing verified QX disease–free oysters in the creeks to remove later for bioassay for metal accumulation;
- a marine park permit for placing and collecting sediment plates outside the bundwall in the marine park; and
- a vegetation management permit under the integrated development assessment system (IDAS) for assessable clearing of native vegetation on freehold land in order to clear the transects for the soils and stratigraphic survey.

As the site borders the Great Barrier Reef World Heritage Area, there were federal government approvals to obtain as well. Several site inspections and meetings with staff from the federal environmental regulator were required in order to get approval and funding for the LATE trial in Hills Creek catchment under the Coastal Acid Sulfate Soils Program of the Natural Heritage Trust. After this was finalised, a referral and decision under the *Environmental Protection and Biodiversity Conservation Act (1999)* were required before LATE could be started in Firewood Creek.

## 4.3 Implementation

### *4.3.1 Tide control and tide gate design*

Major modifications to the existing flap gate structures were required to control the volume of incoming water in order to reach the targeted daily inundation level. Tidal modelling provided a theoretical basis for knowing what invert aperture was required, but what was finally installed to achieve a low cost and reliable control of the invert aperture resulted from an iterative process involving on-site design and manufacture (figure 10).

**Figure 10. Water levels were controlled using manually adjustable flap gates with a moveable hinge allowing the aperture below the gate to be varied.**

As the remediation program progressed, it was recognised that an increase in tidal exchange was required in Firewood and Georges Creek. Figure 11 shows sliding tide gates about to be installed in a new headwall in the upper Firewood Creek area. The resulting increase in tidal exchange has greatly enhanced mangrove re-colonisation.

### *4.3.2 Automated water quality monitoring*

Several key pieces of equipment that were purchased for real-time water monitoring at East Trinity proved unable to cope with the harsh environment. The time interval for cleaning and calibration alone had to be greatly reduced from manufacturer's recommendations. During the early period of LATE, cleaning and calibration of equipment was required more than once a week to deal with extreme iron floc accumulation on sensors (figure 12).

As a result of exhaustive re-design and fabrication on site and in collaboration with suppliers, the water quality monitoring station installations finally established at East Trinity provide a reliable record of water quality (figure 13). However, this environment continues to challenge the adaptive skills of staff.

A large amount of data has been acquired from 10–15 minute interval monitoring from up to 15 stations and stored in a data base. Validation of this data has been a critical aspect of the remediation program.

**Figure 11. Sliding flap gate being installed on the new Firewood Creek headwall to improve tidal exchange in the upper reaches of the catchment.**


**Figure 12. Iron coated water quality sensors.**


**Figure 13. Water quality monitoring station at the Firewood Creek bundwall.**

### *4.3.3 Water treatment*

The initial device used to treat in and outgoing tidal water with hydrated lime was an off the shelf machine used in the mining industry (figure 14). This was a labour intensive device, which had to be constantly manned. An automated machine able to handle 1 tonne bulk hydrated lime bags was subsequently built in collaboration with a commercial organisation following an iterative process (figure 15 and 16).

The initial period of water treatment was guided by a schedule of optimal treatment times based on predicted tide data analysis and surveillance of water quality monitoring data. During the first years of treatment, as well as augmenting incoming water with hydrated lime, outgoing water (pH as low 2.5 in the upper catchment) treatment was also required in order to ensure exiting water was above pH 6. Treatment of incoming water only occurred when the retreating water quality stabilised above pH 6.


**Figure 14. The original manual machine for adding 20 kg bags of hydrated lime to surface waters.**


**Figure 15. Trialling the automated liming machine.**

**Figure 16. Adding hydrated lime slurry to Firewood Creek on an incoming tide.**

### *4.3.4 Groundwater monitoring*

Purging and testing of wells was carried out at frequent intervals initially until stable patterns were observed. Less frequent intervals have subsequently been maintained. Parameters of particular interest in ASS environments include: pH, Electrical conductivity (EC), dissolved oxygen (DO), temperature, chloride to sulfate ratio ($Cl:SO_4$), total iron (Fe), ferrous ion ($Fe^{2+}$), arsenic (As) and aluminium (Al).

### *4.3.5 Strategic water quality sampling*

Sampling is carried out over a full exiting tide cycle, simultaneously at a number of locations. The highest amplitude tides each wet season and dry season are selected in order to sample the worst water quality. Samples are collected at regular intervals until the tide turns, and sub-samples are pre-treated to stabilise any metals prior to despatch for laboratory analysis. Ad hoc sampling is also conducted in response to site conditions and observations.

### *4.3.6 Soil redox monitoring*

To assess the response in soil parameters to LATE, repeat sampling of soil profiles originally sampled before the commencement of LATE are carried out at selected intervals. Redox monitoring sites were established to measure the fluctuation in oxidising and reducing conditions down the soil profile over time, however, many of the sites are no longer safely accessible, with mangrove fern and mangrove recruits creating perfect habitat for crocodiles and poor workplace health and safety (WH&S) conditions.

### 4.3.7 Sediment sampling

By sampling bottom sediments from inside the treated area and from the receiving environment, changes in the levels and form of potentially toxic metals can be assessed.

### 4.3.8 Vegetation and aquatic biota monitoring

Periodic surveys of vegetation and aquatic biota have documented important responses to LATE. Additionally, photographs taken at set intervals at fixed locations across the site have provided a graphic portrayal of vegetation change.

### 4.3.9 Freshwater inundation strategy

An additional measure to augment LATE was successfully implemented at East Trinity at a point on the site at the extreme limit of tidal inundation, where large volumes of freshwater intermixed with salt water. The acidified soils at this point were not responding to LATE. The solution to the problem was to create a pondage through which a permanent low volume freshwater flow is maintained. This was achieved by placing a bund downstream from a point on a permanent stream from which water is piped. The bund has an outlet point at which a slide gate is installed to control flow volume. Lime can be added to the incoming water to promote initial soil remediation processes. However, similar chemical and biological processes are maintained by permanent inundation

### 4.3.10 Skills, workshop and workplace health and safety

The successful implementation of the LATE strategy has largely resulted from the ability to innovate and adapt to changing circumstances. This has required a range of both scientific and trade skills, an understanding of WH&S processes, and a well-equipped workshop. An important part of this has been the low cost provision of access roads and crocodile protection facilities around a large number of operational locations across the site.

Safety precautions and procedures, equipment and personal protective equipment requirements that are appropriate to the site, identified hazards, remediation and monitoring activities need to be documented in risk assessments, standard operating procedures and emergency plans, and implemented in a timely manner that does not impede remediation activities.

# 5. Environmental responses to LATE

## 5.1 Soils

The toxic water that flowed from the site prior to remediation was a classic by-product of drained acid sulfate soils. Prior to remediation, these soils were sampled and analysed in the laboratory. They were re-assessed in 2013 and reported in Smith, Manders and Brough (2016). Titratable actual acidity (TAA) is a comprehensive laboratory method that accounts for all forms of readily available acidity – hydrogen, iron and aluminium, but is expressed in units of equivalent hydrogen ions. Lime assisted tidal exchange (LATE) has decreased TAA by 89% from 66 to 7 mol $H^+$/tonne of soil. A more familiar measure is soil pH which estimates only hydrogen. Field pH is now at 6 to 7, whereas it was between 2.5 and 4 prior to remediation.

Jarosite is another by-product of the oxidation of pyrite, expressed a yellow soil mottle, and was observed in all soil profiles prior to LATE. The literature describes jarosite (which we quantify as retained acidity) as being persistent in the environment. The 2013 survey recorded a substantial decrease in jarosite in the treated areas. This, together with the substantial increase in sulfide levels, supports the contention of Keene *et al* (2010) that jarosite has broken down and pyrite is reforming in a process termed reductive dissolution. All results of the 2013 soil assessment are provided in Smith, Manders and Brough (2016) and summarised in table 2 and figure 17.

Table 2 contains the summary of soil property changes for pre- and post-LATE data for TAA and field pH based on single profile values calculated from the equal area spline. For both TAA and pH the plots portray manifest improvement in the soils of the treated area. Figure 17 displays the range of results for the selected soil parameters for the LATE-treated areas only. It is based on every value above the reduced level in every profile, as opposed to a single spline value for the whole soil profile, as depicted in table 2.

**Table 2. Change in soil properties in response to LATE (spline values).**

| UNITS[1] for TAA, NAS and S | Median value from all sites in the LATE treated area[2] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | TAA | | NAS | | S | | $pH_f$ | |
| | Pre | Post | Pre | Post | Pre | Post | Pre | Post |
| mol $H^+$/t | 0.107 | 0.012 | 0.231 | 0.034 | 0.178 | 0.292 | 3.9 | 6.5 |
| %S | 67 | 7 | 144 | 21 | 111 | 182 | | |

[1]TAA: Total actual acidity; NAS: net acid soluble sulfur (jarosite); S: Sulfide; $pH_F$: field pH.
[2] Based on the equal area spline calculation using all values above the reduced layer for each profile.

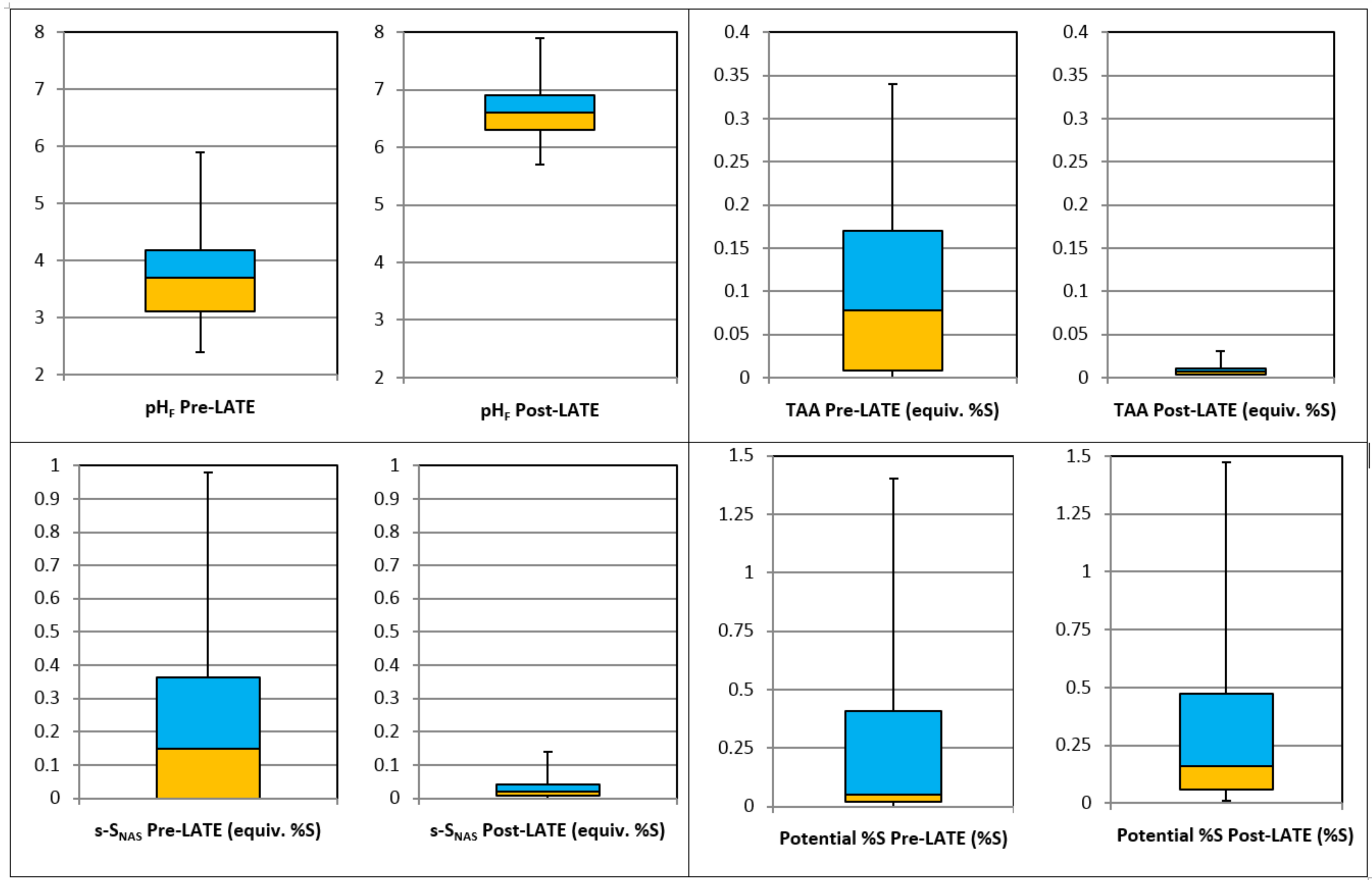


**Figure 17. Distribution of pre- and post-LATE raw values throughout the profile above the reduced layer for pH and selected analytes within treated areas**. The box shows the 25th and 75th percentiles and median, and the whiskers shows the values at the 0 and 100th percentiles, where pH$_F$ is field pH; TAA is titratable actual acidity; s-S$_{NAS}$ is retained acidity (or jarosite quantified as retained acidity); potential %S is potential sulfidic acidity.

