



Assessment of Acid Sulfate Soil Materials (Phase 2) Ramco Lagoon (12046), South Australia

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Report to the Murray-Darling Basin Authority

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EXECUTIVE SUMMARY

An initial Phase 1 acid sulfate soil investigation of Ramco Lagoon (12046) during March 2010 showed acid sulfate soils to be a priority concern within this wetland complex. Based on Phase 1 recommendations, a Phase 2 investigation was undertaken for Ramco Lagoon (12046) to determine the nature, severity and the specific risks associated with acid sulfate soil materials.

The 24 hour **reactive metals** tests were undertaken to determine those metals and metalloids extractable with a moderately strong acid i.e. potentially available from binding sites on soil minerals such as iron (Fe), manganese (Mn) and aluminium (Al) oxides. Although comparisons can be made with soil and sediment quality guidelines, these are defined for total concentrations and not partial extractions. The results showed that concentrations were generally below the sediment quality guidelines (SQG) and soil ecological investigation levels (EIL) for those elements where guidelines are available. The exception was manganese which breached the soil ecological investigation level (EIL) in three of the four samples. Although most metals and metalloids did not breach sediment quality guidelines and soil ecological investigation level trigger values, the concentrations of some elements were high enough that they may impact water quality if mobilised, particularly for aluminium (Al) and iron (Fe) in addition to manganese (Mn).

The **contaminant and metalloid dynamics** tests were undertaken to assess the release of metals during a water extraction, and to assess dynamics in response to saturation over time by incubating soil materials for periods of 1, 7, 14 and 35 days. The degree to which metal and metalloid concentrations exceed ANZECC/ARMCANZ environmental protection guideline values was used to characterise the degree of hazard. For Ramco Lagoon (12046), no metals or metalloids were assigned a high or moderate hazard with concentrations exceeding ANZECC/ARMCANZ environmental protection guidelines by more than 10 times. Arsenic (As), chromium (Cr), copper (Cu), manganese (Mn), vanadium (V) and zinc (Zn) were above the guideline values.

Ramco Lagoon (12046) has been classified as high conservation status by the SA Murray-Darling Basin Natural Resources Management Board (Miles *et al.* 2010). The main hazards considered in this study that may impact on wetland values are acidification, contaminant mobilisation and deoxygenation. The wetland has been allocated a **low** risk rating due to **acidification** and a **medium contaminant** risk rating for **soils**. For **surface waters**, the risk is largely dependent on surface and sub-surface hydrology and is thus scenario dependent. Taking into account the range of likely scenarios, from very low flows (highest risk) to very high flows (lowest risk), the risk to surface waters in the wetland has been allocated a **low** risk rating for **acidification** and a **medium** risk rating for **contaminant mobilisation**. Acidification is likely to occur only locally in sub-surface soils as there is very high alkalinity within most soils which is likely to neutralise acid flux over a larger scale. The highest risk for metals and metalloids is probably related to the metalloid oxyanions arsenic (As) and vanadium (V) as these showed an increase over time and these form oxyanions which may be mobile at higher pH. This risk may increase as Eh was also decreasing, which may lead the reductive dissolution of iron (Fe) and manganese (Mn) oxides/oxyhydroxides and any associated adsorbed metals and metalloids. A monosulfide formation potential test was not undertaken for Ramco Lagoon (12046) as monosulfides were identified previously. The risk associated with **deoxygenation** was determined as **medium**, due to the high water soluble sulfate and presence of monosulfidic materials beneath surface algal mats.

In designing a management strategy for dealing with acid sulfate soils in Ramco Lagoon (12046), other values and uses of the wetland need to be taken into account to ensure that any intervention is compatible with other management plans and objectives for the wetland.

The wetland soils studied were largely dry at the time of sampling with some pools of surface water in lower parts, therefore management options considered should relate to controlling or treating acidification and the protection of connected or adjacent wetlands. Due to the medium risks to the wetland values associated with metal mobilisation and deoxygenation in Ramco Lagoon (12046), a monitoring program is recommended during any disturbance to the soils.

