NSW DPI

Acid Sulfate Soil

Assessments in the Anna Bay Catchment

REPORT TO THE HUNTER-CENTRAL RIVERS CATCHMENT MANAGEMENT AUTHORITY

NSW DEPARTMENT OF
PRIMARY INDUSTRIES

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November 2008

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Cover Photos: Wallis Creek (background); Iron flocculate as evidence of acid sulfate soils in a *Casuarina* forest (left foreground); the main drain of Anna Bay (middle foreground); floodgates on Wallis Creek stained with iron flocculate (right foreground).
Photos by A. Burke.

Executive Summary

The Anna Bay sub-catchment is comprised of a 450 hectare coastal back-swamp, historically known as Murrumburrimbah Swamp. Since initial drainage works in 1897 were carried out to improve agricultural prospects, the drainage network has been considerably extended and discharges into Tilligerry Creek. While this has benefited its intended purposes, in recent years there has been increasing recognition of the potential for negative impacts due to exposure of the underlying acid sulfate soils. Greater movement of acidic groundwater has resulted in fish kills, poor water quality affecting oyster cultivation, reduced stock production and a deterioration in downstream environmental values.

This project was developed in response to the identified issues with funding support from the Hunter Central Rivers Catchment Management Authority. Consultation with landholders in general and in particular the Anna Bay Drainage Union, revealed that there was a common consensus on the way forward. This was to establish suitable means of retaining high groundwater levels, while ensuring better drainage of surface waters following floods and severe rain events.

The NSW Department of Primary Industries undertook extensive site assessments and monitoring, to determine which on-ground works would be most effective at achieving the desired goals. These included a review of all previous studies, water quality monitoring, collection and analysis of soil cores, cross-sectional drain profiling and securing detailed elevation data through land surveys and remote sensing techniques.

These assessments identified two key 'hotspot' areas of soil acidity and led to the development of remediation techniques in consultation with the Drainage Union, landholders and the wider local community. The techniques identified included:

1. Strategic application of lime for all past and future soil disturbance;
2. Raising the height of several side drainage pipes to reduce intersection of the sulfate layer;
3. Installation of a low set weir that would reduce over-drainage at a key hotspot, while widening the drain at that point to ensure drainage capacity is not reduced;
4. Install additional floodgate cells at the existing structure to enhance drainage capacity of the overall system, while modifying one floodgate to enable a controlled degree of tidal exchange.

The on-ground works implementation phase has now commenced. Overall, this project has worked closely with the key stakeholders (the Anna Bay Drainage Union, all relevant landholders and Port Stephens Council) to achieve a 'win-win' situation for all concerned.

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1 Catchment background

1.1 Location

The Anna Bay sub-catchment, part of the Lower Hunter region, is a coastal back-swamp covering approximately 450 hectares of the Tomaree Peninsula of Port Stephens, 60km north of Newcastle on the mid-north coast of NSW (Fig 1). The catchment is mainly low-lying, flat land approximately half of which has been cleared for agricultural use and the remaining is vegetated with predominately *Melaleuca* forests.

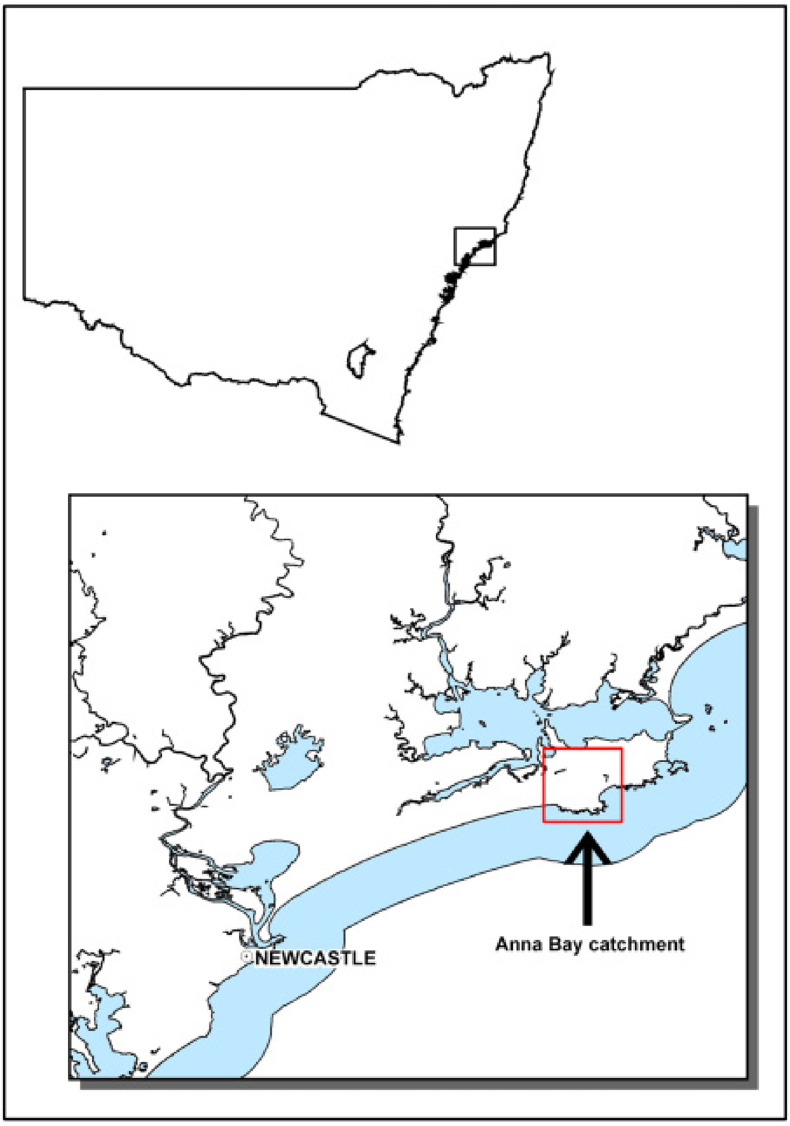

Figure 1 Location of Anna Bay Catchment

1.2 Climate

The Anna Bay sub-catchment is subject to a humid sub-tropical climate characterised by a traditionally wet winter and drier spring/early summer with an average annual rainfall of 1347mm. Figure 2 shows the average monthly rainfall for Nelson Bay, approximately 6km from the upper reaches of the catchment and 12km from the lower reaches.

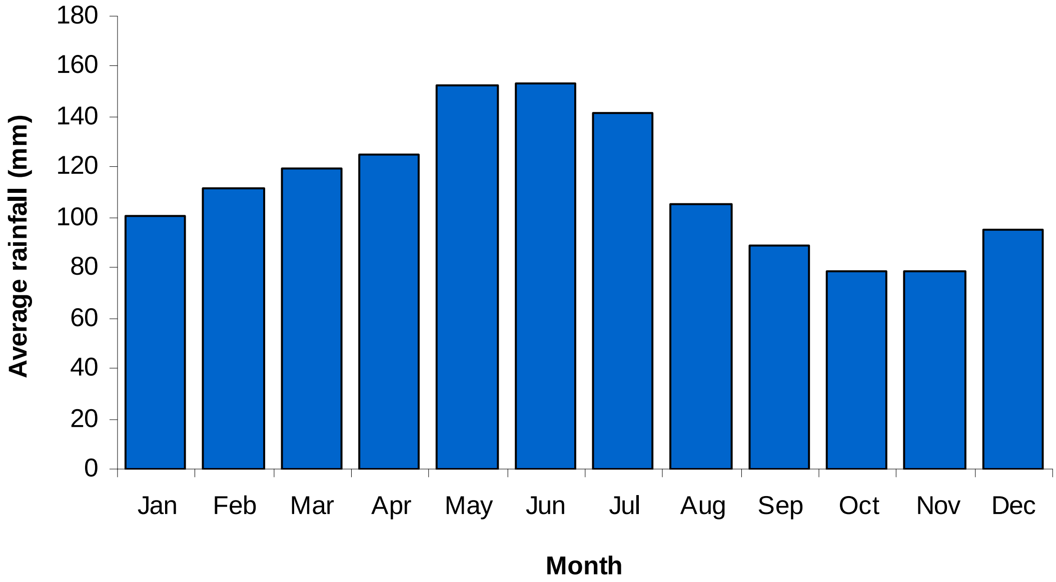

Figure 2: Average monthly rainfall for Nelson Bay (Port Stephens) (source: Bureau of Meteorology)

The average temperature ranges from 18 to 27^{0}C in summer and 7 to17^{0}C in winter. Dominant winds are affected by the topography with prevailing winds in winter from the north-west. In summer, the prevailing winds are from east to south-east, followed by north-east breezes in the afternoon (McManus *et al*, 2000).

1.3 Geology

The Lower Hunter's geology is made up of sediment trapped during the Permian period (~250 million years ago) including coal, conglomerate shales, fluvial sandstones, and Triassic period (~200 million years ago) including shales, and sandstones.

During the Quaternary period (1.8 million to present) sands and fluvial sediments were deposited. Around 130,000-120,000 years ago the sea level was approximately 4 metres higher than today. Over the next 100,000 years the sea level fell to about 120 metres below the level it is today, with the coastline about 25 km further out to sea than it is today.

The soils adjacent to estuaries have resulted from a combination of sediments being washed down the rivers meeting sands deposited by the ocean during its varying sea levels. These soils are sandy and have low fertility and poor structure (McManus *et al*, 2000). Port Stephens is a drowned valley estuary (Roy, 1984).

1.4 Flora

The Lower Hunter region is part of a transition zone for many plant and animal species between the sub-tropical influences of the north and the cooler, less fertile conditions to the south. As a consequence, the vegetation is unique when compared to the neighbouring regions. The flora of the Hunter Valley floor is remarkably diverse, with approximately 2,000 species of vascular plants (DECC, 2006).

Of the 61 vegetation communities that occur in the Lower Hunter, 19 communities are considered to be regionally significant including ten listed endangered ecological communities. The Lower Hunter Region currently has 26 threatened plant species including eight endangered and 18 vulnerable species (DECC, 2006). Vegetation in the region has been largely cleared for agriculture, mining and urban purposes. The vegetation remaining on the valley floor is often highly fragmented and affected by weeds, feral animals and altered fire regimes.

1.5 Fauna

There is a wide array of fauna habitats in the Lower Hunter that are known, or are likely, to support 81 threatened species, including 11 endangered species (DECC, 2006).

1.6 Flood mitigation

In 1897, local workers of the Anna Bay township excavated the main drain from Anna Bay Swamp to Tilligerry Creek to facilitate the removal of surface water, thereby improving soil for agriculture (Anna Bay Public School, 1979). It is not recorded when the first floodgates were installed, but is likely to be concurrent with those first drainage works. The Anna Bay Drainage Union was established in 1910 to manage and maintain the drainage network. The most recent floodgate replacements took place in 1991 and are comprised of threes sets of 3ft by 6ft aluminium flaps with winches. Since occupation in the 1800's there has also been significant use of the groundwater resource of the Tomaree (Anna Bay) sandbeds, potentially lowering water tables in the catchment.

There are four main agricultural drains in the Anna Bay catchment (Main, Back, Boron and Ferntree – see Fig 3) servicing approximately 100 rural properties, which also take stormwater from the One Mile and Anna Bay regions (residential and commercial). Collectively the drains are approximately 15km in length and flow from east to west into Wallis Creek, a natural creek running through a SEPP 14 wetland, into Fenninghams Island creek and then into Tilligerry Creek, a sanctuary zone of the Port Stephens-Great Lakes Marine Park.

In addition to the four main drains, there are numerous smaller drains that form boundaries between properties along the drains. In general, most properties on the main drains have small drains either side of the property discharging into the larger drain.

1.7 Water quality

There have been several studies into acid sulfate soils and water quality of the drainage system of the Anna Bay catchment in the past (Smith,1997, Woods 1997, Envt & Earth Sciences, 2000). These previous investigations found the Main and Back Drains to be contributing low quality water to the Port Stephens Estuary as a result of agricultural run-off and exposure of acid sulfate soils.

1.8 Land use

The Anna Bay catchment has been highly modified for a variety of agricultural and development purposes including cattle grazing, fruit and vegetable produce, horse training and agistment, and residential and commercial zoning.

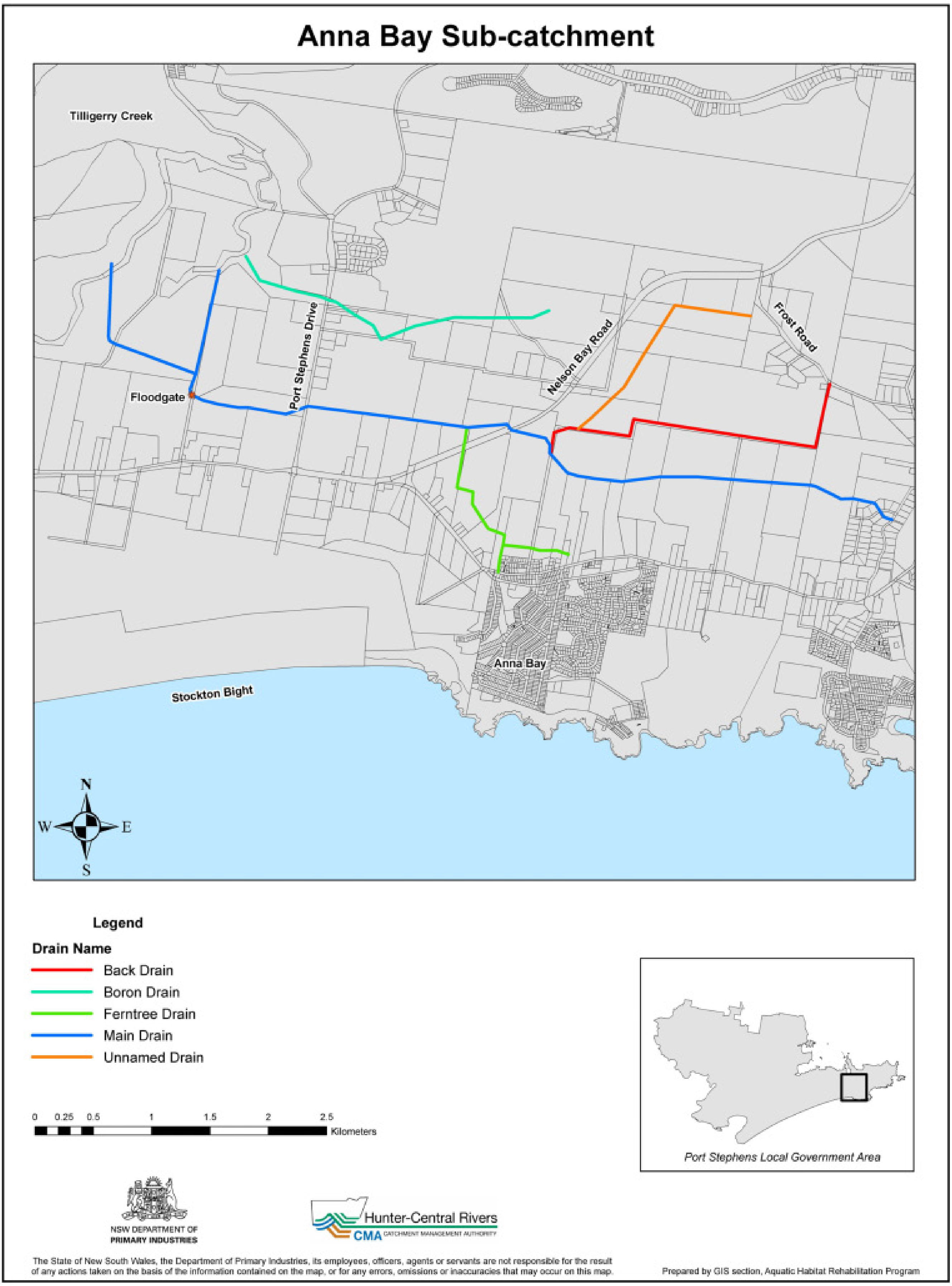

Figure 3 *Anna Bay sub-catchment & drainage system*

2 Acid Sulfate Soil

2.1 Sulfidic sediments

Acid sulfate soil (ASS) is the common name given to naturally occurring soil and sediment containing iron sulfides, principally the mineral iron pyrite, or containing acidic products of the oxidation of sulfides. When sulfides are exposed to air, oxidation takes place and sulfuric acid is ultimately produced when the soil's capacity to neutralise the acidity is exceeded. As long as the sulfide soils remain under the water table, oxidation cannot occur and the soils are quite harmless and can remain so indefinitely (NWPASS, 2000).

ASS were identified in the Netherlands nearly 260 years ago. These soils have since been found to occur worldwide and occupy over one million square kilometres, with major occurrences in Asia, Australia, Africa and Latin America. It has been estimated conservatively that Australia has over 40,000 km^2 of ASS, containing in excess of one billion tonnes of pyrite. Their presence in Australia was recognised only 45 years ago. They were mainly ignored until a massive fish kill in 1987 decimated 23 km of the Tweed River in northern New South Wales and focused attention on the impacts of these soils (NWPASS, 2000).

Coastal ASS occur in every Australian state and the Northern Territory. Using information on conditions necessary for the formation of ASS, together with the known geomorphology of the Australian coastline, it can be predicted that ASS should be found in coastal embayments and estuarine back swamps, with surface elevations less than about 10 m above mean sea level (10 m AHD). Extensive occurrences of ASS are found along the eastern and northern coastline of Australia with smaller areas in southern Western Australia, South Australia, Victoria and Tasmania (Fig 4).

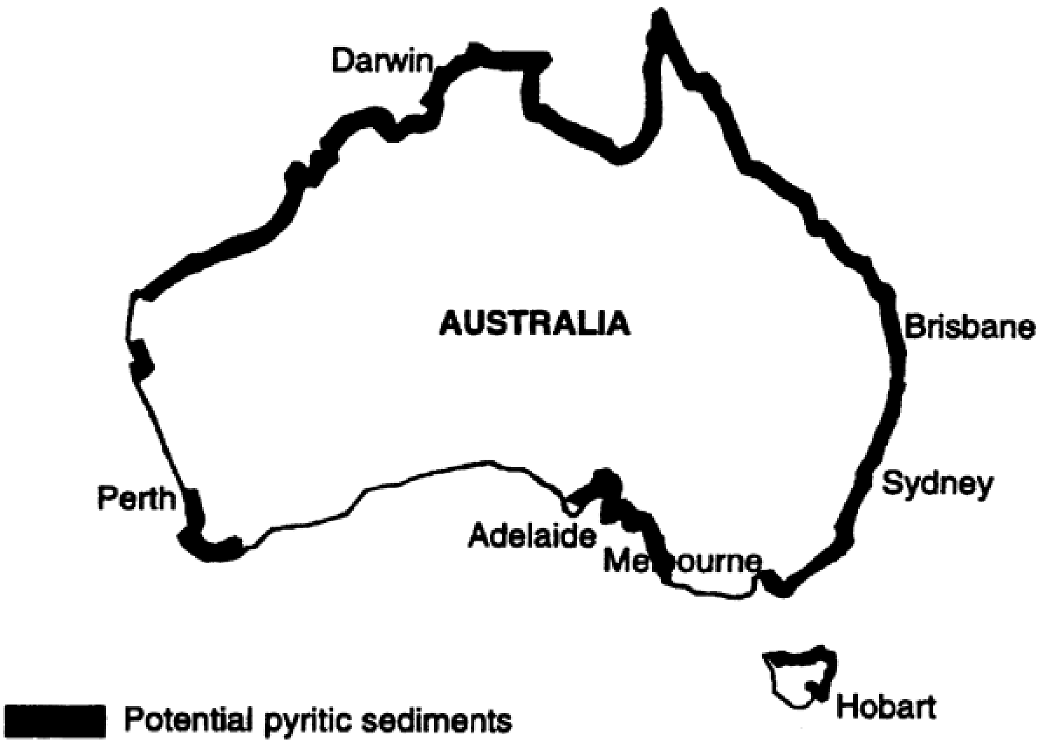

Figure 4 Indicative distribution of coastal acid sulfate soils in Australia (NWPASS, 2000).

Sulfidic sediments are formed in vegetated, low-lying tidal environments when sulfate from sea water is reduced to sulfides by microbes. Sulfides react with iron in the sediments to form iron sulfides (mostly iron pyrite) (Sammut et al, 1996). Holocene-age (<10,000 years BP) sulfidic sediments were formed in estuarine lowlands following the last major sea-level rise and can be found in back-swamps, coastal floodplains, estuarine emabyments and coastal wetlands characterised by shallow water tables (Sammut *et al*., 1996).

In 1996, the then Department of Land and Water Conservation developed an acid sulfate soil risk map for the Port Stephens local government area. These risk maps and subsequent studies (Wood, 1997, Smith, 1997, Carr *et al* 1998) confirmed acid sulfate soils (ASS) occur throughout the Port Stephens area, and in some areas are found less than a metre below the surface.

2.2 Oxidation

Pyrite (or jarosite) is stable under anoxic conditions (water-logged) but on exposure to air, the wet sulfidic soil horizon known as potential acid sulfate soils or PASS will oxidise, forming sulfuric acid (Sammut et al., 1996). Oxidised soil layers are characterised by yellow mottling (Fig 5) and are known as actual acid sulfate soils (AASS).

Figure 5 Yellow mottling of pyrite seen in the bank of the Main Drain, Anna Bay, above the drain water level, The dark band indicates evidence of previous peat fires (photo: S. Walsh)

The acid in turn mobilises iron, aluminium and other metals present in the soil (Indraratna et al., 2005) which leaches into ground water and adjacent drains. Exported iron can oxidise again in waters that are considerable distances away from the source, producing iron oxyhydroxide or hydroxide flocs (iron floc) that coat benthic communities and stream banks (Fig 6) (Sammut et al., 1996).

Figure 6 Wallis Creek floodgates and mangrove community coated in iron floc.
(photo: A. Burke)

2.3 Environmental impacts

Acidification affects both soil and water, and it is now accepted that ASS oxidation has negative impacts on water quality, estuarine habitat, commercial and recreational fisheries, engineering structures, community infrastructure, agricultural productivity, real estate values, scenic amenity and tourism (Rosicky *et al*. 2002).

The impacts associated with ASS are both wide-ranging and severely damaging to the surrounding environment. Discharges of acidic water cause deleterious effects on fish, oysters and a multitude of other aquatic species.

Impacts associated with ASS are most noticeable after rain events following a period of drier conditions. Extended dry periods cause the watertable to lower, further oxidising layers of potential ASS. Drought-breaking rains then flush significant quantities of sulfuric acid and toxic, heavy metals into waterways, resulting in massive fish kills (White *et al.* 1997), diseases such as epizootic ulcerative syndrome (red spot disease, see Fig 7), and reproduction, recruitment and growth problems for aquatic organisms (Sammut, 1996).

Figure 7 Lesions from red spot disease in sand whiting (Source: D. Callinan)

Plants and sedentary gilled organisms that are unable to escape acidified waters are often killed or experience growth and reproduction problems. Oysters that suffer from either frequent or prolonged exposure to acidic conditions, cease feeding and experience breakdown of their shell, exhibit poor growth rates and display gill or organ damage (Dove & Sammut, 2007, Sammut, 2000).

Aquatic habitat is also severely damaged as a result of acid water discharges. When the acidity is buffered, the iron dissolved in ASS-affected water precipitates and can then smother plants and other benthic organisms (Sammut, 2000). High levels of aluminium are not only highly toxic to most aquatic organisms, but also causes particles in the water column to flocculate and settle on the benthos. The resulting water clarity elevates temperature (up to 5^{o} C), allows acid-tolerant plants to saturate the water with oxygen (killing fish through gas bubble disease), and can increase incidence of fish suffering sunburn and melanomas (Sammut, 2000).

2.4 Management of Acid Sulfate Soils

The National Working Party on Acid Sulfate Soils recommends in the 'National Strategy for the Management of Coastal Acid Sulfate Soils' the following overarching national objectives for the management of ASS in Australia:

- Identify and define coastal ASS in Australia
- Avoid disturbance of coastal ASS
- Mitigate impacts when ASS disturbance is unavoidable
- Rehabilitate disturbed ASS and acid drainage

3 Acid Sulfate Soil Assessments in the Anna Bay Catchment

3.1 Project background

The project was developed in response to increasing concern about the condition of the drainage system and the impacts of exposed acid sulfate soils (ASS) entering Tilligerry creek and the Port Stephens-Great Lakes Marine Park. The project has been funded through the Hunter-Central Rivers Catchment Management Authority and is supported by Port Stephens Council and the Anna Bay Drainage Union.

The main aims of the project were to:

1. consult with landholders about the project and educate them about acid sulfate soils;

2. carry out relevant site assessments;

3. undertake remediation works (floodgate management, drain reshaping, and/or installation of water control structures) in consultation with Port Stephens Council;

4. develop a 15 year maintenance agreement between the CMA and the Anna Bay Drainage Union.

3.1.1 Previous acidification event

In June 2006, NSW DPI staff collected data to determine if estuarine acidification was the cause of milky green water in Wallis and Tilligerry Creeks (Dove & McOrrie, 2006) following heavy rain in the local catchment. The pH and salinity of water within this catchment were measured and water samples were collected and preserved for subsequent analysis of ions.

The results confirmed that acidification was occurring in the Wallis and Fenningham's Island Creek systems with aluminium and iron levels in the water alarmingly high. The milky green colour was caused by aluminium floccules suspended in the water column (aluminium concentrations in water samples taken were 60,400 µg/L at the floodgate and 5,760 µg/L 2.5km downstream in the estuary. Both of these figures exceed ANZECC guidelines. There was also extensive and substantial coating of iron oxyhydroxide floccules in the upper reaches of Wallis Creek below the floodgate and in the Main Drain (iron concentrations in water samples taken were 70,650 µg/L at the floodgate and 9,750 µg/L 2.5km downstream in the estuary (see Section 3.3.4 for ANZECC trigger values). The iron floccules observed in the water near the floodgate were mobilised into Tilligerry Creek and caused oyster shells to appear a red/orange colour (see Fig 9) and subsequently oyster growing operations were affected for an extended period.

The high levels of aluminium and iron experienced during this acidification event was likely due to a combination of factors. The prevailing weather conditions prior to the event may have been conducive for oxidising the catchments' acid sulfate soils after a dry summer, and then flushing the acid products into the estuary with heavy rainfall in autumn and early winter (Dove, 2006).

Previous research has shown that sites exposed to ASS-affected water can have a significantly higher level of oyster mortality than sites not affected and mortality increases with prolonged exposure (Dove & Sammut, 2007).

Figure 8 Wallis Creek waters milky green with aluminium floc (Photo: M. Dove). Water in this creek is generally dark brown.

Figure 9 Oysters removed from Fenninghams Island Creek coated in iron oxyhydroxide floccules discharged from the Main Drain (Photo: B. Perkins).

3.2 Methods

The *Remediation of the Anna Bay Drainage Catchment* project was developed by NSW Department of Primary Industries (NSW DPI) to determine options that:

a) retain groundwater (to offer improved opportunities for wet pasture grazing in tandem with better acid sulfate soil management), while
b) improve the removal of surface waters during flood periods by maintaining / enhancing the flood mitigation capacity of the system.

In order to do this, a number of complementary methods were used for the site assessments at Anna Bay. These are summarised in the table below and locations of assessments are shown in Figure 10. The assessments are outlined in more detail in the following table.

Table 1 Site assessment methods

Method	**Rationale**
Landholder consultation	Establish existing information
Review all previous studies	Establish existing information
Water quality	Regular ‘snapshot’ sampling at strategic locations to identify areas in need of intensive site assessment
Water samples	Baseline information to quantify Total Titratable Acidity, chloride / sulphate ratios and associated heavy metals leaving the system
Water levels	Establish water levels over a range of climatic conditions and tidal variations; determine existing gate leakage
Flow rates	Establish quantity of water moving through the system
Soil cores	Determine if a relationship between surface elevation and depth of sulfidic horizon exists. Test for whether acids are sulfidic or organic in nature. Link results to previous survey work undertaken by Wood (1997) and Env. & Earth Sci. (2000a and b)
Drain profiles	Identify the existing drainage capacity of the system
LiDAR	Provide broad-scale elevation data accurate to +/- 0.15m
K_{sat} pits	Determine soil hydraulic conductivity and the potential for saline intrusion
EM38	Measure the apparent electrical conductivity (EC_a) of soil in situ

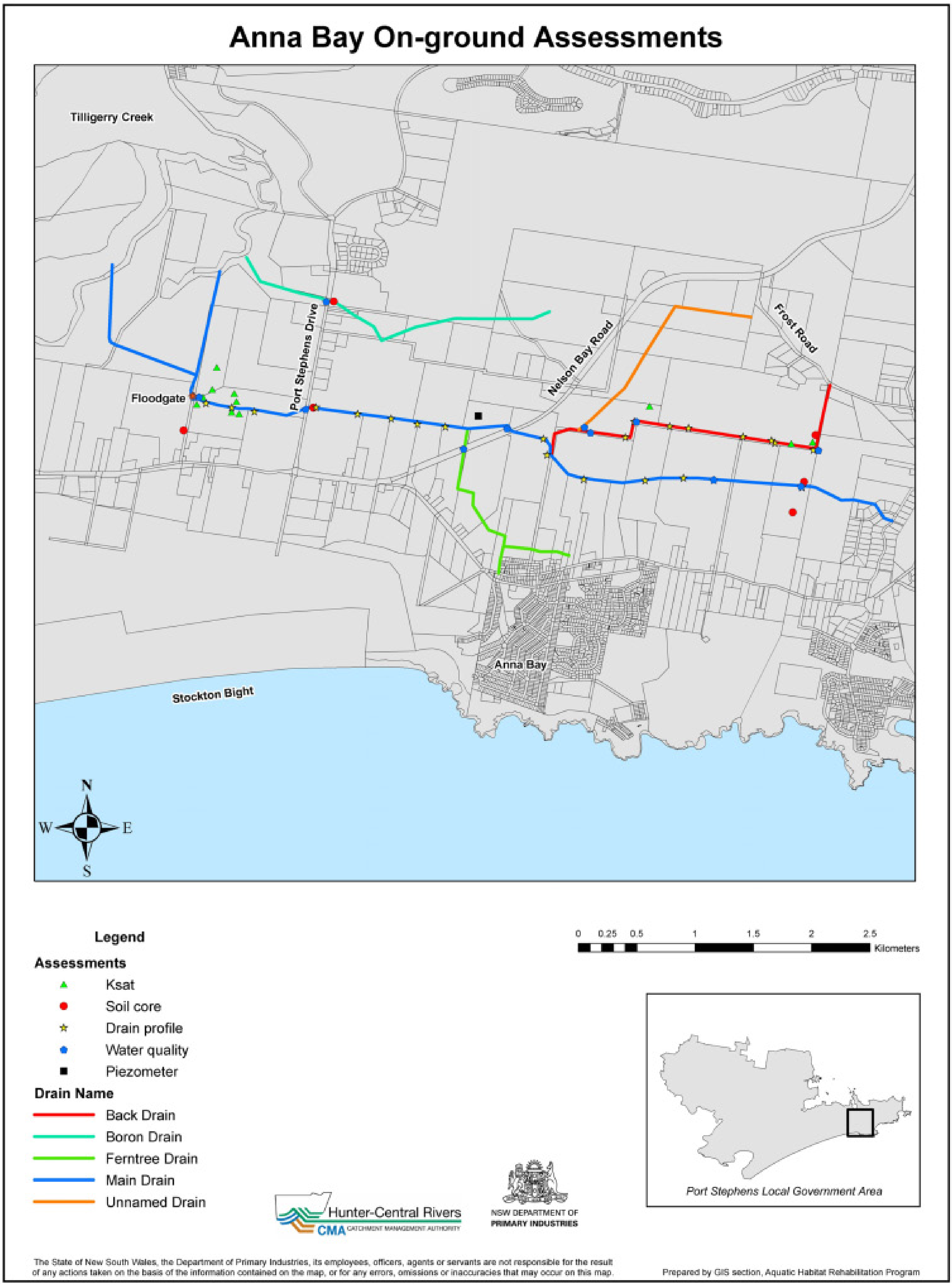

Figure 10 *Location and type of on-ground assessments carried out in the Anna Bay catchment from September 2007 to April 2008.*

3.2.1 Landholder consultation

Several meetings were held with the Anna Bay Drainage Union (The Union) to discuss the project and remediation options. It was agreed that remediation works would need to improve the removal of surface water post flood while maintaining sufficient ground water to reduce any impacts from acid sulfate soils. This would be done through works identified following the detailed site assessments.