The changes in soils brought about by LATE have been dramatic and unprecedented. What was previously known about ASS chemistry indicated that the remediation process would take many decades, or that it may not occur to any significant extent. It was therefore important that concurrent with the remediation program, research was carried out that sought to understand the fundamental chemistry associated with daily tidal flushing. This research has brought about a scientific paradigm shift in the understanding of ASS chemistry in the context of tidal exchange. Discussed in more detail in section 6, this research has shown that changes brought about by LATE at East Trinity revolve around the interaction of soil biota and soil chemistry, the dynamics of tidal hydrology and its impact on the very dynamic movement of iron species across the tidal gradient, from less than zero to 0.5 m AHD.

### *5.1.1 Freshwater treatment*

Not all of the land below 0.5 m AHD has been treated by LATE. The area referred to as the peat swamp occurs on the eastern margin of the site adjacent to Hills Creek.

This area was not responding to LATE. It was hypothesized that being located at the interface of tidal and freshwater, and distant from the mouth of the creek and the hydrated lime treatment point, the daily tidal exchange process was having little effect on the peat swamp soils.

Water from Hills Creek was diverted into the upper part of the swamp through a pipe and drain system, and a containment bund was constructed across the lower boundary of the swamp. A slide gate in the bund allows water to slowly return to Hills Creek and hence maintain flow through the swamp. While not responding as rapidly as LATE-treated soils, the peat swamp soils have now responded well to permanent freshwater inundation.

Freshwater inundation has brought about a dramatic change to the peat swamp with respect to soil pH (figure 18a) and vegetation (figure 19). However, laboratory results indicate that these soils have not responded in the same way as the LATE-treated soils. This is explained in detail in Smith, Manders and Brough (2016), but in summary, the appreciable drop in pH from field to laboratory $pH_{KCl}$ (figure 18b) indicates that the peat swamp samples still contained acid volatile sulfur compounds which rapidly oxidise subsequent to sampling and prior to analysis. Longer term LATE-treated soils show little difference in field and laboratory pH, other than what would be expected in going from a water extract to a KCl extract. However, the peat swamp soils align with the LATE-treated soils with respect to the dissolution of jarosite and the accumulation of sulfur.

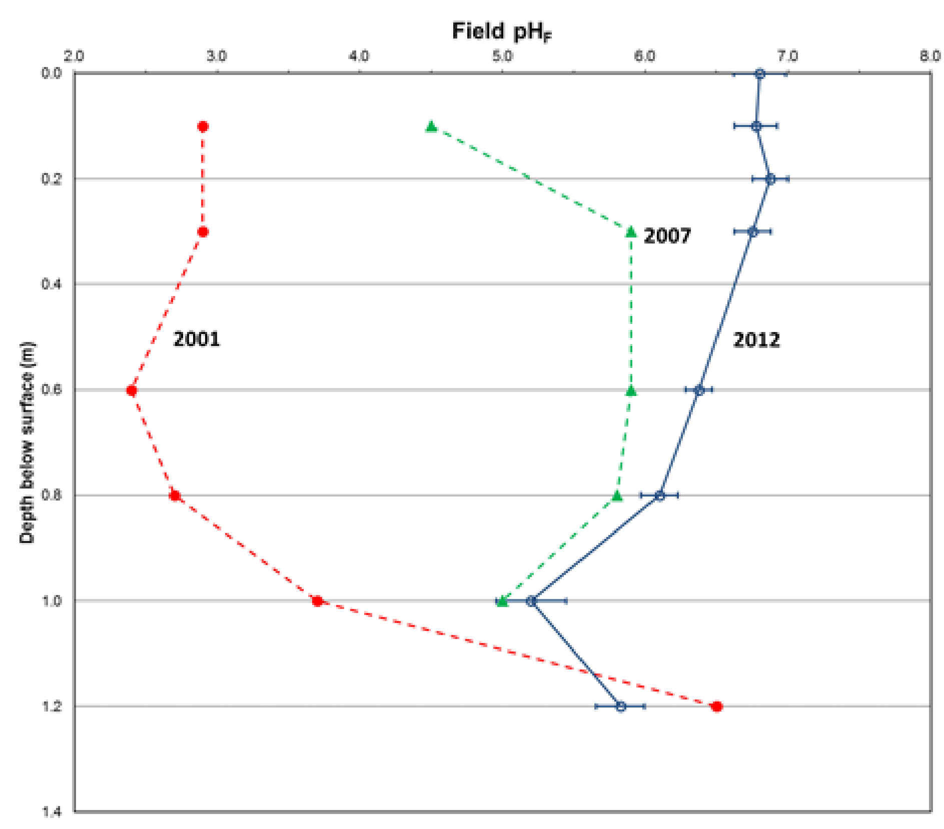


**Figure 18a. Site 86, Peat Swamp before and after freshwater inundation.** $pH_F$ (field measurement 1:5 water)

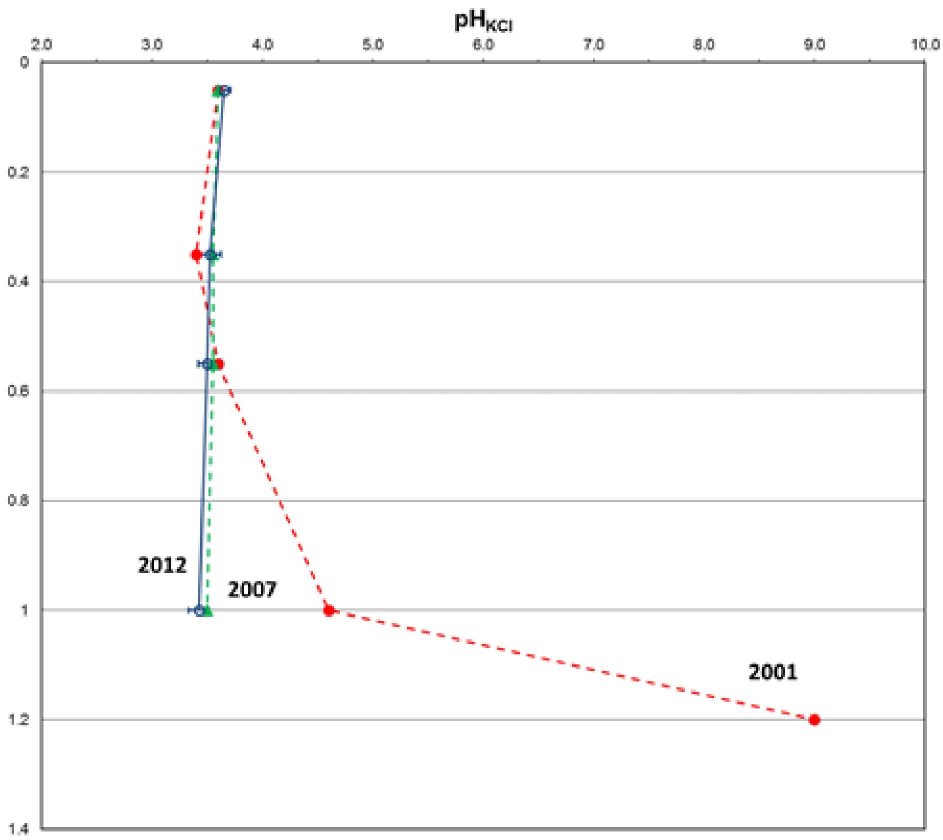


**Figure 18b. Site 86, Peat Swamp before and after freshwater inundation**. $pH_{KCl}$ (laboratory measurement).


**Figure 19. Visual change to Hills Creek Peat Swamp over time in response to freshwater inundation**. a. Aerial view of the Peat Swamp in 2006 showing *Melaleuca* die off and iron staining. b. Aerial view of Peat Swamp 2013 showing vegetation recovery and absence of iron staining. c. Typical understorey view in 2006 showing highly acidic surface water and iron stained soils. d. Same view as c in May 2015.

## 5.2 Water quality

Water quality at the East Trinity site has responded to the changes in the soil chemistry that LATE has brought about. Prior to the commencement of remediation activities pH of drain water was extreme, often as low as pH 3 (figure 20). This is in keeping with early reports on the water quality in Firewood Creek, which document a toxic, acidic freshwater/brackish dominated system (Hicks, Bowman & Fitzpatrick 1999; Russell & Helmke 2002). Under LATE and an attenuated estuarine tidal regime, water quality parameters have improved markedly.


**Figure 20. Acid drain water in Firewood Creek catchment before LATE commenced.**

Water quality monitoring is an integral part of the LATE strategy, providing early warning against discharge of poor quality water from the site, indicating acidic areas that require targeted treatment, measuring the effectiveness of the remediation works, and providing background data for associated scientific studies. A network of surface water quality monitoring stations have been located across the site since 2001 (figure 21). Each records pH, electrical conductivity and temperature at 10-minute intervals. Stations have data logging and telemetric capability, and automatically download to the DES network. The stations located at the bundwall also record dissolved oxygen and water height as water flows in and out of the site. Water samples are taken for laboratory analysis at an extended number of locations across the site in both the wet and dry season, and in response to onsite events and observations.

### *5.2.1 Attenuation of acidity*

The quality of water exiting the East Trinity site has improved over time in response to LATE. Plots of the daily minimum pH value averaged over 30 days, give an indication of the trends in the worst water quality (figure 22). For all stations a clear tidal signal is visible, and large rainfall events result in extreme freshwater (~pH 6) flooding and temporary reduction in pH. Figure 22 shows the increase in pH over time (indicating a reduction in acidity) of water exiting the site.

Hills Creek received hydrated lime treatment on both incoming and outgoing tides from August 2001. This was maintained though the commencement of controlled LATE (2003) to ensure that the pH of exiting water remained above 6. The trend line (Hills Ck bund) shows this to be the case with the pH dropping to between 6 and 6.5 in early years, but by 2014, the lowest pH is maintained around pH 7 by passive LATE. The data for George Creek (George Ck bund) is from new floodgates installed in 2009 to improve tidal exchange and reconnect the former creek channel that was blocked nearly 40 years ago by the construction of the bundwall.


**Figure 21. Map of the East Trinity site showing some of the 12 water monitoring locations, drains and creeks.**

Acidic water (pH <5) at the original Firewood Creek floodgates (Firewood Ck bund) prior to hydrated lime augmentation and controlled tidal exchange (commencing in 2006), becomes neutral to alkaline (pH 7–7.5) over time under LATE. As a consequence of repeated floodgate vandalism, some opportunistic tidal exchange occurred prior to the start of controlled LATE in 2006. There was also some hydrated lime treatment of the main Firewood Creek channel. Firewood Ck bund 2 in this figure is a second set of tide control gates installed in the upper reaches of Firewood Creek in 2009 to improve tidal exchange. A similar trend of increasing pH with time is observed here.

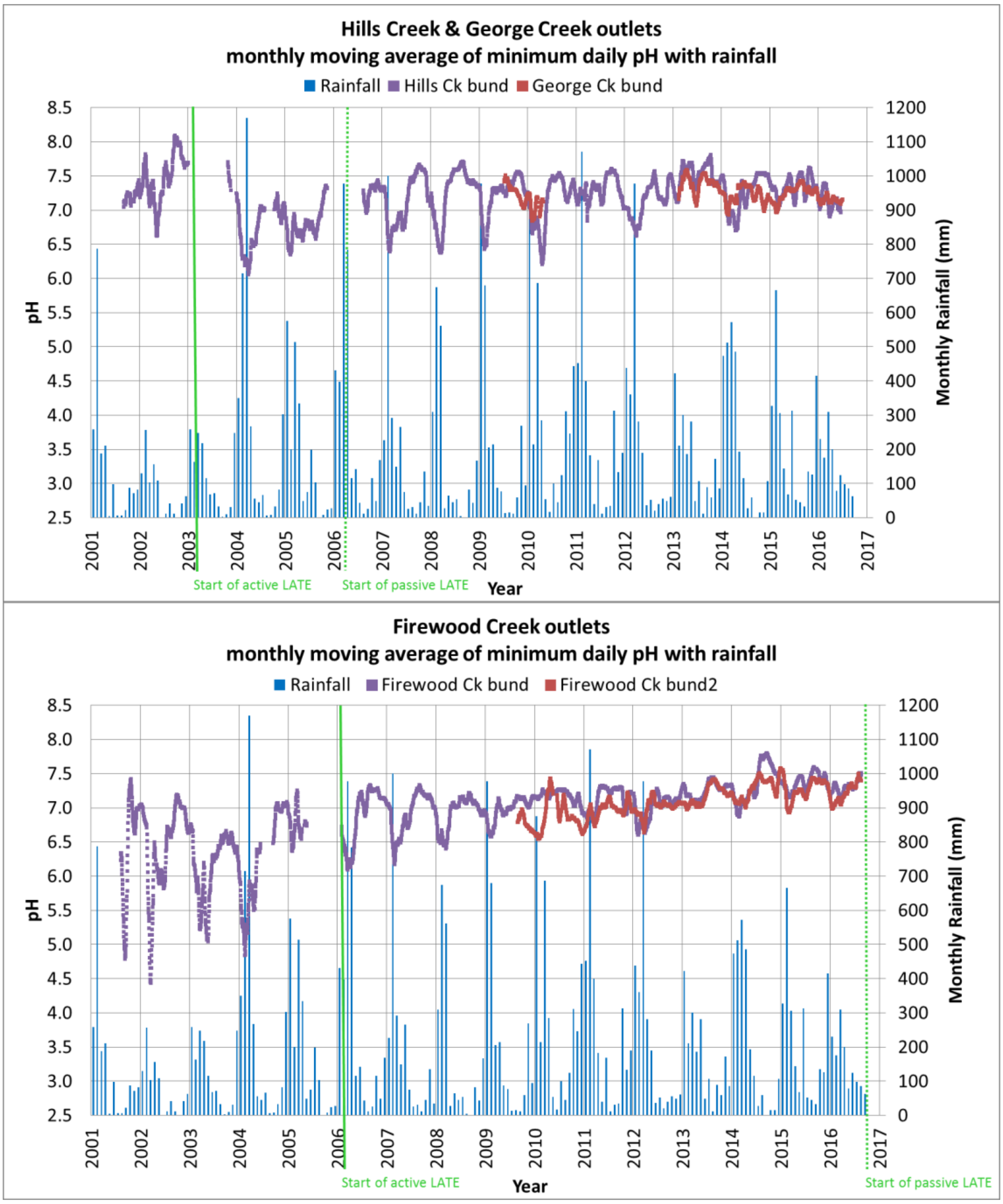


**Figure 22. Time series of minimum pH (calculated as a monthly average) with monthly rainfall at the East Trinity bundwall (outlet) stations.**

A more dramatic improvement in the 30-day average of the daily minimum pH value over time is seen at the Smoko Road monitoring station (figure 23). This station records data on water leaving Magazine Creek as it enters the Firewood Creek system through a large drain. Again, a tidal signal and pH decrease associated with large rainfall events is evident. The extremely low initial pH at the Smoko Road monitoring point (pH<4) increases as soil acidity in the area decreases over time in response to LATE.