1. INTRODUCTION

At its March 2008 meeting, the Murray–Darling Basin Ministerial Council discussed the emerging issue of inland acid sulfate soils and the associated risks to Murray–Darling Basin waterways and agreed that the extent of the threat posed by this issue required assessment. The purpose of the Murray–Darling Basin Acid Sulfate Soils Risk Assessment Project was to determine the spatial occurrence of, and risk posed by, acid sulfate soils at priority wetlands in the River Murray system, wetlands listed under the Ramsar Convention on Wetlands of International Importance and other key environmental sites in the Murray–Darling Basin. The project involved the selection of wetlands of environmental significance, as well as those that may pose a risk to surrounding waters. These wetlands were then subjected to a tiered assessment program, whereby wetlands were screened through a desktop assessment stage, followed by a rapid on-ground appraisal, and then detailed on-ground assessment if results of previous stages indicated an increased likelihood of occurrence of acid sulfate soils.

Detailed assessments of acid sulfate soils within the Murray-Darling Basin (MDB) are conducted as a two-phase process under the MDB Acid Sulfate Soils Risk Assessment Project (ASSRAP). Phase 1 investigations are initially undertaken to determine whether or not acid sulfate soil materials are present in the study area, and provide characterisation of the properties and types of acid sulfate soils. Phase 2 investigations are only conducted if the acid sulfate soil materials from Phase 1 are determined to be a priority concern for the study area and, based on Phase 1 recommendations, selected samples undergo further investigations to determine the nature, severity and the specific risks associated with the acid sulfate soil materials. Phase 2 activities include: (i) soil laboratory analysis to confirm and refine the hazards associated with contaminant mobilisation and/or deoxygenation, (ii) a risk assessment, and (iii) interpretation and reporting, including discussion on broad acid sulfate soil management options.

Detailed Phase 1 acid sulfate soil assessments were undertaken at almost 200 wetlands and river channels throughout the Murray-Darling Basin. In South Australia, 56 wetlands along the River Murray between Lock 1 and Lock 5 were investigated by CSIRO Land and Water (Grealish *et al.* 2010). From these Phase 1 investigations, 13 wetlands were selected for further investigation. Nearly all of the wetlands along the River Murray between Wellington and Blanchetown (Lock 1) in South Australia also received detailed Phase 1 acid sulfate soil assessments (Grealish *et al.* 2011) and of these 23 wetlands were selected for further investigation in Phase 2. This included some wetlands below Lock 1 from earlier studies (Fitzpatrick *et al.* 2008; Fitzpatrick *et al.* 2010).

Following the Ramco Lagoon (12046) Phase 1 assessment (Grealish *et al.* 2010) and the priority ranking criteria adopted by the Scientific Reference Panel of the MDB ASSRAP (see Table 1-1), Ramco Lagoon (12046) was selected for Phase 2 detailed assessment. The Phase 1 assessment sampled from 8 sites along two transects (Figure 1-1). The Phase 1 assessment identified no high priority sites based on the presence of sulfuric materials, no high priority sites based on the presence of hypersulfidic materials, 6 high priority sites based on hyposulfidic materials with $SCR \geq 0.10\%$ and 8 moderate priority sites based on the presence of hyposulfidic materials with $SCR < 0.10\%$. Phase 2 investigations were carried out on selected surface soil samples from 2 sites (12046_6 and 12006_8) identified in the Phase 1 assessment (Grealish *et al.* 2010).

The soils were clays, and the wetland was dry at the time of sampling, but with surface pools in the lower parts in the south of the wetland (see cover picture). Net acidities were generally low, varying overall from -2280 to 99 mol H^+ /tonne. However, only five sub-surface soils had positive net acidity. The wetland was well buffered, with ANC varying from 0 to 17 % ANC, and a median of 0.6 % ANC.

Table 1-1 Priority ranking criteria adopted by the Scientific Reference Panel of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project, from MDBA (2010).