The Union agreed to sign a 15-year maintenance agreement between them and the Hunter-Central Rivers Catchment Management Authority to ensure any remediation works carried out during the project would be maintained over that period.

A meeting was held in June 2008 between NSW DPI and The Union to discuss the results of the detailed site assessment which identified 'hotspot' areas of soil acidity and remediation options for the drainage system. These options include:

1. Strategic application of lime for all past and future soil disturbance;
2. Raising the height of several side drainage pipes to reduce intersection of the sulphate layer;
3. Installation of a low-set weir that would reduce over-drainage at a key hotspot, while widening the drain at that point to ensure no loss of drainage capacity;
4. Install additional floodgate cells at the existing structure to enhance drainage capacity of the overall system, while modifying one floodgate to enable a controlled degree of tidal exchange.

3.2.2 Review of existing studies and reports

In the past there have been three main investigations into ASS in the Anna Bay catchment. These studies were carried out 8 and 11 years ago from time of writing (Smith 1997, Wood 1997, Environmental & Earth Sciences, 2000a & 2000b) and were reviewed for this report.

3.2.3 Water quality

Water quality monitoring using a Horiba U-10 multi-parameter probe (pH, electrical conductivity, dissolved oxygen, temperature and salinity) was conducted in situ at low tide on a weekly basis at 12 locations throughout the Anna Bay drainage system (on the Main, Boron, and Ferntree drains and two unnamed side drains. See Fig 11 for locations).

This component of the site assessments was carried out between 13th February and 11th April 2008 – a period of around two months. Additional monitoring took place both before and after that period on a more opportunistic basis.

In addition, an Insitu Troll 9500 data probe was installed in Fenninghams Island Creek to gauge pH and EC as a result of drain discharge. The probe took measurements every 20 minutes while deployed. This was deployed from 28th September 2007 to 9th April 2008 (Fig 11).

Environmental & Earth Sciences (2000a) previously installed a datalogger which measured EC and pH near Fenningham's Island (Fig 11).

Water quality parameters were also recorded for groundwater in the K_{sat} pits (see section 3.2.10).

3.2.4 Flow rates

Flow rates were measured using a 50mm Braystroke Current Meter during a single day's low, mid and high tides at sites 1 -9 of the water quality monitoring locations to determine the quantity of water moving through the system. Water samples were also taken for each site at each of these times for laboratory analysis (see section 3.2.5 below).

In tandem with the water quantity, the water quality analyses enable a robust estimate to be made of total available acidity (and heavy metal) export before any on-ground change is effected.

3.2.5 Water samples

In total, 40 water samples were taken for laboratory analysis for total acidity, pH, EC, total dissolved solids, chloride, sulfate, aluminium, arsenic, boron, calcium, cadmium, cobalt, chromium, copper, iron, potassium, magnesium, manganese, molybdenum, sodium, nickel, phosphorous, lead, sulphur, selenium and zinc. Samples were collected at all sites at low tide on one occasion and at all sites at high tide and Sites 1 - 9 only at mid tide and low tide on another occasion.

Each site was sampled at high, mid and low tides on the 7th of March. This date was about one week after a previous rain event of 80mm.

3.2.6 Water levels

Odyssey capacitive water level recorders were deployed in 2008 immediately upstream and downstream of the floodgate and at the Nelson Bay Road culvert 2.3km upstream of the floodgate (water quality site 6) to continuously (every 30 minutes) record water levels. This component of the site assessments was carried out between 11th August and 26th September 2008 – a period of approximately 6 weeks.

Groundwater levels were also recorded in the soil cores (see Section 3.2.7) and K_{sat} pits (see section 3.2.10).

Figure 11   Water quality monitoring sites in the Anna Bay catchment (Imagery: Google Earth)

3.2.7 Soil profiles

Soil morphological assessment and soil profile descriptions were carried out by DPI's soil chemist Roy Lawrie using methods as detailed in *Australian Soil and Land Survey Field Handbook* (McDonald *et a*l 1990) and sampling, handling and transport of soil samples were undertaken according to *Acid Sulfate Soils Laboratory Methods Guidelines* (Ahern *et al* 2004).

The intention was to establish the depth to sulfuric (actual ASS containing pyrite and iron oxide mottling) and sulfidic (potential ASS containing jarosite, shells or with a positive peroxide test) horizons. For these purposes, a truck mounted, hydraulically-operated auger was used to penetrate through the dense surface layers where necessary. A gauge auger was then deployed to sample the softer sediments to a depth of 1.5 metres.

Six cores were taken at the sites seen in Figure 12.

The soil profile descriptions and sampling include:

- Record of each borehole location using GPS and record of surface elevation;
- Field texture, colour, presence of mottles (including presence of jarosite);
- Field pH peroxide test (pH_{FOX}) of soil every 0.10 m down the profile.
- Record of shell abundance and size distribution if present in soil;
- Soil samples taken at 0.1 m intervals or less down the profile ensuring that every soil horizon is sampled;
- Allowing approximately 0.5 kg of soil per sample for laboratory analysis ensuring that a sealed plastic bag is used and clearly labelled with project/site number and depth of sample;
- Record of groundwater depth from the soil surface.
- Collection of groundwater sample for laboratory analysis i.e. pH, EC, chloride, sulfate, aluminium, calcium and iron.
- Samples were immediately frozen after collection and dispatched to the NSW DPI Diagnostic and Analytical Services, Wollongbar for detailed analysis of the parameters detailed in Appendix 5.

Laboratory Analysis

Standard methods for analysing the existing acidity (ie. actual and retained acidity) of the potential acid production from oxidation of iron sulfides in estuarine and coastal sediments were followed according to *Acid Sulfate Soils Laboratory Methods Guidelines* (Ahern *et al* 2004).Two main suites of analyses will normally be required for most acid sulfate soil situations:

- the ***chromium suite*** or
- the ***SPOCAS suite***.

— details of these methods are found in Ahern *et al* 2004.

All soil and water samples were analysed by a NATA (National Association of Testing Authorities) accredited laboratory.

3.2.8 Drain profiles

Bathymetric profiles were developed for the Main and Back drains. Transects were placed across the drain where there was a change in depth or shape of the drain (Fig 13) and measurements were taken at 25 or 50cm intervals and surveyed to establish elevation (Australian Height Datum - AHD) (see Appendices 6 and 7). Major changes in drain depths were determined initially using a hand-held sounder; which enabled an assessment to be made of the number of profiles required. The position, width, invert and depth of any side drains were also recorded.

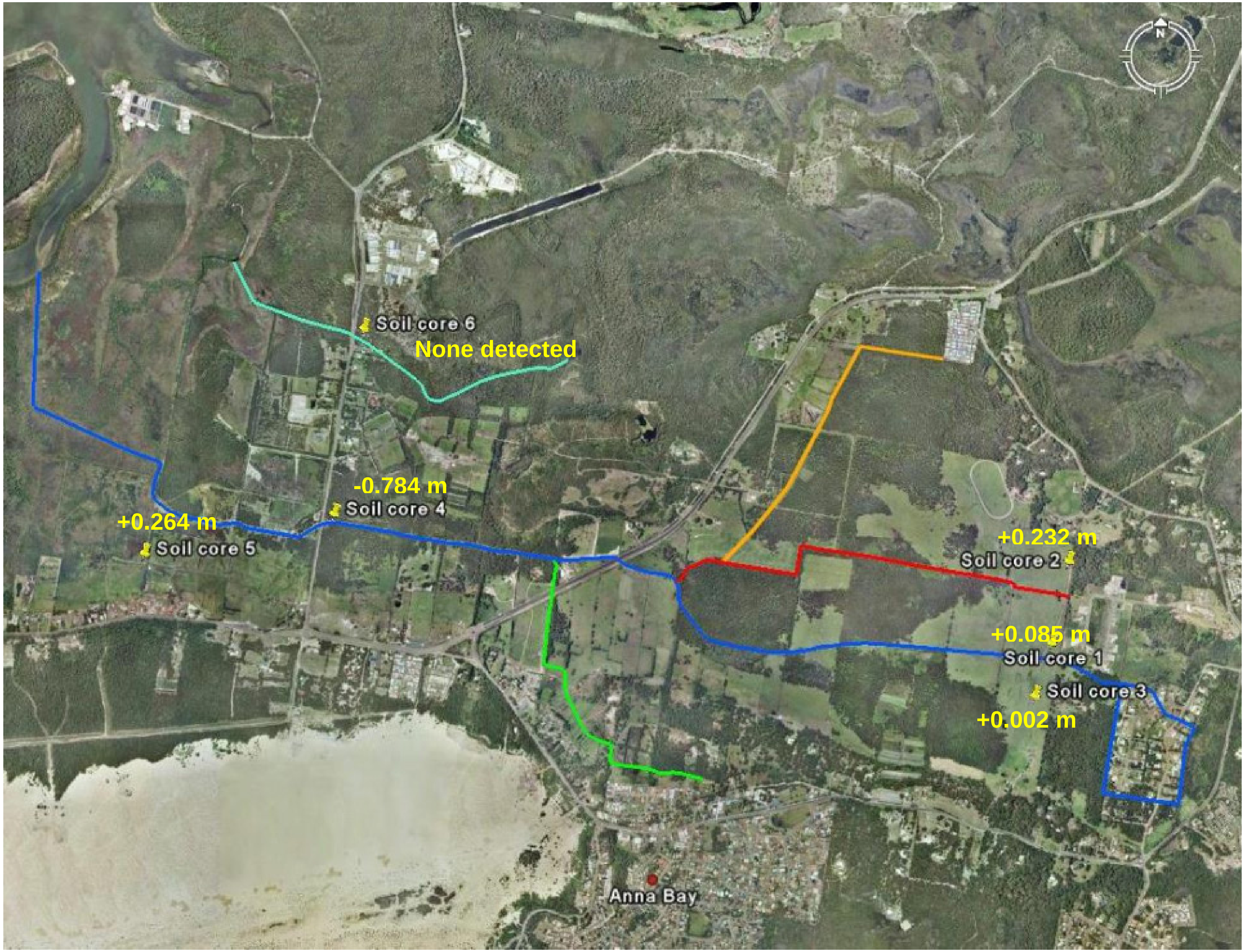

Figure 12 Soil core locations with approximate elevations of sulfidic layer in yellow (AHD) (Imagery: Google Earth).

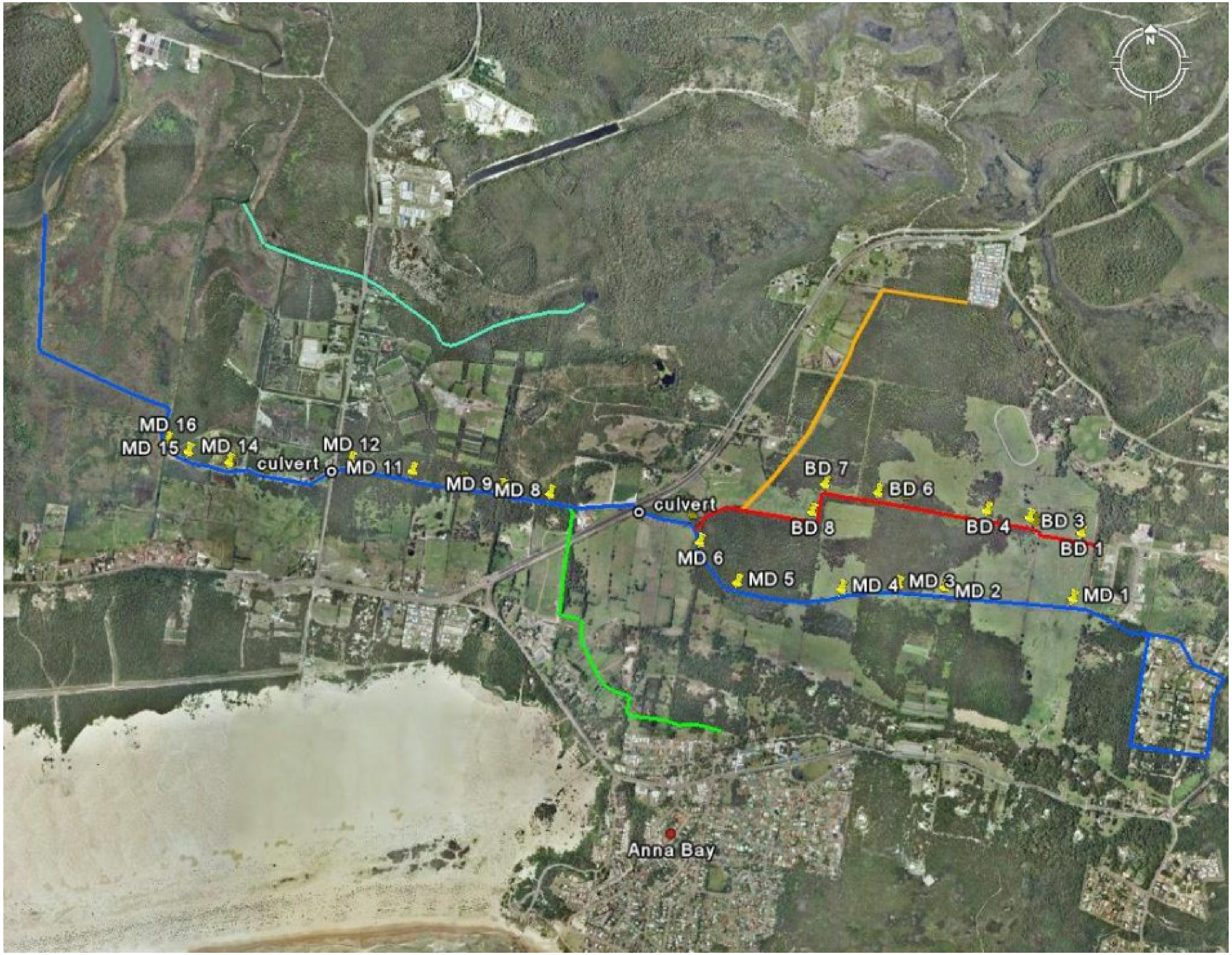

Figure 13 *Location of drain transects along the Main Drain (MD) and Back Drain (BD) (Imagery: Google Earth).*

3.2.9 Airborne Laser Scanning (LiDAR)

LiDAR is high resolution elevation data used in determining the drainage capacity of the sub-catchment. The data had been collected previously by Fugro Spatial Pty Ltd for the Port Stephens local government area and was purchased jointly by NSW DPI, Port Stephens Council and Hunter Water Corporation.

3.2.10 Hydraulic conductivity

Saturated hydraulic conductivity (K_{sat}) of the soil was assessed at 11 points along the Main and Back drains using the method for K_{sat} pit tests as described by S.G. Johnston & P.G. Slavich (2003) (see Fig 14 for pit locations).

These assessments were carried out to help determine whether substantial lateral groundwater seepage (to the drain / from the drain) is likely to occur and also what hydrological pathway (groundwater seepage or surface runoff) may dominate the acid flux.

3.2.11 EM 38 transects

Line transects were conducted using a Geonics EM38 electromagnetic induction soil conductivity meter. The EM38 is a field survey instrument that measures the apparent electrical conductivity (EC_a) of soil in situ. Two types of ECa measurements can be made using the EM38 instrument i.e horizontal readings (EMh) at the surface and vertical reading (EMv) to a depth of 1.5m. If EMh > EMv then salts are highest near the soil surface. In low lying floodplain environments high EC_a readings can be indicative of oxidised acid sulfate soils or areas of past tidal inundation (Clay & Hirst, 2004).

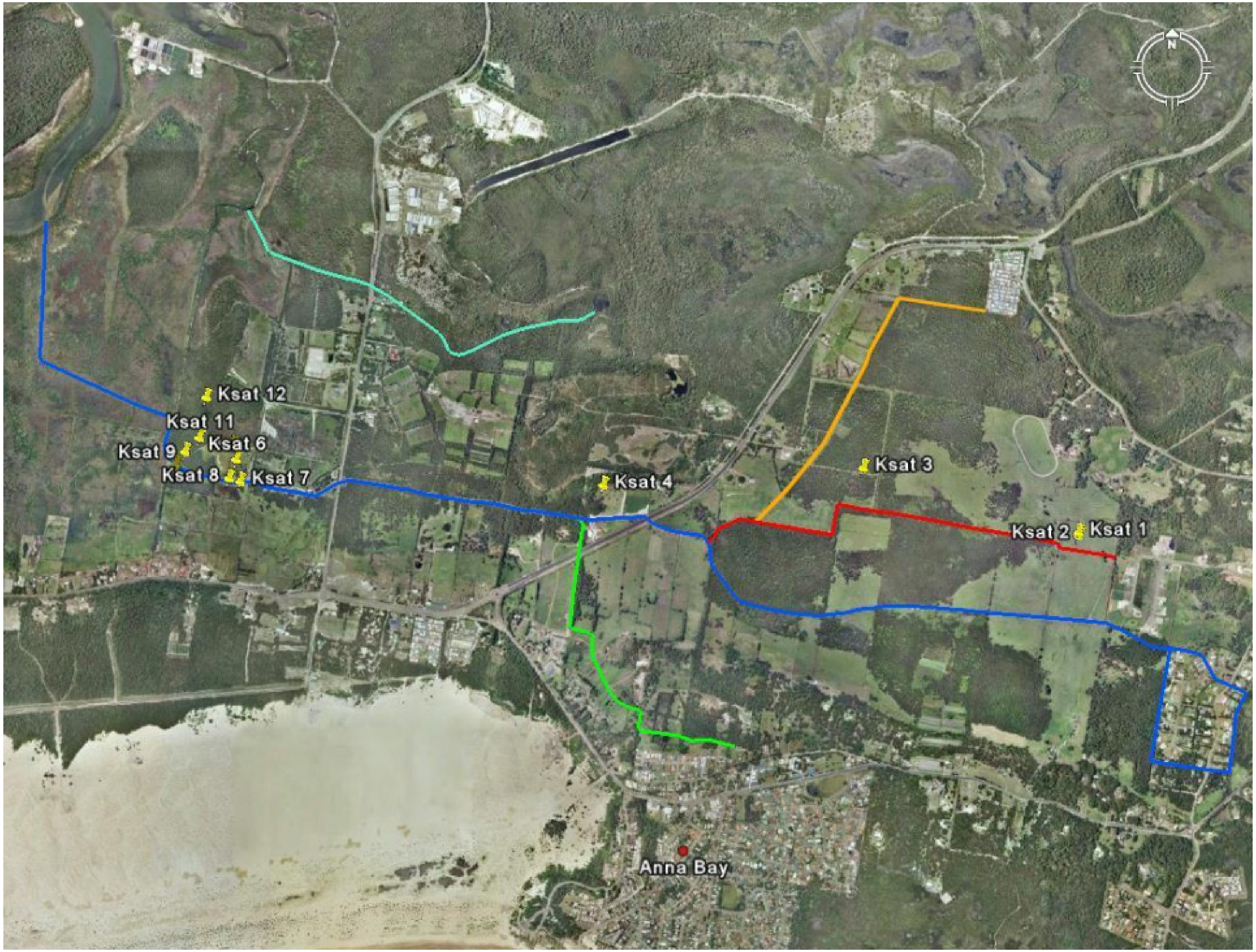

Figure 14 Hydraulic conductivity (K_{sat}) pit location map (NB Ksat 11 is adjacent to Ksat 9) (Imagery: Google earth).

3.3 Results

3.3.1 Literature review

Wood (1997) found that the soil in all sites tested was of a high potential acidity and moderately acidic at the time of sampling. The PASS layer was located at all sites between 20 – 100 cm below the surface. This study confirmed there to be PASS and ASS with soil pH prior to testing between 3.4 and 3.8 and after oxidation between 2.0 to 3.9. Samples were also tested using peroxide oxidisable sulfuric acidity (POSA) and many samples tested were classified as ASS.

Groundwater monitoring during the study found a correlation between rainfall and the pH of groundwater and drain water. When there was a large rainfall event the groundwater pH lowered and then the drain water pH lowered as a result of groundwater being flushed into the drainage system.

Smith (1997) found the pH of the water in the Main Drain to drop downstream of its confluence with the Back Drain and that the Back Drain experienced the lowest mean pH of the drains. Smith (1997) also found mean EC readings in the lower catchment west of Port Stephens Drive to be much higher than the upper catchment due to passage of saline water through the floodgates extending up to Port Stephens Drive.

Field observations of ASS were also made during this study as follows:

- jarosite in drain spoil along drain banks;
- presence of hydrogen sulfide gas noticeable around drains, especially after a rainfall event;
- waterplant growth in drains indicative of acidic water conditions (Cape waterlily);
- presence of iron and iron flocs.

Environmental & Earth Sciences (2000) study commissioned by Port Stephens Council found the catchment to be an extremely flat area (elevation and slope gradients below 3 m and 3 deg respectively) and supported the DLWC assessment of the area as high risk ASS, although the study also found there is variation in sulphide levels both laterally and with depth. The study also found consistently low soil pH (<4.5 and as low as 2) and a good correlation between soil texture and sulphide content (more sulphide in clays than sands).

Soil testing was conducted along the Main and Back Drains and showed ASS within 1 metre across this area. Un-reacted soil sulfides with a potential for further oxidation were found within 30cm of the surface.

While groundwater was found close to the surface, any long term de-watering would expose significant quantities of ASS. Dewatering could occur due to droughts or over-drainage and pumping of the groundwater. A conclusion of this study was that "The major risk with respect to acid production through the oxidation of sulfides in the study area, will be uncontrolled excavation or water table lowering."

Recommendations made by Environmental & Earth Sciences are to raise the invert of the floodgates to above Mean Sea Level (MSL) and remediate drains to ensure drainage capacity is maintained.

Following on from this report, Environmental & Earth Sciences developed strategic guidelines for managing ASS in the Port Stephens and Anna Bay catchments (ESS, 2000). The guidelines recommend:

- Remediate drains to ensure they do not intercept ASS layers;

- "The ideal remediation strategy for these drains is to widen and in-fill to the upper ASS/groundwater layer. In order to ensure that ASS is not exposed at the surface adjacent to the drain by this operation, the spoil used to infill drains should not be topsoil. This strategy is however dependent on up-slope drain gradients, and alternative measures, including raising head works flood gate levels and placing drop boards in drains to back up waters can be used to raise the watertable in drainage lines";

- Validation and on-going monitoring to ensure that disturbance has not caused environmental degradation.

3.3.2 Field observations

Throughout the study period visual observations were made of the system, some of which were symptomatic of acid sulfate soils:

- large amounts of iron floc discharging through the system into Fenninghams Island Creek after heavy rainfall and drain cleaning (occurring simultaneously);

- iron floc was observed by oyster researchers moving through the estuary past the Port Stephens Research Centre 2.5km downstream of the floodgate;

- Main drain always flowing downstream on an outgoing tide;

- sulphurous smell (hydrogen sulfide gas) noticeable from properties adjacent to drains, especially the small drain at the floodgate;

- groundwater flowing into the drain from macropores after cleaning approx 1 ft above drain water level;

- little evidence of any aquatic life (single moribund eel approx. 15 cm observed gasping on drain bank near Port Stephens Drive). Mullet once observed upstream of the floodgate when the gate was jammed open;

- land of elevations of 0.5m AHD remain inundated for several weeks after a rainfall event;

3.3.3 Water Quality

Water quality testing carried out in situ at 12 locations throughout the catchment measured pH, dissolved oxygen (mg/L) and electrical conductivity (EC – ms/cm). The average of each parameter for each site can be seen in Figure 15 and all results are shown in Appendix 1.

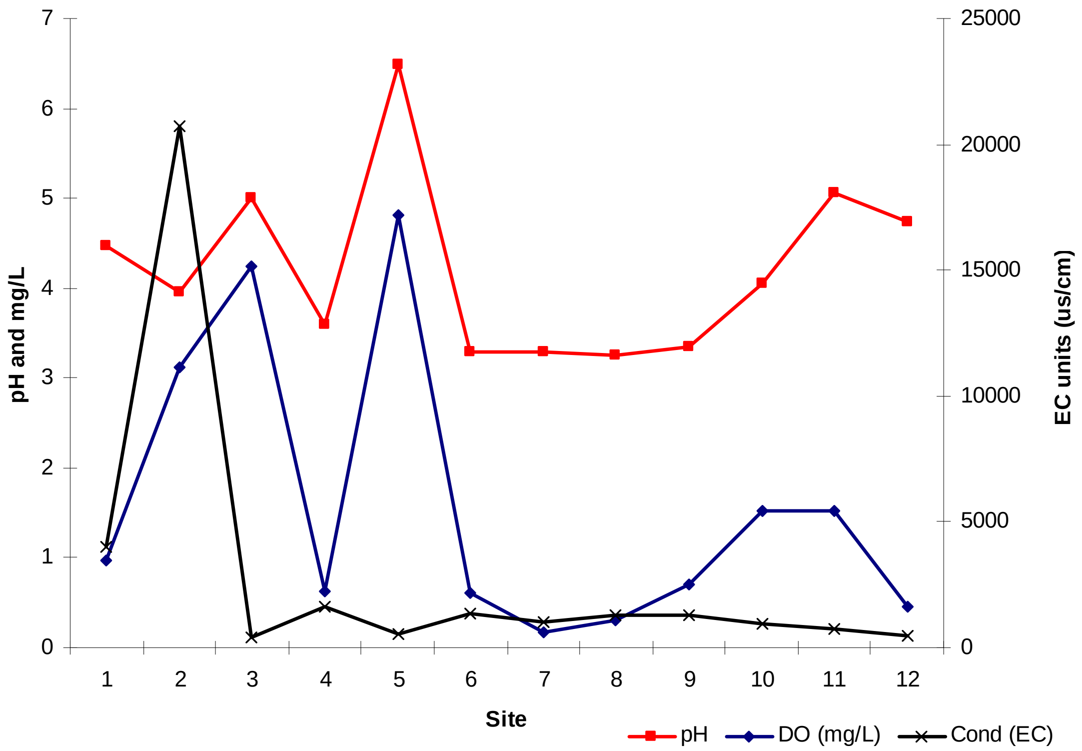

Figure 15 Average pH, EC and dissolved oxygen for field testing at 12 locations.

❖ pH

In situ water quality testing identified Sites 6 to 9 to exhibit the lowest average pH values (3.29, 3.29, 3.24, and 3.35 respectively). The results show low pH levels at Sites 10 to 6 (Fig 15), with six being the first sampling point downstream of the confluence of the Back Drain and the Main Drain. The Back Drain and an unnamed drain feeding into it had the lowest pH values measured across the 12 sampling sites (Sites 7, 8 and 9).

The Ferntree and Boron Drains had the highest average pH levels (pH 6.49 and pH 5, respectively). Neither of these drains has a floodgate and both are observed to continually flow except the Ferntree on a high tide when the Main Drain flows back into it until the tide turns. The Boron has no connection to any of the other main drains in the catchment.

The quality of the groundwater was measured for some Ksat pits and the soil core holes which all had a pH lower than 5. The lowest was found in soil core 1 (pH 2.9) at the top of the catchment, followed by Ksat pit 2 (pH 3.48) near the floodgate.

These results are similar to those found in 1997 which also showed a trend for higher pH further upstream and the worst pH levels found in the Back Drain (Smith, 1997). Figures 16 and 17 show this trend across all the sites sampled in the current study compared to 1997 and for the sites only in the Main Drain.

Average pH levels measured during the present study are lower than those reported by Wood (1997) and Smith (1997). Whether this is due to increased oxidation of pyritic products or changes in rainfall patterns is uncertain.

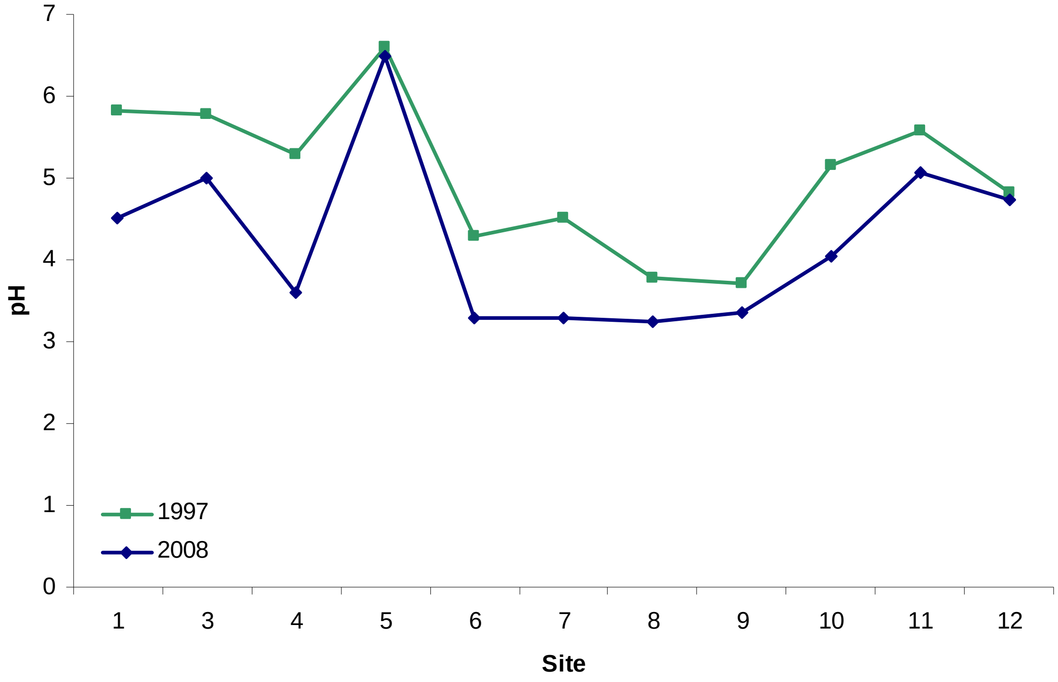

Figure 16 Average pH for sites sampled in 2008 compared to 1997 (Smith; Wood).

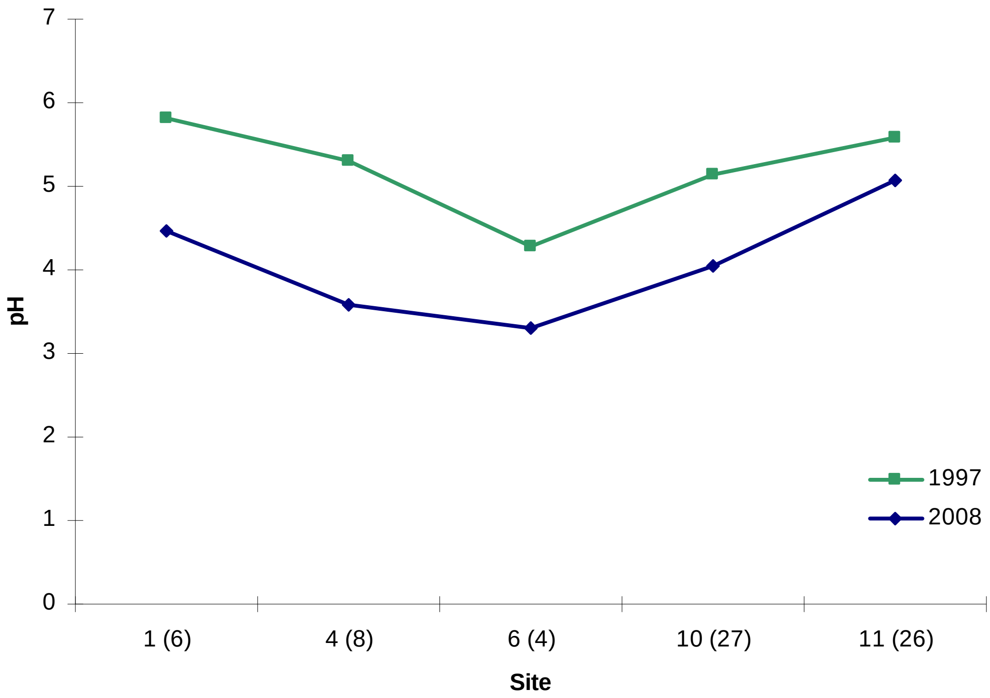

Figure 17 Average pH for Main Drain sampling sites upstream of the floodgate in 2008 compared to 1997 (Smith; Wood).

❖ **Electrical conductivity (EC)**

The electrical conductivity (EC) ranged from an average of 0.37 to 20.7ms/cm. Sites 1 and 2 had the highest EC reading (4.03 and 20.7ms/cm, respectively) both of which are in close proximity of the floodgate and exposed to a certain amount of saline estuary water that often enters the drain through leaking gates.