Figure 23 also highlights the effectiveness of active LATE in maintaining the pH of exiting waters above pH 6, despite highly acidified (low pH) inputs from the upper catchment areas.

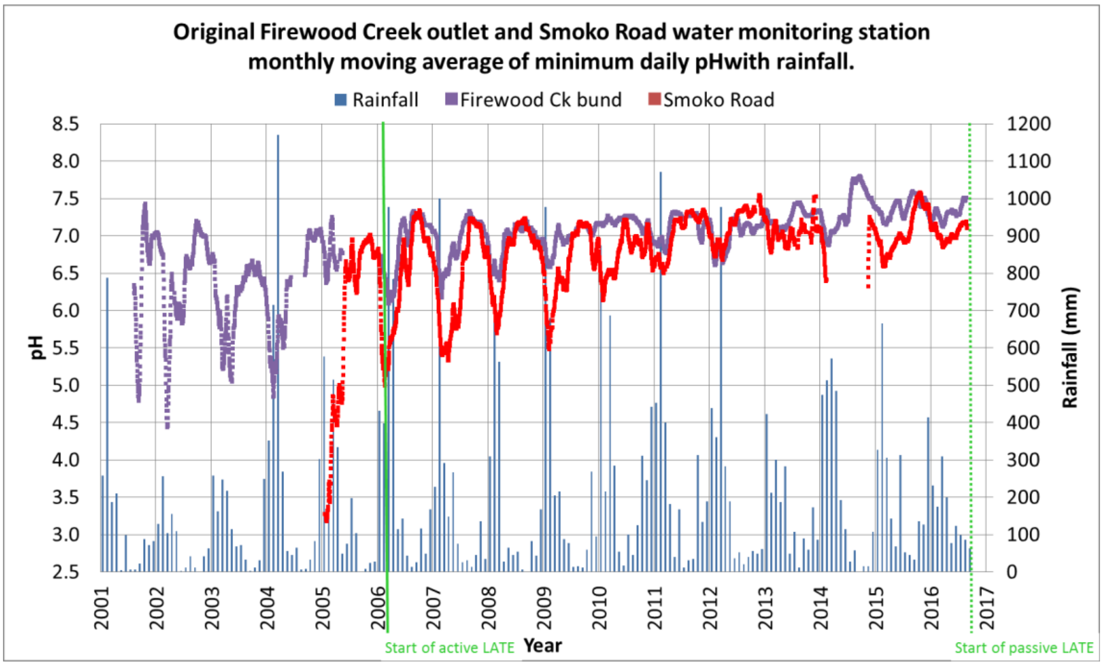


**Figure 23. Rainfall and pH at Firewood Creek bundwall and Smoko Road water monitoring stations showing the attenuation of acidity within the site and over time.**

### *5.2.2 Attenuation of metals*

An integral part of the LATE remediation strategy is the precipitation of metals within the confines of the East Trinity site, rather than allowing them to remain in solution and exit to Trinity Inlet with the ebb tide.

Poor water quality in Firewood Creek has been well-documented (Russell 1980; Olsen 1983; Russell & Helmke 2002; Russell & McDougall 2003). Prior to the commencement of LATE in the Firewood Creek catchment there was opportunistic tidal exchange (through a repeatedly vandalised floodgate) as well as some hydrated lime treatment of the main Firewood Creek channel. However, it was not controlled, active lime assisted tidal exchange. After more than a decade of active LATE, the construction of additional floodgates to improve tidal exchange (July 2009) and incremental increases in the maximum level of tidal exchange, a trial of passive LATE for maintenance of water quality on Firewood Creek commenced in October 2016.

The following graphs show key metals being attenuated along 450 m of Firewood Creek between the Firewood Creek upper monitoring station and the Firewood Creek bundwall station, and over time from 2001–2016 (Figures 24–27), in response to LATE. These graphs also highlight the mobilisation of dissolved iron and other metals at the commencement of LATE. Reductive dissolution of jarosite (and other oxidation minerals) releases dissolved iron (and other metals) into the soil pore water (Keene *et al* 2012), and tidal forcing and cyclic reversal of hydraulic gradients generates substantial pore water exchange with the overlying waters (Johnston *et al* 2010).