Priority	Soil material
High Priority	<p>All sulfuric materials.</p> <p>All hypersulfidic materials (as recognised by either 1) incubation of sulfidic materials or 2) a positive net acidity result with a Fineness Factor of 1.5 being used).</p> <p>All hyposulfidic materials with S_{CR} contents $\geq 0.10\%$ S.</p> <p>All surface soil materials (i.e. within 0-20 cm) with water soluble sulfate (1:5 soil:water) contents $\geq 100 \text{ mg kg}^{-1} \text{ SO}_4$.</p> <p>All monosulfidic materials.</p>
Moderate Priority	<p>All hyposulfidic materials with S_{CR} contents $< 0.10\%$ S.</p>
No Further Assessment	<p>Other acidic soil materials.</p> <p>All other soil materials.</p>

A summary of the soil laboratory analyses undertaken as part of the Phase 2 assessment and the sample selection criteria for each analysis is given in Table 1-2. Soil samples identified to undergo Phase 2 laboratory analysis are primarily from the surface and near-surface layers, as these are the soils most likely to have initial contact with water. A list of the samples selected for Phase 2 analysis for Ramco Lagoon (12046) is presented in Table 1-3.

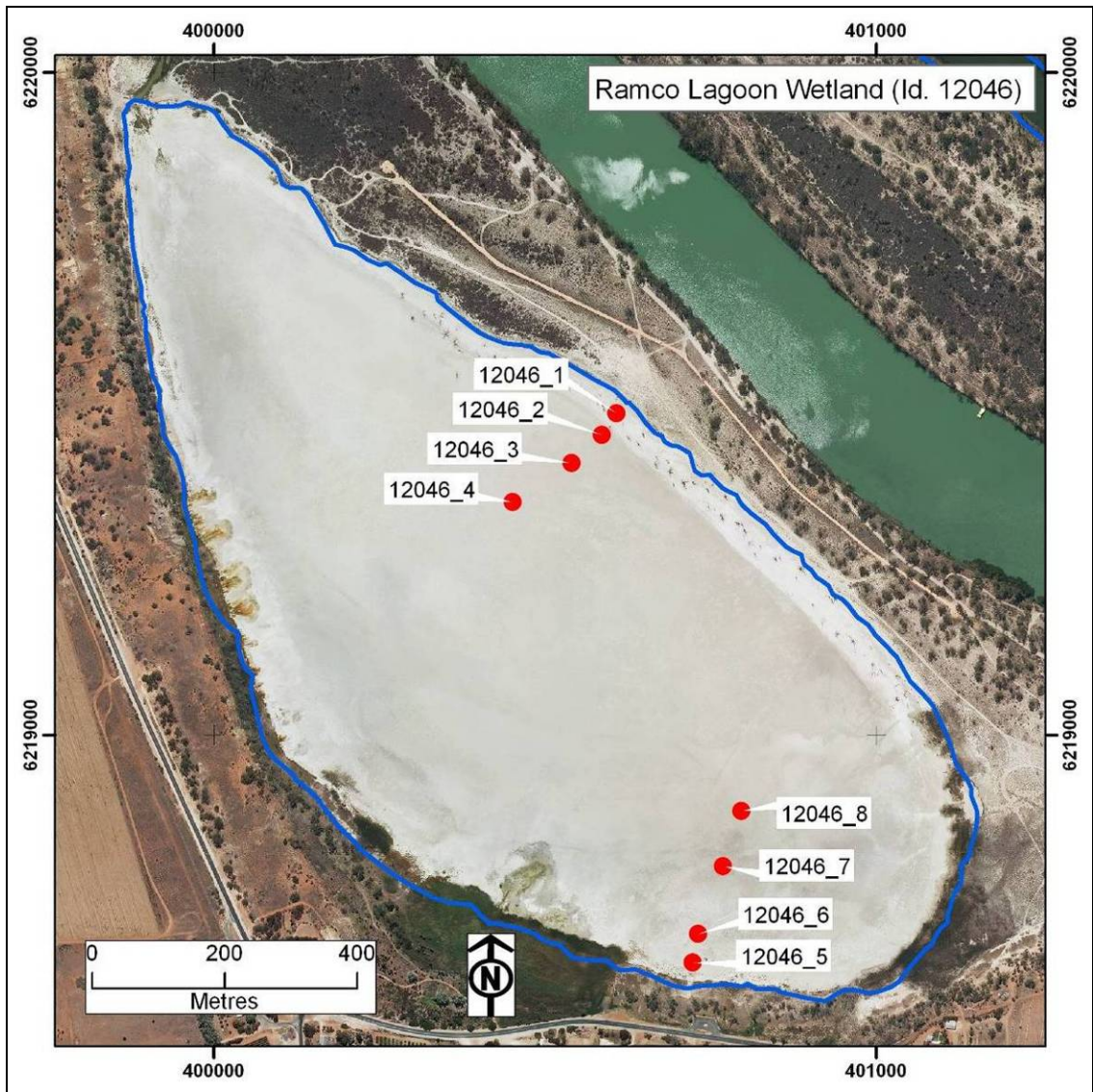


Figure 1-1 Ramco Lagoon (12046) aerial photograph with Phase 1 sampling sites identified.

Table 1-2 Rationale for Phase 2 sample selection, from MDBA (2010).

Parameter	Samples selected
Reactive metals	Conducted on selected upper two surface samples.
Contaminant and metalloid dynamics	Conducted on selected upper two surface samples.
Monosulfide formation potential	Conducted on surface samples of dry sites that meet the water extractable sulfate criteria for monosulfides.
Mineral identification by X-ray diffraction (XRD)	Conducted on a limited number of selected crystals and minerals (if present). Most likely to be associated with sulfuric layers to confirm acid mineral presences.
Acid base accounting data	Conducted only on samples from wetlands below Lock 1 and Burnt Creek/Loddon River if not previously analysed and $\text{pH}_{\text{KCl}} < 4.5$.

Table 1-3 Summary of Ramco Lagoon (12046) samples analysed for Phase 2 assessment.