Site 2 had a significantly higher EC than that found at the floodgate site itself, where presumably, leakage of the gates account for the relatively high salt levels. It is presumed that these extremely high levels at site 2 are a result of marine waters entering the site, finding subsequent egress more difficult due to localised elevation levels / inverts and becoming hyper-saline through evaporation.

These hyper-saline conditions are thought to have negative impacts on facilitating the release of toxic quantities of heavy metals, in particular iron and aluminium. At present, the surface of the site is covered with a thick layer of mono-sulfidic products.

Figure 15 shows that the influence of salt water can extend as far as the Nelson Bay Road culvert.

❖ ***Troll 9500* data probe**

The *Troll 9500* data probe was installed in Fenninghams Island Creek (Fig. 11) to gauge pH and conductivity as a result of drain discharge. The results are shown in Appendix 2 and rainfall for the same period is shown in Appendix 3 for comparison.

The results confirm anecdotal information that heavy rainfall in the catchment will initially cause a decrease in conductivity as estuarine water is diluted or displaced by rain water surface runoff discharging from the drain and pH remains stable (between 6.5 and 8.5 fluctuating with the tide).

This is followed by a drop in pH several weeks after the event when the surface runoff has been removed and groundwater base flows are moving into the drain and out into the estuary. Groundwater will move laterally into the drain once the drain water level is below that of the groundwater. Groundwater is shallow in the Anna Bay catchment (during this study it was found 17 to 60cm below the surface).

Appendix 2 shows a significant drop in pH in late January 2008 through to mid February. This could be a culmination of heavy rainfall during December 2007 (198mm) and more in January 2008 (94.5mm). Low pH was also experienced in late February and early March due to 263mm of rain in February.

Data collected by a datalogger installed by Environmental & Earth Sciences (2000) showed that there was a good relationship between water depth due to tidal inflows and Total Dissolved Solids (TDS), EC, pH and temperature. The data also showed that during periods of low tidal variation (neap tides) the variation in pH and TDS was much less pronounced.

3.3.4 Water Samples

The water samples collected during the current project were tested by the Wollongbar Agricultural Institute's Diagnostic & Analytical Services in accordance with National Association of Testing Authorities (NATA) accredited requirements. Samples were tested for pH, electrical conductivity (EC), Chloride, Sulfate, total dissolved solids, 20 dissolved elements and metals and acidity (as calcium carbonate). All results are shown in Appendix 4.

❖ **pH**

Overall, Anna Bay is characterised by low pH values. Analysis shows that all but two of the 12 sites have a pH below 5 and the majority of sites have a pH below 4 (Fig

18). The two exceptions are Sites 3 and 5. Site 3 (Boron Drain) runs independent of any of the other drains and does not have floodgates, Site 5 (the Ferntree Drain) takes stormwater from the Anna Bay township and rural properties adjacent to the drain and flows into the Main Drain. Site 3 was consistently pH 5.3 during all tide levels measured. Site 5 had the highest pH during mid and high tide (pH 7.5 and 8), though it dropped significantly on low tide (pH 3.6).

The laboratory testing confirmed the in situ testing results for Sites 6 – 9 which again had the lowest pH values of the 12 sites. Site 6 ranged from pH 3.1 – 3.3, Site 7 was consistently pH 3.2, Site 8 ranged from pH 3.1 – 3.2, and Site 9 was consistently pH 3.3.

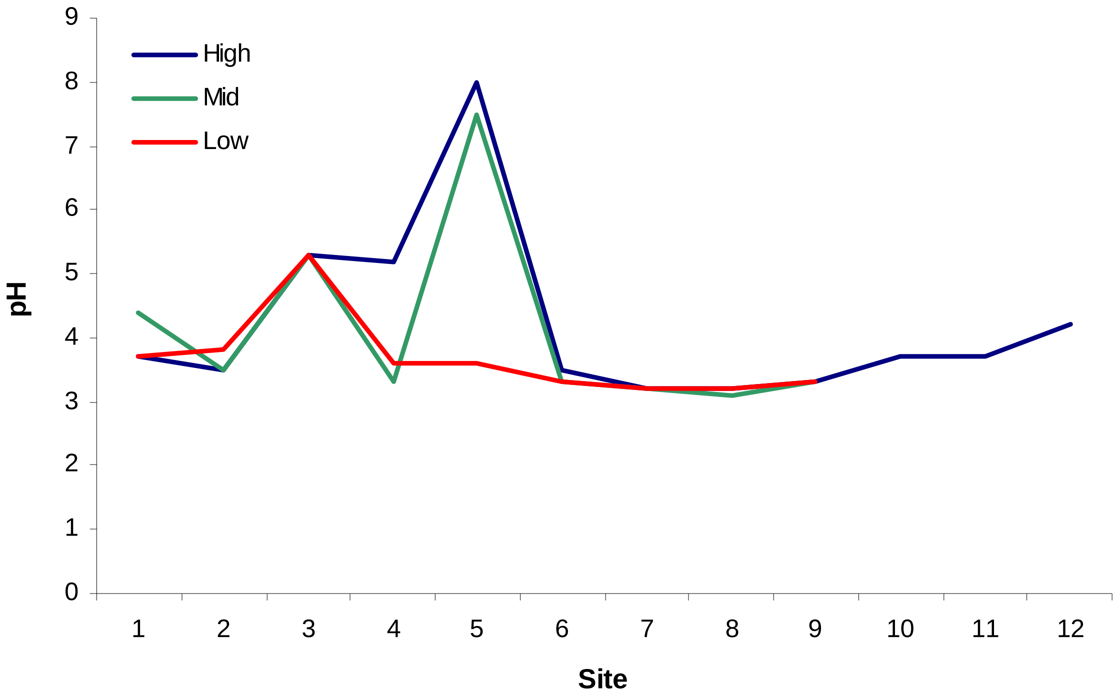

Figure 18 pH levels for water samples collected at high, mid and low tides.

❖ **Iron**

Currently in Australia there is insufficient data to derive a reliable trigger value for iron levels in freshwater systems. It is recommended to use the Canadian guideline level of 300µg/L as an interim level (ANZECC, 2000). This is represented in yellow in Figure 19.

In water samples analysed, only Site 5 (Ferntree Drain) had iron levels below the recommended 300 µg/L (57 – 100 µg/L). Site 2 had the highest value of 130 000 µg/L (sample taken at low tide) followed by Sites 6 (47 000 – 48 000 µg/L), 7 (55 000 – 57 000 µg/L), 8 (84 000 – 95 000 µg/L), and 9 (58 000 – 94 000 µg/L) (see Fig 19).

Orange-brown flocs (iron hydroxide or oxyhydroxide) were observed in all drains (except the Ferntree and Boron Drains) which all had pH below 5. The floc is transported downstream in suspension and coated the drain banks, drain beds, culverts, and floodgates. The flocs were also observed downstream of the floodgate and coated young and established mangroves.

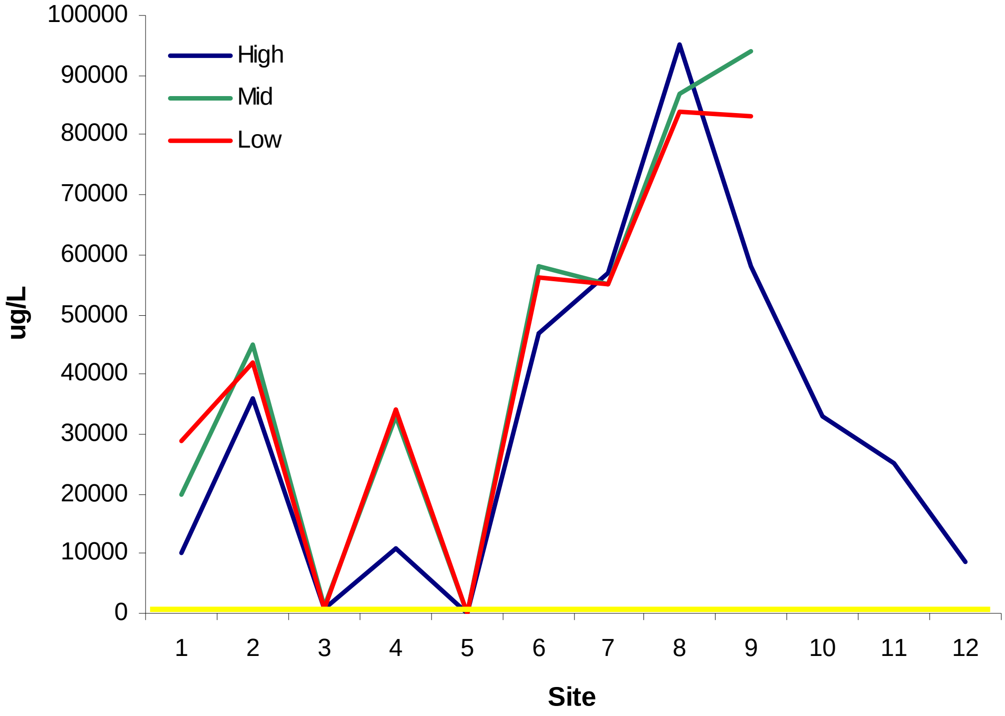

Figure 19 Iron levels in water samples collected at high, mid, and low tide.

❖ **Aluminium**

Freshwater systems with a pH > 6.5 have a trigger value for aluminium concentration of 55µg/L (ANZECC, 2000). This is represented in yellow in Figure 19. Site 5 was the only site to have pH values over 6.5 and was below the trigger value with an aluminium concentration of 30 – 31 µg/L (Fig. 20).

Freshwater systems with a pH < 6.5 have a trigger value of 0.8µg/L for aluminium concentration (ANZECC, 2000). All other sites were well above the recommended trigger value (the lowest being Site 11 at low tide with a concentration of 190 µg/L) with a range between 190 – 17,000µg/L. Sites 6 to 9 exhibited the highest concentrations of aluminium with values above 5,000µg/L (Fig 20).

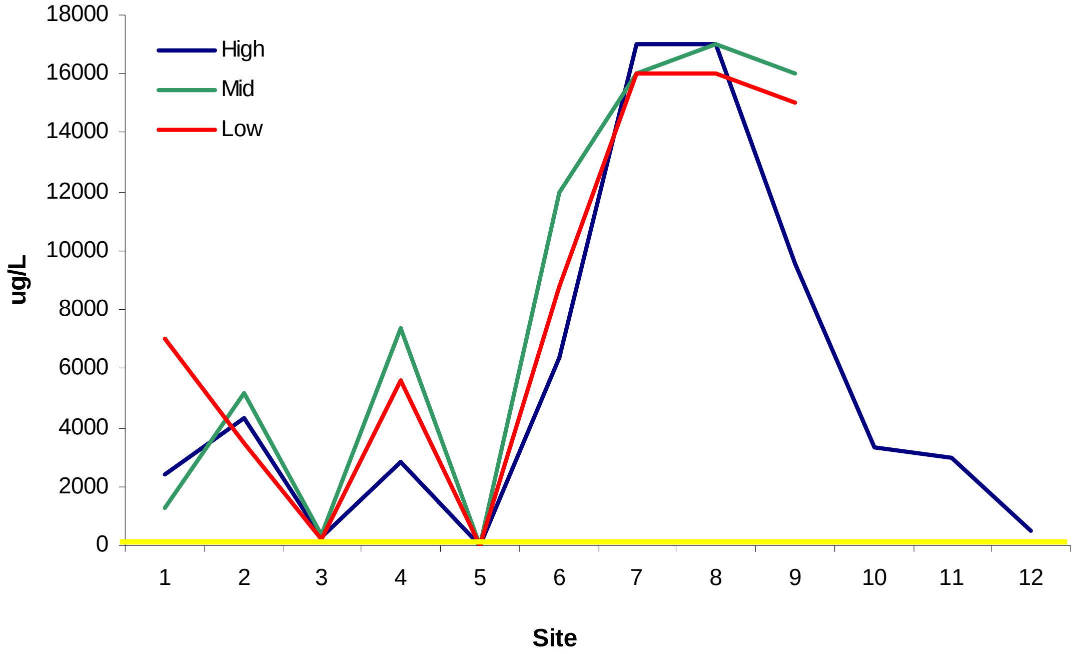

Figure 20 Aluminium levels in water samples collected at high, mid, and low tide.

❖ Other potential toxicants

Eighteen other potential toxicants were detected in the water samples analysed for the Anna Bay catchment. Table 2 lists these and compares the levels to recommended ANZECC trigger values for moderately to highly disturbed systems.

Table 2 Other ions measured in the water samples collected

Toxicant	ANZECC trigger value (µg/L)*	Range in water samples (µg/L)#
Arsenic	24 (As III), 13 (AsV)	<30 – 42^
Boron	370	20 – 2,500
Calcium	na	1,400 – 190,000
Cadmium	0.2	<10
Cobalt	1.4	<10 - 26
Chromium	3.3 (Cr III), 1.0 (Cr VI)	<10 – 45^
Copper	1.4	<10
Potassium	na	1,200 – 220,000
Magnesium	na	2,300 – 680,000
Manganese	1,900	<10 - 460
Molybdenum	34	<10 - 26
Sodium	na	22,000 – 7,100,000
Nickel	11	<10 - 72
Phosphorus	na	<30 - 190
Lead	3.4	<20
Sulfur	na	1,900 – 540,000
Selenium	11	<70
Zinc	8	<10 - 170

*for protection of 95% of species (slightly – moderately or highly disturbed ecosystem)
#all metals were measured as mg/L and have been converted for comparison
^samples were tested for total content only

❖ **Chloride to Sulfate ratio**

The chloride / sulfate ratio (Cl/SO_4) is a useful measure of the origin of samples analysed. Marine based salts contain sodium chloride, while sulfidic salts contain sulphur. A high ration indicates that salts encountered are predominantly of marine origin, while conversely, a low value (less than 4) highlights that sulfidic products are the main source as a result of PASS oxidation (Mulvey, 1993).

Cl/SO_4 results from water samples tested show little variation during high, mid and low tides across all sites with the exception of Site 1 at mid and high tide (Fig 21). Results also show Sites 3 to 12 exhibited a Cl/SO_4 of 2 or less. Site 1 was less than 2 during low tide (as water is discharged from the drain). Site 2 did not have a Cl/SO_4 below 5 due to elevated levels of marine salts.

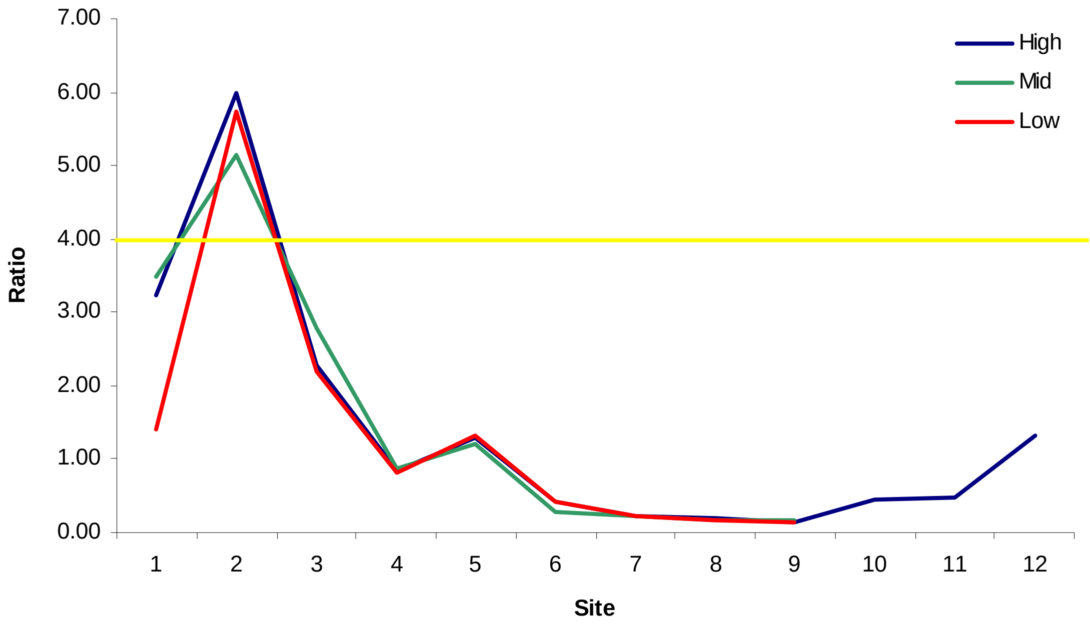

Figure 21 Cl/SO_4 in water samples collected at high, mid, and low tide.

Overall, results of the water sample testing indicate oxidation of ASS has and is occurring. Sites 2, 6, 7, 8, and 9 exhibit the lowest pH levels and highest levels of aluminium and iron. Site 2 also contained the highest levels of calcium, magnesium, sulfur, and sodium (Appendix 4). The results also confirm those from in situ testing.

3.3.5 Water levels

The three Odyssey capacitive water level recorders were removed from their locations and the data downloaded on 26th September 2008.

Figure 22 shows the tidal variations recorded by all 3 in-stream loggers. The water levels recorded at low tide were similar for the 3 locations, however at high tide both the upstream and low point recorders appear to show tidal influence. The floodgates allow some leaking though this is not significant and would not reach the low point. The drainage system is constantly flowing, moving ground water out during drier times as the drain level falls, and as such water backs up in the Main Drain during in-coming tides and decreasing on the out-going tide as the gates open. This is particularly evident after 4th September when the catchment experienced 200mm of rain in four days (Fig 22). The downstream recorder continues to vary with the tides but water levels recorded by the upstream and low point recorders show an increase in the drain water level as it fills with surface water runoff. The water level increases in the drain during the high tide and discharges on the outgoing tide. The upstream and low point recorders show higher levels at low tide after the rainfall due to now shallower groundwater actively discharging into the drain. The downstream recorder also shows a higher low tide after this rainfall event which could be due to the amount of water discharging from the drain during that tide keeping the low tide elevated.

Water levels downstream of the floodgate and upstream at the low point from 11th August to 26th September fluctuate tidally and with rainfall as shown in Figure 23. The catchment experienced regular rainfall over this period, most notably in early September (206mm in 4 days). After periods of rainfall, water levels increased in the drain at high tide, while the gates were closed, from less than 0.4 AHD to over 0.8 AHD. Over-topping of the banks was never recorded during these periods of heavy rainfall or reported anecdotally from landholders.

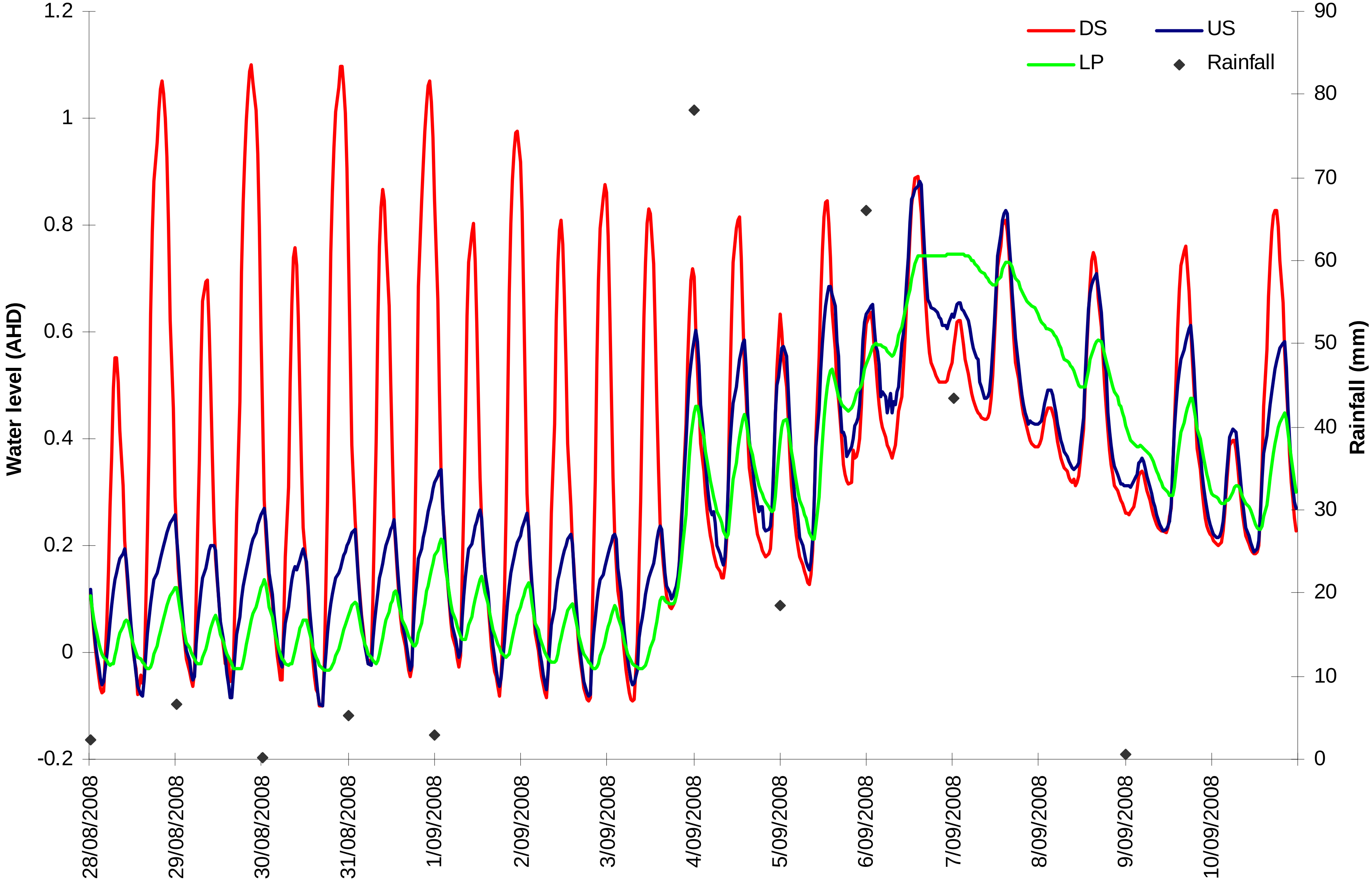

Figure 22 *Example of 14 day dataset comparing water levels upstream and down stream of the floodgate and 2.3km upstream at Nelson Bay Rd before and after heavy rainfall (rainfall source: www.weatherzone.com).*

Figure 23 Comparative water levels (AHD) and rainfall (mm) at Anna Bay over 6 weeks (rainfall source: www.weatherzone.com).

3.3.6 Soil profiles

A total of six soil cores were taken across the catchment. Laboratory testing of the soil profiles was undertaken by the Wollongbar Agricultural Institute's Diagnostic & Analytical Services and interpreted by Roy Lawrie (NSW DPI soil chemist). Elevations of the sulfidic layer in the cores taken are shown in Table 3 and core locations and surrounding land elevations are shown in Figure 26. For ground water and soil testing results see Appendix 5.

Table 3 Elevation of sulfidic layer

Core	Depth to sulfidic (cm)	Depth to ground water (cm)	Elevation (AHD) of sulfidic layer
1	60	27	+0.085
2	55	60	+0.232
3	100	40	+0.002
4	110	40	-0.784
5	50	10	+0.364
6	None present (sand)	30	-

3.3.6.1 Acid Sulfate Soil Inspection (Roy Lawrie, NSW DPI)

Soil profiles were inspected at 6 locations, 3 in a transect at the top of the catchment, 2 close to Port Stephens Drive to the west, and one near the floodgate at the western end of the study area.

The pyritic layer was detected in the field using the peroxide test on undisturbed cores collected with a 50mm diameter corer, or a gouge auger, to enable boundaries between subsoil layers to be accurately determined. Field testing, showing vigorous effervescence with peroxide revealed that sulfidic soil material was present on 5 of the 6 profiles, all within waterlogged dark clayey sediments. However, testing at 10cm depth intervals indicated that the top of the sulfidic sediment did not correspond with the top of the dark clayey layer.

The elevation of the sulfidic material varied between +0.364 to -0.784 AHD (at the top of the layer). The most elevated PASS layer was at Sites 2 and 5, both situated within 200m of sandy ridges; Site 3 was further along (about 300m) with the PASS surface close to 0m AHD. Site 4 was approximately 600m from the nearest sandy ridge and held sulfidic material below -0.7 AHD.

Oxidation of the sulfidic layer appears to be significant, but not extensive. Visual evidence, in terms of profile features such as jarosite mottles or iron-rich concretions, is weak and patchy. Water quality data, however, indicates that oxidation is occurring, and acid water is present in drains and groundwater.

Previous studies (Envir. & Earth Sci.,2000) detected PASS at some sites below a depth of 1m (1 and 27) and testing at one of these (27, top of the catchment) revealed total actual acidity (TAA) and exchangeable aluminium were significantly elevated (at 0.8 – 0.9m depth) in the layer above the sulfidic material. This shows that it has been acidified by oxidation of the underlying sulfides. Drainage water from this layer is likely to be extremely acidic.

Laboratory testing of ground water during the current study revealed a minimum pH of 2.9 in Core 1 (at a depth of only 27cm), with a sulfate concentration more than 20 times higher than the chloride. Core 1 also had flecks of jarosite at a depth of 60 – 80cm and laboratory testing of this Core revealed an elevated level of TAA (see Stored Acidity below). Low ground water pH was detected at other sites, but sulfidic material was absent at Core 6 (adjacent to the Boron Drain) where the profile is very sandy. Decomposition of organic matter can also acidify ground water in the absence of acid sulfate soils which needs to be taken into account when considering remediation strategies.

3.3.6.2 Stored Acidity in Anna Bay Soils (Roy Lawrie, NSW DPI)

Samples of all 6 profiles were tested for stored acidity, and other properties likely to affect water quality. Ground water was also tested in the soil core hole, and testing revealed a close association with soil properties.

Core 1 has an elevated level of TAA, peaking at 390 moles H^+/t at a depth of 80 – 90cm from the surface, a zone between the sulfidic material beneath it and a layer containing yellow jarosite mottles above it. Every sample from the top metre of the profile reordered a TAA over 200 moles H^+/t. It has the highest level of stored acidity found in the 6 soil profiles. Sulfate levels in the soil are also very high, peaking at 2700 mg/kg (in the sulfidic (PASS) layer at 135 – 145cm below the surface). The ratio of chloride to sulfate found in the ground water reflects this dominance of sulfate, generated by oxidation of sulfides.

By contrast, samples from Core 6, a deep sandy profile adjacent to the Boron Drain, have a maximum TAA of 58 moles H^+/t and a top sulfate level of only 13 mg/kg. A low TAA was also found near the floodgates (at Core 5). Here, the highest TAA is in the topsoil (50 moles H^+/t) with lower amounts in the subsoil, even though field testing revealed sulfides. As such, a minimal amount of oxidation had occurred or there has been some neutralisation of acid. The ground water was acidic (pH 4.0) when sampled, and sulfide concentrations were elevated (almost equal to the chloride level). Sulfate levels in the soil were high, especially at depth, peaking 640 mg/kg at a depth of 50 – 60cm. It is possible that the location of Core 5 is prone to inundation by king tides. This process would provide some neutralisation of stored acidity and also help to waterlog the subsoil, reducing oxidation of the sulfidic layer. The vegetation here (water couch, spike rush, and swamp oaks) suggest this area is frequently waterlogged.

Further east of the floodgate at Core 4, TAA is high peaking at 250 moles H^+/t in the subsoil at a depth of 100 -110cm. Sulfide oxidation is significant as the source of acid, indicated by the high sulfate concentrations in the profile (2100 mg/kg at 100 – 110cm depth). The ground water here was also rich in chloride, a feature associated with the low elevation (profile surface only 0.32 AHD). Full of salt, probably from a history of tidal flooding in the past, the soil has retained much of the acidity produced by occasional drying of the deep sulfidic layer (located -0.784 AHD). TAA remains high near the surface, with 190 moles H^+/t at a depth of 25 – 35cm.

The high TAA levels at Cores 1, 2, and 4 are in profiles dominated by clay subsoils. At Core 3, the profile is more sandy (sandy clay loam below the sandy loam topsoil) and levels of stored acidity are lower with TAA peaking at 140 moles H^+/t. The ground water however was extremely acidic when sampled (pH 3.7), and was enriched with sulfate and low in Chloride. This area is remote from the influence of the tide and supports patches of clover which is sensitive to salt. Acid produced here by drying of the sulfidic layer (below 100cm depth) appears to have moved upwards, driven by evapotranspiration by pastures, closer to the soil surface, helped by the permeable nature of the sandy profile.

3.3.7 Drain profiles

In total, 16 and 8 transects were completed on the Main and Back Drains, respectively. The maximum depth of the Main Drain ranged between -0.769 and -1.653 AHD with a width of approximately 6m in the upper catchment up to 13.5m at the Wallis Creek floodgates. The maximum depth of the Back Drain ranged between +0.560 to -1.009 AHD with a width of between 3 and 5 metres (see Table 4 and

Appendix 6 and 7). When consulting the Figure 13 for profile locations, MD1 is the Main Drain at the floodgate up to MD16 at the top of the catchment and BD1 is the top of the Back Drain down to BD8 near its confluence with the Main Drain.

Table 4 Drain profiles for the Main and Back Drains showing widths and maximum depths (AHD) of each profile.

Site	AHD	Width(m)*
MD1	-0.974	6.0
MD2	-0.773	8.0
MD3	-0.769	9.5
MD4	-1.015	7.0
MD5	-0.981	8.5
MD6	-1.101	6.5
MD7	-0.833	9.5
MD8	-1.303	9.5
MD9	-1.648	9.5
MD10	-1.333	10.0
MD11	-1.473	9.0
MD12	-1.641	9.0
MD13	-1.653	13.0
MD14	-1.391	12.0
MD15	-1.161	11.5
MD16	-1.485	13.5
BD1	+0.560	3.0
BD2	+0.323	5.25
BD3	-0.018	3.75
BD4	-0.453	4.5
BD5	-0.694	4.25
BD6	+0.043	3.5
BD7	-1.009	3.5
BD8	-0.535	5.0

*measured from closest high point on bank adjacent to drain

3.3.8 Airborne Laser Scanning (LiDAR)

Airborne Laser Scanning, commonly known as LiDAR, was mapped to establish elevations of the Anna Bay catchment. The catchment is very low-lying with elevations generally between 0 and 2m AHD (Figure 24). Land between Port Stephens Drive and the floodgate is particularly low, between 0 - 0.5m AHD and increasing by only 1 to 1.5m AHD to the top of the catchment.