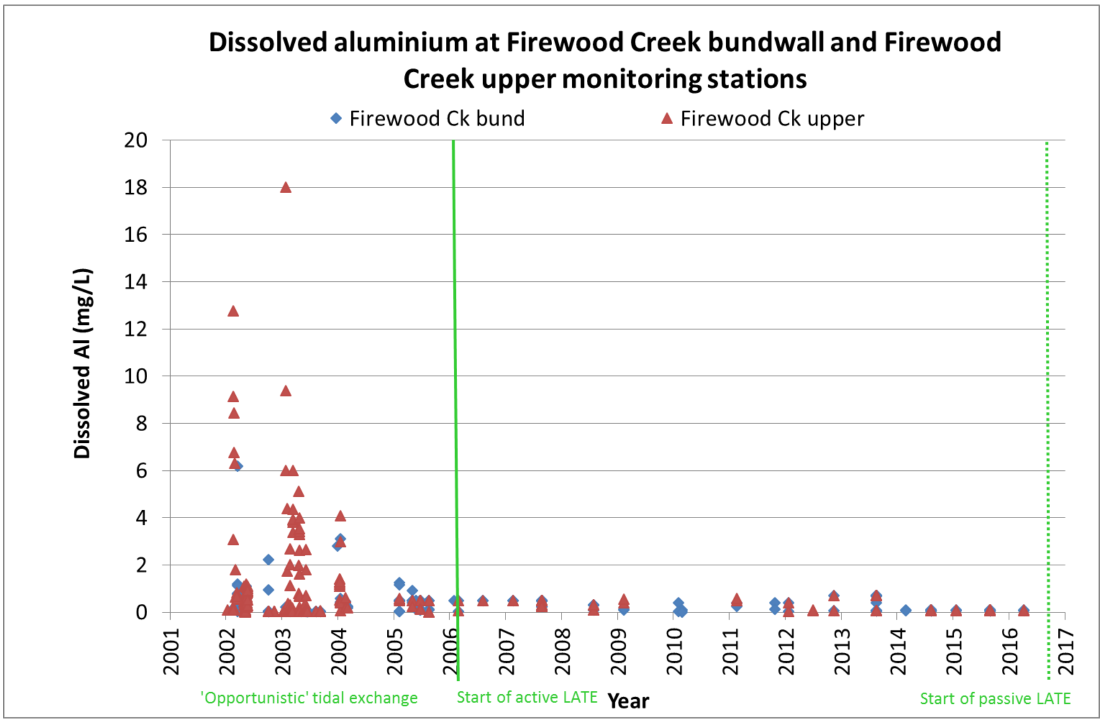


**Figure 24. Attenuation of dissolved aluminium along Firewood Creek and over time.**

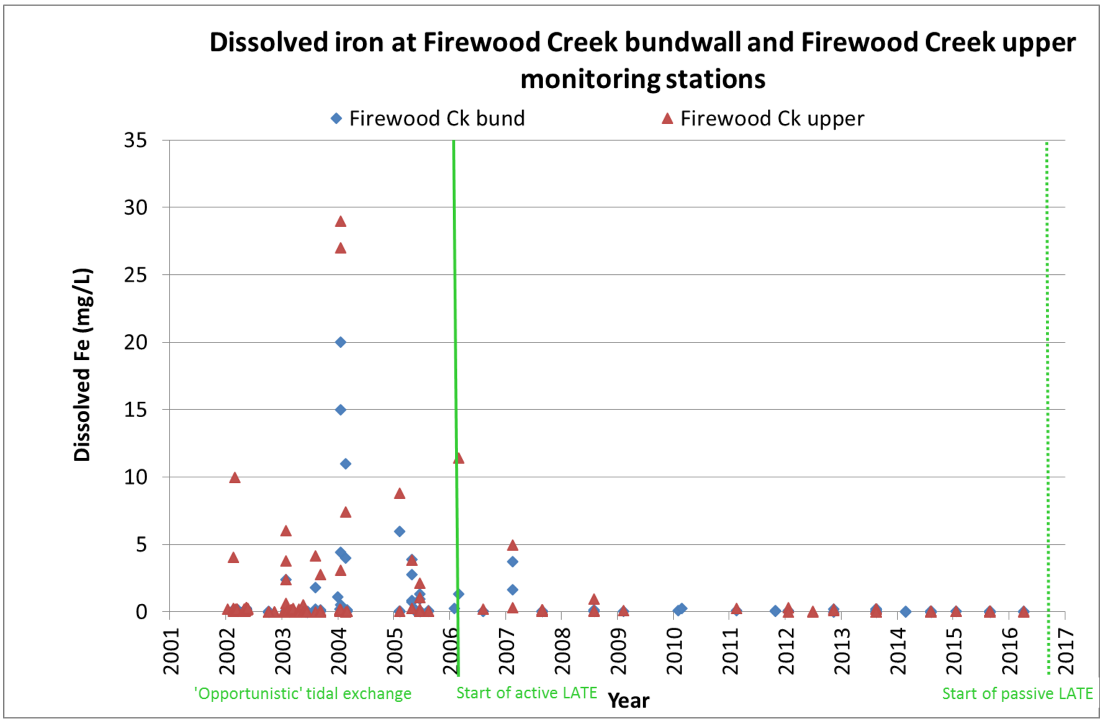


**Figure 25. Attenuation of dissolved iron along Firewood Creek and over time.**

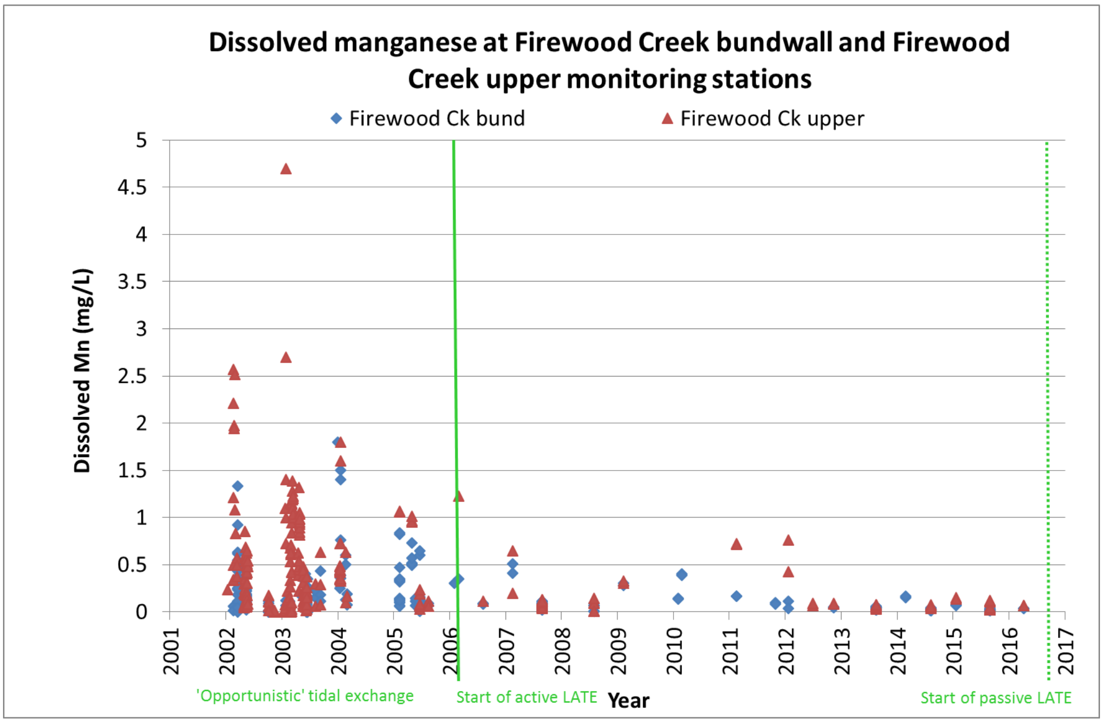


**Figure 26. Attenuation of dissolved manganese along Firewood Creek and over time.**

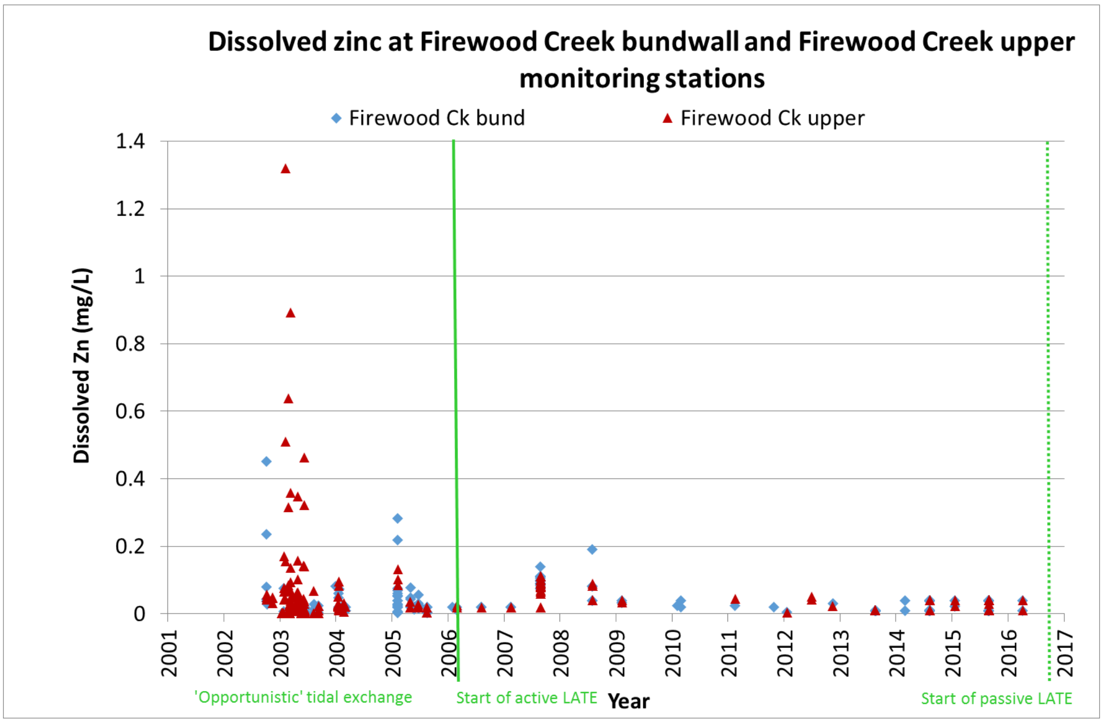


**Figure 27. Attenuation of dissolved zinc along Firewood Creek and over time.**

Similarly, figure 28 shows the attenuation of dissolved iron between the upper catchment drain (drain d32) and the Hills Creek bundwall (Hills Ck bund) water monitoring stations. The exception to this is the elevated dissolved iron levels at the bundwall seen during February 2005 when a temporary break in hydrated lime treatment occurred at Hills Creek, resulting in poor quality water exiting the site. Treatment recommenced in mid-2005.

### *5.2.3 Freshwater treatment*

As mentioned in section 5.1, the soils in the peat swamp at the upper limit of tidal inundation were not responding to LATE due to poor tidal exchange. As a result, the stagnant end of the drain in that location (drain d8) recorded a total iron level of 410 mg/L and titratable acidity of 1478 mg/L $CaCO_3$ to pH 8.3 (January 2003). The monitoring station at the outfall of drain d32 (in figure 28) to Hills Creek remained acidic (pH <4) unless the tide was pushing hydrated lime treated water back up the drain (figure 28). A trial involving freshwater inundation was therefore commenced by constructing 2 ponded areas through which freshwater from Hills Creek was circulated. These were completed in late 2010.

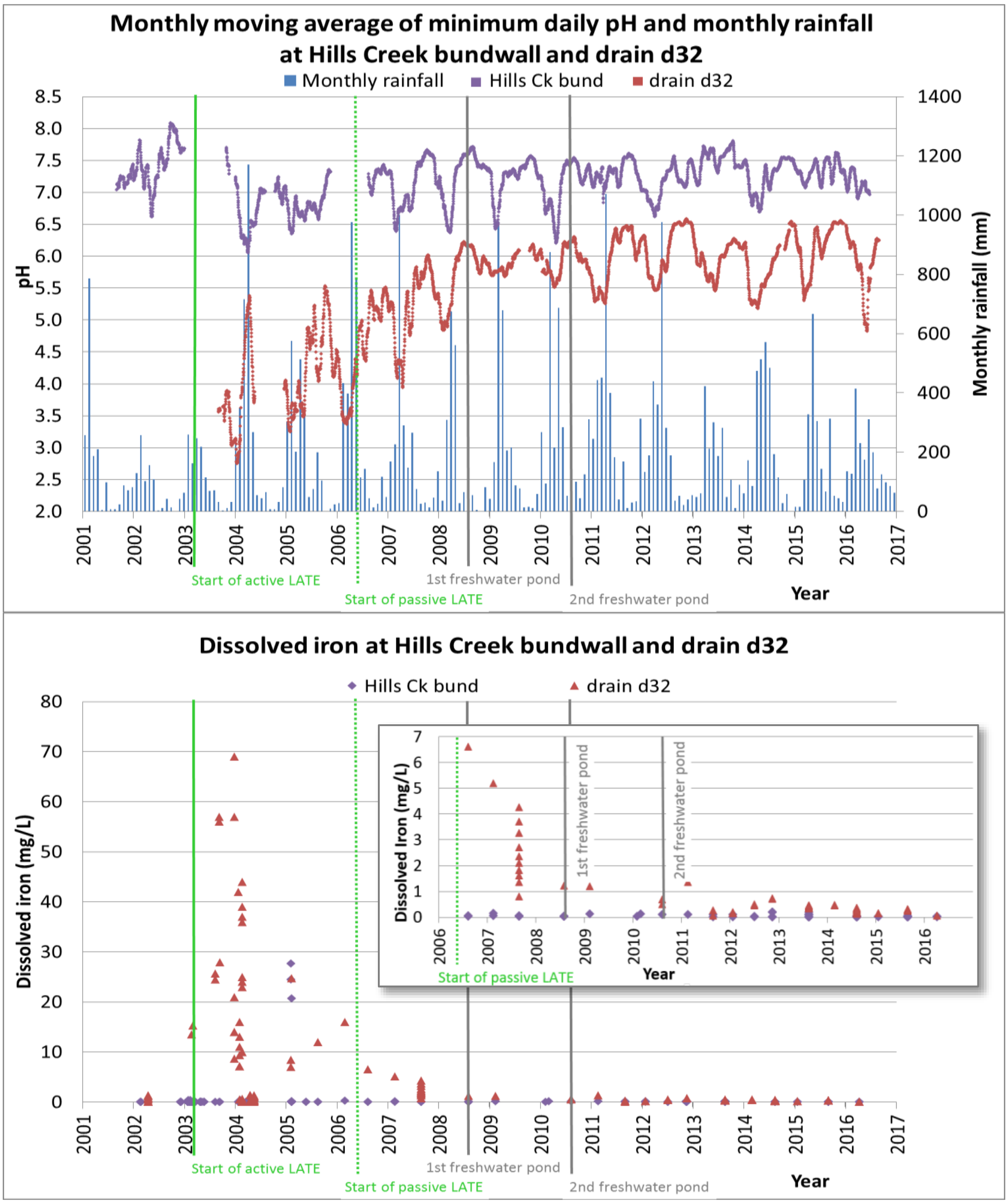


**Figure 28. 30 day moving average of daily minimum pH and monthly rainfall, and dissolved iron at the Hills Creek bundwall and at drain d32 which drains an area formerly at the upper limit of tidal exchange, and now under freshwater inundation**. The inset shows details of changes in dissolved iron since the introduction of freshwater treatment, which are otherwise lost in the scale of the graph.

The water in drain d32 now rarely drops below pH 5 (figure 28). Despite the permanent presence of water, the *Melaleucas* in the ponded areas are still alive, unlike those in the areas receiving seawater inundation. Wet season pH drops associated with rainfall indicate that some soil acidity is still being mobilised, but not to the same extent as before the freshwater swamp was established. Similarly, dissolved iron is attenuated over time and within the site.

## 5.3 Vegetation

In its natural state up until the early 1970s East Trinity was a functioning tidal wetland environment containing seven distinct mangrove communities, as well as samphire flats, chenier sand ridges and some coastal lowland rainforest (Newton, Addicott & Bannink 2014). Analysis of 1952 black and white aerial photography (Werren 1995) before the development of the East Trinity site shows mangrove associations across the majority of the site (figure 29). Substantial parts of the East Trinity site were unsuited to mangrove growth. Most of these areas supported samphire species (claypan/samphire units), with some areas to the north of Hills Creek mapped as Landward Associations and Landward Avicennia (Werren 1995).

The 1970's land clearing, exclusion of tidal water, drainage and subsequent acidification produced major changes in the vegetation (Newton, Addicott & Bannink 2014). Samphire communities were heavily degraded and all but one of the mangrove communities (*Lumnitzera racemosa* and *Avicennia marina)* disappeared. *Melaleuca leucadendra* colonised many areas that were previously mangrove dominated, even where the soil pH was below pH 3. The lowland forest in the elevated north-eastern section of the property remained largely unaffected (Newton, Addicott & Bannink 2014).

Werren (1995) states that mangrove production for the whole of Trinity Inlet was estimated to be between 66–174 tonnes of carbon per day. On that basis, the mangroves that were lost from the East Trinity site as a result of development may have contributed close to 5 percent of the Trinity Inlet production.

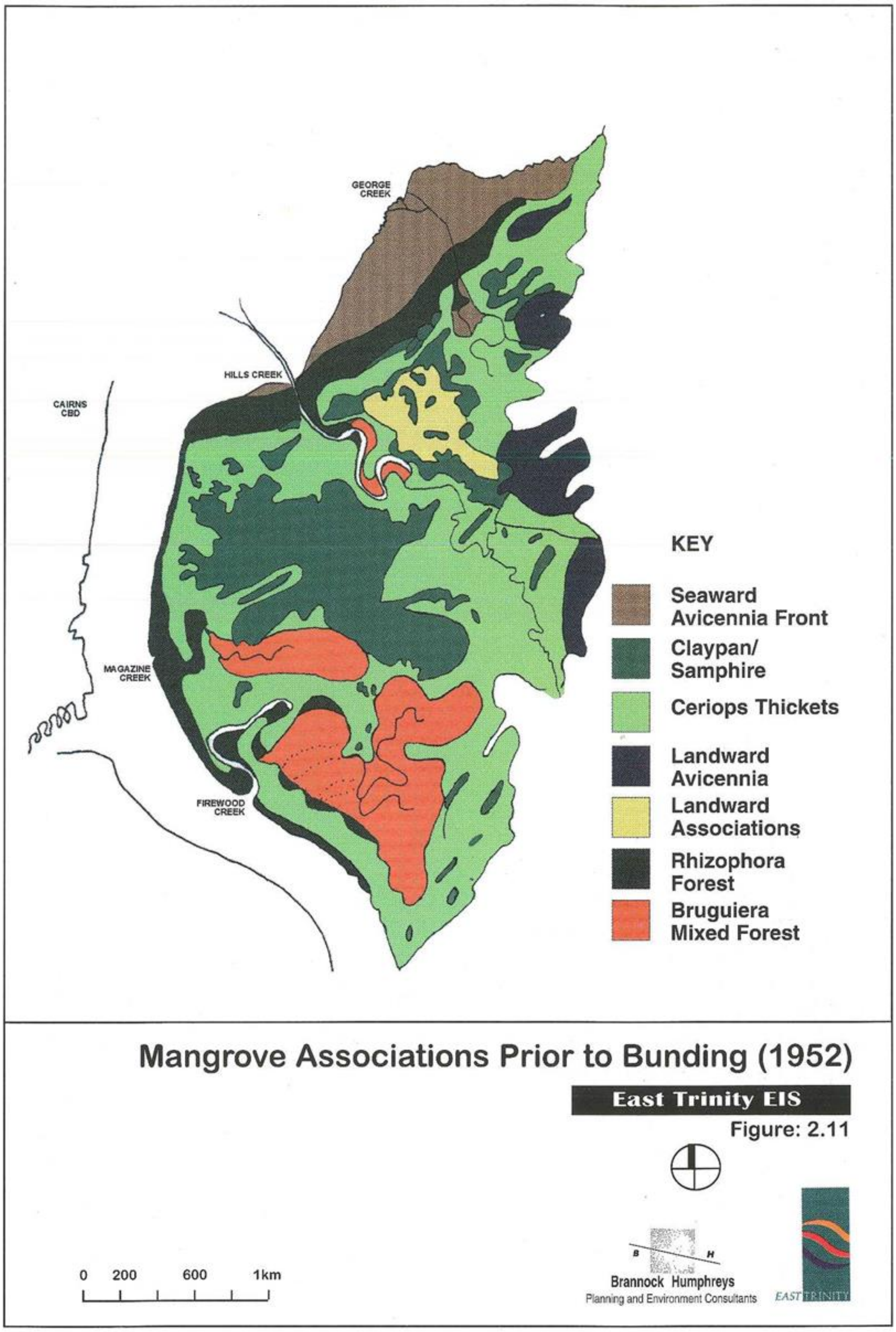


**Figure 29. Mangrove associations prior to bunding (based on 1952 aerial photo interpretation)** (Werren 1995).

### 5.3.1 Vegetation monitoring surveys

The highlights of vegetation surveys carried out in 2002, 2006, 2008 and 2014 follow.