Soil Laboratory Test	Ramco Lagoon (12046) samples	Depth of sample (cm)	Number of samples analysed
Reactive metals	12046_6.1	0-5	4
	12046_6.2	5-10	
	12046_8.1	0-5	
	12046_8.2	5-10	
Contaminant and metalloid dynamics	12046_6.1	0-5	4
	12046_6.2	5-10	
	12046_8.1	0-5	
	12046_8.2	5-10	
Monosulfide formation potential	-	-	0
Mineral identification by X-ray diffraction (XRD)	-	-	0

2. LABORATORY METHODS

2.1. Laboratory analysis methods

2.1.1. Summary of laboratory methods

A list of the method objectives for the Phase 2 assessment are summarised below in Table 2-1. All soil samples analysed in this Phase 2 assessment were collected and subsequently stored as part of the Phase 1 field assessment.

Table 2-1 Phase 2 data requirements - list of parameters and objective for conducting the test, from MDBA (2010).

Parameter	Objective
Reactive metals	Assists with determining impacts on water quality by determining weakly to moderately strongly bound metals.
Contaminant and metalloid dynamics	Assists with determining impacts on water quality by simulating longer time frames that create anaerobic conditions. Identifies metal release concentrations that may occur over a 5 week time frame.
Monosulfide formation potential	Determine relative propensity for monosulfides to form following inundation.
Mineral identification by X-ray diffraction (XRD)	Characterisation and confirmation of minerals present.

Guidelines on the approaches that were followed as part of this Phase 2 assessment are presented in full in the detailed assessment protocols (MDBA 2010).

2.1.2. Reactive metals method

The guidelines for the reactive metals method are outlined as an addendum to the detailed assessment protocols (MDBA 2010). In this method, samples were prepared by disaggregation (not grinding) using a jaw crusher, and then sieved to include only the <2 mm fine earth fraction. A total of 2.5 g soil was added to 40 ml of 0.1 M HCl, gently mixed for 1 hour and filtered through a pre-acid washed 0.45 µm nitro-cellulose filter. The metals examined comprised silver (Ag), aluminium (Al), arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), vanadium (V) and zinc (Zn).