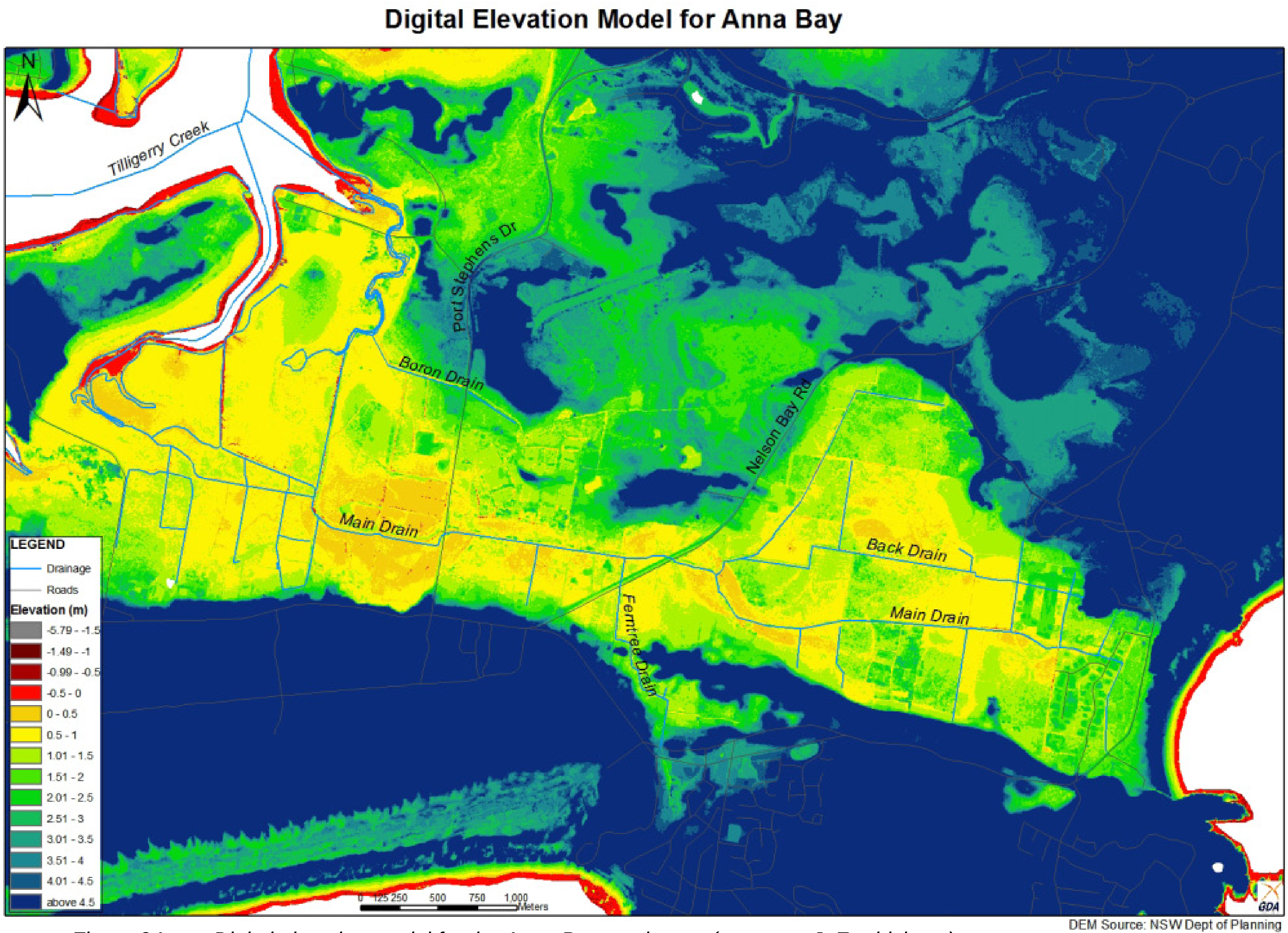

Figure 24 Digital elevation model for the Anna Bay catchment (courtesy: J. Fredrickson)

3.3.9 Hydraulic conductivity

In total 12 hydraulic conductivity pits were excavated across the Anna Bay catchment. The results of K_{sat} testing showed a varied soil landscape with extremely conductive (porous) soils in the upper reaches of the drain at One Mile in which water could move laterally more than 550m per day. The mid section of the drain near the Nelson Bay Road culvert and in the soil landscape next to the floodgates on the north side also exhibited extremely conductive soils with water potentially moving between 45 and 110m per day. The soil east of the floodgates up to Port Stephens Drive was low in conductivity with water expected to move laterally 1.5m or less a day. K_{sat} results are shown in Table 5 with example graphs in Figures 25 and 26.

Table 5 Hydraulic conductivity (K_{sat}) of soil tested

Pit	**Bail**	**Depth to ground water (cm)**	**Initial K_{sat} result**	**Further analysis#**	
				Bouwer and Rice (1983) K_{sat} (m day^{-1})	*Boast and Langebartel (1984) K_{sat} (m day^{-1})*
1	-	27	Extreme	-	-
2	1	38	Extreme	633.21	623.61
2	2	38	Extreme	568.77	560.16
3	1	18	Moderate	3.99	3.85
3	2	18	Moderate	1.37	1.32
4	1	21	Extreme	93.20	89.93
4	2	21	Extreme	113.79	109.80
5	1	31	Moderate	6.17	6.42
6	1	40	High	7.71	8.20
6	2	40	High	8.84	9.41
7	-	> 50	*	-	-
8	-	> 50	*	-	-
9	-	> 50	*	-	-
10	-	> 50	*	-	-
11	1	26	Extreme	46.31	53.07
11	2	26	Extreme	45.40	52.02
12	1	17	High	10.98	15.44
12	2	17	High	11.91	16.74

*Groundwater too low to test K_{sat}. #Analysis courtesy S. Johnston

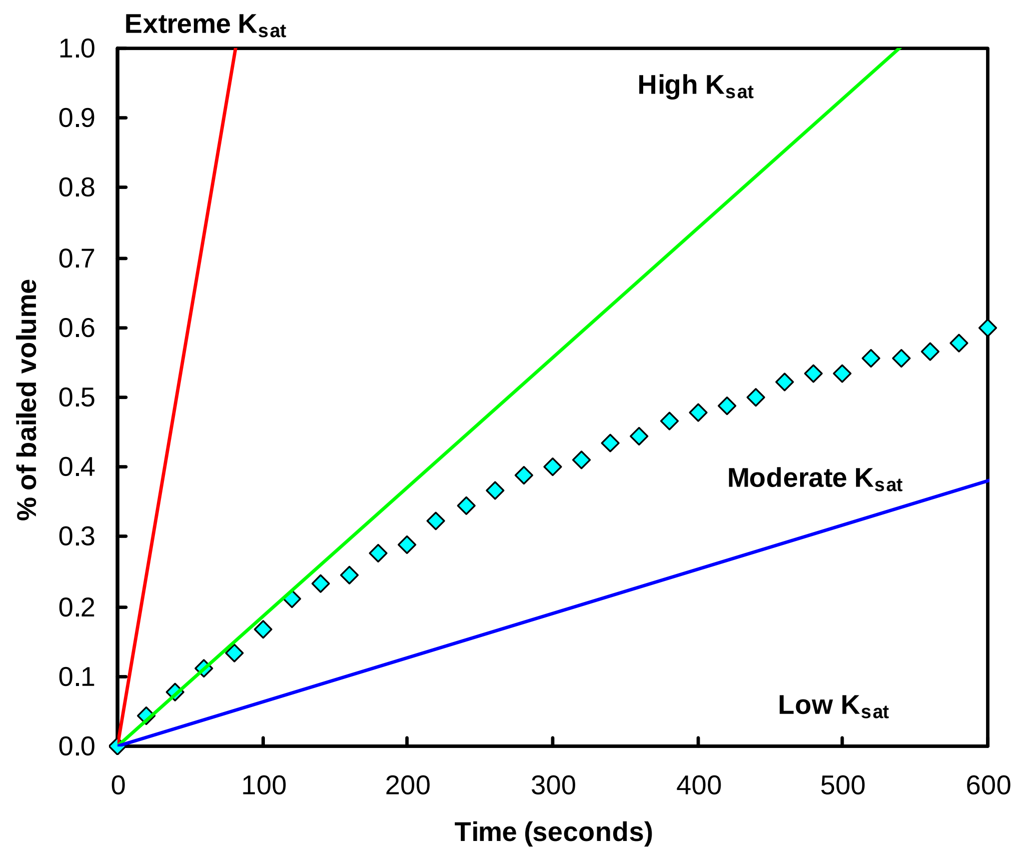

Figure 25 Ksat pit 5 showing moderate hydraulic conductivity.

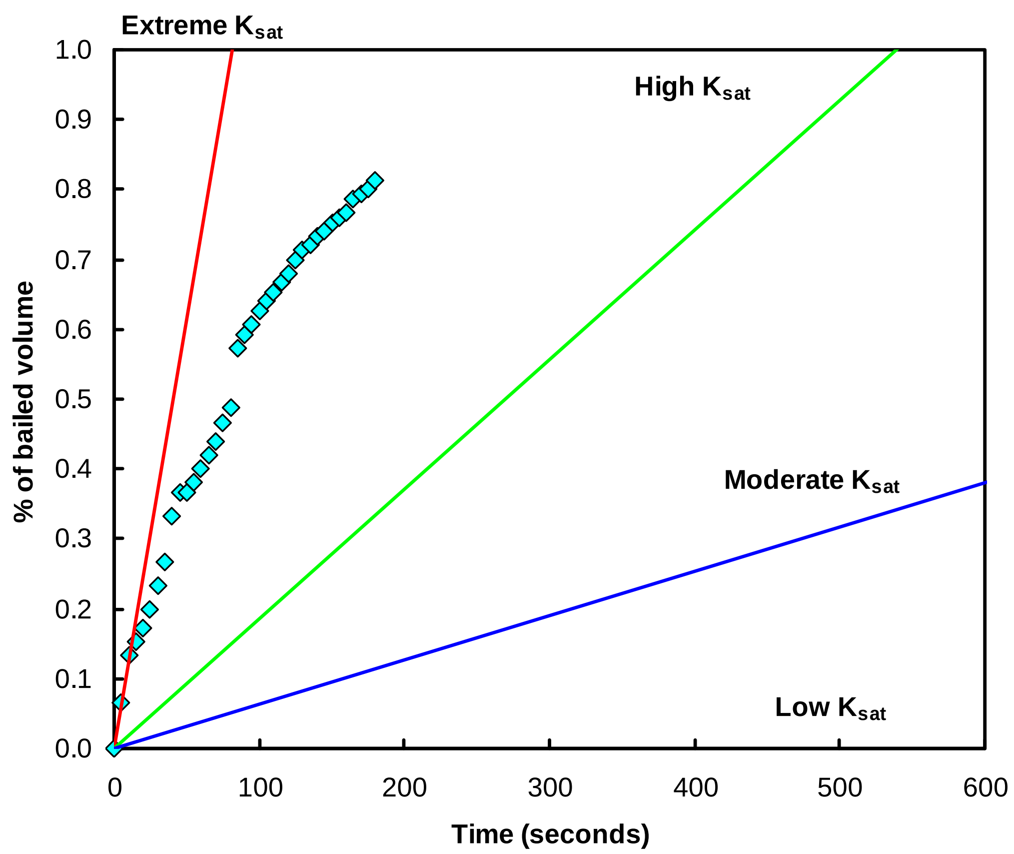

Figure 26 Ksat pit 10 showing high to extreme hydraulic conductivity.

The low hydraulic conductivity recorded in pits 7 to 10 could not accurately show the conductivity of the soil as Ksat testing relies on reaching the groundwater at a maximum depth of 0.5m. This was not achieved at these sites and retesting after a period of heavy rainfall could have different results when the groundwater level has increased to a sufficient level for testing.

The pit number 4 also had another pit excavated immediately adjacent to it. Both pits showed limited ingress of groundwater before reaching a layer that was of a more sandy composition (at around 50 cm depths). On reaching this layer, water immediately began to fill the pit at an extremely rapid rate.

Discussions with local landholders indicated that this was a common feature – a sand layer that was filled with fresh water and could be accessed by spear point at will. Future assessments of K_{sat} at Anna Bay would need to take account of this sand layer through a concurrent assessment of soil horizons and type.

3.3.10 EM 38 transects

An EM38 transect was carried at only one location in the catchment due to weather and time constraints. Use of the EM38 requires dry conditions and due to heavy rainfall and the nature of the catchment (surface water remaining for several weeks) further transects could not be carried out during the assessment timeframe. It is recommended that it should be done so in dryer spring months.

The results of the EM 38 transect carried out are shown in Figure 27.

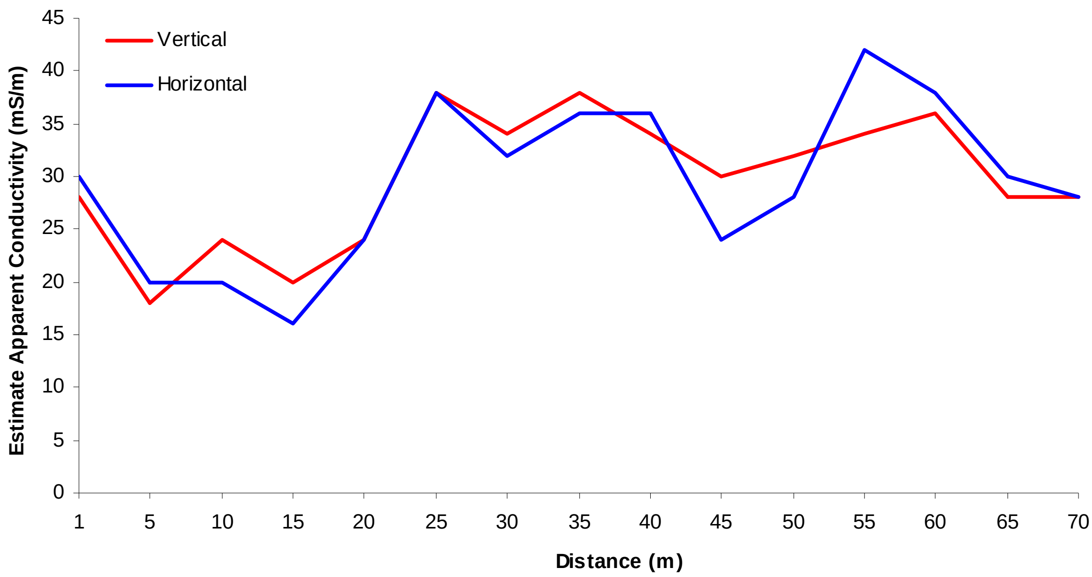

Figure 27 *Soil conductivity results at surface (horizontal) and approximately 1.5m depth (vertical)*.

The results of this transect show that total apparent conductivity (EC_a) at this site is not very high with both vertical (EC_v) and horizontal (EC_h) readings below 100 mS/m (see Table 6). The EC_a is constant from depth to surface so migration of ions appears to be through the profile (possibly due to regular wetting and drying cycles).

The EC_v and EC_h changed across the transect with a trend of low values near the drain and increasing with distance away from the drain. This may be due to the local landscape with elevations decreasing away from the drain (as is common within the catchment) and acid salts potentially accumulating in the lower areas. The evapo-transpiration potential of the mature trees could also be leading to a lowering of ground water under the vegetation and consequent concentration of acid salts. This area was previously burnt and iron floc was noticeable on the surface in patches away from the drain. Generally though, acid scalds are around 300 to 500 mS/m and marine influenced readings are usually above >500 mS/m (Hirst, pers. comm) and such high readings were not recorded here.

Further investigation into the total apparent soil conductivity in the Anna Bay catchment is required.

Table 6 Apparent Electrical Conductivity levels in coastal floodplains (Clay & Hirst, 2004).

Apparent Electrical Conductivity (mS/m)	**Low**	**Medium**	**High**	**Very High**
Estuarine clay dominated landscapes (coastal floodplains)	< 100	100-200	200-400	>400

4 Discussion and recommendations

The Anna Bay sub-catchment is a 450-hectare back-swamp that receives considerable annual average rainfall (1347mm). Since the late 19th century agricultural drains have been excavated to improve the area for farming with the drainage system flowing into Tilligerry Creek. In more recent years, the system provides drainage for a growing urban area and is managed by the Anna Bay Drainage Union. The Union has been responsible for the maintenance of the Main Drain to ensure the system maintains its flood mitigation capacity. The Main Drain is 'cleaned' annually where an excavator travels along its bank removing weeds and in the past has also removed bed and bank material to widen and deepen the drain exposing the potential acid sulfate soil (PASS) layer causing oxidation and creation of actual acid sulfate soils (AASS). Drain maintenance also leads to the disturbance and mobilisation of monosulfidic black ooze (MBO) within the drain water which are known to cause rapid deoxygenation and acidification of water bodies. MBO has been observed in the Anna Bay catchment (see recommendations) including in the Main Drain.

The water discharging into Tilligerry Creek from the Anna Bay catchment (through its drainage system) is in all likelihood causing environmental, economic and social impacts on the Port Stephens community. Water quality in the Anna Bay drainage system rarely met the criteria set by the ANZECC water quality guidelines for the protection of aquatic ecosystems.

The Port Stephens – Great Lakes Marine Park is being adversely affected by poor water quality discharging into Tilligerry Creek and from there into the Port Stephens estuary. The water is highly acidic and contains elevated levels of iron, aluminium and other toxic heavy metals associated with the oxidation of acid sulfate soils. Tilligerry Creek is an important nursery ground for recreational and commercial fish (e.g. flathead, bream, and snapper) and crustaceans (e.g. crabs, prawns) and poor water quality is likely to be having adverse impacts on the ecosystem. In 2006/07 the oyster industry of Port Stephens (Sydney Rock, Pacific, and spat) was worth $5.5 million (Sakker, 2008). In recent years, poor water quality from acid discharge, urban and agricultural runoff has resulted in oyster farmers being unable to harvest in sections of Tilligerry Creek. Research has found acid discharge impacts oyster growth and survival with young oysters being particularly susceptible to shell perforation and death (Dove & Sammut, 2007).

In addition to the impacts on the local oyster industry, the Anna Bay drainage system discharges into Wallis and Fenninghams Island Creeks, both important marine park sanctuary zones. Rehabilitation action is required to prevent the deterioration of water quality and to reduce the risk of serious impacts on the aquatic ecosystem of the affected area. If successful, rehabilitation work should benefit the aquaculture industry, the Marine Parks Authority and the commercial and recreational fishing industries.

The detailed site assessments carried out for this project confirmed that oxidation of sulfidic material (PASS) has, and is, occurring in the catchment forming AASS. PASS has been identified in the catchment less than 1 m below the surface and in some areas less than 0.5m. Exposure of PASS, less than 1 m below the surface, is likely to occur during dry times when the system is draining ground water, lowering the water table below that of the PASS, allowing for oxidation and formation of AASS. During the study, ground water was observed pouring out of macro-pores into the Main Drain due to the drain water level being below that of the water table. This groundwater seepage is one of the main ways groundwater acidified by ASS enters a drainage system (Johnston *et al*, 2003). Water in the Anna Bay drainage system is constantly flowing downstream to the floodgate during low tides even during dry periods.

Based on the detailed site assessments, a risk map of the sub-catchment has been produced (Fig 28). Acid sulfate soils appear to underlay the entire sub-catchment. However, some sites were worse than others. The two areas shown in Figure 28 in green (Boron and Ferntree drains) are those which consistently showed relatively good water quality figures. Towards the back of the system (Sites 10 to 12) the situation was consistent with acid generation and export, but certainly not to the levels associated with the red zones – particularly the dark red areas. These should be viewed as the core 'hot spot' areas of Anna Bay.

The western-most hot spot is consistent with some of the lowest elevation country in the sub-catchment. The dark red feature overlays a *Casuarina* swamp immediately upstream of the main floodgates where a small drain runs to the north of the Main Drain. This small drain (WQ Site 2) consistently recorded some of the poorest water quality of all sites tested. Examination of aerial photography shows that this site is serviced by another drain which appears to be channelling salt water into the *Casuarina* swamp.

Salinity testing showed that the site is generally more saline than ocean water. It is likely that the topography and drainage infrastructure of the *Casuarina* swamp is allowing salt water to enter it but reducing its egress. Evaporation is then leading to increasing salinities. Recent research is suggesting that these hyper-saline conditions are very likely to be exacerbating the naturally acidic conditions and making toxic levels of iron, and aluminium in particular, more readily available (Slavich, pers comm). The presence of large amounts of iron mono-sulfides (Fig 32) are a strong indicator that this process is occurring. In terms of management, keeping salt water from entering the area and gradually flushing the sulfidic products out with freshwater (rainfall) would be the recommended approach. It should be noted that this process may take months or years and may cause transitional deteriorations in water quality, particularly after heavy rainfall.

The eastern-most hot spot encompasses the area to the immediate east of Nelson Bay Road, and particularly the mature paperbark forest in-between the Main and Back drains. Water quality results are consistently poor in this area. Elevation information shows this area to be particularly low. The mature paperbark swamp is more than likely leading to significant drawdown of the groundwater, especially during extended droughts. Any reduction in groundwater levels would see a significant deterioration in water quality at this location. Management of this hot-spot would involve ensuring that groundwater levels were maintained above the local sulfidic horizon.

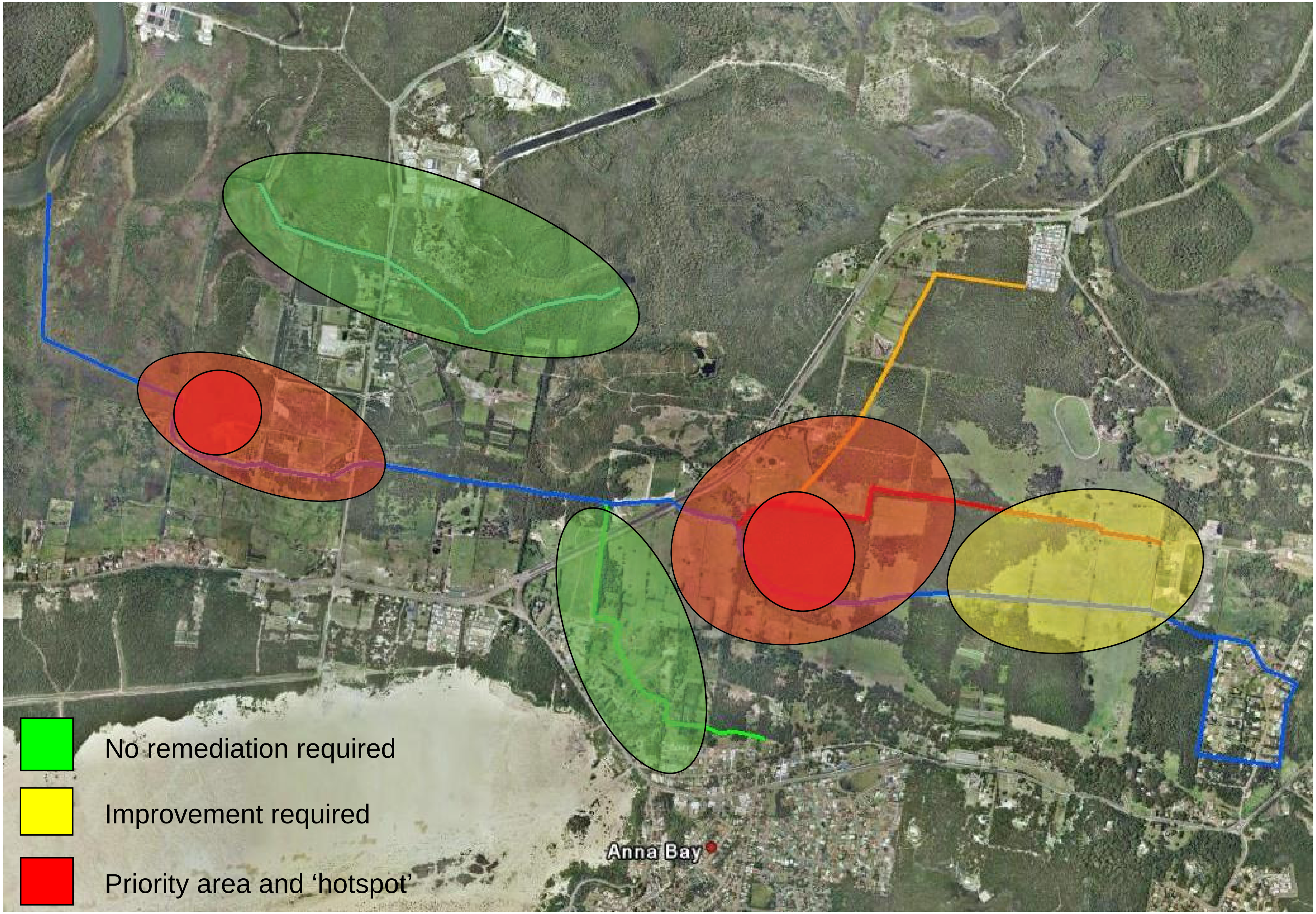

Figure 28 Risk map identifying priority areas for remediation works and areas where improvement is required.

4.1 Remediation options

There are a number of remedial options that have the potential to significantly improve water quality within the Anna Bay drainage system. Remediation will not completely solve the problem or remove ASS impacts entirely but will improve water quality and reduce ASS oxidation. Consequently these options should minimise the impacts of ASS currently being experienced in the estuary. The remedial options have been discussed with, and will be carried out in conjunction with, Port Stephens Council and the Anna Bay Drainage Union.

There are several rehabilitation works recommended to be undertaken as shown in Figure 30.

1. Installation of a low set weir that would reduce over-drainage at a key hotspot, while widening the drain at that point to ensure drainage capacity is not reduced.

Management of the eastern-most hotspot will require the installation of a submerged water control structure in the Main Drain on the south side of the Nelson Bay Road (Fig 29). Water control structures are used to maintain a constant level of water in the drain that is set above the PASS layer to maintain anoxic conditions. To minimise oxidation of the sulfidic layer, the invert of the structure is recommended to be +0.1m AHD.

Water above this level will flow over the structure, similar to a weir. A submerged structure is considered the most appropriate for this system to ensure flood mitigation capacity is maintained. The drain will be widened at the point of the structure for this reason also. Similar methods have been used in the northern rivers region and have been successful in reducing groundwater gradients and acid export via groundwater seepage (Johnston *et al*., 2004).

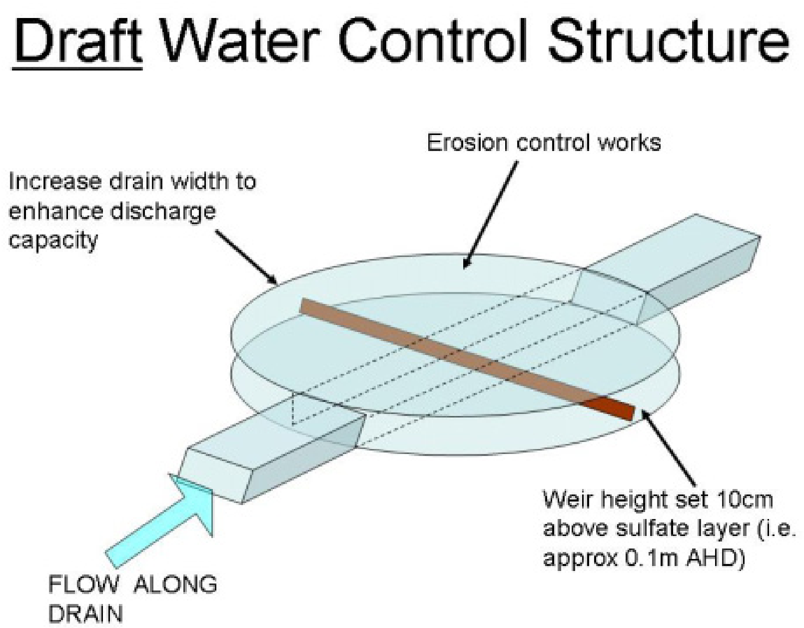

Figure 29 Proposed water control structure

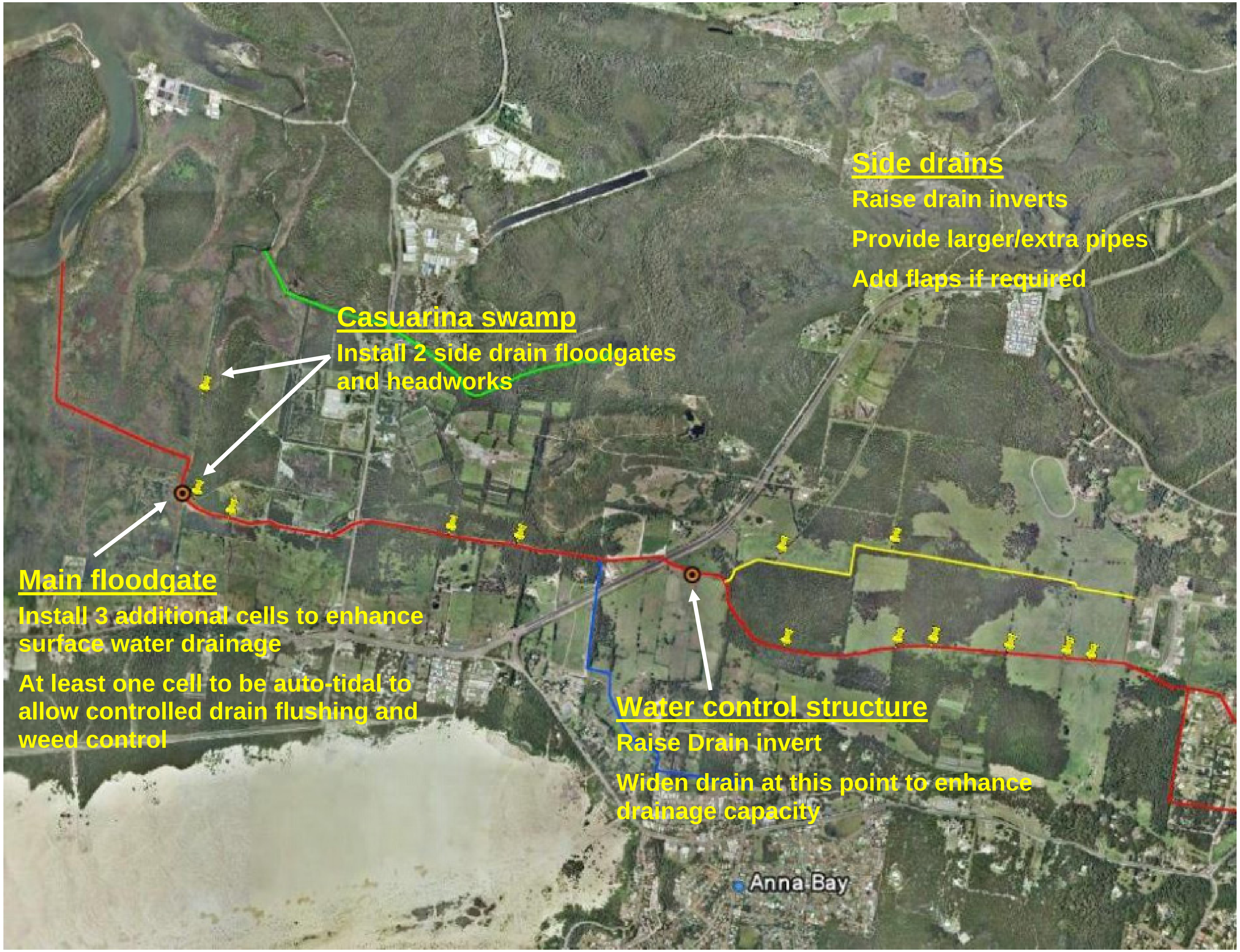

Figure 30 *Management recommendations for the Anna Bay drainage system. Side drains located with yellow place marks*

2. Raising the height of several side drainage pipes to reduce intersection of the sulphate layer

There are approximately 15 side drains which flow into one of the main drains within the Anna Bay system, which are located below the sulfidic layer. During dry periods these promote oxidation and contribute acid water. It is proposed to raise the invert of those smaller systems above the local acidic layer (generally at around 0 – 0.1 m AHD).

To facilitate this, new pipes will be set above this level to keep water in the side drains above the PASS layer, further reducing acid export into the main system. To maintain the drainage capacity of the side drains, extra pipes (with flaps if desired by landholders) will be installed at the required level.

3. Install additional floodgate cells at the existing structure to enhance drainage capacity of the overall system, while modifying at least one floodgate to enable a controlled degree of tidal exchange

At the bottom of the catchment there is currently a 3-cell winch floodgate maintained by the Union. The Union has proposed a 6-cell floodgate system made of reinforced aluminium to improve flood mitigation. Installation of this structure will occur simultaneously with the water control structure on the provision that a minimum of 1 cell will be fitted with an auto-tidal gate (Fig 31).

Figure 31 Tidal floodgate which opens and closes as downstream water levels lower and raise the float.

Floodgate management has been used as a way of managing ASS and improving fish passage in the northern rivers and Shoalhaven regions of NSW. Opening of floodgates to allow tidal flushing can dilute and neutralise acid drain water, reducing concentrations of iron and aluminium (Johnston *et al*, 2003). There are also many other benefits to floodgate management including improved fish passage, less monosulfidic black ooze (currently in the Main Drain), fewer nutrients and algal blooms, and improved weed control for farmers (Johnston *et al*, 2003).

4. Installation of floodgates to control water exchange at the western-most hotspot

The rehabilitation of the *Casuarina* swamp, located near the Anna Bay floodgates, is essential as the water quality entering the Wallis Creek estuary off this site is of very poor quality. Inspections of the site found MBO just below the surface (Fig 32) and high levels of aluminium, iron and other heavy metals.

Figure 32 Monosulfidic black ooze at Site 2 in the Casuarina forest floor (Photo: A.Burke).

There are two rehabilitation actions recommended for this site:

1) Installation of two floodgates at either end of the site. This aims to maintain water levels within the drains above the sulfuric layer. One gate will be auto-tidal to control exchange of tidal waters; and

2) With the installation of the floodgates, raise the invert to above the local sulfuric horizon to ensure that the groundwater stays above the PASS layer.

Figure 33 shows the locations of the drains where floodgates are recommended to be fitted. The flushing of saltwater from this site should minimise the acid sulfate soil problem and help improve the water quality discharging from this system.