Stanton and Stanton (2002) at the commencement of LATE:

- Most communities were secondary, bearing no resemblance to original vegetation in floristics or structure.
- The exception being the lowland forest in the north east of the site. This included impressive stands of *Melaleuca leucadendra* forest and a small area of vine forest dominated by feather palms, a community which is rare and extremely fragmented within the Wet Tropical lowlands.
- Of the regrowth and altered communities that dominate the site, *Melaleuca leucadendra* was one of the dominant species, found in a range of structures from tall open forest to low woodland and open woodland.
- Areas of dieback of *Melaleuca leucadendra*, attributed to unfavourable soil conditions due to LATE, were rapidly advancing so that the extent observed during site visits in 2002 appeared to be considerably greater than the area represented on the 2001 aerial photos.

Stanton (2006) at the commencement of passive LATE in the Hills Creek system, and active LATE in Firewood Creek catchment:

- Large areas of *Melaleuca leucadendra* communities were dying back, with mangrove fern *Acrostichum aureum* forming dense ground cover on the margins, and rapidly colonising bare areas.
- Early succession to mangrove communities is continuing under the Melaleucas that died before 2002, with *Avicennia marina* often a prominent shrub beneath the dead trunks of the former *Melaleuca* forest.

3D Environmental (2009) as passive LATE continued in Hills Creek catchment and active LATE in Firewood Creek system:

- Colonising halophytic forblands, ferns and mangrove shrublands had increased by 50 hectares or 6% of the site at the expense of exotic grassland communities and colonisation of *Melaleuca* forest areas where mangroves originally occurred.
- A range of woodland, open forest, grassland and vineland communities were in the process of structural and floristic adaptation to the changing edaphic conditions.
- There may be changes to the structure and composition of the natural mangrove communities within the site, which may be caused by changes to the tidal regime and increased fluctuations in fresh water.

Newton, Addicott and Bannink (2014) under passive LATE in Hills Creek catchment and active LATE in the Firewood system:

- The changes in vegetation noted in earlier reports continue to occur.
- Notable growth in the area of *Acrostichum aureum* (mangrove fern) fernlands and mangrove communities containing *Avicennia marina, Exocoecaria agallocha, Brugiera gymnorhyza,* and *Lumnitzera racemose*.
- The above has occurred into former halophytic forblands, mixed forbland-grassland-fernland communities and areas of former and recent *Melaleuca leucadendra* dieback.

- While *Acrostichum aureum* fernlands continue to turn into either mangroves or low *Melaleuca leucadendra* woodlands their net overall area has increased.
- *Melaleuca leucadendra* shrublands have increased particularly into former grasslands (12 hectares), however, there are now larger areas of more mature *Melaleuca leucadendra* low woodland and open woodlands. Intuitively, they are maturing from shrublands of the same species mapped in 2008 (4 hectares), but they have also appeared in areas previously mapped as grassland (17 hectares) and *Acrostichum aureum* (12 hectares).
- The most notable reduction in vegetation has been in the grasslands, particularly those dominated by exotic species (down by 54 hectares) or *Imperata cylindrica* (down by 31 hectares). These have been largely invaded by *Melaleuca leucadendra*, turning into shrublands and low woodlands and by the native grass *Phragmites karka*. Grasslands of the latter have increased in area, sometimes in association with *Acrostichum aureum* (17 hecatres).
- The dieback of open forests of *Melaleuca leucadendra* impacted by the tidal areas continues, with some stands that were healthy in 2008 now in decline (27-hectare loss). *Acrostichum aureum* fernlands now occupy much of the earlier mapped dieback of *Melaleuca leucadendra* (15-hectare change).
- The mosaic of forest types mapped in the north-east of the site remains unaffected by the reclamation. This area contains of concern regional ecosystems 7.2.8 and 7.3.25 and a small area of endangered regional ecosystem 7.3.6. Small patches of regional ecosystem 7.2.8 are found in four other small areas. The endangered regional ecosystem 7.3.12 occurs along Hills Creek (Newton, Addicott & Bannink 2014).

The secondary communities at East Trinity are very dynamic and complex (figures 30–33). Changes in management regime are undoubtedly influencing the direction and speed of the changes. Under the current tidal exchange regime (consistently wetting to 0.5 m AHD), it is unlikely that the property will be covered in halophytic and mangrove communities to the extent it once was. The last 12 years of mapping also shows that under the current management the remnant regional ecosystems will be maintained, some secondary communities may eventually resemble those that existed before clearing and in more elevated areas of grassland and non-estuarine woodland communities may persist. Continued monitoring and mapping of the East Trinity property would document the nature of these future changes (Newton, Addicott & Bannink 2014).

Selected paired photos showing vegetation changes brought about by LATE:

**Figure 30. Aerial view of the southern Firewood Creek area in 2006 as active LATE commenced in Firewood Creek, and 2015.**

**Figure 31. Aerial view of the Firewood Creek oxbow in 2010 and 2015 while Firewood Creek was undergoing active LATE.**


**Figure 32. Looking upstream from the Firewood Upper monitoring station in 2003 before active LATE commenced and in 2016 just before the start of passive LATE.**

**Figure 33. Drain d10 in 2006 when active LATE commenced in Firewood Creek and 2016 just before the start of passive LATE.**

## 5.4 Aquatic Biota

### *5.4.1 Fish kills at East Trinity*

Prior to the commencement of LATE, there were anecdotal and documented accounts of fish kills following seawater exclusion and drainage of the site. One anecdotal account tells of 'truckloads' of dead fish trapped behind the newly constructed tide gates on Hills Creek following a Christmas eve downpour.

The first recorded fish mortality in the vicinity of East Trinity occurred in 1972, only 2 years after site works began (Russell & McDougall 2003). Olsen (1983) records a correlation between these fish deaths, heavy rain and subsequent flushing of the East Trinity site and pH as low as 3.9. Between 1977 and 1980, Department of Primary Industries Fisheries Officers investigated the water quality of Firewood Creek and 4 fish kill events, and concluded that the mortalities were due to the low pH water being flushed from the East Trinity site (Garrett 1978; Russell 1980; Russell & McDougal 2003).

Russell and Helmke (2002) found that within the East Trinity site (upstream of the bundwall), only 3 freshwater or euryhaline species were recorded and the pH of Firewood and Magazine Creek was pH<4 with increased total dissolved iron (up to 168 mg/L) and aluminium concentration (up to 70 mg/L) for most of the year.

### *5.4.2 Impacts of disturbed ASS*

In eastern Australia, the link between disturbed ASS, environmental degradation and fish deaths is now well documented, particularly in northern New South Wales (Callinan *et al* 1995; Sammut, White & Melville 1996; Roach 1997; Kroon 2005; Kroon & Ansell 2006), and south-eastern Queensland (Preda & Cox 1998; Cook *et al* 2000b).

Disturbance and/or drainage of formerly benign pyritic sediments leads to pyrite oxidation and the production of acid within the soil porewater. Export of this acidity (and any other elements, metal and metalloids liberated from the acidic breakdown of soil minerals) into drains, creeks and estuaries is predominantly associated with rainfall events (Wilson, White & Melville 1999). Consequently, there is correlation between rain events and the occurrence of fish kills (Olsen 1983).

Various site- and niche-specific mechanisms have been identified as causal agents for the impairment and death of aquatic biota in the waterways of disturbed ASS landscapes. Fish may be injured by exposure to low pH alone (McDonald 1983), but often there are also biotoxic concentrations of heavy metals, with inorganic monomeric aluminium identified as a primary cause of injury and mortality in fish (Driscoll *et al* 1980; Cook *et al* 2000b). However, high concentrations of calcium, silicon and organic carbon have been shown to lessen the toxicity of inorganic aluminium to fish (Driscoll *et al* 1980; Callinan *et al* 1995). Sammut *et al* (1995) cites an inability to escape from ASS leachate washed into previously circumneutral pH sites as a cause of fish mortality.

Low dissolved oxygen is a noted cause of anoxia in acidic waters (Callinan *et al* 1995). This is particularly relevant to ASS landscapes, as soluble iron ($Fe^{2+}$) is a product of pyrite ($FeS_2$) and monosulfide (FeS) oxidation. Ferrous ion ($Fe^{2+}$) rapidly oxidises to ferric iron ($Fe^{3+}$), a reaction which can deoxygenate the water in a matter of minutes.

Epizootic ulcerative syndrome (EUS) associated with dead fish is a consequence of leachate from ASS effecting aquatic habitats (Sammut *et al* 1995). Oxidation and hydrolysis reactions produce iron and aluminium floc that can smother benthic communities Cook *et al* (2000b). Simpson and Pedini (1985) also note that iron deposits can coat the gills of aquatic fauna, impairing gas exchange. They also found that iron hydroxide can coat the benthic algae, making them inedible for higher trophic organisms.

### *5.4.3 Impacts of LATE*

Russell and McDougall (2003) note that few attempts have been made to monitor the impact of a large-scale ASS remediation on the aquatic biota. With the existence of good quality baseline data, the East Trinity ASS remediation program provided a unique opportunity to identify and quantify changes in resident fish and crustacean communities and water quality before, during and after controlled LATE.

Russell, Preston and Mayer (2011) repeated the 2001–2002 study of Russell and McDougall (2003) from November 2003 to February 2005. These studies monitored the aquatic biota across the active or during phase of LATE. Gil nets were used to sample fish and round collapsible crab pots were set to sample crabs in both Hills and Firewood Creeks. There was a progressive increase in fish species richness, diversity and abundance in Firewood Creek between 2001 and 2005, while both species richness and diversity were relatively stable in Hills Creek over the same period.

The penaeid prawn *Fenneropenaeus merguiensis* was a major component of the cast net catches in the lower sections of both Firewood and Hills Creeks but its relative abundance decreased upstream of the tidal gates on the seawall.

Well-established stocks of predominantly juvenile, male mud crabs *Scylla serrata* resident upstream of the tidal gates indicated suitable habitats with acceptable water and sediment quality and adequate availability of food. Mud crabs were used as a bio-indicator for the presence of heavy metals and metalloids in a biologically available form, as they are a bottom-feeding scavenger that consumes a variety of plant and animal material (Russell & McDougall 2003).

The regular fish kills that occurred prior to the management regime abated and, overall, the implementation of the rehabilitation program is yielding positive benefits for the local fisheries, as there has been sufficient net improvement in the health of the system to allow rapid recolonisation by a relatively large number of estuarine fish. Russell, Preston and Mayer (2011) also predicted that the changes in mangrove, fish and crustacean communities would be likely to continue for several years before stabilisation occurs.

With the cessation of hydrated lime additions to Hills Creek and the drainage network that feeds it in 2006, LATE shifted from active to passive treatment in this catchment. Active treatment and hydrated lime additions to Firewood Creek however continued until October 2016. The September 2015 survey by Sheaves and Abrantes (2016) sampled fish and crustaceans in Hills, Firewood and See Lee Creeks. This study repeated the cast net and crab pot sampling, but did not sample water quality or analyse crab tissue, and was unable to use gill nets due to a total gill net closure for the whole of Trinity Inlet. Coupled with just a single sampling event, it is not possible to make absolute conclusions and more meaningful comparisons with the earlier longer term studies of Russell and Helmke (2002), Russell and McDougall (2003) and Russell, Preston and Mayer (2011).

However, with caveats on equipment and temporal variability not being captured in an environment that is known to be seasonal, dynamic and variable, Sheaves and Abrantes (2016) have reported:

- 1516 fish from 22 species were caught in 154 cast nets, giving a mean catch per unit effort (CPUE) of 9.8 individuals per net. All fish were small and three trophic groups dominated the community: pelagic planktivores, bentho-pelagic invertebrate feeders and phyto-detritus feeders. These were all estuarine species, as opposed to Russell, Preston and Mayer (2011) who found occasional marine vagrants.
- CPUE, a measure of relative abundance, concurred with the earlier study in that there was considerable variation in catches between sites. With the CPUE highest at Hills Creek downstream of the floodgates, followed by Hills Creek immediately upstream of the floodgates, and Firewood Creek downstream of the floodgates. Whereas See Lee Creek, the reference site flowing into Trinity Inlet to the south had intermediate (10.6 individuals/net) and Firewood Creek upstream and Little Hills Creek Drain the lowest catches (Sheaves & Abrantes 2016). For most sites, CPUE values are higher than those reported by Russell, Preston and Mayer (2011).
- Similar results were found for species richness (the average number of species per net).
- Both species richness and CPUE results from the sites downstream of the Hills and Firewood Creek floodgates were comparable or even better than results found for the reference site during this study, suggesting that the fish community of the two impacted creeks has responded well to the remediation program (Sheaves & Abrantes 2016).
- Non metric multidimensional scaling (nMDS) compares different locations of data for selected criteria. nMDS ordination comparing assemblage composition of common fish species in cast nets between the 2003–05 and the 2015 study found that differences among sites were maintained over time indicating that the fish community composition of affected creeks as reported by Russell, Preston and Mayer (2011) had reached a stable state (Sheaves & Abrantes 2016). This could indicate an improvement in fish community, but may also result from the use of different cast nets. It may also stem from the original study covering 15 months and including periods of lower and higher fish abundance, while the timing of the present study could have coincided with a period of recruitment of some species, leading to higher CPUE.
- Only one prawn species, the banana prawn *Fenneropenaeus merguiensis* was recorded, as opposed to five species recorded by Russell, Preston and Mayer (2011). This is probably due to the differences in sampling effort and time over which the study was conducted (1 vs. 15 monthly samples).
- Both female and male mud crabs (*Scylla serrata*) were recorded at all sites. Catches were slightly lower than those reported by Russell, Preston and Mayer (2011) (86 vs. average 112 crabs per month), again, probably due to the differences in sampling duration. There were no differences in the proportion of females were captured, whereas the earlier study had a much higher proportion of males. This difference can be explained by the fact that the single sampling event

of the 2015 study did not incorporate seasonal movement of females out of the estuaries.

- In addition to *S. serrata*, 12 blue swimmer crabs, *Portunus pelagicus*, were caught. This species was caught in Hills Creek downstream of the floodgates and in See Lee Creek. This species was not recorded in the 2003–05 study.

There have also been a number of preliminary snorkel surveys conducted in select streams in the coastal region from Trinity Inlet south to Russell Heads in attempt to document the distribution of amphidromous cling gobies (Brendan Ebner, TropWATER, JCU, pers. comm.). Amphidromous species live and breed in freshwater but migrate to the ocean and back in their early developmental phases. Cling gobies have been found to occupy a subset of coastal streams in the Australian Wet Tropics and have highly localised distributions and limited suitable habitat (Ebner & Thuesen 2010, Ebner *et al* 2011, Thuesen *et al* 2011). Four of these cling goby species are conservation listed either under state or national legislation. A very brief visit to Hills Creek in September 2013 revealed the presence of adults of what is now one of the state listed species, the Emerald cling goby, *Stiphodon pelewensis* (formerly known as *S. atratus*) (Ebner, Donaldson & Thuesen, unpubl. data). The presence of this species is an exciting finding that demonstrates that upstream migration of juveniles from the ocean through the estuary and into the stream has been achieved. The viability of Hills Creek for supporting breeding adult populations of the various cling goby species remains to be determined.

Overall, results suggest that the fish community has recovered well after the implementation of the LATE program and conclude as Russell, Preston and Mayer (2011), support healthy populations of fish and crustaceans, with no significant differences in fish species diversity found between the impacted Hills and Firewood Creeks and the nearby See Lee Creek, a non-impacted, reference site.

The on-site staff have also noted an increase in the abundance and size of crocodiles (figure 34).

**Figure 34. Sightings of large crocodiles are becoming more frequent as healthy communities of fish and crustaceans are re-established under lime assisted tidal exchange.**

## 5.5 Avian species

A total of 136 species of birds have been observed at East Trinity since the rehabilitation began. An enormous diversity of birdlife has been noted at East Trinity in recent times (figure 35). The species observed includes brahminy kites, ospreys, spoonbills, storks, cormorants, ducks, stilts, egrets, lapwings, lorikeet, parrots, cuckoos, honeyeaters, terns, doves, herons, drongos and bush-hens (Smith & Venables 2014). Reports suggest that the expansion of mangrove and other higher elevation wetlands associated with the rehabilitation are likely to have benefited a number of bird species, including some internationally important shorebird species listed in bilateral migratory bird agreements with China (CAMBA), Japan (JAMBA) and the Republic of Korea (ROKAMBA). Recently a new wader roosting site has emerged in mangroves on the northern boundary of the East Trinity area and it seems this may be significant in the regional context (Smith & Venables 2014).

**Figure 35. Ducks and Jabiru on the freshwater Swamp.**

# 6. The research that explains the success of LATE

The CRC CARE-funded research conducted at East Trinity has resulted in a paradigm shift in the understanding of ASS remediation. The pathway to this understanding commenced with two critical observations, which guided the various research pathways that led to groundbreaking insights.

The early observations concerned hydrology and jarosite. Despite conventional wisdom, jarosite was observed to be breaking down after only a short period of LATE (Keene *et al* 2010). Similarly, against predictions, tidal exchange was creating a very dynamic hydrological environment in the acidified layers of the tidal plain. These two observations subsequently were linked in the research pathways involving iron chemistry and organic matter in an alkaline soup created initially by seawater and hydrated lime.

## 6.1 Hydrology of the tidal plain

The sloping tidal plain over which daily tidal exchange occurs at East Trinity extends for up to 300 meters rising from 0 m to 0.5 m AHD. The acidified layers are up to 1.5 m deep and overlie the impermeable, reduced (sulfidic) layers (figure 36).

Johnston *et al* (2010) found that the upper acidified soil layers were highly permeable, enabling the free movement of water both vertically and horizontally. The conditions favoured a fluctuating groundwater situation with considerable potential for pore water movement and solute exchange. The incoming tide rapidly flooded the ground surface of the upper intertidal zone, with slower profile drainage during ebb tide, alongside groundwater upwelling, leading to oscillating hydraulic gradients – referred to as hydraulic asymmetry. This tidal forcing and cyclic reversal of hydraulic gradients (predominantly effluent gradients in the intertidal zone) are the mechanisms for substantial pore water exchange between sediments and overlying waters.

In summary, the flood tide is characterised by a positive downward gradient favouring infiltration and surface cover, and the ebb tide experiences a negative gradient favouring upwelling and therefore upward advection of pore water.

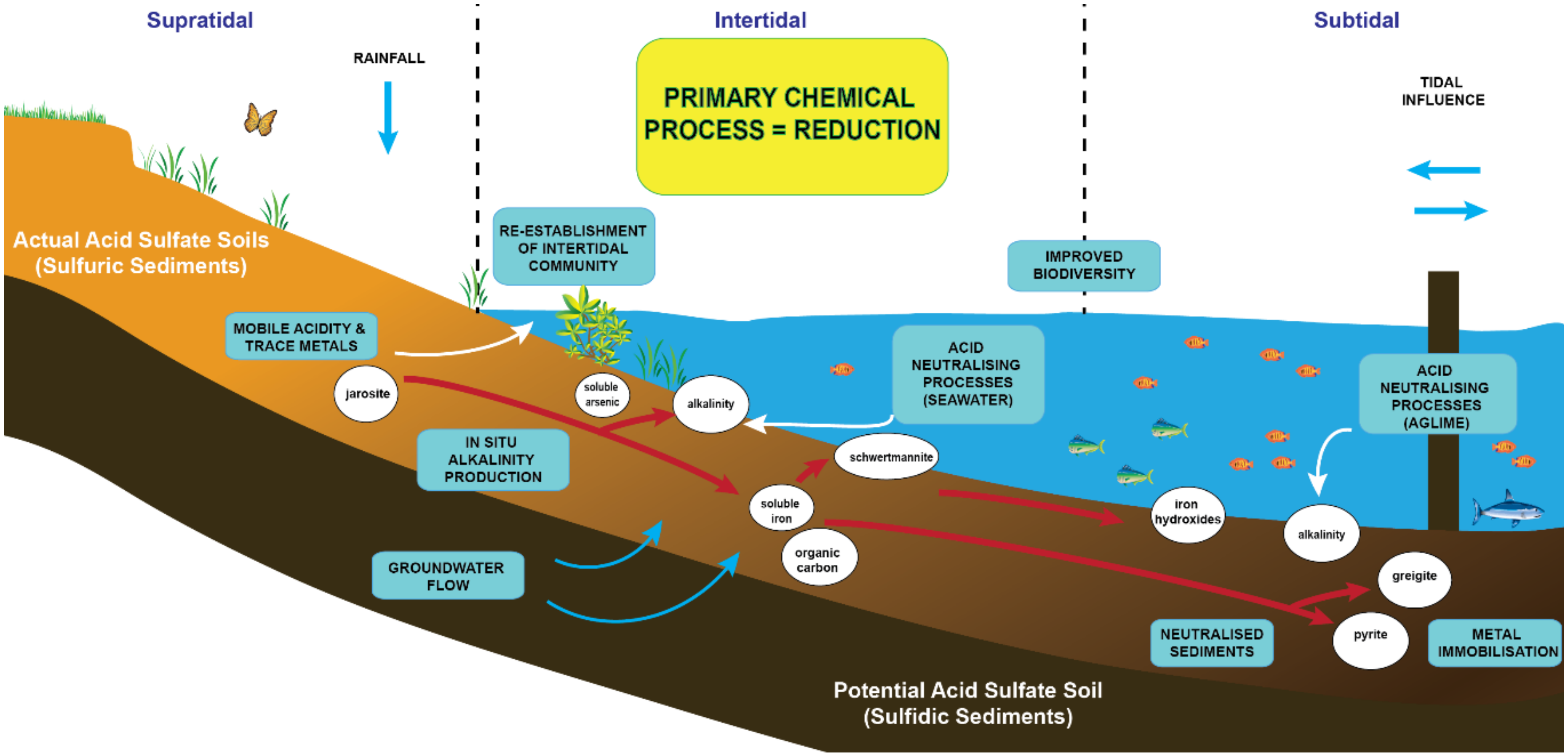


**Figure 36. Conceptual model of environmental changes following implementation of the LATE bioremediation strategy** (Adapted from Ward, Sullivan and Bush 2013)

## 6.2 Jarosite breakdown, iron release and pyrite formation

Jarosite is an iron mineral commonly found in oxidised ASS. Within months of LATE commencement, the typically sharply defined pincushion crystal form of jarosite was observed at a microscopic scale to be disintegrating into smaller, sub rounded, pitted and etched crystals (Keene *et al* 2010). This feature had been predicted to take decades to occur.

Reductive dissolution is the term used to describe the breakdown of jarosite and other products of drained marine muds, such as schwertmannite (another iron mineral), which releases copious amounts of ferrous ion. Jones *et al* (2006) demonstrated that reductive dissolution is mediated by iron reducing bacteria at circumneutral pH. Keene *et al* (2012), confirmed this to be the case at East Trinity.

The implication of the release of ferrous ion in pHs above 6 was its role in catalysing the formation of goethite (an iron oxyhydroxide) from schwertmannite. Goethite is a red staining mineral readily observed on the soil surface in response to LATE. Its presence is favourable to sulfate reduction, that is, the reformation of pyrite, and this is exactly what was detected in the lower elevations of the tidal plain. This finding was counter to all previous understandings.

## 6.3 Ferrous ion distribution in pore-water

Hicks, Bowman and Fitzpatrick (1999) and Johnston *et al* (2011) recognised that the vertical distribution of the ferrous ion at East Trinity is markedly different from what is normally reported in CASS where peak concentrations occur close to the source of oxidising pyrite near the boundary between sulfuric and sulfidic layers. Ferrous ion concentrations in pore water at East Trinity are extremely high across the former sulfuric layer and peak in the upper intertidal zone. This finding is a key component of explaining the success of LATE and is directly linked to the reductive dissolution of jarosite.

## 6.4 Tidal forcing and iron chemistry

The mineral transformations associated with the breakdown of jarosite are closely linked to the hydrology of the intertidal zone, and result in differing zones of mineral formation (Johnston *et al* 2010). Tidal forcing caused the ferrous ion in pore waters to come to the surface. At the supra-tidal zone, which experiences less frequent inundation and buffering, it was found that ferrous ion oxidises to ferric ion which in-turn has the potential to release acid. At this upper tidal zone, pH in surface accumulations was found to be around 3 at a time when the level of inundation had reached between 0.3 m and 0.4 m AHD. In contrast, pHs in the intertidal zone are around 6–7. A positive correlation between pH and tidal frequency was established.

Clear distinctions developed in the mineralogy between the upper, mid and sub-tidal zones. The ferrous mineral, schwertmannite, characterised the low pH upper tidal zone. The prevalence of goethite and lepidocrocite in the mid intertidal zone was of particular significance. The conversion of schwertmannite to goethite can take several years (Bigham *et al* 1996). A very rapid ferrous iron catalysed pathway can transform schwertmannite to goethite and lepidocrocite under anoxic conditions at pH >6 (Burton *et al* 2008a, 2008b). Conditions in the intertidal zone at East Trinity were ideal for the rapid weathering of schwertmannite, explaining the prevalence of goethite and lepidocricite after tidal inundation. As expected, pyrite began to accumulate in the former sulfuric layers in the intertidal zone at East Trinity – the product of sulfate reducing conditions (Keene *et al* 2011, 2012).