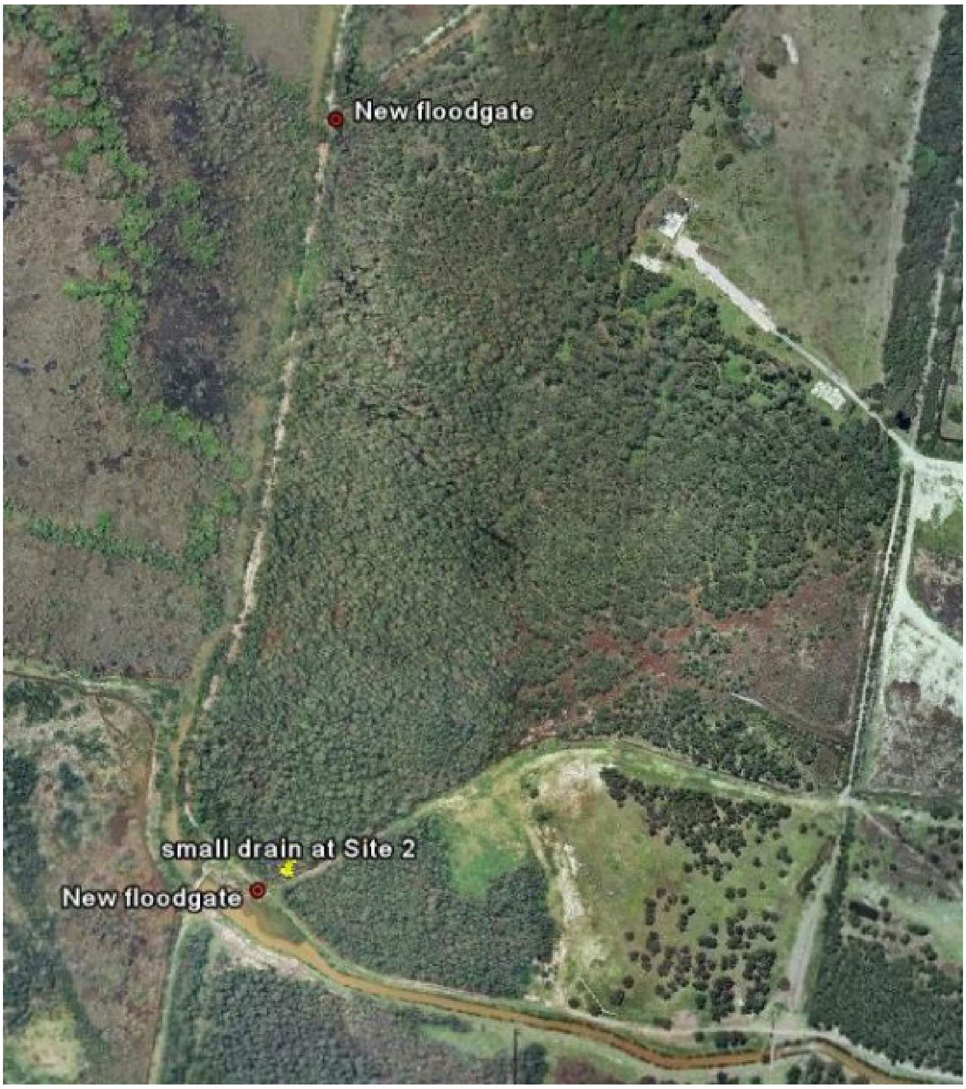

Figure 33 Location of Site 2 and proposed floodgates.

5. Strategic application of lime for all past and future soil disturbance

Any remediation works carried out will require application of mixing agricultural lime into the spoil removed from the drain to neutralise potential acid production when the spoil dries out. This will be applied at a rate of 75 kg / m^3 unless NATA-accredited laboratory testing shows otherwise.

6. Consultant review

An independent water hydrologist was engaged to review the above remediation recommendations. The Water Research Laboratory, University of NSW was contracted for this review (see Appendix 8).

5 Future Considerations

The Anna Bay drainage system currently receives stormwater from the Anna Bay and One Mile Beach residential areas. Development of these areas has increased significantly since the drains were first constructed and the increased discharge of stormwater into the drainage system has resulted in the drains operating at or beyond their original design capacity. During the assessment of future developments in the Anna Bay catchment consideration should be given to potential increases in stormwater discharge and what measures may be needed to retain the drainage capacity of the system and prevent any further declines in water quality.

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Appendix 1 Water quality testing results (in situ) for 12 sites in the Anna Bay drainage system from September 2007 to April 2008.

Site No	Date sampled	Time	Tide*	EC (ms/cm)	EC (us/cm)	pH	sal (%)	temp (°C)	DO (mg/L)	Flow^ (m/s)	Depth (cm)	Comments
4	12/09/2007	14:15	L,O	1.500	1500	2.70	1	17	na	M	na	
6	12/09/2007	14:25	L,O	1.300	1300	2.40	1	17	na	M	na	
1	12/09/2007	14:40	L,O	3.500	3500	4.00	2	17	na	M	na	
3	28/09/2007	15:45	L,O	0.330	330	4.50	0	20	na	L	na	water clear but tanin stained
4	28/09/2007	15:50	L,O	1.300	1300	2.90	1	21	na	L	na	water turbid and grey colour
6	28/09/2007	16:15	L,O	1.400	1400	2.80	1	20	na	L	na	water turbid and red colour
1	28/09/2007	16:00	L,O	5.700	5700	4.90	3	21	na	L	na	water turbid and green colour
1	28/09/2007	16:03	L,O	4.700	4700	4.90	2	21	na	L	na	water turbid and green colour
4	4/10/2007	9:00	L,O	1.400	1400	3.10	1	20	na	M	na	
6	4/10/2007	9:10	L,O	1.300	1300	2.70	1	19	na	M	na	
1	4/10/2007	9:20	L,O	6.800	6800	5.80	3	20	na	M	na	
1	4/10/2007	9:20	L,O	5.100	5100	5.90	3	20	na	M	na	
4	13/11/2007	17:00	L,O	1.200	1200	3.30	1	23	na	M	na	water turbid orange/brown
6	13/11/2007	16:30	L,O	1.200	1200	2.90	1	25	na	M	na	water turbid orange/brown
1	13/11/2007	16:45	L,O	3.600	3600	5.60	2	24	na	M	na	water turbid orange/brown
4	31/01/2008	11:45	L,O	4.170	4170	5.90	2.1	26.4	na	M	na	water turbid and grey colour
6	31/01/2008	12:00	L,O	1.530	1530	5.08	0.7	25.3	na	L	na	water turbid and orange/brown
1	31/01/2008	12:15	L,O	9.340	9340	6.77	5.1	27.5	na	L	na	water turbid and grey colour
1	13/02/2008	9:40	L,O	1.540	1540	3.62	0.007	20.8	0.43	M - H	na	water turbid and orange/brown
2	13/02/2008	9:45	L,O	16.800	16800	3.92	0.99	21.7	2.55	M - H	na	water clear but dark brown almost black
3	13/02/2008	12:00	L,O	0.420	420	5.05	0.01	21.5	3.85	H	na	water clear but tanin stained
4	13/02/2008	11:50	L,O	1.320	1320	3.71	0.05	21.3	0.45	M	na	water turbid and orange/brown
5	13/02/2008	11:40	L,O	0.550	550	6.45	0.02	20.4	3.47	L	na	water clear but slightly brown
6	13/02/2008	11:30	L,O	1.150	1150	3.44	0.05	21.2	0.35	M	na	water turbid and brown
7	13/02/2008	11:10	L,O	0.844	844	3.45	0.03	22.2	0.13	M	na	water clear but slightly brown
8	13/02/2008	11:00	L,O	1.080	1080	3.27	0.04	21.7	0.30	M	na	water clear but slightly brown
10	13/02/2008	10:40	L,O	0.877	877	3.82	0.03	21.6	0.29	L	na	water turbid and brown
11	13/02/2008	10:25	L,O	0.530	530	4.07	0.002	20.4	0.10	none	na	water clear but dark brown, choked with reeds
12	13/02/2008	10:15	L,O	0.700	700	5.38	0.03	21	0.22	L	na	water clear but brown, choked with reeds
1	13/02/2008	15:40	H	1.570	1570	3.80	0.07	22.6	2.5	none	na	water brown and turbid
2	13/02/2008	15:45	H	16.200	16200	na	na	na	na	na	na	water clear but dark brown almost black
3	13/02/2008	16:05	na	0.419	419	5.15	0.01	21.9	3.74	M - H	na	water clear but tanin stained
4	13/02/2008	15:55	na	1.360	1360	3.86	0.06	21.3	0.41	none	na	water turbid and orange/brown
1	19/02/2008	14:44	L,O	5.460	5460	3.72	0.29	23.1	0.94	M - H	na	water orange and turbid

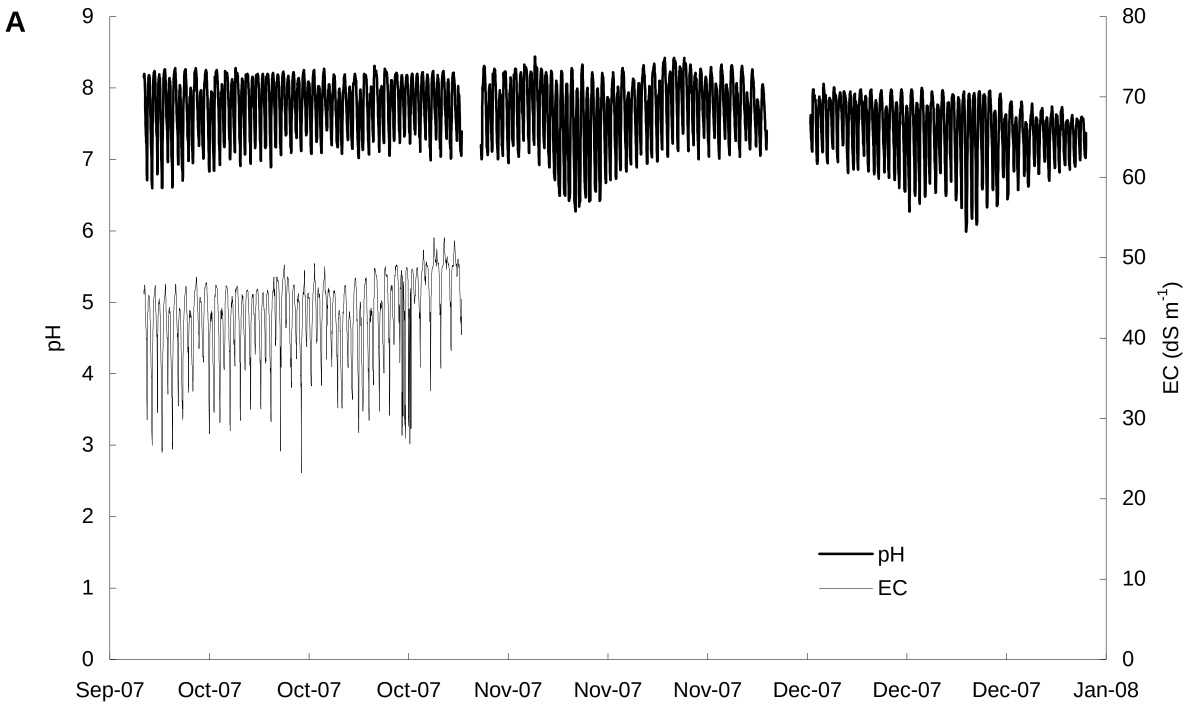
Site No	Date sampled	Time	Tide*	EC (ms/cm)	EC (us/cm)	pH	sal (%)	temp (°C)	DO (mg/L)	Flow (m/s)	Depth (cm)	Comments
2	19/02/2008	14:49	L,O	14.100	14100	3.37	0.81	25.2	3.26	M	na	water brown, clear[#]
3	19/02/2008	17:00	L,O	0.450	450	5.21	0.01	22.1	3.96	M	na	water clear and tanin stained (dark brown)
4	19/02/2008	16:55	L,O	1.580	1580	3.67	0.07	22.6	0.43	H	na	water clear but orange
5	19/02/2008	15:20	L,O	0.545	545	6.79	0.02	22.4	5.95	L	na	water clear
6	19/02/2008	15:25	L,O	1.380	1380	3.31	0.06	22.6	0.71	L	na	water brown and turbid
7	19/02/2008	15:30	L,O	0.970	970	3.27	0.04	23.5	0.21	L	na	water clear and brown
8	19/02/2008	15:40	L,O	1.350	1350	3.34	0.06	22.8	0.35	L	na	water clear and tanin stained (dark brown)
9	19/02/2008	15:35	L,O	1.320	1320	3.38	0.06	23	0.39	L	na	water clear and tanin stained (dark brown)
10	19/02/2008	16:40	L,O	1.040	1040	3.86	0.04	23.3	1.48	L	na	water brown and slightly turbid
11	19/02/2008	16:15	L,O	0.834	834	5.46	0.03	23.1	0.90	none	na	water brown and turbid
12	19/02/2008	16:25	L,O	0.519	519	4.25	0.02	22.2	0.01	L	na	water clear and brown
1	26/02/2008	8:00	L,O	4.380	4380	3.58	0.22	21.5	0.76	M	na	water orange tinged and turbid
2	26/02/2008	8:05	L,O	32.400	32400	3.91	2.1	20.6	3.42	L	na	water dark brown, banks orange
3	26/02/2008	8:25	L,O	0.483	483	5.53	0.02	21.6	5.81	L - M	na	water dark brown, tanin stained
4	26/02/2008	8:20	L,O	1.550	1550	3.46	0.07	21.4	0.33	M	na	water orange tinged and turbid
5	26/02/2008	8:35	L,O	0.531	531	6.70	0.02	20.6	1.31	L	na	water clear
6	26/02/2008	8:40	L,O	1.440	1440	3.21	0.06	21	0.15	L	na	water orange tinged and turbid
7	26/02/2008	8:50	L,O	1.170	1170	3.19	1.83	20.9	0.05	none	na	water clear but brown, iron floc
8	26/02/2008	8:55	L,O	1.590	1590	3.16	0.07	21.2	0.27	none	na	water clear but brown, iron floc
9	26/02/2008	9:00	L,O	1.590	1590	3.40	0.07	20.9	1.56	none	na	water clear but brown, iron floc
10	26/02/2008	9:35	L,O	0.806	806	3.64	0.03	20.7	2.30	none	na	water brown slightly turbid but mostly clear
11	26/02/2008	9:20	L,O	0.725	725	5.61	0.03	20.9	1.48	L	na	water orange tinged and turbid
12	26/02/2008	9:15	L,O	0.582	582	5.20	0.002	19.7	1.49	none	na	dark brown (very shallow approx. 20cm depth)
4	4/03/2008	16:15	L,O	na	na	3.68	0.7	na	na	H	na	iron flocs in water
6	4/03/2008	16:20	L,O	na	na	3.40	0.5	na	na	H	na	iron flocs in water
1	5/03/2008	14:20	L,O	1.180	1180	4.12	0.08	22	1.2	0.275	na	orange, large amount of large iron particles
2	5/03/2008	14:40	L,O	16.800	16800	3.70	0.95	24.1	3.41	0.366	na	clear, ormage tinge, banks with ornage floc
3	5/03/2008	17:25	L,O	0.353	353	4.81	0.01	21.8	3.84	0.226	na	clear, dark brown, tanin stained
4	5/03/2008	17:20	L,O	1.490	1490	3.50	0.06	21.6	0.89	0.415	na	brown, turbid, obvious iron particles
5	5/03/2008	15:00	L,O	0.536	536	6.56	0.02	20.6	5.58	0.058	na	clear, lilies and fish
6	5/03/2008	15:55	L,O	1.280	1280	3.42	0.05	21.4	0.33	0.178	na	brown, turbid
7	5/03/2008	16:05	L,O	0.990	990	3.35	0.04	22.8	0.14	0.000	na	clear, tanin stained
8	5/03/2008	16:08	L,O	1.220	1220	3.19	0.05	22.6	0.36	0.047	na	clear, tanin stained
9	5/03/2008	16:12	L,O	1.170	1170	3	0.05	22	0.61	0.058	na	clear, tanin stained
10	5/03/2008	17:00	L,O	1.050	1050	4.21	0.04	23	1.02	na	na	brown, turbid
11	5/03/2008	16:44	L,O	0.792	792	4.95	0.03	22.5	2.04	na	na	brown, turbid, gambusia
12	5/03/2008	16:40	L,O	0.543	543	3.93	0.02	20.6	0.44	na	na	clear, shallow, tanin stained

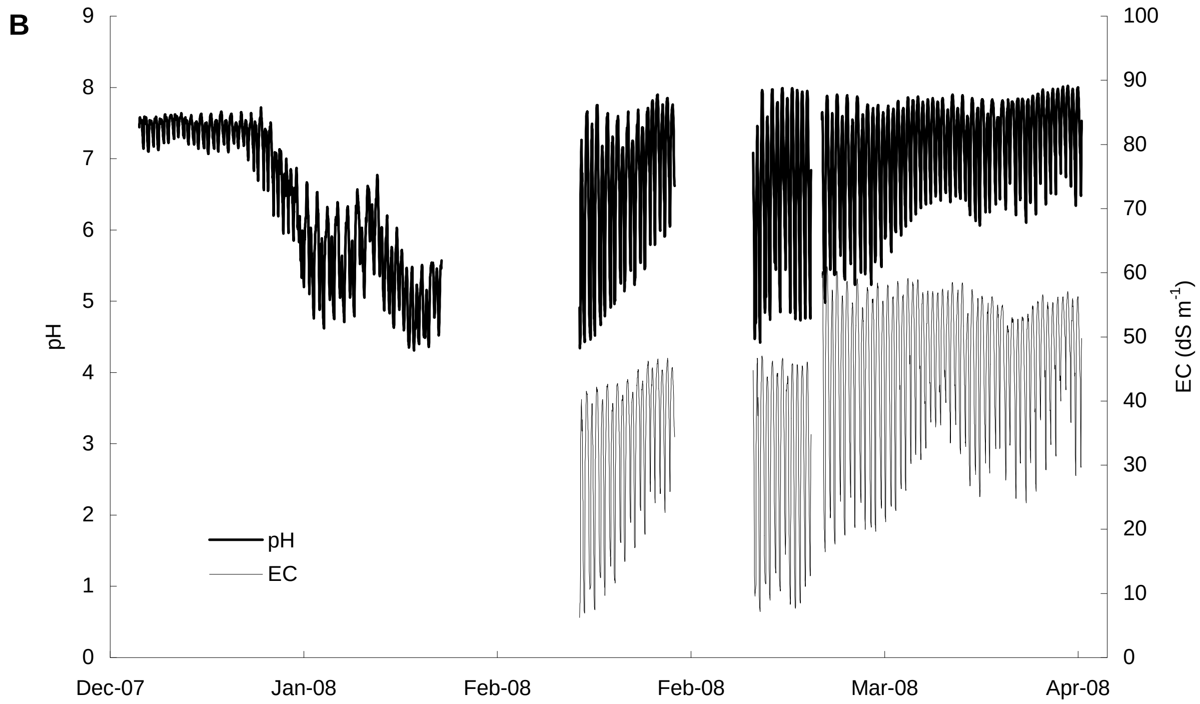
Site No	Date sampled	Time	Tide*	EC (ms/cm)	EC (us/cm)	pH	sal (%)	temp (°C)	DO (mg/L)	Flow (m/s)	Depth (cm)	Comments
1	7/03/2008	12:15	H	17.400	17400	4.85	0.87	23.4	2.18	0.047	132	orange, turbid. 200ml sample taken
2	7/03/2008	12:20	H	13.600	13600	3.61	0.8	23.6	3.55	0.000	27	brown, turbid. 200ml sample taken
3	7/03/2008	12:50	H	0.384	384	4.95	0.01	21.7	3.94	0.400	27	clear, dark brown, tanin stained[#]
4	7/03/2008	12:40	H	1.550	1550	3.45	0.07	22	0.05	0.000	67	orange, turbid[#]
5	7/03/2008	13:10	H	0.543	543	6.17	0.02	20.1	1.02	0.000	58	clear[#]
6	7/03/2008	13:20	H	1.230	1230	3.38	0.05	22.7	0.53	0.000	73	orange, turbid[#]
7	7/03/2008	13:35	H	0.979	979	3.27	0.04	22.8	0.15	0.000	39	clear, tanin stained, iron on vegetation[#]
8	7/03/2008	13:40	H	1.280	1280	3.30	0.05	22.3	0.34	0.000	22	clear, tanin stained, iron on vegetation[#]
9	7/03/2008	13:45	H	1.240	1240	3.40	0.08	22.3	0.64	0.000	66	clear, tanin stained, iron on vegetation[#]
10	7/03/2008	14:35	H	1.070	1070	3.91	0.04	22.3	1.29	0.000	50	orange, turbid[#]
11	7/03/2008	14:05	H	0.489	489	4.07	0.01	21.2	0.07	0.000	115	orange, turbid[#]
12	7/03/2008	14:15	H	1.060	1060	4.56	0.04	22.5	1.30	0.000	17	orange, turbid[#]
1	7/03/2008	15:15	M	7.940	7940	5.08	0.41	23.2	0.66	0.303	117	orange, turbid[#]
2	7/03/2008	15:25	M	15.100	15100	3.49	0.87	25.1	3.77	0.245	14	brown, turbid[#]
3	7/03/2008	16:30	M	0.355	355	4.97	0.01	22.8	3.82	0.432	48	clear, dark brown, tanin stained[#]
4	7/03/2008	16:25	M	1.550	1550	3.61	0.07	23.1	0.28	0.527	68	brown, turbid, iron floccules[#]
5	7/03/2008	15:38	M	0.546	546	6.10	0.02	21.5	5.72	0.000	48	clear[#]
6	7/03/2008	15:45	M	1.290	1290	3.23	0.05	22.3	0.86	0.150	64	brown, turbid[#]
7	7/03/2008	15:55	M	1.010	1010	3.22	0.04	24.2	0.17	0.045	38	clear, tanin stained, iron on vegetation[#]
8	7/03/2008	16:00	M	1.280	1280	3.18	0.05	23.5	0.33	0.079	20	clear, tanin stained, iron on vegetation[#]
9	7/03/2008	16:15	M	1.250	1250	3.31	0.05	22.7	0.65	0.049	72	clear, tanin stained, iron on vegetation[#]
1	7/03/2008	16:45	L,O	2.420	2420	4.02	0.14	23.4	0.54	0.174	111	orange, turbid[#]
2	7/03/2008	16:55	L,O	15.500	15500	3.71	0.97	25.2	4.23	0.213	10	brown, turbid[#]
3	7/03/2008	18:00	L,O	0.354	354	4.87	0.01	22.8	3.83	0.383	24	clear, dark brown, tanin stained[#]
4	7/03/2008	17:55	L,O	1.430	1430	3.64	0.06	22.7	0.43	0.542	48	orange, turbid[#]
5	7/03/2008	17:05	L,O	0.608	608	6.21	0.02	22.9	9.86	0.000	48	clear[#]
6	7/03/2008	17:10	L,O	1.420	1420	3.33	0.06	22.2	0.43	0.104	55	orange, turbid[#]
7	7/03/2008	17:20	L,O	1.000	1000	3.26	0.04	23.6	0.29	0.039	21	clear, tanin stained, iron on vegetation[#]
8	7/03/2008	17:25	L,O	1.300	1300	3.20	0.05	23.5	0.32	0.000	21	clear, tanin stained, iron on vegetation[#]
9	7/03/2008	17:30	L,O	1.080	1080	3.31	0.04	22.3	0.54	0.000	51	clear, tanin stained, iron on vegetation[#]
1	12/03/2008	9:15	L,O	2.290	2290	3.49	0.1	20.7	0.74	M	na	orange, turbid, iron floc
2	12/03/2008	9:20	L,O	19.800	19800	3.86	1.18	20.5	3.37	M	na	orange/brown, slightly turbid
3	12/03/2008	9:35	L,O	0.380	380	4.89	0.01	20.7	3.74	M - H	na	dark brown (tanin stained), clear
4	12/03/2008	9:30	L,O	1.380	1380	3.73	0.06	20.6	0.63	H	na	orange, turbid, iron floc
5	12/03/2008	9:45	L,O	0.533	533	6.16	0.02	19.8	0.97	L - M	na	clear
6	12/03/2008	9:50	L,O	1.270	1270	3	0.05	21	0.84	M	na	brown, turbid
7	12/03/2008	9:55	L,O	0.970	970	3.23	0.04	20.2	0.18	none	na	clear, tanin stained

Site No	Date sampled	Time	Tide*	EC (ms/cm)	EC (us/cm)	pH	sal (%)	temp (°C)	DO (mg/L)	Flow (m/s)	Depth (cm)	Comments
8	12/03/2008	10:00	L,O	1.200	1200	3.31	0.05	20.1	0.20	none	na	clear, tanin stained
9	12/03/2008	10:05	L,O	1.250	1250	3.42	0.05	20.3	0.44	none	na	clear, tanin stained
10	12/03/2008	10:20	L,O	0.980	980	4.10	0.04	20.7	1.55	none	na	orange/brown, turbid
11	12/03/2008	11:00	L,O	0.868	868	5.23	0.03	20.4	1.35	none	na	brown, turbid
1	3/04/2008	15:30	L,O	4.880	4880	3.85	0.26	20.8	2.14	M	na	orange, turbid, iron floc[#]
2	3/04/2008	15:35	L,O	29.500	29500	5.27	1.98	19.3	1.54	M	na	orange/brown, slightly turbid[#]
3	3/04/2008	16:15	L,O	0.249	249	5.14	0	19.6	4.71	M - H	na	clear, dark brown, tanin stained[#]
4	3/04/2008	15:45	L,O	1.280	1280	3.44	0.05	20.6	1.24	M - H	na	orange, turbid[#]
5	3/04/2008	15:00	L,O	0.524	524	6.57	0.02	19	6.54	L - M	na	clear[#]
6	3/04/2008	15:20	L,O	1.290	1290	4	0.06	19.5	1.47	M	na	orange, turbid[#]
7	3/04/2008	15:40	L,O	couldn't access - gate locked								
8	3/04/2008		L,O	couldn't access - gate locked								
9	3/04/2008		L,O	couldn't access - gate locked								
10	3/04/2008	13:55	L,O	0.791	791	4.65	0.03	19.7	2.52	L	na	orange/brown, turbid[#]
11	3/04/2008	13:25	L,O	0.720	720	5.03	0.03	19.2	3.31	L	na	orange/brown, turbid[#]
12	3/04/2008	13:20	L,O	0.053	53	5.41	0.2	18.2	0.38	L	na	brown, clear, little water. 500ml sample taken

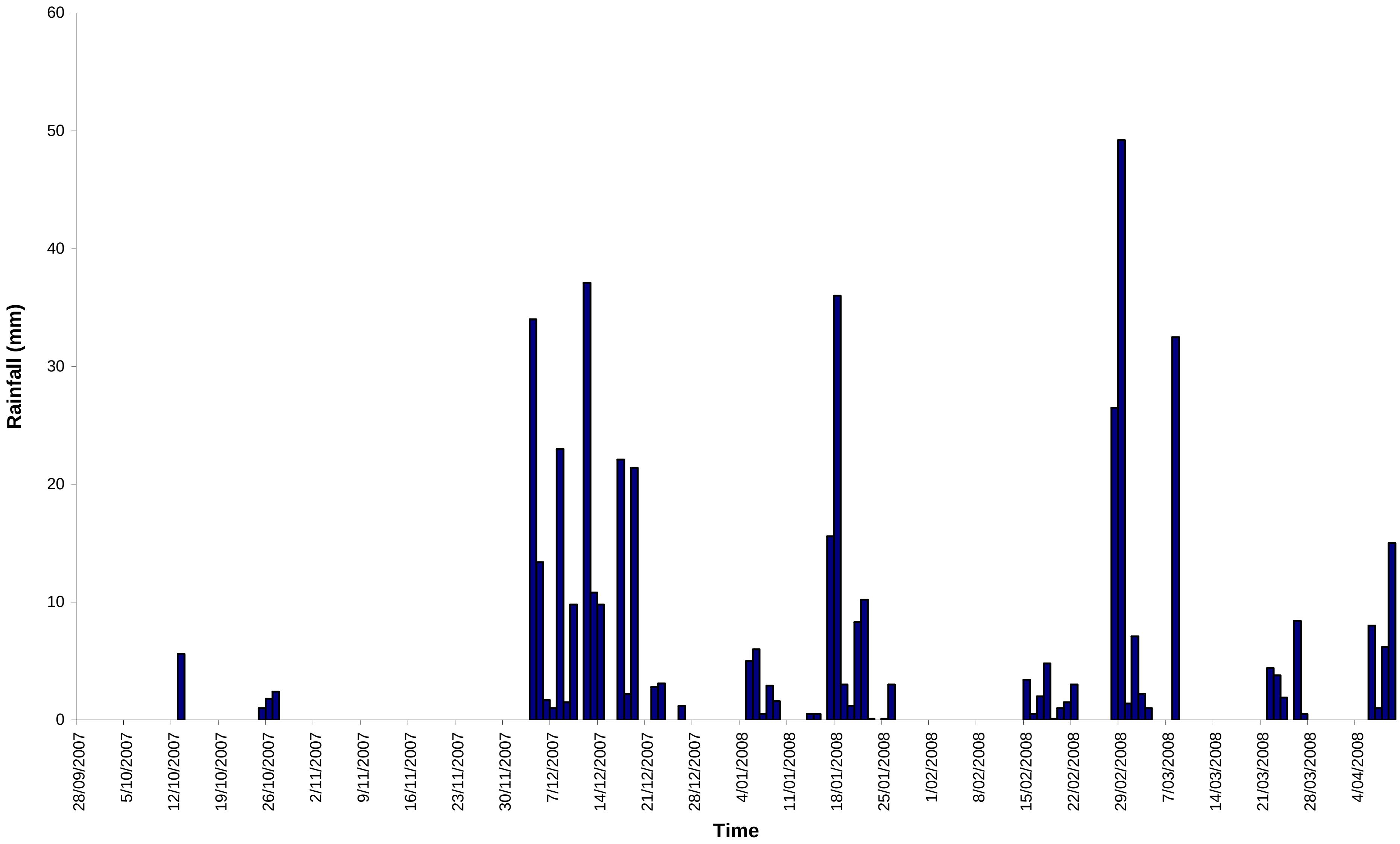
* L,O = low, outgoing tide, H = high tide, M = mid-tide.
^ L = low flow, M = medium flow, H = high flow where flow was observed not measured.
[#] water sample taken for laboratory analysis

Appendix 2 pH and EC from the In-Situ submersible data logger from October to December 2007 (A) and January to April 2008 (B). Some EC data is missing due to probe fouling. (Courtesy: M. Dove)





Appendix 3 Daily rainfall in the Anna Bay catchment from September 2007 to April 2008 (source: Bureau of Meteorology)



Appendix 4 Laboratory testing results for water samples collected in the Anna Bay drainage system.