## 6.5 Organic matter: the kick starter and more

As previously mentioned, iron reducing bacteria mediate the initial reductive dissolution of jarosite when tidal waters first entered the former sulfuric layers. While there was knowledge of functional guilds of bacteria involved in such a process, little was known about their origins and distributions in CASS environments and their relationships to tidal cycling and the availability of nutrients and electron acceptors.

A comprehensive assessment of iron and sulfate reducing bacteria by Ling *et al* (2015), provided critical insights into the success of LATE. Previous studies had established that iron-reducing bacteria (IRB) can out compete sulfate reducing bacteria (SRB) for limited electron donors when the environment is non-limiting in ferric ion. Ling *et al* (2015) hypothesised and proved that increases in the concentrations of organics in CASS systems decrease this competition by increasing thermodynamic energy availability relative to enzyme kinetics – thus favouring sulfate reduction. Their key conclusions were:

- The relatively high organic carbon content (20% by weight) of the surface soil (O horizon) most likely results from a mode of origin and preservation uniquely associated with flooded CASS environments.
- A major source of organic matter at East Trinity was from the death of *Melaleuca spp.* as well as from former Mangrove species.
- The unusual preservation of organic carbon and organic acids results from organo-mineral interactions – e.g. with secondary iron minerals such as ferrihydrite and goethite.
- Organic matter decay from *Melaleuca spp*. is associated with particular organic acids termed pentacyclic triterpenoids (PT’s) that have a high reactivity so that their abundance in East Trinity sediments is a rare occurrence.
- Under reducing/anoxic conditions in sediments, PT’s are transformed by microbially-mediated A ring degradation and progressive aromatization reactions during early diagenesis – the breakdown of PT’s to component acids e.g. acetate which is the most common organic substrate for sulfate reduction.
- The 16s rRNA gene sequencing results revealed that the East Trinity wetland has significant microbial diversity (a large range of alpha diversity indices or species richness within communities). Microbial diversity is strongly influenced by pH, redox status and organic matter content and type. For various sites investigated, those with the more neutral pH, higher organic matter content, and oscillatory redox fluctuations had the higher microbial diversity.
- Proteobacteria, particularly delta class are the most abundant phylum at East Trinity and these exhibit a predominance of SRB. They were in abundance in the upper depths of sampled profiles suggesting a degree of tolerance to periods between tidal inundation and/or rapid changes in SRB activity with tidal fluctuation.
- The high concentration and multiple types of organic matter present facilitates co-habitation of different metabolic guilds (e.g. nitrate versus sulfur reducing ability) and these normally compete for a limited energy resource.

- The high organic matter resource at East Trinity allows the iron and sulfate reducing guilds to co-exist, so that re-precipitation of iron sulfide minerals will thermodynamically favour iron, sulfate and elemental sulfur reduction by removing the products of these metabolic reactions.
- The poorly crystalline ferrous ion minerals derived from the reductive dissolution of jarosite act as a relatively labile electron acceptor for iron reducing bacteria, suggesting that microorganisms exhibit a relatively rapid response to tidally generated redox fluctuations.
- Sulfate reduction by organic acids (e.g. acetates) produces more alkalinity in the system in the form of bicarbonates.

## 6.6 Sources of alkalinity

An estimate of the relative contribution from the four sources generating alkalinity over a 6-year period of LATE in Firewood Creek were provided in Johnston *et al* (2012). Tidal exchange and iron reduction contribute the overwhelming proportion of alkalinity. What is important to note concerning the lime contribution relates to the treatment of exiting tidal water during the early stages of LATE. During this period, hydrated lime augmented tidal water at a pH of 8–9 entered and saturated highly acidic soils. On retreat, the pH had fallen to as low as 3 to 4 within the internal drain and creek systems and so had to be treated to ensure its pH on entering the external environment was kept above 6. This was an onerous task during the early months of LATE, especially in the Hills Creek area where tidal inundation to 0.5 m AHD occurred from the outset. Had hydrated lime not been added to entering water, the task of treating exiting water may have been made more difficult. The difficulty was not as great in the subsequently treated Firewood Creek as a decision was made to incrementally raise the inundation level.

## 6.7 Cautionary implications for LATE

A detailed study of the shallow surface sediments found some interesting heterogeneity and large variations in pH in pore water samples (Johnstone *et al* 2011). While pH as low as 3.5 were recorded, these were very localised and confined to the upper tidal slope in contrast to the extensive acidification of surface waters prior to remediation. Similarly, pore water aluminium (mainly $Al^{3+}$) levels at this location were significantly elevated. While tidal overtopping is an obvious pathway for mobilisation of both $H^+$ and Al to the water column, pH levels in Firewood Creek were comparable to those in receiving waters in Trinity Inlet. Sampling of exiting water over the last two years at the two Firewood Creek outlets does not indicate elevated Al levels (DES East Trinity Water Quality Database).

Arsenic (As) levels in surface pore water were below detection levels in pore water but were elevated in the water column at lower elevation zone of the tidal slope where it is positively correlated with ferrous ion and associated with the reductive dissolution of As bearing ferric oxides in surface sediments (Johnston *et al* 2011). However, As levels in Firewood Creek were comparable with Trinity receiving waters.

As would be expected, alkalinity ($HCO^-{}_3$) in the water column progressively decreased upslope with incoming tidal water, underlining the more vulnerable status of the land at the upper extent of tidal inundation. This may have implications for calcifying benthos species dependant on aragonite and calcite for recolonisation. The saturation index for both substances was found to be substantially depressed at upper slope locations compared to receiving waters. This could impact on the capacity for shell building.

This work was completed in April 2008 when tidal inundation had reached between 0.3 to 0.4 m AHD. Inundation levels subsequently reached 0.5 m AHD in March 2010 and have been maintained since. The question therefore raised is: what impact has the higher and longer period of inundation had on the status of the entire tidal slope and the upper slope in particular?

Claff *et al* (2011) examined the partitioning of metals (Fe, Cr, Cu, Mn, Ni and Zn) between the acidified surface soil (0–0.1 m) and the un-oxidised sub soil (1.3–1.5 m) in both a treated and untreated soil at East Trinity. The surface of the untreated soils lost Cr, Cu, Mn and Ni compared to the deeper un-oxidised layer and only minor losses of Fe and Zn occurred. In the LATE remediated site, all metals except for Fe were sequestered or immobilised in the surface soil through the accumulation of iron oxides, organic matter and pyrite.

## 6.8 Summation of how LATE success has been explained

The twice daily entry and retreat of tidal water (augmented initially with hydrated lime) into the highly permeable acidified sulfuric layers of an AASS creates cyclical change of hydraulic gradients. Positive downward gradients favour infiltration and overtopping of the surface in flood tides. Negative gradients favour upwelling in early ebb tide phases. This induces substantial pore water exchange between sediments and overlying waters.

The dieback of *Melaleuca spp.* and former mangrove species results in a huge increase of carbon in tidal surface waters and provides the energy source necessary for microbial reduction, raising the soil waters to pH 5. A positive feedback cycle then occurs, where released ferrous ion is able to attach to jarosite, causing structure to collapse, hence making the mineral more susceptible to microbial reduction. These processes raise the pH above the critical threshold of 6. Above pH 6, ferrous ion, together with bacteria, then acts as a catalyst for the reduction of both sulfate and iron minerals.

Sulfate reduction is favoured in a kinetically driven microbial metabolism process involving organic acids derived from the breakdown of an abundant supply of organic matter. A by-product of this process was found to be the production of bicarbonate, which further neutralises soil acidity and promotes beneficial microbial weathering of acid minerals. This production of bicarbonate is what represents an ecosystem shift – it becomes self-propelling towards a stable, neutral and healthy soil-wetland system with good quality water.

A summary of geochemical processes underpinning the success of LATE are shown on figure 37.


**Figure 37. A summary of geochemical processes underpinning the success of LATE.**

## 6.9 Future research

Research areas under current study and of future interest include:

- The environmental stability of iron sulfide minerals in the sea-water and freshwater wetland soil systems, and its interactions with trace elements under fluctuating reducing and oxidising conditions;
- Biogeochemical model development to enhance the transferability to other environmental settings;
- Quantitative ecological assessment of the remediation strategy – terrestrial and aquatic;
- Wetland terrestrial weed management strategy to build the overall ecosystem services of the East Trinity wetland as a Site of International Significance for Wetland Restoration Studies;
- Detailed studies to determine the links between ASS and the health of estuarine habitat and coral reef;
- Effect of mineral transformations on nutrients, metals and carbon; and
- Biogeochemical modelling to predict long-term stability of the remediation strategy.

# 7. Transferability guidelines for LATE

The East Trinity ASS remediation strategy is well on the way to returning a major environmental hazard to its former status as a functioning tidal wetland. Importantly, the experience derived from the management of the strategy, underpinned by the knowledge gained by the associated research program, provides a basis for applying the strategy elsewhere.

There are three main elements to assessing whether a degraded ASS site is suitable for applying LATE. The first and most important is site assessment of critical environmental components. These are listed in table 3; however, a fundamental requirement of the environmental assessment is that the majority of tides must push seawater over the bulk of the AASS in order for LATE as it operates at East Trinity to be considered as a remediation strategy for the site. The other elements involve on-site practical and scientific management capabilities, and administration matters that facilitate environmental management practices. Table 3 provides a brief description of the key elements to be considered when assessing alternate sites for applying the LATE remediation strategy.

**Table 3. Transferability guidelines for LATE.**

| Elements | Guideline | Comment |
|---|---|---|
| **Site assessment** | | |
| Digital elevation model | An accurate (digital) elevation model based on a standard datum (such as the Australian Height Datum), for example using laser altimetry and detailed bathymetry. | This provides the baseline information for generating a tidal model, establishing a network of tide height gauges and linking soil and landscape features to elevation. |
| Tide data | Acquire local predicted and validated tide height data based on a standard height datum. | In addition to input into tide modelling, this is used to graph daily tide patterns. Tide height patterns over time interacted with site elevation and soil acidity information portray the inundation level that provides consistent wetting of acidified soils. |
| Soil | Map and understand the distribution and characteristics of ASS, ideally carried out in conjunction with deep stratigraphic drilling. | Standard ASS soil analyses are imperative to assign key attributes to mapping units. An assessment of the permeability of soil layers should be included. |
| Organic matter | Assess the type and level of organic matter (OM). | The research has shown that OM is critical to the biogeochemical pathways that promote successful remediation. The absence of OM may necessitate some form of organic carbon addition, and perhaps the introduction of bacteria of suitable metabolic guilds. |
| Stratigraphy | Deep drilling to model underlying stratigraphy and geomorphological history with respect to ASS formation. | Understanding the relationship of surface landscape features to underlying layers provides a basis for predicting the hydrological dynamics resulting from the re-introduction of tidal waters and improves the confidence of spatial mapping of surface soils. |
| Groundwater | Specific deep drilling to assess both deep and shallow groundwater properties. Establish groundwater monitoring wells in the process. | Linked to the stratigraphic model, the impact of re-introduced tidal water can be predicted with respect to groundwater reserves and saline encroachment into adjacent lands |

| | | |
|---|---|---|
| Tide modelling | A model that is based on the DEM and all relevant hydrological features and infrastructure e.g. tide gate dimensions, to run inundation level scenarios. | The model is primarily used to link varying tide gate apertures to inundation levels. |
| **Capabilities** | | |
| Tide control | Essential if the re-introduction of full tidal flow is not feasible. | Simple and reliable tide gate control mechanisms that allow easy variation of the opening aperture. Fish passage requirements should be considered. |
| Water treatment | A capability to treat tidal water to enhance buffering capacity of incoming water and neutralise acidity of outgoing water. | Automated equipment that allows large quantities of neutralising agent to be pumped and distributed evenly across water bodies is desirable. The associated capability to transport and lift up to 1 tonne neutralising agent quantities is also required. |
| Water quality monitoring | Real time collection of key parameters involving sensors, data loggers and telemetry for surface waters and equipment. Groundwater well monitoring equipment. | Sufficient strategically located stations to monitor internal and point of exit water quality. Capability to regularly clean and calibrate equipment, as well as remotely interrogate sensors. WH&S consideration is needed where hazards such as crocodiles exist. |
| Water quality sampling | The preparedness to carry out periodic water quality sampling for laboratory analysis. | Involves strict protocols, designated equipment, on site pre-laboratory sample preparation and storage in a dedicated clean room. |
| Data management | Appropriate data bases are required for analysis, storage, quality control and retrieval of soil, water, photographs and other monitoring needs. | Large quantities of data will be generated so that it is essential at the outset to have robust and reliable data base facilities in place to regularly carry out surveillance and quality assurance and control. |
| Access | Appropriate vehicles and roads and tracks to access key locations in all but totally flooded conditions. | In characteristically hazardous and difficult terrain, the provision of access is a crucial and costly matter. WH&S considerations are required. |
| Skill mix | A diversity of expertise, both in-house and with partners, including on-site skills has been a key component of the | A skill mix that spans relevant scientific disciplines, trades and machinery operators will facilitate an efficient and cost effective remediation program. On-site staff will require a |

| | | |
|---|---|---|
| | LATE success. A future remediation program will only benefit from such a mix. | well-equipped workshop to carry out the range of fabrication, repair and maintenance tasks that are part of everyday operations. |
| **Administration** | | |
| Approvals | A scan of what State and Federal approvals may be required to carry out this type of environmental change/management. | |
| Neighbour issues | Maintain communication with neighbours to ensure full awareness of the remediation program and to deal with emergent issues. | |
| Governance | Provide a long term funding stream for operations and implementation, and investment for research and development, innovation and system improvement. | |
| Ecological baseline monitoring | In addition to the requisite soil and water monitoring, arrangements for periodic surveying of changes in vegetation, aquatic biota and avian populations are desirable. | A record of these changes adds to knowledge and documents success. |

# 8. The future of East Trinity and LATE

The future of the East Trinity site can be seen as having two distinct dimensions. The first is ASS management, the second is the host of land management issues spanning indigenous involvement, eco-tourism, eco-education, non-tidal area management, infrastructure, dredge spoil placement and funding.