Client ID	Lab No	EC	pH	Chloride mg/L 0.25	Acidity, as $CaCO_3$ mg/L 14	Sulfate mg/L 3	Chloride / Sulfate ratio	Total Dissolved Solids mg/L 2
Site 1	4369	4500	3.8	1100	46	320	3.44	320
Site 2	4371	30000	4.7	7300	380	1300	5.62	16000
Site 3	4364	170	5.4	36	20	23	1.57	160000
Site 4	4370	1400	3.4	220	85	240	0.92	2500
Site 5	4368	550	8	63	<14	50	1.26	410
Site 6	4373	1500	3.1	150	190	320	0.47	670
Site 10	4365	170	5.5	130	120	180	0.72	480
Site 11	4363	680	4.7	100	52	130	0.77	390
Site 12	4367	560	4.6	150	130	67	2.24	25000
Ksat 2	4366	48000	4.9	10000	260	1800	5.56	570
Casuarina swamp	4362	39000	4	8500	310	1600	5.31	20000
Site 1 HT sample 1	4374	5100	3.7	710	88	220	3.23	2700
Site 2 HT sample 1	4375	9300	3.5	2700	150	450	6.00	5300
Site 3 HT sample 1	4376	220	5.3	48	16	21	2.29	110
Site 4 HT sample 1	4377	210	5.2	100	58	120	0.83	290
Site 5 HT sample 1	4378	430	8	57	17	44	1.30	320
Site 6 HT sample 1	4379	1200	3.5	130	170	300	0.43	640
Site 7 HT sample 1	4380	1100	3.2	73	250	310	0.24	560
Site 8 HT sample 1	4381	1400	3.2	94	320	490	0.19	790
Site 9 HT sample 1	4382	1000	3.3	31	250	210	0.15	630
Site 10 HT sample 1	4383	1000	3.7	120	120	260	0.46	640
Site 11 HT sample 1	4384	1000	3.7	110	91	230	0.48	620
Site 12 HT sample 1	4385	220	4.2	36	51	27	1.33	180
Site 1 mid sample 1	4386	5600	4.4	1600	75	460	3.48	3300
Site 2 mid sample 1	4387	12000	3.5	3500	180	680	5.15	6800
Site 3 mid sample 1	4388	300	5.3	81	21	29	2.79	250
Site 4 mid sample 1	4389	1800	3.3	300	150	340	0.88	980
Site 5 mid sample 1	4390	560	7.5	65	<14	54	1.20	340
Site 6 mid sample 1	4391	1200	3.3	98	230	340	0.29	660
Site 7 mid sample 1	4392	1100	3.2	74	270	310	0.24	610
Site 8 mid sample 1	4393	1400	3.1	87	330	480	0.18	830
Site 9 mid sample 1	4394	1300	3.3	77	310	470	0.16	800
Site 1 LT sample 1	4395	2000	3.7	420	120	300	1.40	1100
Site 2 LT sample 1	4396	10000	3.8	3500	170	610	5.74	6000
Site 3 LT sample 1	4397	160	5.3	44	59	20	2.20	120
Site 4 LT sample 1	4398	1400	3.6	240	130	290	0.83	790
Site 5 LT sample 1	4399	1400	3.6	74	14	56	1.32	310
Site 6 LT sample 1	4400	1300	3.3	150	190	350	0.43	700
Site 7 LT sample 1	4401	1100	3.2	71	250	300	0.24	550
Site 8 LT sample 1	4402	1300	3.2	82	290	460	0.18	820
Site 9 LT sample 1	4403	1200	3.3	62	280	410	0.15	770
Mcleay sample 1	4404	610	5.3	67	36	140	0.48	370
Mcleay sample 2	4372	890	4.1	160	50	170	0.94	4400

NSW DPI Diagnostic and Analytical Services. NATA accredited laboratory 14173.

Client ID	Lab No	Al	As	B	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Se	Zn
		mg/L 0.03	mg/L 0.03	mg/L 0.02	mg/L 0.02	mg/L 0.01	mg/L 0.01	mg/L 0.01	mg/L 0.01	mg/L 0.02	mg/L 0.4	mg/L 0.01	mg/L 0.01	mg/L 0.01	mg/L 0.07	mg/L 0.01	mg/L 0.03	mg/L 0.02	mg/L 0.2	mg/L 0.07	mg/L 0.01
Site 1	4369	2.9	<0.03	0.25	57	<0.01	<0.01	0.011	<0.01	2.6	30	82	0.2	<0.01	580	0.016	0.054	<0.02	110	<0.07	0.037
Site 2	4371	0.66	0.042	1.4	170	<0.01	<0.01	0.037	<0.01	130	150	490	0.11	0.026	4200	0.012	0.07	<0.02	410	<0.07	0.016
Site 3	4364	0.29	<0.03	0.023	1.4	<0.01	<0.01	<0.01	<0.01	0.87	1.2	3.3	<0.01	<0.01	24	<0.01	<0.03	<0.02	1.9	<0.07	<0.01
Site 4	4370	4.5	<0.03	0.076	42	<0.01	<0.01	<0.01	<0.01	8.7	9	23	0.27	<0.01	130	0.024	<0.03	<0.02	89	<0.07	0.071
Site 5	4368	<0.03	<0.03	<0.02	41	<0.01	<0.01	<0.01	<0.01	0.057	4.9	12	<0.01	<0.01	40	<0.01	<0.03	<0.02	18	<0.07	<0.01
Site 6	4373	7.1	<0.03	0.072	35	<0.01	0.013	<0.01	<0.01	40	7.8	20	0.36	<0.01	99	0.034	<0.03	<0.02	120	<0.07	0.084
Site 10	4365	2	<0.03	0.086	34	<0.01	<0.01	<0.01	<0.01	21	5.9	14	0.23	<0.01	75	0.017	<0.03	<0.02	66	<0.07	0.04
Site 11	4363	0.19	<0.03	0.092	29	<0.01	<0.01	<0.01	<0.01	11	4.9	12	0.19	<0.01	64	0.012	0.038	<0.02	49	<0.07	0.031
Site 12	4367	0.42	<0.03	0.027	3.4	<0.01	<0.01	<0.01	<0.01	37	4.7	5.6	0.056	<0.01	65	<0.01	<0.03	<0.02	21	<0.07	0.017
Ksat 2	4366	0.96	0.042	1.7	180	<0.01	<0.01	0.045	<0.01	35	220	680	0.025	0.024	7100	<0.01	0.19	<0.02	530	<0.07	<0.01
Casuarina swamp	4362	1.7	<0.03	2.5	190	<0.01	<0.01	0.044	<0.01	64	210	680	0.094	0.017	5400	<0.01	0.17	<0.02	540	<0.07	0.019
Site 1 HT sample 1	4374	2.4	<0.03	0.18	33	<0.01	<0.01	<0.01	<0.01	10	19	56	0.14	<0.01	390	0.014	0.045	<0.02	80	<0.07	0.02
Site 2 HT sample 1	4375	4.3	<0.03	0.51	60	<0.01	<0.01	0.018	<0.01	36	56	160	0.15	0.012	1600	0.019	0.092	<0.02	170	<0.07	0.03
Site 3 HT sample 1	4376	0.28	<0.03	<0.02	1.6	<0.01	<0.01	<0.01	<0.01	0.88	1.4	4	<0.01	<0.01	31	<0.01	<0.03	<0.02	2.8	<0.07	<0.01
Site 4 HT sample 1	4377	2.8	<0.03	0.036	16	<0.01	<0.01	<0.01	<0.01	11	3.6	11	0.14	<0.01	61	0.014	<0.03	<0.02	45	<0.07	0.031
Site 5 HT sample 1	4378	<0.03	<0.03	<0.02	29	<0.01	<0.01	<0.01	<0.01	0.072	3.2	7.7	0.02	<0.01	30	<0.01	<0.03	<0.02	13	<0.07	<0.01
Site 6 HT sample 1	4379	6.4	<0.03	0.089	38	<0.01	0.014	<0.01	<0.01	47	7.9	19	0.37	<0.01	83	0.034	<0.03	<0.02	110	<0.07	0.083
Site 7 HT sample 1	4380	17	<0.03	0.031	20	<0.01	0.018	<0.01	<0.01	57	5.3	14	0.23	0.015	56	0.052	<0.03	<0.02	120	<0.07	0.1
Site 8 HT sample 1	4381	17	<0.03	0.029	44	<0.01	0.026	<0.01	<0.01	95	8.1	19	0.46	0.015	63	0.072	<0.03	<0.02	170	<0.07	0.16
Site 9 HT sample 1	4382	9.6	<0.03	<0.02	27	<0.01	0.016	<0.01	<0.01	58	4.8	11	0.28	0.014	34	0.044	<0.03	<0.02	100	<0.07	0.096
Site 10 HT sample 1	4383	3.3	<0.03	0.11	43	<0.01	<0.01	<0.01	<0.01	33	5.3	16	0.31	<0.01	69	0.025	<0.03	<0.02	91	<0.07	0.056
Site 11 HT sample 1	4384	3	<0.03	0.12	45	<0.01	<0.01	<0.01	<0.01	25	5.6	18	0.32	<0.01	70	0.024	<0.03	<0.02	91	<0.07	0.05
Site 12 HT sample 1	4385	0.51	<0.03	<0.02	1.5	<0.01	<0.01	<0.01	<0.01	8.6	2	2.3	0.024	<0.01	22	<0.01	<0.03	<0.02	7.7	<0.07	<0.01
Site 1 mid sample 1	4386	1.3	<0.03	0.32	59	<0.01	<0.01	0.013	<0.01	20	34	100	0.18	<0.01	790	0.016	0.056	<0.02	160	<0.07	0.025
Site 2 mid sample 1	4387	5.2	<0.03	0.63	74	<0.01	<0.01	0.022	<0.01	45	67	190	0.12	0.014	1900	0.019	0.1	<0.02	220	<0.07	0.032

Client ID	Lab No	Al mg/L 0.03	As mg/L 0.03	B mg/L 0.02	Ca mg/L 0.02	Cd mg/L 0.01	Co mg/L 0.01	Cr mg/L 0.01	Cu mg/L 0.01	Fe mg/L 0.02	K mg/L 0.4	Mg mg/L 0.01	Mn mg/L 0.01	Mo mg/L 0.01	Na mg/L 0.07	Ni mg/L 0.01	P mg/L 0.03	Pb mg/L 0.02	S mg/L 0.2	Se mg/L 0.07	Zn mg/L 0.01
Site 3 mid sample 1	4388	0.33	<0.03	0.027	2.1	<0.01	<0.01	<0.01	<0.01	1	1.9	5.1	<0.01	<0.01	40	<0.01	<0.03	<0.02	3.6	<0.07	<0.01
Site 4 mid sample 1	4389	7.4	<0.03	0.12	45	<0.01	0.013	<0.01	<0.01	33	14	31	0.34	0.012	170	0.034	<0.03	<0.02	120	<0.07	0.086
Site 5 mid sample 1	4390	0.031	<0.03	<0.02	40	<0.01	<0.01	<0.01	<0.01	0.1	4.7	11	0.016	<0.01	42	<0.01	<0.03	<0.02	18	<0.07	0.015
Site 6 mid sample 1	4391	12	<0.03	0.044	30	<0.01	0.017	<0.01	<0.01	58	6.3	17	0.34	0.013	68	0.047	<0.03	<0.02	120	<0.07	0.1
Site 7 mid sample 1	4392	16	<0.03	0.026	19	<0.01	0.017	<0.01	<0.01	55	5.2	14	0.22	0.011	56	0.051	<0.03	<0.02	110	<0.07	0.091
Site 8 mid sample 1	4393	17	<0.03	0.03	43	<0.01	0.026	<0.01	<0.01	87	8	19	0.46	0.02	62	0.072	<0.03	<0.02	170	<0.07	0.17
Site 9 mid sample 1	4394	16	<0.03	0.02	42	<0.01	0.025	<0.01	<0.01	94	7.5	18	0.45	0.021	55	0.069	<0.03	<0.02	160	<0.07	0.15
Site 1 LT sample 1	4395	7	<0.03	0.12	45	<0.01	0.011	<0.01	<0.01	29	15	38	0.25	0.01	250	0.028	<0.03	<0.02	120	<0.07	0.06
Site 2 LT sample 1	4396	3.5	0.037	0.54	61	<0.01	<0.01	0.02	<0.01	42	58	170	0.097	<0.01	1700	0.015	0.086	<0.02	190	<0.07	0.021
Site 3 LT sample 1	4397	0.24	<0.03	<0.02	1.4	<0.01	<0.01	<0.01	<0.01	0.82	1.2	3.2	<0.01	<0.01	26	<0.01	<0.03	<0.02	2.5	<0.07	<0.01
Site 4 LT sample 1	4398	5.6	<0.03	0.088	38	<0.01	0.011	<0.01	<0.01	34	8.3	25	0.29	0.013	130	0.028	0.039	<0.02	99	<0.07	0.07
Site 5 LT sample 1	4399	<0.03	<0.03	<0.02	40	<0.01	<0.01	<0.01	<0.01	0.091	4.8	12	0.012	<0.01	45	<0.01	<0.03	<0.02	20	<0.07	<0.01
Site 6 LT sample 1	4400	8.8	<0.03	0.076	45	<0.01	0.016	<0.01	<0.01	56	7.7	21	0.43	0.015	95	0.042	<0.03	<0.02	130	<0.07	0.09
Site 7 LT sample 1	4401	16	<0.03	0.028	19	<0.01	0.017	<0.01	<0.01	55	5.1	14	0.22	0.012	56	0.049	<0.03	<0.02	110	<0.07	0.094
Site 8 LT sample 1	4402	16	<0.03	0.027	43	<0.01	0.024	<0.01	<0.01	84	7.7	18	0.44	0.021	60	0.068	<0.03	<0.02	160	<0.07	0.15
Site 9 LT sample 1	4403	15	<0.03	0.022	42	<0.01	0.023	<0.01	<0.01	83	6.7	16	0.41	0.023	48	0.063	<0.03	<0.02	150	<0.07	0.13
Mcleay sample 1	4404	0.25	<0.03	<0.02	39	<0.01	<0.01	<0.01	<0.01	9	4.3	11	0.14	<0.01	46	0.015	0.033	<0.02	56	<0.07	0.031
Mcleay sample 2	4372	2.7	<0.03	0.06	39	<0.01	<0.01	<0.01	<0.01	4.1	6.8	16	0.21	<0.01	80	0.016	0.054	<0.02	66	<0.07	0.042

NSW DPI Diagnostic and Analytical Services. NATA accredited laboratory 14173.
Al – Aluminium, As – Arsenic, B – Boron, Ca – Calcium, Cd – Cadmium, Co – Cobalt, Cr – Chromium, Cu – Copper, Fe – Iron, K – Potassium, Mg – Magnesium, Mn – Manganese, Mo - Molybdenum, Na – Sodium, Ni - Nickel , P – Phosphorus, Pb – Lead, S – Sulfur, Se – Selenium, Zn – Zinc.

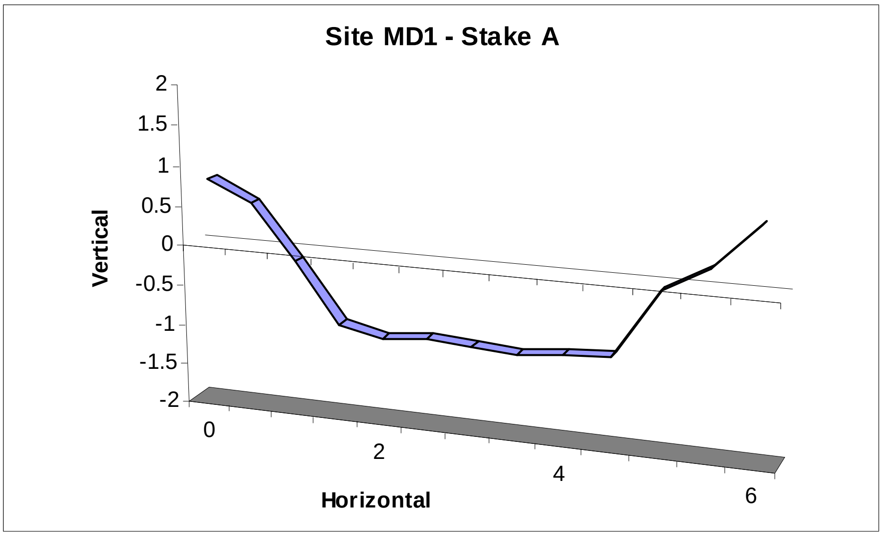
Appendix 5 Laboratory testing results of soil core samples and groundwater

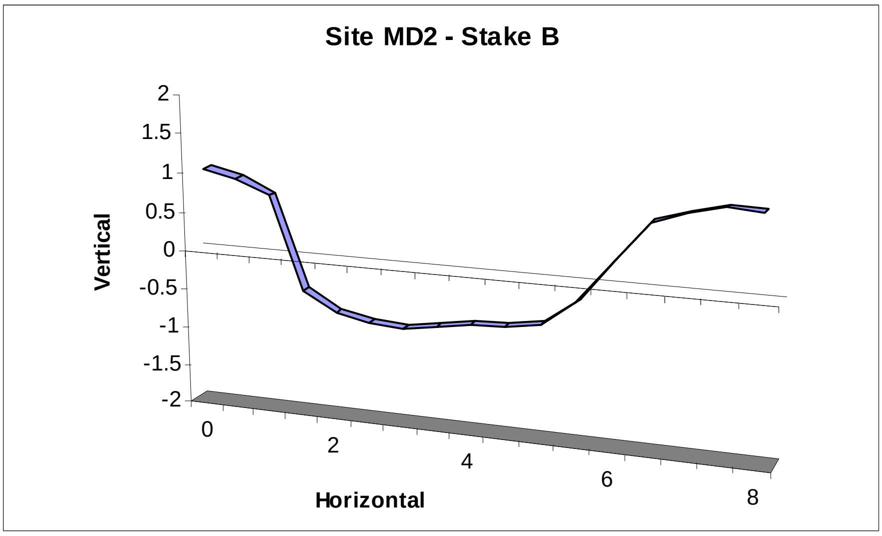
Core	Depth	EC (us/m)	pH	Colwell Phosphorous (mg/kg)	KCl Sulfur (mg/kg)	Total Actual Acidity (moles H^+/t)
1	0-10	na	na	55	55	240
	15-25	na	na	6.1	160	300
	40-50	na	na	15	390	300
	80-90	na	na	71	1800	390
	135-145	na	na	25	2700	210
2	0-10	na	na	220	23	15
	20-30	na	na	690	22	95
	40-50	na	na	27	41	230
	60-70	na	na	26	820	290
	100-110	na	na	6.4	1100	98
	140-150	na	na	6.7	290	35
3	0-10	na	na	470	56	91
	25-35	na	na	45	170	140
	50-60	na	na	26	140	70
	90-100	na	na	6.7	280	70
	120-130	na	na	5.3	160	42
4	0-10	na	na	30	85	66
	30-40	na	na	16	260	190
	50-80	na	na	17	290	150
	80-90	na	na	16	520	160
	100-110	na	na	19	2100	250
5	0-10	na	na	99	120	50
	25-35	na	na	6.4	42	39
	50-65	na	na	6.1	640	48
	90-100	na	na	5.7	490	16
6	0-10	na	na	7.9	13	31
	30-40	na	na	24	11	58
	65-75	na	na	14	7.7	31
	85-95	na	na	6.2	5.2	16

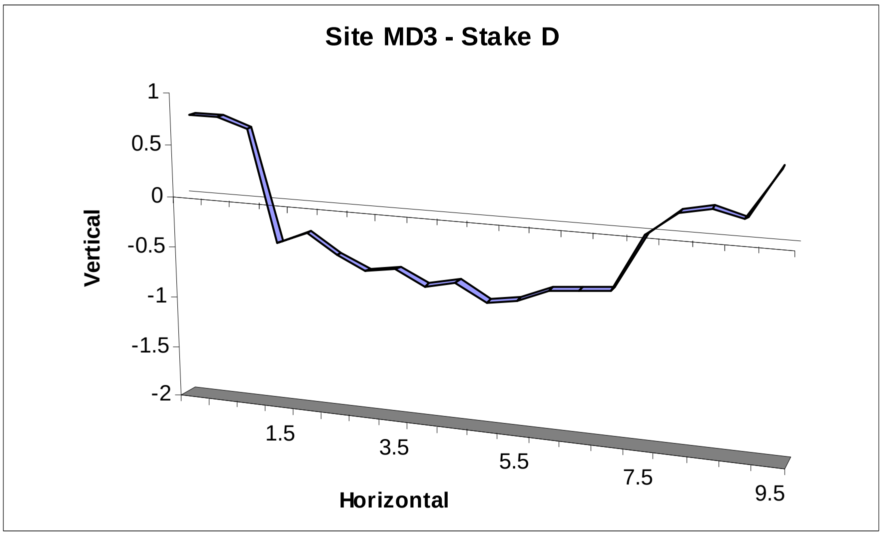
Site No.*	pH	EC (µS/cm)	Chloride (mg/L)	Sulfate (mg/L)	Cl/SO_4 Ratio	GW Depth (cm)
1GW	2.9	1800	16	420	0.04	27
4 D	3.5	530	26	30	0.9	na
4 GW	3.7	4900	670	290	2.3	40
3 GW	3.7	990	46	190	0.2	40
2 GW	4.2	240	18	8	2.3	60
1 D	4.3	560	40	33	1.2	na
6 GW	4.9	170	31	15	2.1	30
6 D	4.9	170	28	20	1.4	na
5 GW	5.6	210	16	6.7	2.4	10

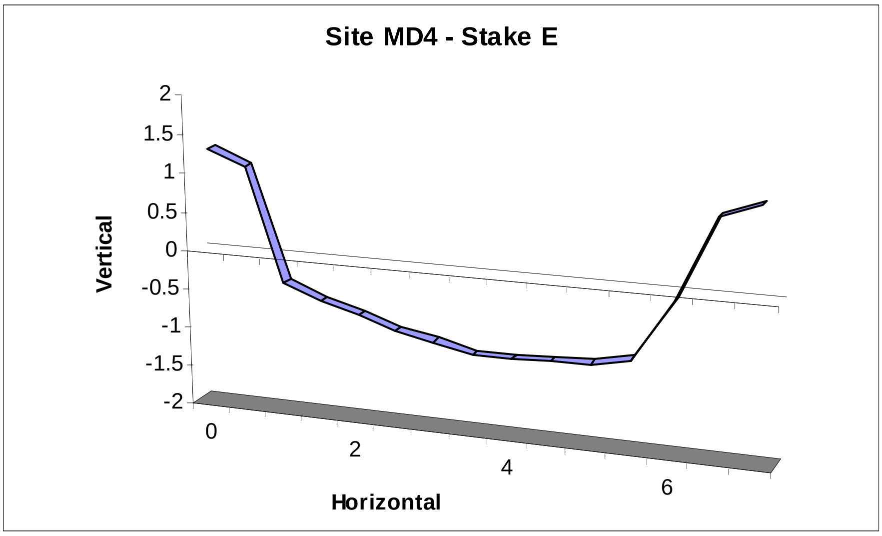
* GW = groundwater, D = drain water

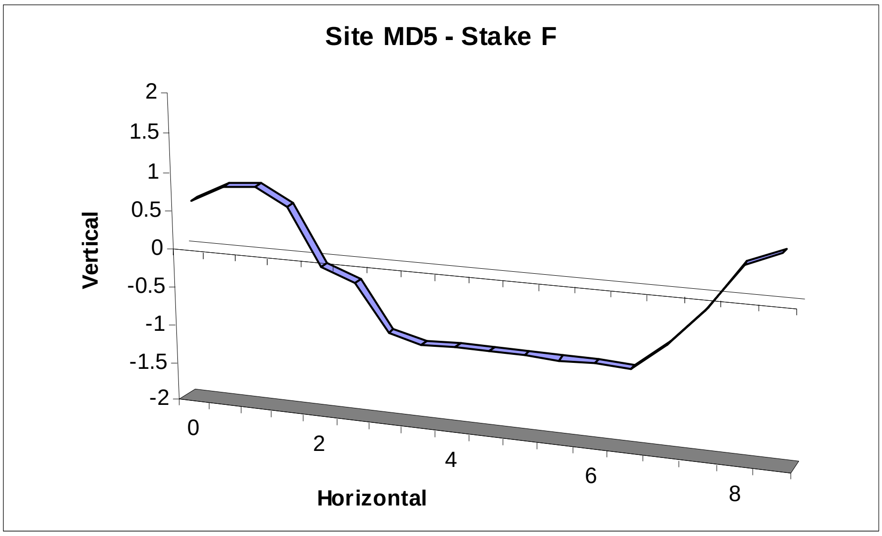
Appendix 6 Main Drain profiles








Site MD4 - Stake E
Vertical
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
2
4
6
Horizontal


Site MD5 - Stake F
Vertical
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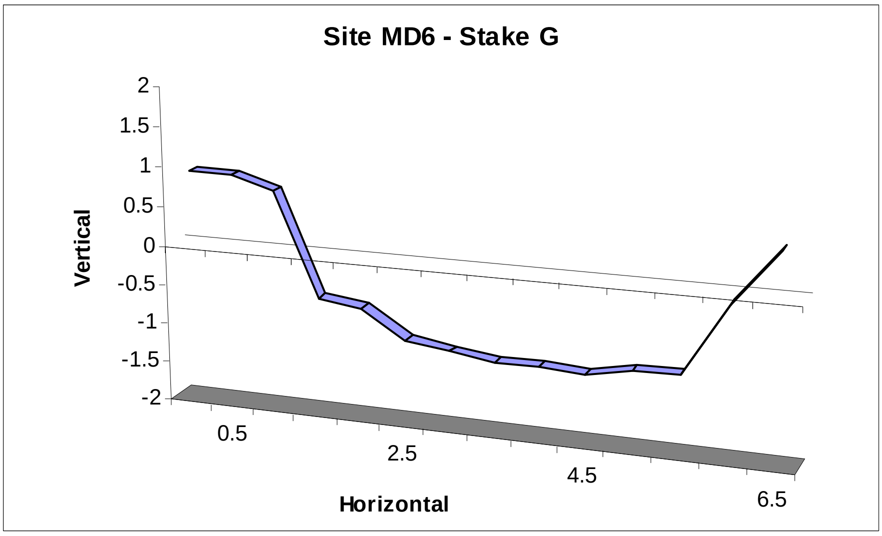
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
2
4
6
8
Horizontal


Site MD6 - Stake G
Vertical
2
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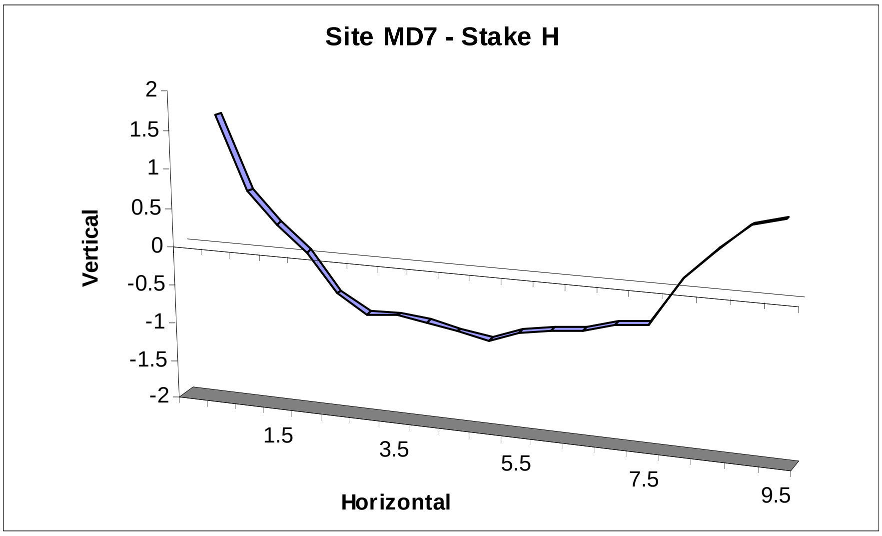
1
0.5
0
-0.5
-1
-1.5
-2
0.5
2.5
4.5
6.5
Horizontal



Site MD7 - Stake H
Vertical
Horizontal
2
1.5
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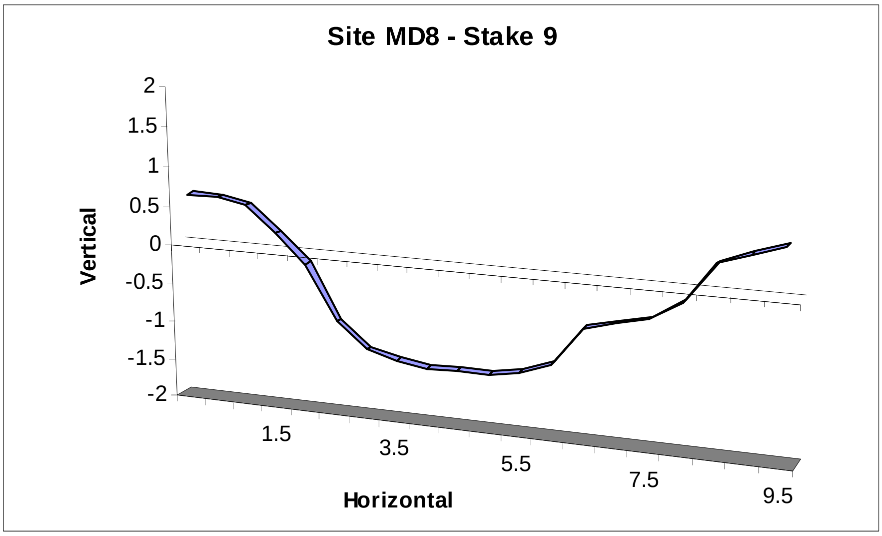
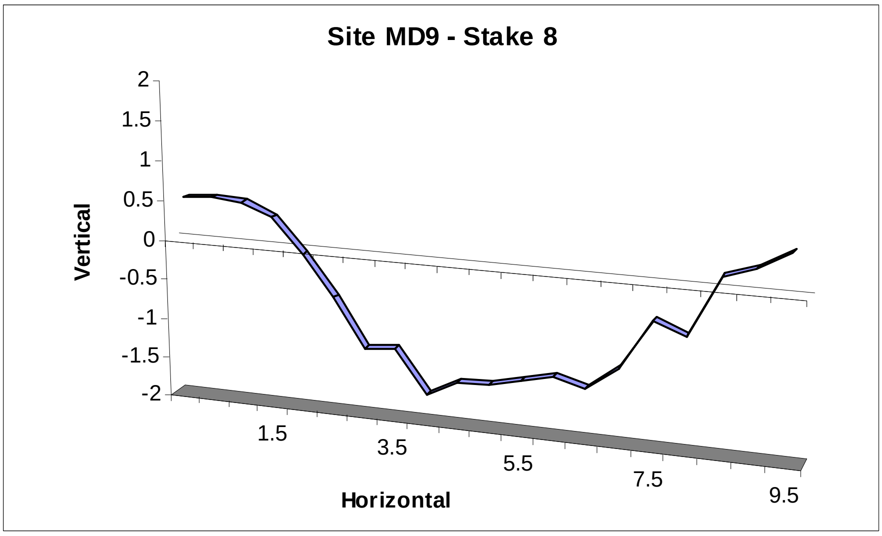
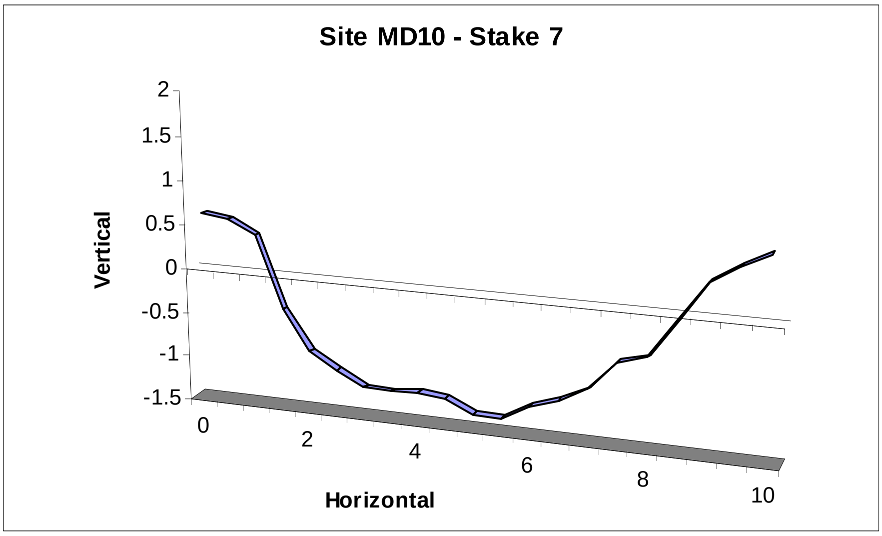
0.5
0
-0.5
-1
-1.5
-2
1.5
3.5
5.5
7.5
9.5



Site MD8 - Stake 9
Vertical
Horizontal
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1.5
3.5
5.5
7.5
9.5



Site MD9 - Stake 8
Vertical
Horizontal
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1.5
3.5
5.5
7.5
9.5


Site MD10 - Stake 7
Vertical
2
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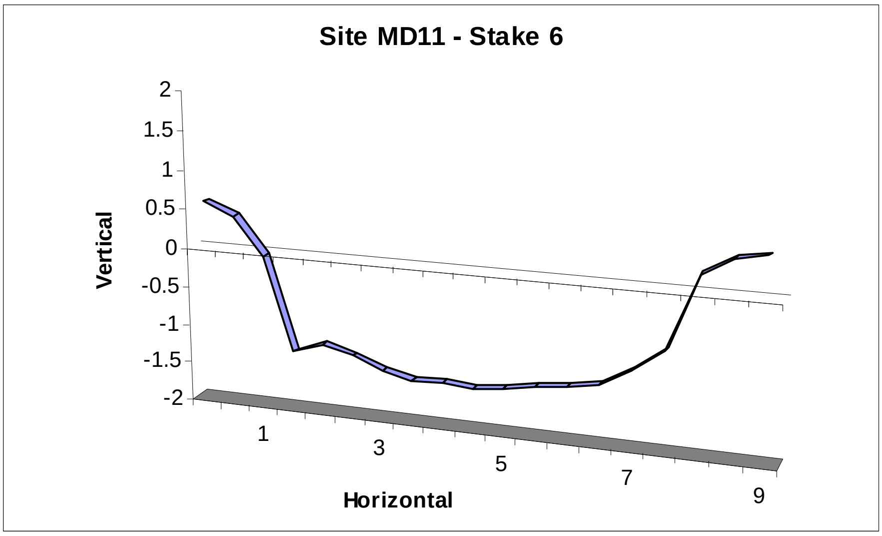
1
0.5
0
-0.5
-1
-1.5
0
2
4
6
8
10
Horizontal


Site MD11 - Stake 6
Vertical
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1
0.5
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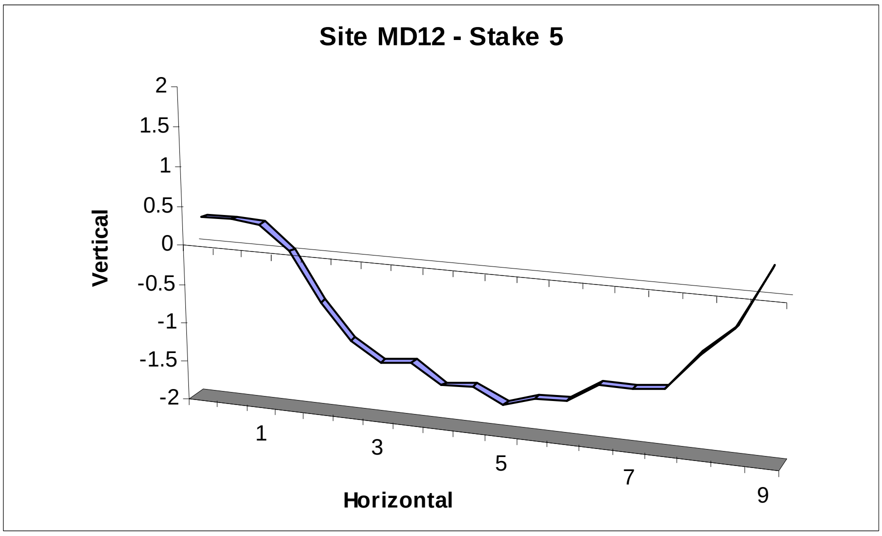
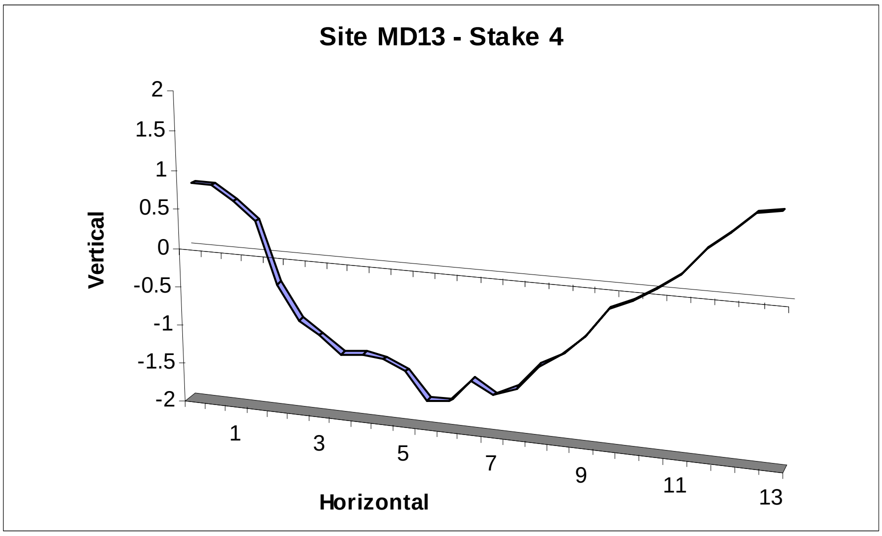
-0.5
-1
-1.5
-2
1
3
5
7
9
Horizontal


Site MD12 - Stake 5
Vertical
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1
3
5
7
9
Horizontal


Site MD13 - Stake 4
Vertical
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1
3
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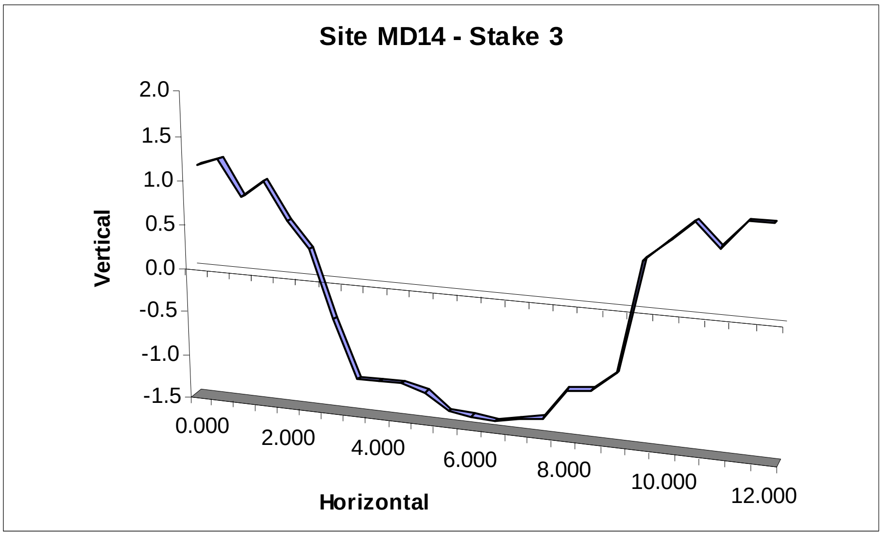
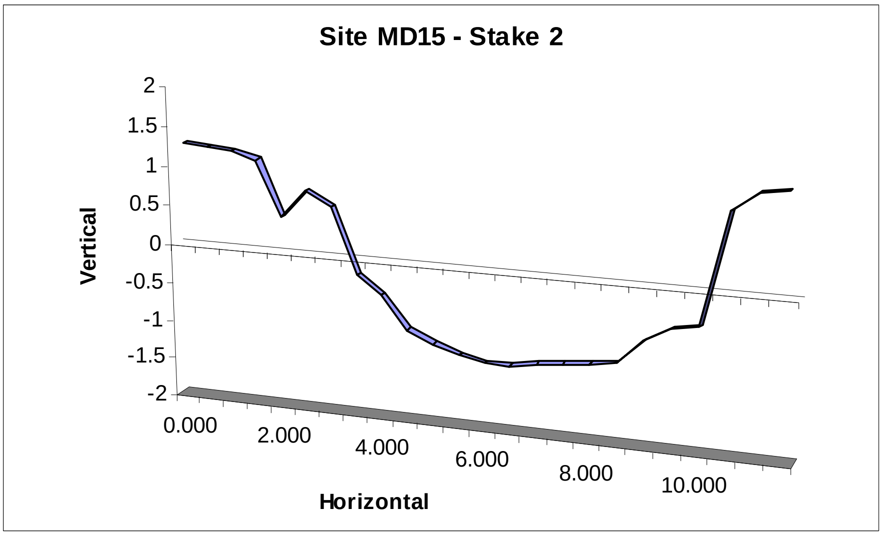
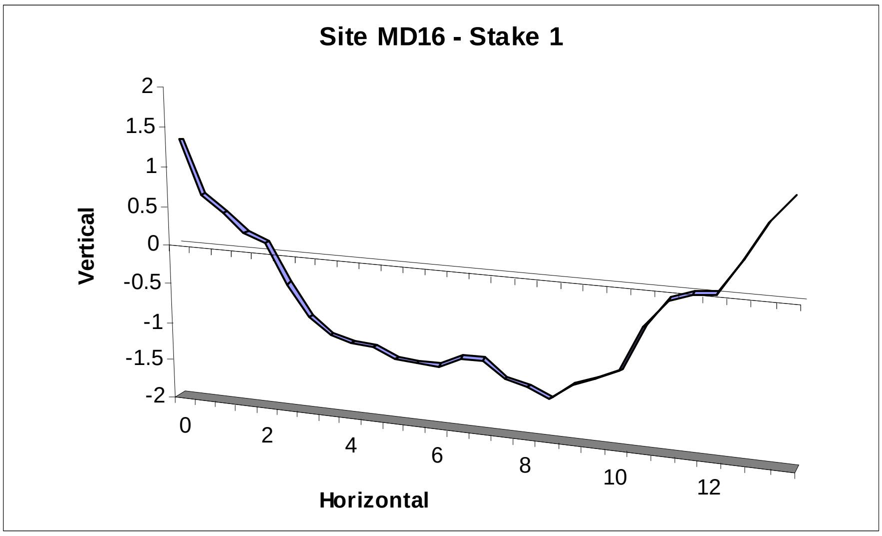
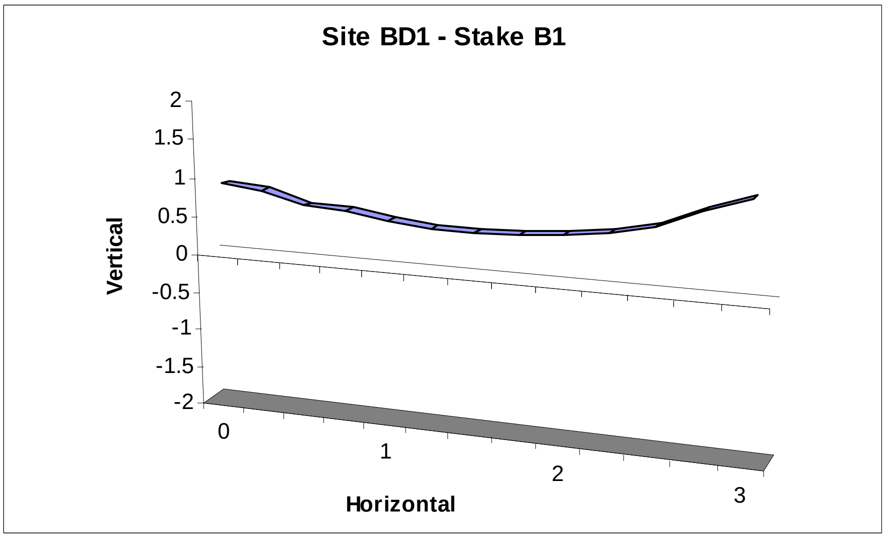
7
9
11
13
Horizontal

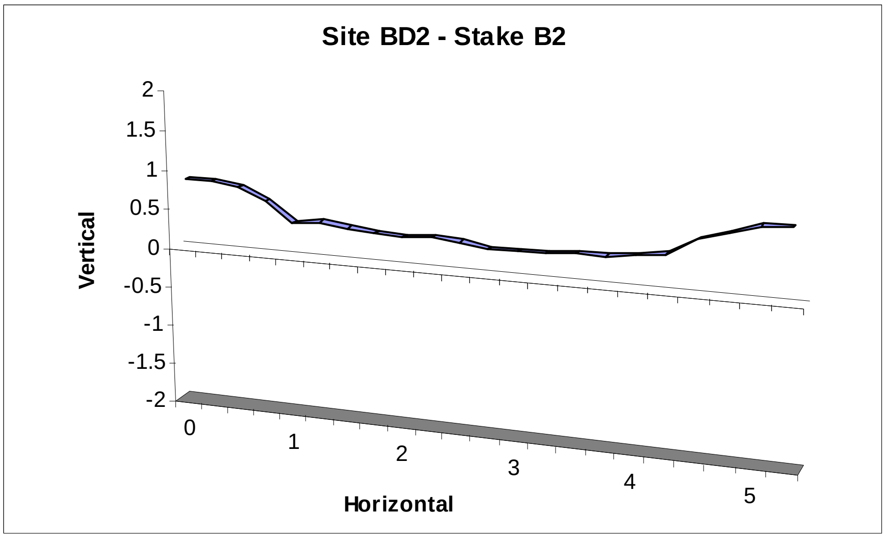

Site MD14 - Stake 3
Vertical
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0.000
2.000
4.000
6.000
8.000
10.000
12.000
Horizontal

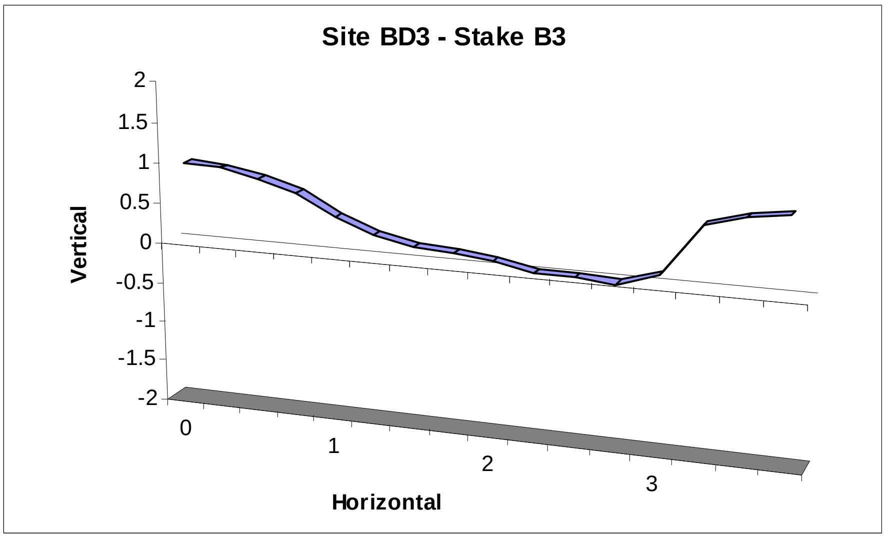

Site MD15 - Stake 2
Vertical
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.000
2.000
4.000
6.000
8.000
10.000
Horizontal

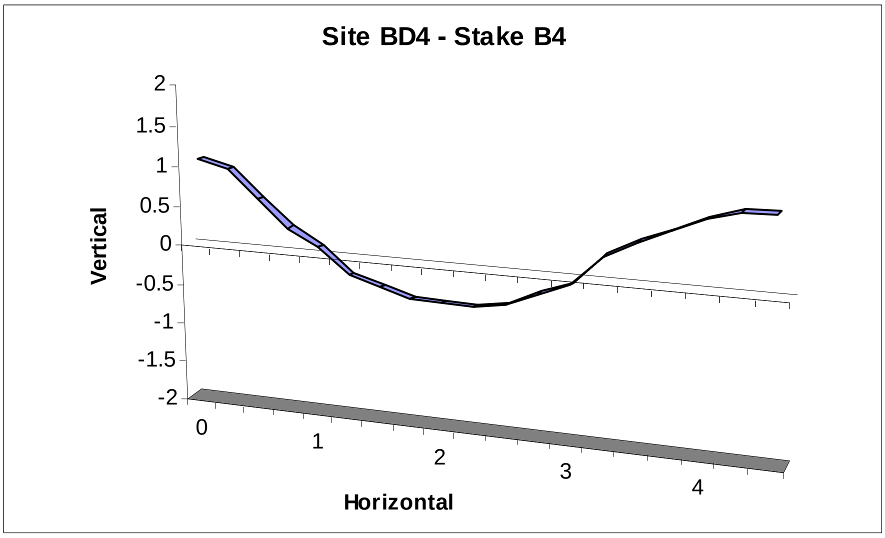

Site MD16 - Stake 1
Vertical
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
2
4
6
8
10
12
Horizontal

Appendix 7 Back Drain profiles








Site BD4 - Stake B4
Vertical
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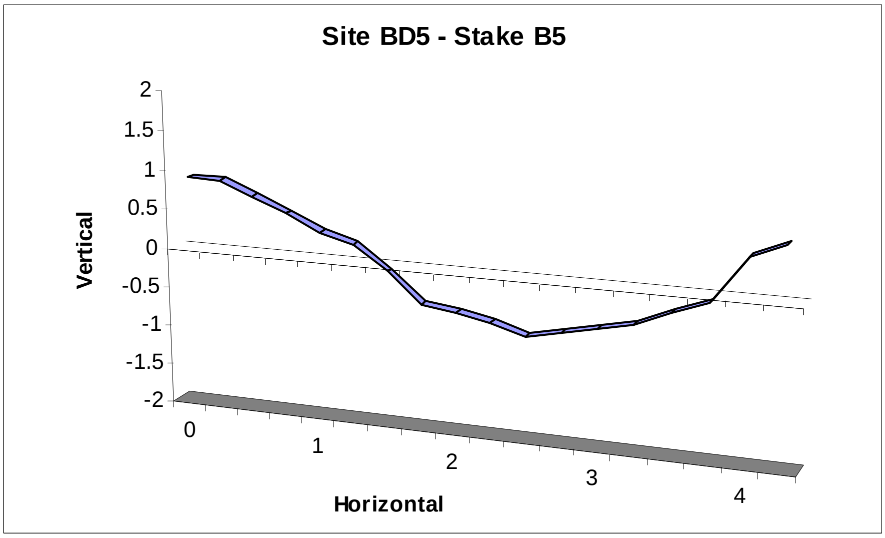
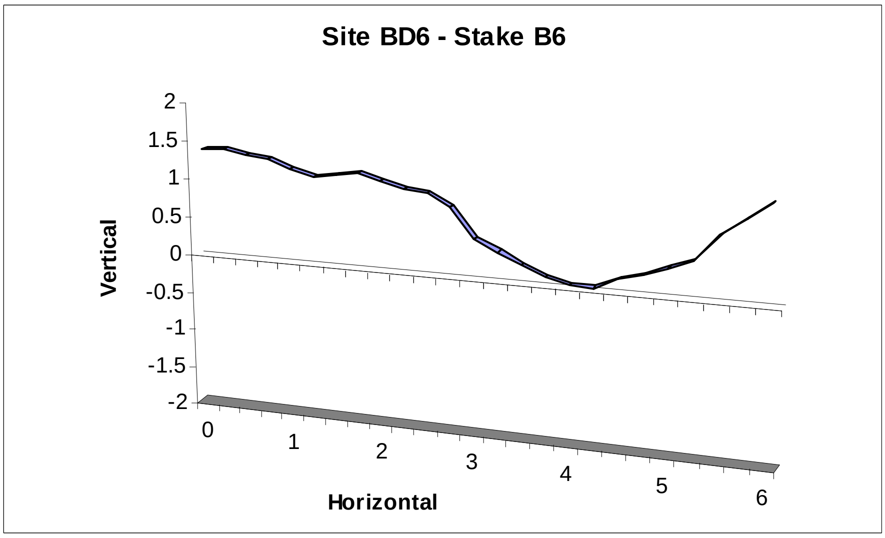
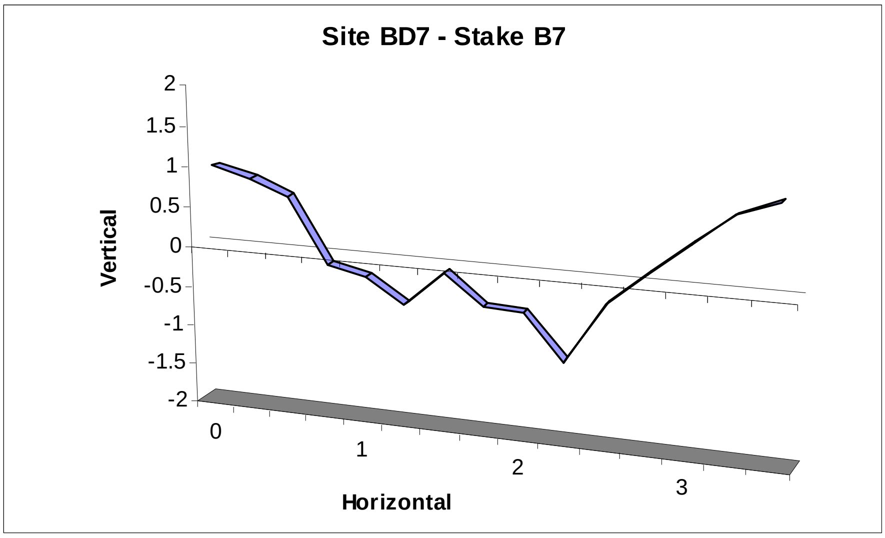
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
1
2
3
4
Horizontal


Site BD5 - Stake B5
Vertical
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
1
2
3
4
Horizontal


Site BD6 - Stake B6
Vertical
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
1
2
3
4
5
6
Horizontal


Site BD7 - Stake B7
Vertical
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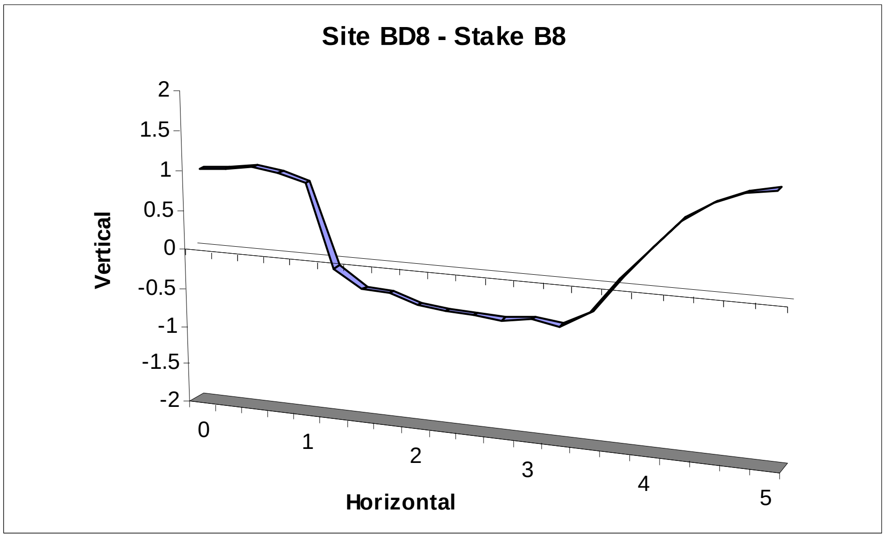
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
1
2
3
Horizontal


Site BD8 - Stake B8
Vertical
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
1
2
3
4
5
Horizontal

Appendix 8 Consultant review of remediation recommendations

WATER RESEARCH LABORATORY: WORKING PAPER #1

1. BACKGROUND INFORMATION PROVIDED

Prior to the site visit a document titled “Acid Sulphate Soil Assessments in the Anna Bay Catchment” (DPI, 2008) was provided by NSW Department of Primary Industries (DPI). In addition to this document a number of EXCEL spreadsheets were provided that contained water level data from on-site monitoring locations. This information was reviewed by Dr William Glamore of the Water Research Laboratory (WRL).

The DPI 2008 report provided relevant information concerning the extent and impact of acid sulphate soils in the Anna Bay sub-catchment based on targeted field investigations. These investigations include water quality sampling, soil coring and testing, limited flow measurements, LiDAR scanning, physical soil investigations and EM transects. Where available the field investigations had been supplemented with previous literature. Based on this information, acid hotspots within the catchment were proposed by DPI. Remediation options to ameliorate these hotspots are provided in the report.

In addition to the above report, two EXCEL spreadsheets were received from DPI with data pertaining to water levels across the drainage system (KAR 001 water levels 260908.XLS) and total actual acidity measurements with depth (TAA vs. elevation SJ edit.XLS). The water level spreadsheet contains adjusted water level data from three sites (one immediately downstream of the tidal floodgates, one immediately upstream of the tidal floodgates and one 2.3 kms upstream of the floodgates) for a period from 11th August 2008 to 26th September 2008. Rainfall data was also plotted against the water level data. The total actual acidity (TAA) spreadsheet provides TAA results adjusted to Australian Height Datum (AHD) for 4 bores sampled within the Anna Bay catchment.

2. ONSITE RECONNAISANCE

On October 9th 2008 Dr William Glamore from WRL visited the Anna Bay sub-catchment and inspected several parts of the drainage system. The onsite reconnaissance was undertaken with the assistance and guidance of DPI staff. During the day long visit Dr Glamore examined several locations where remediation options have been proposed. At each location the proposed remediation measures were discussed.

The onsite reconnaissance included the following sites (marked on Figure 1):

- Site 1: a small drainage system downstream of the tidal floodgates,
- Site 2: the tidal floodgates site,
- Site 3: a right-bank drainage canal immediately upstream of the tidal floodgates,
- Site 4: the series of culverts along Port Stephens Drive,

- Site 5: the Main Drain culverts at Nelson Bay Road,
- Site 6: the confluence of the Back Drain and the Main Drain and,
- Site 7: upstream catchment of the Main Drain near the new housing developments.

Prior to and at the conclusion of the onsite reconnaissance, brief meetings were held at the DPI office. Discussions at the end of the day included a floodplain engineer from the Port Stephens Council and a representative from the local drainage union.

3. SITE DESCRIPTION

Based on the available background information and the onsite reconnaissance, a brief description of the site as interpreted by WRL is provided below.

The Anna Bay sub-catchment is a 450-hectare low-lying coastal floodplain (Figure 2). To reduce groundwater logging and ensure that surface waters are efficiently removed from the site following rainfall, a series of surface drains were constructed in a piecemeal fashion. Over time this has lead to the development of an inefficient drainage system that requires significant ongoing maintenance including dredging works. A local drainage union ensures that the system operates in the most efficient manner possible. While the system has provided marginal agricultural drainage, increased urbanisation of the catchment will likely result in reduced drainage capacity.

Drainage of the sub-catchment has decreased groundwater tables and, where prevalent, oxidised sulfidic sediments. The oxidation by-products are typical of other acid sulphate soil hotspot sites throughout coastal NSW and include low pH levels, high concentrations of aluminium and iron and associated increased cation solubility. The total actual acidity levels measured at various locations indicate a high concentration of acidity contained within the phreatic zone. Limited information is available regarding the flux of contaminants through the drainage system.

The tidal floodgates at the downstream end of the system ensure that the a hydraulic gradient is maintained across the drainage system, with water levels immediately upstream of the floodgates consistently drained to the lowest tidal level. Under prolonged dry conditions with limited upland and groundwater discharges, the tidal floodgates ensure that groundwater levels close to the drain are maintained at or near the low tide level. Groundwater levels at some distance inland from the drains would be largely influenced by evapotranspiration. The extent of the inland area influenced by the floodgates is largely a factor of the lateral hydraulic conductivity of the soil.

Drainage of the sub-catchment during dry periods would result in the oxidation of pyritic material in close proximity to the drains. Recharge of the groundwater (due to rainfall) and subsequent drainage will promote leaching of the acidic products into the surface water drains. In clayey or fine sand soils, this flooding/drainage process is not likely to promote the transport of contaminants from areas within the middle of paddocks (say distances greater then 20 m inland). Transport of these contaminants is likely to occur during moderate to large floods when water is ponded on the surface for several days or in soils with contiguous macropores that promote lateral transport.

Though the current drainage system maintains low drain water levels during dry periods, it appears that the system is not efficient during wet periods. During, and in the ~7 days following large rainfall events, flood waters must drain from the paddocks and groundwater system into the surface water canals and eventually into the main drain. Once within the main drain, flows are constrained by the network of culverts and available hydraulic head. Of particular concern is the culvert system along Port Stephens Drive (Figure 3) which has a relatively high invert level and a small cross-sectional area (in comparison to the channel dimensions).

Across the entire drainage system, discharge only occurs when water levels in the main drain are equal to or above water levels on the tidal (downstream) side of the floodgates. While this is likely to occur during large floods, during dry period it predominately occurs during the ebb tide. As such, water typically accumulates behind the tidal floodgates during the flood tide at a rate less then the rate of tidal rise. The flaps of the tidal floodgates do not appear to be restricting the discharge as there does not appear to be any headloss across the structure during high flows (as evidence by the upstream and downstream water level records shown in Figure 4). There are no water level measurements from upstream/downstream the Port Stephens Drive or Nelson Bay Road culverts to determine their impact on restricting drainage.

Overall, the system appears to be over drained during dry periods and hydraulically inefficient during wet periods. Thus, the optimal mitigation measure for acid sulphate soils would be to increase water levels and buffering capacity during low flows without impacting drainage during high flows. This could be achieved via a series of well engineered mitigation measures installed at key locations within the drainage system.

4. PROPOSED MITIGATION MEASURES

The mitigation measures proposed in the Draft Management Plan (DPI, 2008) include:

1. Strategic application of lime for all past and future soil disturbances;
2. Raising the height of several side drainage pipes to reduce intersection of the sulphate layer;
3. Installation of a low set weir that would reduce over-drainage at a key hotspot, while widening the drain at that point to ensure drainage capacity is not reduced;
4. Install additional floodgate cells at the existing structure to enhance drainage capacity of the overall system, while modifying one floodgate to enable a controlled degree of tidal exchange.

The remainder of this section discusses the individual mitigation measures and provides professional engineering advice based on our understanding of the drainage system.

4.1 Strategic Application of lime for all past and future soil disturbances

WRL supports this mitigation measure. All lime applications should be undertaken as per methods outlined in the NSW Acid Sulphate Soil Manual. It is assumed that this includes application of lime to spoil taken from the dredged drains.

4.2 Raising the height of several side drainage pipes to reduce intersection of the sulphate layer;

Dr William Glamore inspected two locations where the drainage pipes are proposed to be modified and discussed several other sites (but did not visit) where the drainage pipes were to be raised and replicated. Issues associated with these modifications at specific locations are discussed below.

Proposed Action: Modification of the drainage network downstream of the floodgates (Figure 5).
This site is located downstream of the floodgates (Site 1, Figure 1) and is open to tidal forces. The objective at this site is to maintain an elevated groundwater table, upgrade the decrepit culvert and enhance tidal flushing.

At this location it appears that a coffer dam had been previously installed to eliminate tidal water getting into the drain. When the dam was operational, water behind the dam was most likely pumped out leaving the drain completely dry. Upon visiting the site the coffer dam was no longer in use and the culvert running under the access path was in poor condition. DPI (2008) has proposed replacing the existing culvert with a larger pipe and a tidal gate.

WRL recommends that the proposed works be re-examined. Enlarging the pipe may allow for a larger tidal prism within the drain that may assist in wetting and drying (i.e. recharging) of the surrounding soils and potentially cause scouring of the bed. This may encourage additional acidic groundwater to be transport into the drainage network. Further a tidal gate would be of limited value at this site as it will not assist in maintaining elevated water levels and would limit the quantity of tidal water permitted within the system (due to the small aperture within the tidal gate).

WRL recommends that the existing culvert be replaced with a similar size culvert and that the culvert be fitted with slots to allow for the emplacement of drop board weirs on the upstream side of the culvert. Once in position the drop boards will retain the water within the drain, maintaining an elevated watertable and reducing groundwater gradients. The sand levee that runs along the western extent of the drain could also be intersected with a series of pipe culverts to assist with tidal flushing between the drain and the area to the west, which is rich in mangrove and salt marsh species. These pipes could have one-way flaps attached that allow water to discharge into the drain but do not permit reverse flow into the wetland. Finally, break-out points should be placed along the eastern boundary of the drain so that drainage water is easily transported into the adjacent paddocks.

Proposed Action: Modification of the drainage network upstream of the floodgates (Figure 6).

This site is located upstream of the tidal floodgates (Site 3, Figure 1). The primary objective is to maintain an elevated drain water level to reduce pyrite oxidation and acid drainage.

This drain runs north-south and discharges into the basin upstream of the tidal floodgates along the main drain. Currently at the discharge point there is a small culvert but it is hard to determine the dimensions of the pipe due to plant growth. The primary objective with this site is to increase the drain water level and thus reduce groundwater seepage and pyrite oxidation. It was proposed by DPI that this culvert be replaced with a new pipe culvert.

WRL recommends that the existing pipe culvert remain in place and that an adjustable weir structure be installed in the drain. The weir (potentially a v-notch weir) could be set at a height that would maintain an elevated groundwater table and be installed at a significantly cheaper cost then a new culvert. The weir could be constructed out of marine grade plywood and pushed into the ground. Bank armour (i.e. cement bags or similar) should be located around the edges to reduce scour. A picture of a similar weir structure is shown in Figure 7. Once installed the v-notch weir should be adjusted to a height that maintains an adequate upstream water level, sufficient to limit pyrite oxidation, without significantly reducing upstream drainage.

Proposed Action: Increasing the number of drainage pipes within other drains.
WRL staff were not able to visit the sites where it is proposed that a single drainage pipe be elevated and replaced by two drainage pipes. However, it is worth noting that if the drainage pipe is currently not restricting flow, the addition of a second discharge pipe culvert will not necessarily increase drainage.