## 8.1 ASS management

***It is critical that the tidal regime is maintained. Failure to do so will rapidly return the site to an acid and heavy metal producing source and cause the death of the floral and faunal species that have returned in response to LATE.***

Maintaining the current tidal inundation level to 0.5 m AHD will require that tide control structures are kept in working order and that periodic checking of tide gauges occurs. Alternatively, the current electronic water height monitoring could be kept in place. Additionally, real time water quality monitoring should be maintained at all entry and exit points on watercourses to the property. It would also be important to have a water treatment capability to deal with any emergent acid source. This would mean having ready access to equipment and soluble neutralising agent. Hydrated lime has a useful shelf life of 12 months so that storage management is important.

Smith, Manders and Brough (2016) describe a band of acidified land between the current 0.5 m AHD upper inundation level and 1 m AHD. This land does not produce sufficient acid to be detected in any of the water quality monitoring sites. However, if tidal inundation levels were to be raised, it would need to be well-planned, strictly controlled and approved by relevant experts. The approval is necessary as beyond 0.5 m AHD, there is less frequent tidal inundation and so longer periods of drying leading to more potential for ASS oxidation and subsequent acid discharge. However, this band was found to have less acidity than what is currently inundated and if the increased inundation is carried in small increments over extended periods of time and with strategic hydrated lime addition, it potentially can be executed without deleterious effect.

Raising the inundation level has other implications which need to considered, namely the impact on neighbours and the reduced site access. The latter can be offset but at the cost of alternate or raised carriageways.

## 8.2 Building on current knowledge

What has been achieved at this site to date has created new knowledge on a number of fronts, but the remediation processes put in place have not reached an end point. What has been achieved has implications for future coastal management in the context of rising sea levels and for tidal wetland management in general. An opportunity would therefore be lost if both research and strategic ecological monitoring was not maintained to build on current knowledge. Real-time surface water monitoring must continue to provide an indicator of the continued stability of the system and any long term trends, as well as recording the impacts of extreme weather or tide events. As discussed in section 6.9, Future research would pursue:

- iron compound interaction with trace elements;
- carbon availability; and
- the tracking and understanding of geochemical processes as remediation processes advance.

The following parameters would be appropriate to assess periodically:

- laboratory analysis of water samples for key parameters in both wet and dry seasons, and at the bottom of the lowest tides;
- vegetation change including specific mangrove re-colonisation studies;
- aquatic biota – the last assessment did not adequately replicate earlier work; and
- key ASS criteria.

As part of any aquatic biota assessment, the efficacy of the new tide control gates could be evaluated.

## 8.3 Infrastructure

There are new concrete headwall structures in place on upper Firewood and Georges Creek that have a long-term life expectancy. However, the old structures on Hills and lower Firewood Creeks are 40 years old and have an undetermined life expectancy, as do the bridges that traverse these structures and elsewhere on-site. Most of the floodgates themselves are new but the condition of the old concrete needs to be monitored.

## 8.4 Eco-tourism and indigenous culture values

In purchasing the site, the Queensland Government's objective was to remediate the severe acid sulfate soils at East Trinity, and retain the green tropical backdrop to Cairns. Added to this, a community group has sought to promote the establishment of a wetland park on the site as an eco-tourism/eco-education destination. Local tourist business interests also supported this concept as a short day destination alternative to the many distant offerings as the site can be reached in 10 minutes by boat from Cairns.

This concept is already being fulfilled in a low key fashion by *Mandingalbay Yidinji Eco-Cultural Nature Based Tourism* run by the Mandingalbay Yidinji Aboriginal Corporation (MYAC). The East Trinity site is an Indigenous Protected Area (IPA) and they are conducting tours of East Trinity and adjacent IPA land to the east. Participation rates are already healthy without having done any formal advertising (Dwayne Mundraby pers. comm.). MYAC are also carrying out feasibility plans for tourist infrastructure facilities. A complete account of the MYAC's vision for the site is set out in the *Strategic Plan for Mandingalbay Yidinji Country 2009* (Mandingalbay Yidinji Aboriginal Corporation 2009).

Similarly, the eco-education opportunities are already being fulfilled in that regular visits are being made by local schools and student from national and international universities have visited or carried out studies.

With large parts of the site now progressing towards a healthy estuarine system under passive LATE remediation, the potential for East Trinity to yield environmental, economic and social outcomes is starting to be explored.

## 8.5 Land beyond the tidal front

Exotic species management is an issue for the areas above the limit of consistent tidal exchange. Between 2008 and 2013 there was an increase in the shrub land dominated by exotic species, especially those dominated by *Spathodea campanulata* (African tulip trees) and *Psidium guajava* (guava) (Newton, Addicott & Bannink 2014). Guava has also increased in grassland in the centre of the site (Newton, Addicott & Bannink 2014). With appropriate exotic species management, the land above the tidal limit potentially could support the return of native fauna such as kangaroos and cassowaries, the latter in the intact heritage listed lowland forest in the northeast corner of the site.

## 8.6 Funding

Any form of management of the site in future will obviously require funding. The Queensland Government has funded the entire remediation program to date, with partners largely funding the research. There is a need to secure long-term funding for infrastructure, ongoing monitoring of water and key ASS parameters, and periodic surveys of aquatic biota and vegetation. It is understood that the Queensland Government is currently reviewing the activities at East Trinity with a view towards developing a long-term plan for passive LATE and site maintenance.

## 8.7 Dredge spoil placement

The East Trinity site is currently one of the locations being considered for the placement of dredge spoil from Trinity Inlet as part of the Cairns Shipping Development Project. A previous proposal involved coverage of the majority of the site including the remediated area.

The current proposal to expand the Port of Cairns is expected to cost $120 million and:

- improve economic benefits due to increased cruise ship visitations to Cairns;
- enable future expansion of the HMAS Cairns Navy base and provide access for the existing RAN LHD; and
- increase channel resilience against extreme weather events and improved efficiencies for bulk cargo ships accessing the Port of Cairns (Ports North 2017).

The environmental impact statement (EIS) includes baseline studies for two land-based disposal options (the East Trinity site and the Barron delta area) for the significantly reduced capital dredge volume of 1 million cubic metres (Ports North 2017). It is worth noting that preliminary studies for the EIS indicate that 75% of this material will be PASS. Ports North expects to submit the draft EIS report by June 2017. In December 2016 the Coordinator-General extended the project declaration lapse date from 30 June 2017 to 31 December 2017 (Department of State Development 2016).

The environmental implications of placing dredge spoil containing ASS on land are not fully understood, particularly on a coastal wetland. Dredge spoil issues should logically be investigated as part of any future ASS research, both in terms of the appropriate assessment of the spoil itself and placement techniques.

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# Appendix 1

## Geomorphology and stratigraphy of the East Trinity site

Drilling carried out at East Trinity by Graham and Larsen (2003) resulted in a stratigraphic model (Figure A1) which confirms that the first depositional phase was associated with the 7,000 years before the present shoreline advance, over a terrestrial incline. This transgressive phase created a blanket of sediment below an aquatic wedge. A period of stability ensued during which a second depositional phase (referred to as estuary bay marine muds) occurred when sediments infilled the wedge of water above the transgressive sediments in a low energy environment. These bay muds are pyritic (sulfidic) but are self-neutralising if oxidised as they contain microscopic calcitic organisms, *foraminifera* (Chaproniere 2002). The final depositional phase occurred when the shoreline subsequently retreated to the present level as a result of hydro-isostatic uplift of the Cairns coast (Chappell *et al* 1982, Hopley 1982).

The Graham and Larsen model for East Trinity indicates that components of the estuary bay sediments have remained intact, whereas other areas were eroded by stream action and then replaced by back-filling with pyritic sediments as the shoreline retreated. These back filling pyritic sediments at East Trinity occur up to an elevation of approximately 1 m Australian Height Datum (AHD) and supported mangrove communities prior to being drained in the 1970s.

The sediments containing *foraminifera* that were not eroded have subsequently been covered by material from only the highest tides. These areas became hyper-saline and were colonised by samphire vegetation communities. The surface of these sediments occurs predominantly at an elevation of 1–1.5 m AHD.

The arc shaped sandy chenier ridges formed by storm surge action during shoreline retreat are non-sulfidic, but can overlie sulfidic material. The surface of the chenier ridges occurs from 1.5–2.5 m AHD. Land between 1 and 2 m AHD typically has non-sulfidic material to a depth of 1.5 m, below which an approximately 1 m thick sulfidic layer occurs. The surface material is dominantly of terrestrial origin. Land above 2 m AHD is non-sulfidic and of terrestrial origin.

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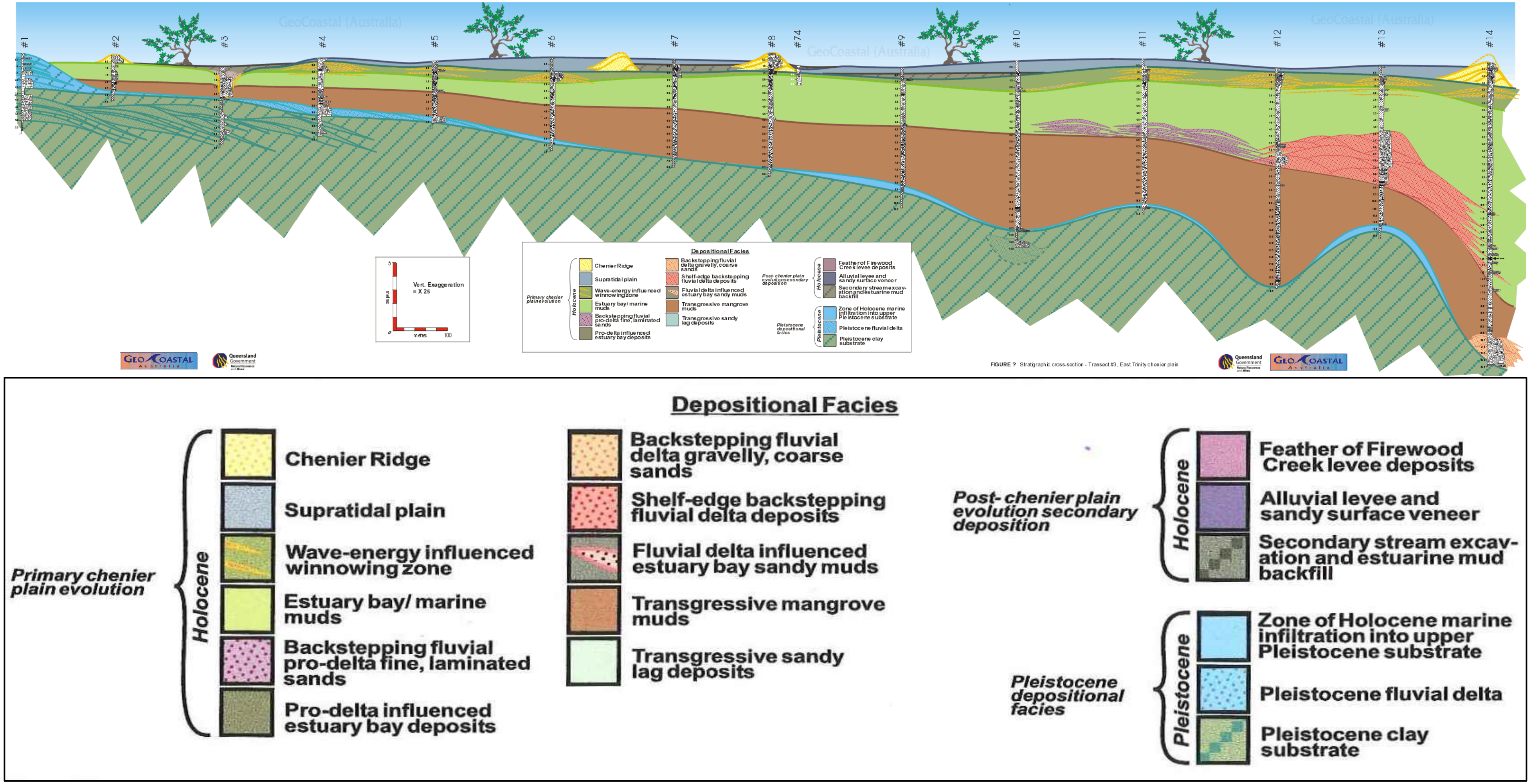


**Figure A1. Stratigraphic cross-section of the East Trinity site.**

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