4.3 Installation of a low set weir that would reduce over-drainage at a key hotspot, while widening the drain at that point to ensure drainage capacity is not reduced;

A low-set weir has been proposed by DPI (2008) for the region downstream of the confluence of the Main and Back Drains. It is proposed that the weir would elevate the groundwater table during dry periods while not reducing drainage flood capacity (maintained by widening the channel).

WRL recommends that an alternative option is also considered. Based on our understanding, the primary area of concern is associated with waters within the Back Drain. However, the primary flooding concerns are associated with sub-urban developments in the upstream reaches of the Main Drain. As such, a mitigation measure that would achieve a favourable environmental outcome, while simultaneously reducing flooding concerns, is to place the water control structure on the Back Drain (Site 6, Figure 1).

There are a number of structures that may be suitable to the Back Drain site. Based on previous experiences a self-tilting regulating weir might be an ideal structure. This type of structure has been successfully installed in other acid sulphate soil affected drains in the Shoalhaven. A picture of an installed self-tilting weir is given in Figure 8.

A self-tilting weir is installed within a low-set headwall structure. The headworks can be made from marine ply or sulphate resistant concrete with support structures. Once the headworks are installed to a known invert level the self-tilting weir is installed.

The weir operates using a simple set of floats and pulleys. During dry periods the floats on the weir would be at a low water level. This would raise the weir plate (i.e. put the plate at a steep angle), ensuring that an elevated upstream water level is maintained. When the water level rises during rainfall events, the floats would rise and the plate would flatten ensuring that the flood waters can pass unimpeded and the surface waters can discharge. The structure requires limited on-going maintenance, no power and can be adjusted to a range of invert levels.

Regardless of the structure chosen to maintain elevated water levels in the back drain, an assessment needs to be made regarding the impact of the elevated water levels on upstream drainage. The results of any investigation should provide the invert levels for the base of the weir plate and headworks. The complexity of the investigation is dependent on the concerns related to the upstream landholders and related land use. If the upstream landholders are not concerned with a potential rise in groundwater levels or a slight reduction in drainage then a relatively simple investigation could be undertaken. Conversely, a more detailed investigation may be required, including numerical flood modelling, if there is significant concern.

4.4 Install additional floodgate cells at the existing structure to enhance drainage capacity of the overall system, while modifying one floodgate to enable a controlled degree of tidal exchange.

The Anna Bay Drainage Union has proposed major infrastructure works to install additional floodgate cells at the existing structure with the anticipation that this will increase drainage capacity of the overall system. Although currently not available for review, Dr William Glamore of WRL was advised that this recommendation is based on a report completed several years ago.

WRL strongly recommends that this option be reconsidered. Based on observations during the field visit, the installation of additional floodgate cells at the existing structure will do little to increase drainage of the overall system. In its current state, the floodgates are not likely to induce significant headloss (as shown in Figure 4) and the flow capacity of the floodgates cells is significantly greater then the Port Stephens Drive culverts located ~870 m upstream.

If the upstream and downstream channels remain unchanged the installation of additional floodgate cells are not likely to increase system drainage. The additional cells may increase drainage downstream of Port Stephens Drive but this is most likely to occur during dry periods and would result in the further lowering of the groundwater levels. Without additional information it is in our opinion that the resources allocated to the floodgate works would be better spent on upgrading the Port Stephens Drive culverts and selected dredging works at locations in the drainage channel.

Modifying one floodgate to enable a controlled degree of tidal exchange should also be undertaken with caution. Modifying one cell to include a small aperture and tidal gate will result in high velocities through the gate aperture on the rising tide. This may:

- Place large drag forces on the gate that exceed the buoyant lifting force and hence cause the tidal gate to close during the flood tide;
- Cause vibrations on the gate which are structurally unsound,
- Create a jet that induces scour of bed sediments including mono-sulfidic black oozes;
- Suck fish and other marine life into the jet, which may effect fish buoyancy and reduce health.

To avoid these unwanted outcomes the objectives of the tidal restoration works should be examined. If the objective is to increase tidal flushing to enhance the transport of buffering agents upstream of the floodgates then an alternative design may be desired. Conversely, if the objective is to permit fish passage then a larger floodgate opening may be considered (to reduce entrance velocities). If upstream flooding becomes a concern then the Port Stephens Drive culverts could be fitted with one-way flaps to eliminate tidal flushing. Nonetheless, fundamental engineering principles should be applied prior to installing any modified floodgates.

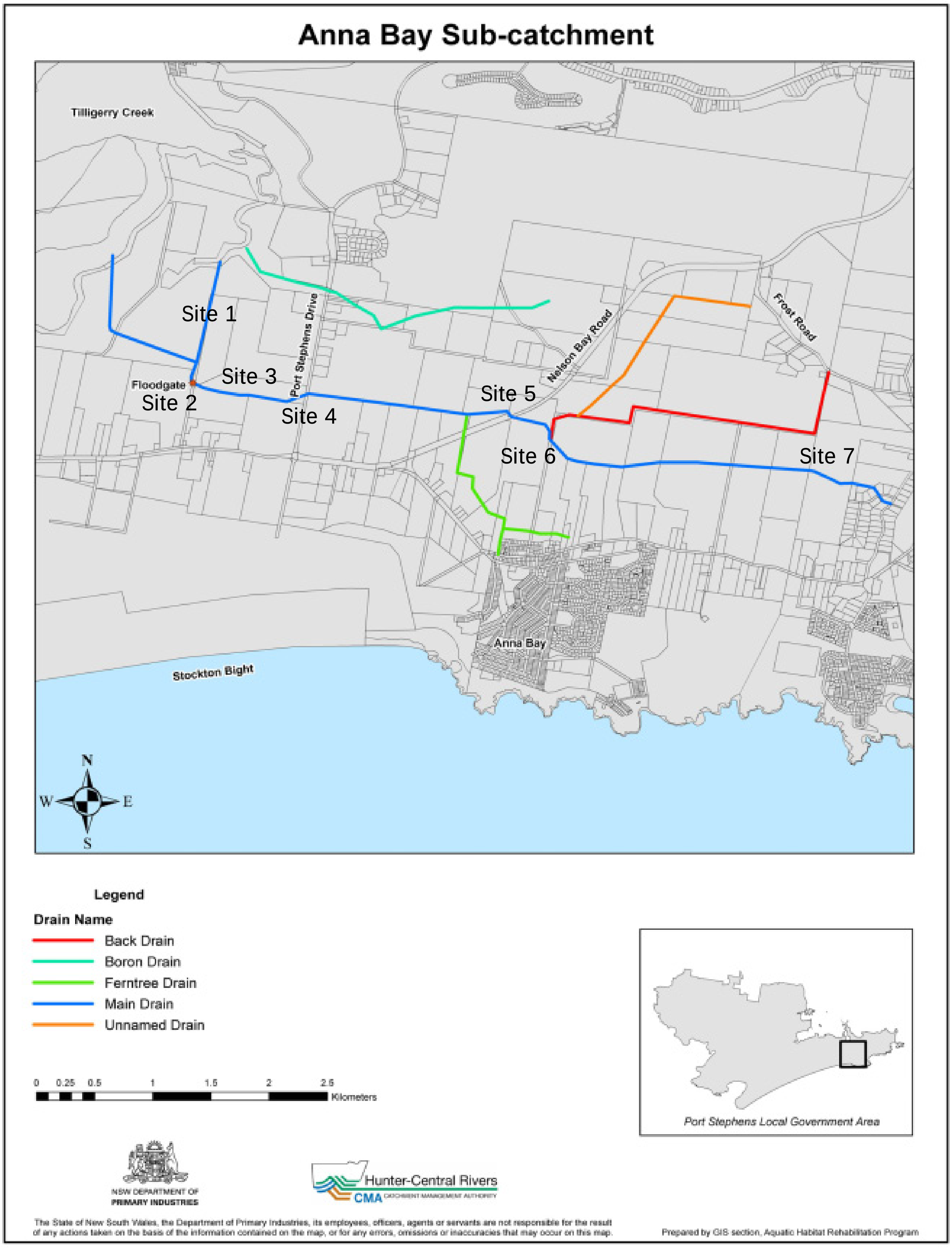
5. SUMMARY

Thank you for the opportunity to provide this letter report. Based on the review of the available information and the one-day site visit, the mitigation measures have been assessed and several alternative strategies have been highlighted. The alternative suggestions should provide considerable cost savings, maintain the environmental benefits and reduce risk. To ensure that the alternative suggestions are properly designed, WRL recommends undertaking some fundamental data gathering of water levels at key locations within the drainage network. Assessing the data would provide a much better understanding of the drainage system and could form the basis of a hydrological model, if required.

WRL has extensive experience in the design and installation of modified floodgates, assessing system hydraulics and undertaken hydrologic modelling. Please advise if you would like us to further detail any of the above suggestions, review any additional information that may come to hand or to visit DPI to further discuss the suggestions within this letter report.

6. REFERENCE

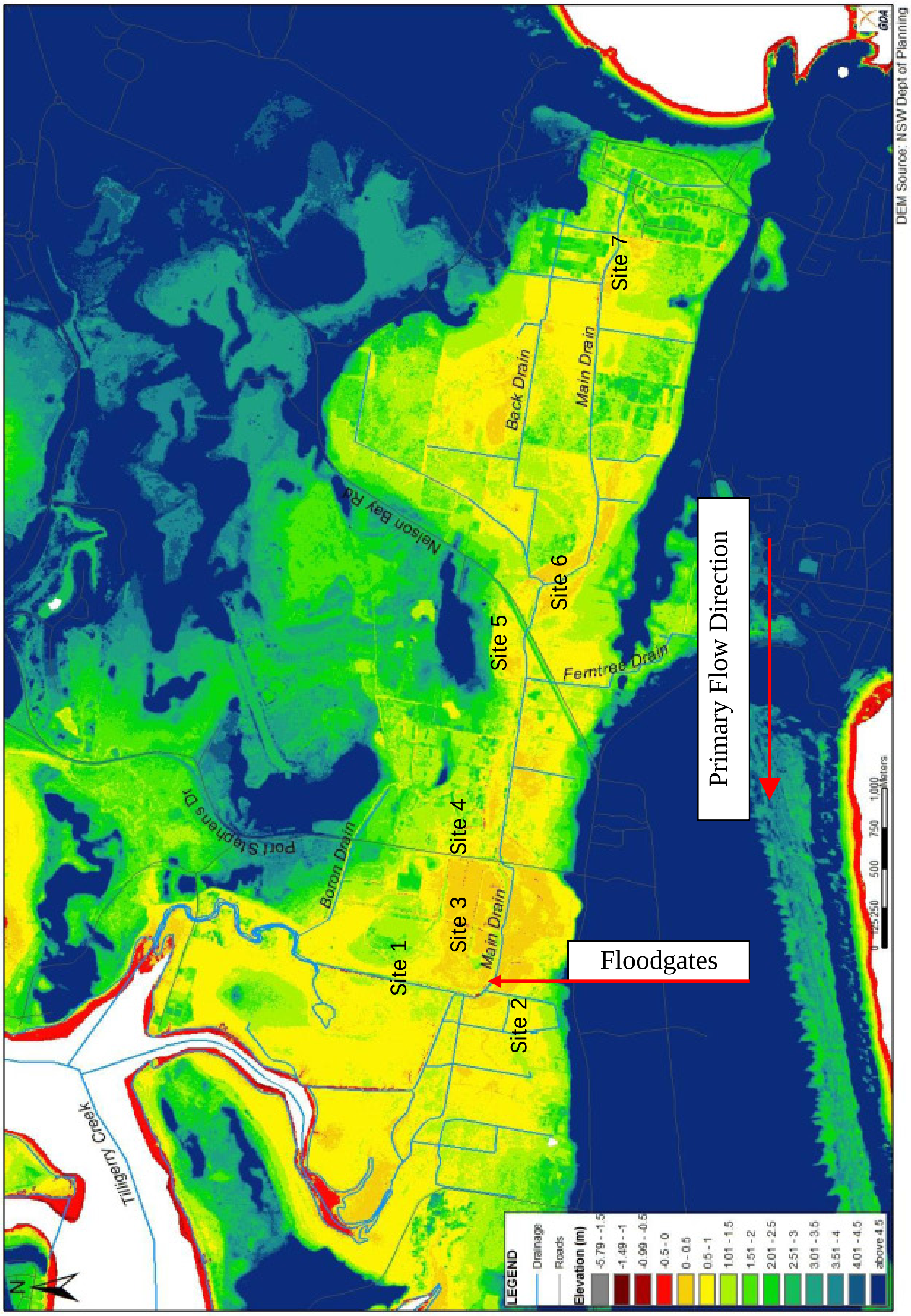
NSW Department of Primary Industries (2008) Acid Sulfate Soil Assessments in the Anna Bay Catchment. August 2008 Draft Report.



Source: DPI (2008)

WRL Report No. L08087	ANNA BAY SUB-CATCHMENT	Figure 1

Digital Elevation Model for Anna Bay



Source: DPI (2008)

WRL Report No. L08087	ANNA BAY SUB-CATCHMENT: DIGITAL ELEVATION MODEL	Figure 2

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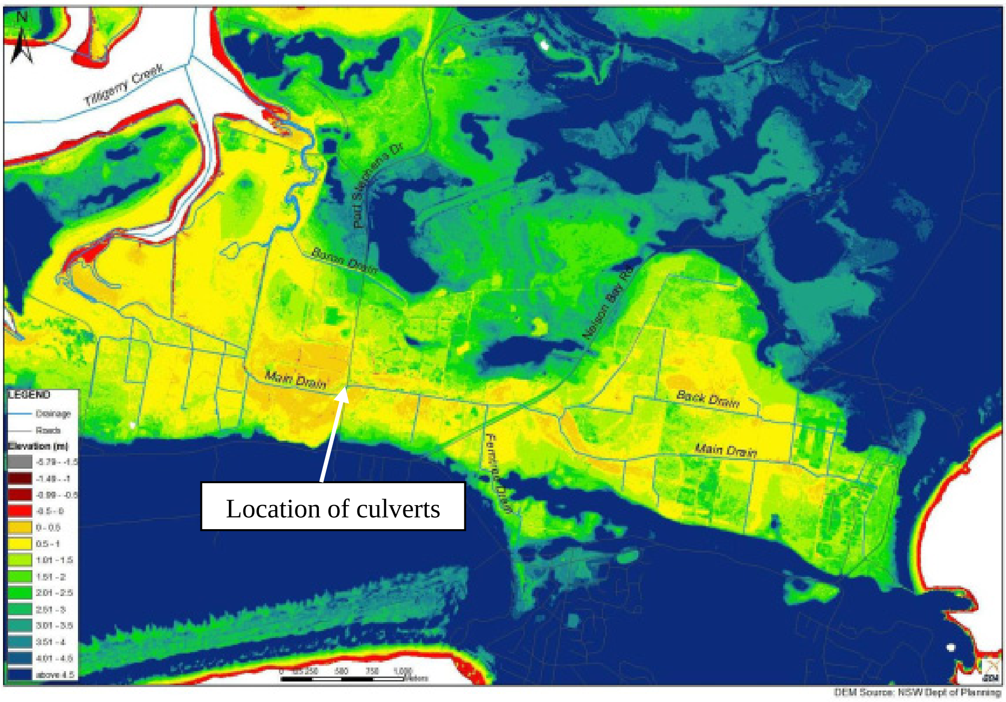
Digital Elevation Model for Anna Bay



Modified from source: DPI (2008)

WRL Report No. L08087	PORT STEPHENS DRIVE CULVERTS	Figure 3

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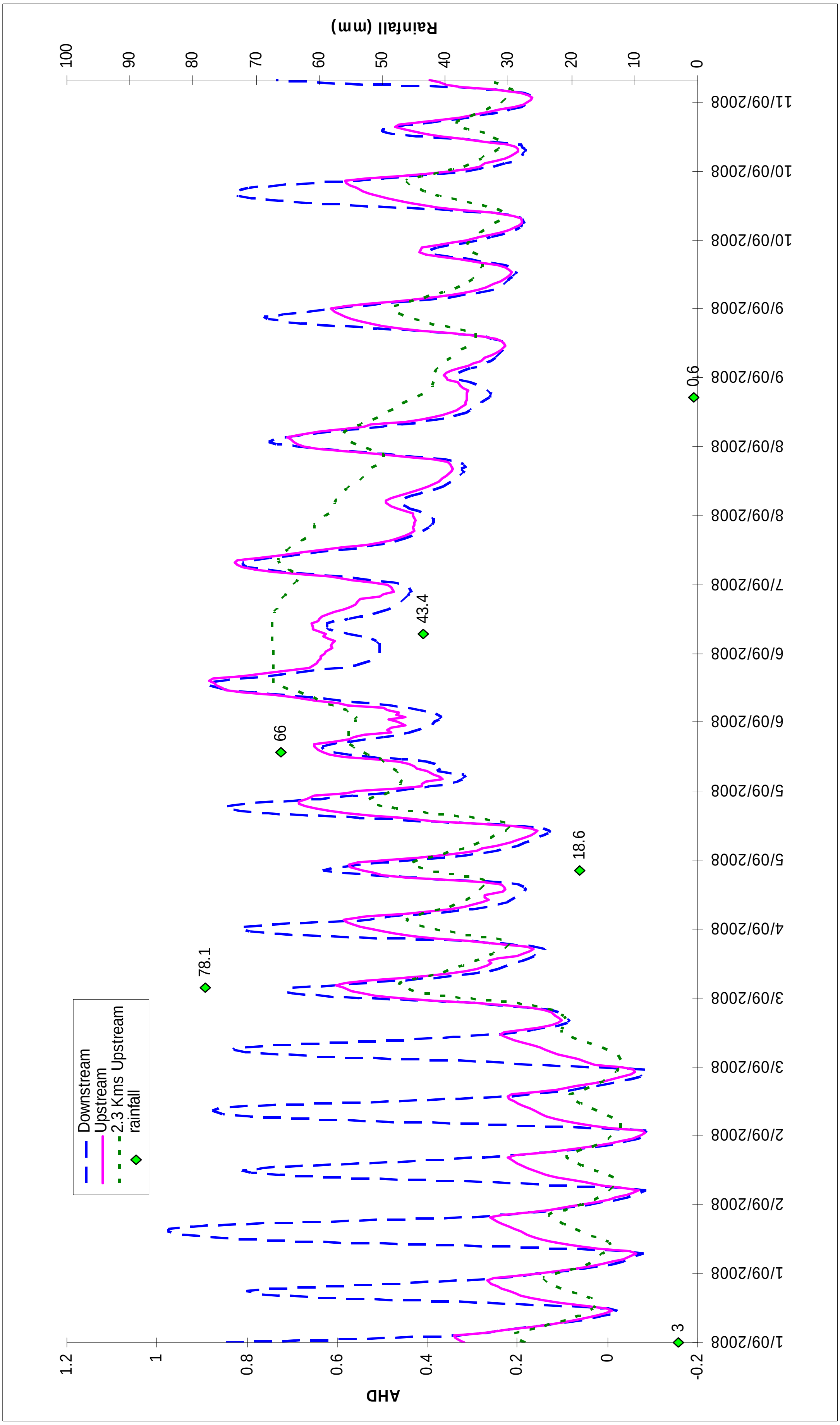


Modified from source: DPI (2008)

WRL Report No. L08087	WATER LEVEL DATA IN THE VICINITY OF THE TIDAL FLOODGATES	Figure 4 p25_32.bps

Digital Elevation Model for Anna Bay

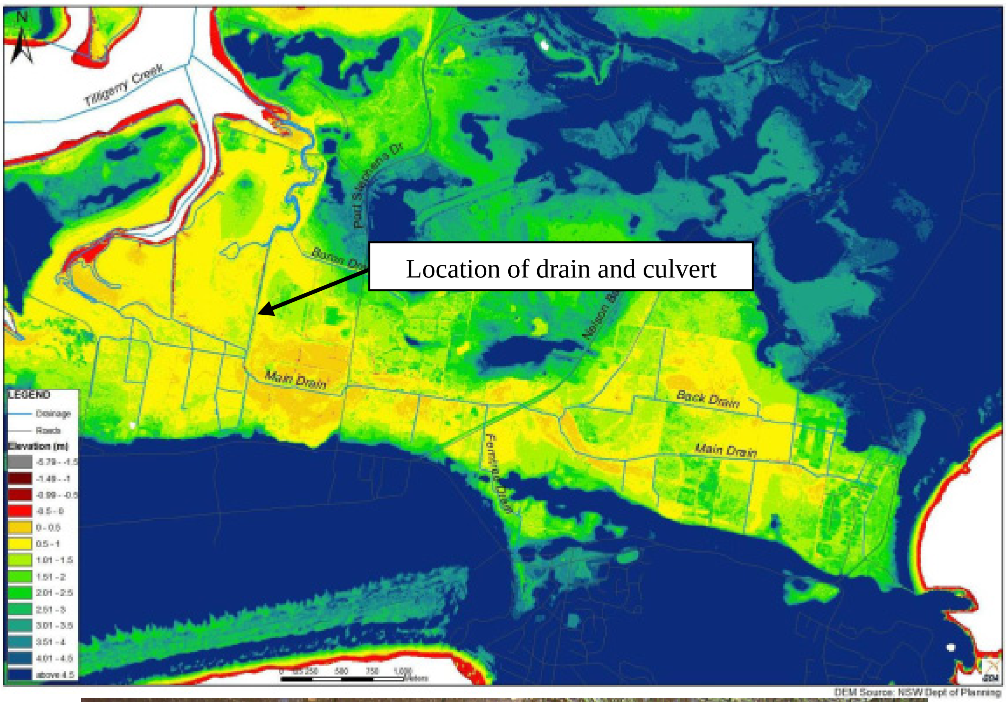
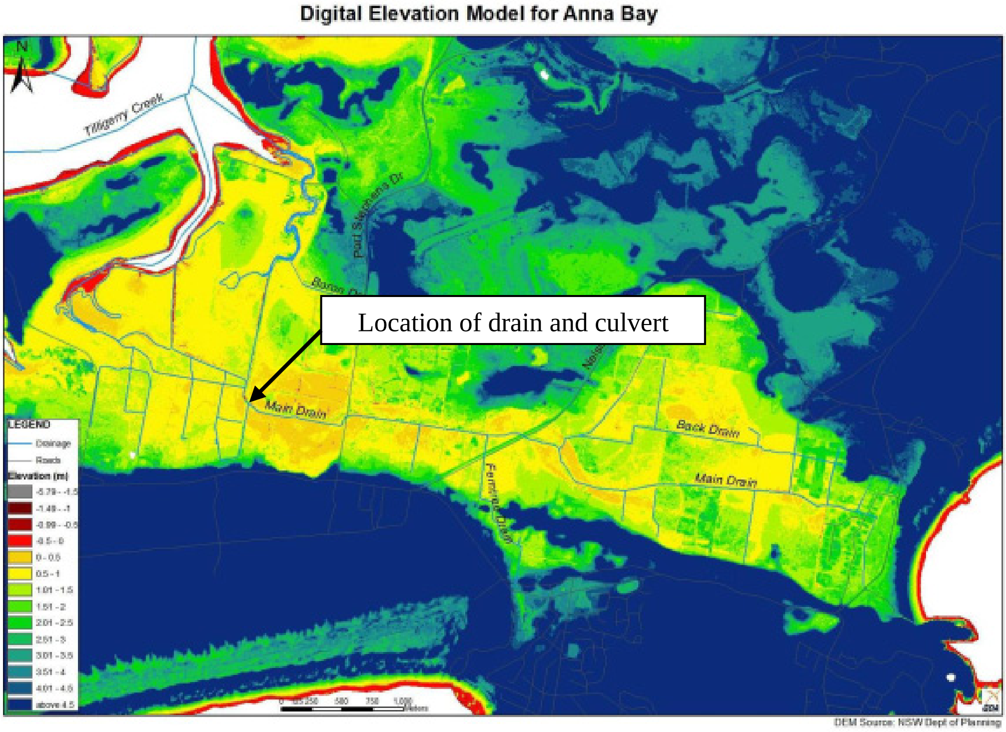


Image is shown looking downstream from culvert.
Note remnant coffer dam and current state of culvert.

WRL Report No. L08087	DRAINAGE WORKS DOWNSTREAM OF FLOODGATES	Figure 5

p25_32.bps

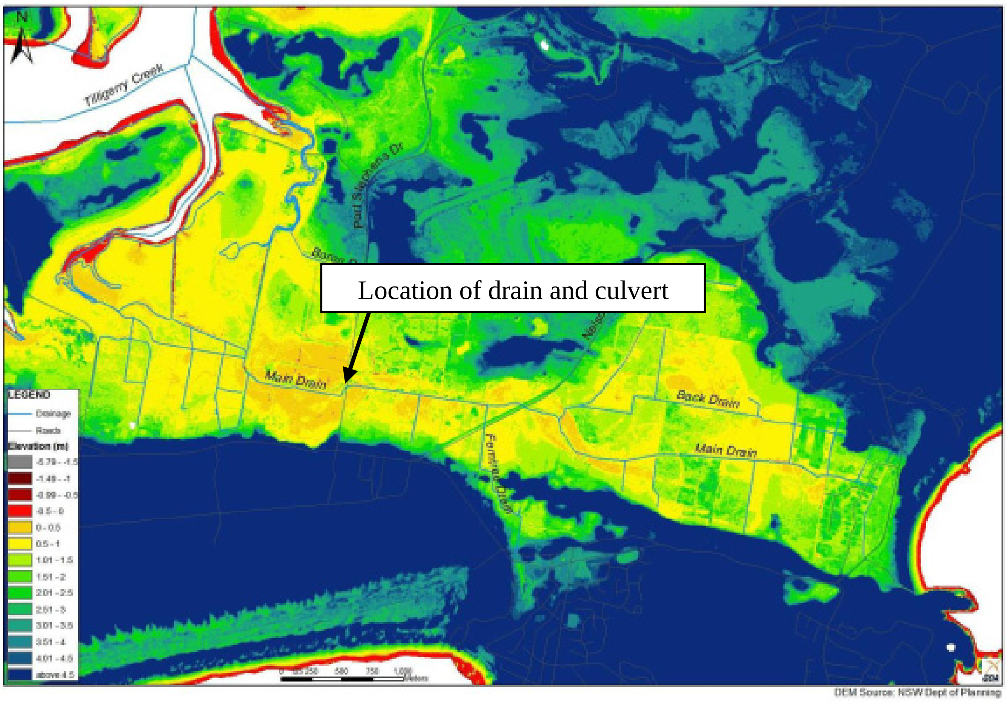


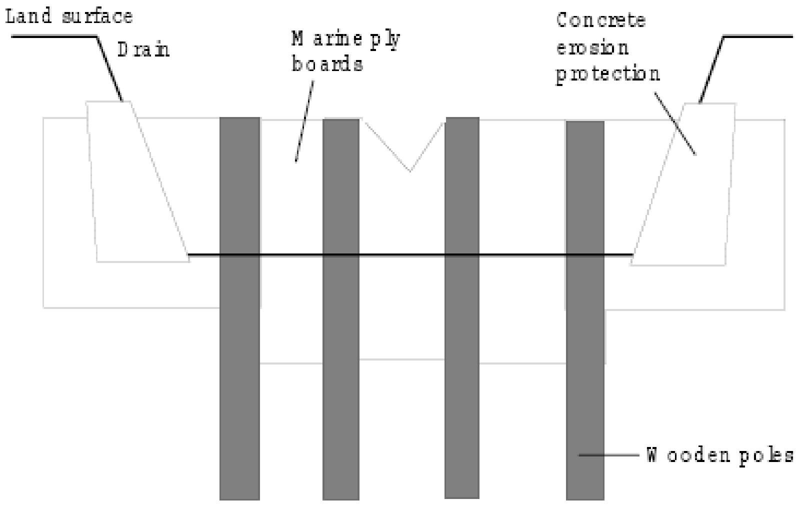
Images showing drainage system upstream of the floodgates.

WRL Report No. L08087	DRAINAGE WORKS UPSTREAM OF FLOODGATES	Figure 6

p25_32.bps

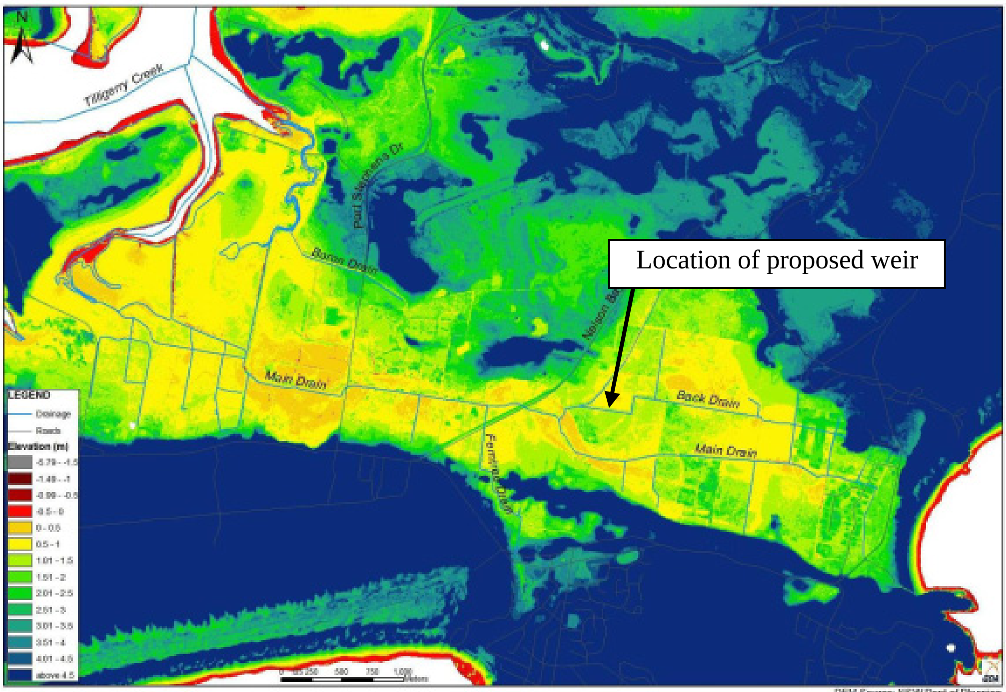
Digital Elevation Model for Anna Bay

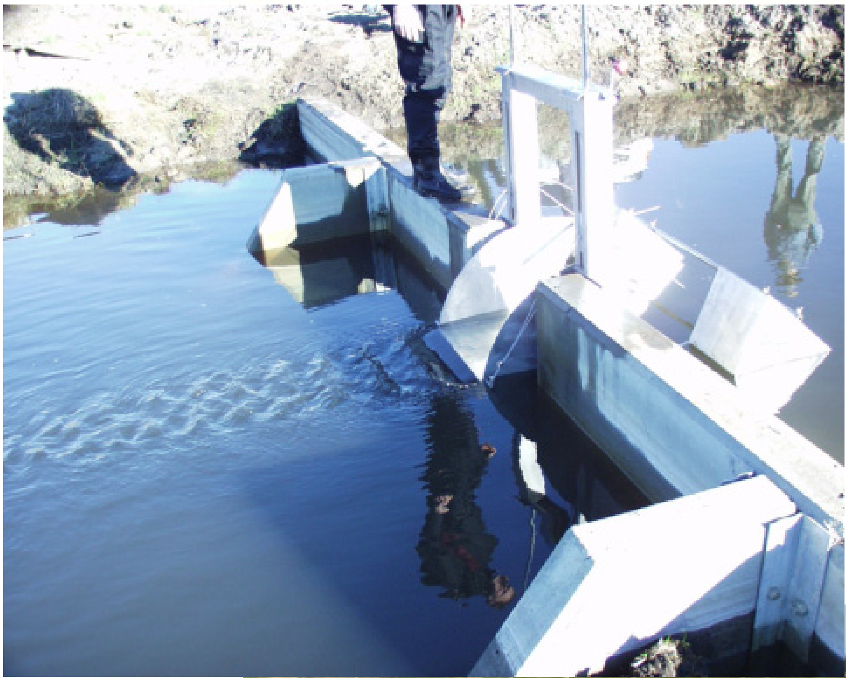




WRL Report No. L08087	V-NOTCH WEIR AS PROPOSED FOR UPSTREAM DRAIN	Figure 7 p25_32.bps

Digital Elevation Model for Anna Bay





WRL Report No. L08087	SELF TILTING WEIR AS PROPOSED FOR BACK DRAIN	Figure 8 p25_32.bps

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aquatic habitat rehabilitation
making more fish
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