2.1.3. Contaminant and metalloid dynamics method

The guidelines for the contaminant and metalloid dynamics method are outlined in Appendix 7 of the detailed assessment protocols (MDBA 2010). The contaminant and metalloid dynamics method was designed to determine the release of metals and metalloids in soils after 24 hours. The data represent the availability of metals and metalloids from a weak extraction (water, and thus easily bioavailable) of saturated soils, and for dry wetland soils, those easily mobilised from mineral surfaces and readily soluble mineral phases (such as salts). The exercise was repeated in a batch process for longer time periods (7 days, 14 days, 35 days). The latter approach was aimed at understanding changes in concentrations over time. This is particularly important for dried soils which have been in contact with the

atmosphere. The soil materials and the release/uptake of metals/metalloids are expected to change as the chemical environment changes from oxidising to reducing. The data can be compared to existing water quality guidelines, although care should be taken when extrapolating to surface waters without knowledge of hydrological conditions and natural chemical barriers. The impact on surface waters will be governed by the upward chemical flux which is a function of soil type, water flow, diffusion and the chemistry of the soils near the sediment-water interface.

Redox potential (Eh) and pH were determined using calibrated electrodes linked to a TPS WP-80 meter; Eh measurements were undertaken in an anaerobic chamber to minimise the rapid changes encountered due to contact with the atmosphere, and are presented relative to the standard hydrogen electrode (SHE). Specific electrical conductance (SEC) was determined using a calibrated electrode linked to a TPS WP-81 meter. All parameters were measured on filtered (0.45 µm) water samples.

2.1.4. Monosulfide formation potential method

The guidelines for the monosulfide formation potential method are outlined in Appendix 8 of the detailed assessment protocols (MDBA 2010). In this study 3.6 g/L sucrose was used as an organic substrate instead of the 7.2 g/L outlined in the protocols. In addition to sampling after seven weeks, water samples were collected and analysed immediately after inundating the soils (i.e. Day 0). The pore-water pH and Eh were determined at Day 0.

The reactive iron (Fe) fraction in field moist sediments was extracted using 1.0 M HCl (Claff *et al.* 2010). The ferrous iron (Fe²⁺) and total iron (Fe²⁺ + Fe³⁺) fractions were immediately fixed following extraction. The ferrous iron trap was made up from a phenanthroline solution with an ammonium acetate buffer (APHA 2005), and the total iron trap also included a hydroxylamine solution (APHA 2005). The iron species were quantified colorimetrically using a Hach DR 2800 spectrophotometer.

Redox potential and pH were determined using calibrated electrodes linked to a TPS WP-80 meter; Eh measurements are presented versus the standard hydrogen electrode. In this study the solid phase elemental sulfur fraction was extracted using toluene as a solvent and quantified by high-performance liquid chromatography (HPLC) (McGuire and Hamers 2000). Pore-water sulfide was preserved in zinc acetate prior to determination by the spectrophotometric method of Cline (1969).

2.1.5. Mineral identification by x-ray diffraction

The guidelines for mineral identification by x-ray diffraction are outlined in the detailed assessment protocols (MDBA 2010).

2.2. Quality assurance and quality control

For all tests and analyses, the quality assurance and quality control procedures were equivalent to those endorsed by NATA (National Association of Testing Authorities). The standard procedures included the monitoring of blanks, duplicate analysis of at least 1 in 10 samples, and the inclusion of standards in each batch.

Reagent blanks and method blanks were prepared and analysed for each method. All blanks examined here were either at, or very close to, the limits of detection. On average, the frequencies of quality control samples processed were: 10% blanks, 10% laboratory duplicates, and 10% laboratory controls. The analytical precision was ±10% for all analyses. In addition, for all samples, reactive metals and contaminant and metalloid dynamics tests were duplicated. For the reactive metals, two International Standards (Reference Stream Sediment STSD-2 and STSD-3 Canadian Certified Reference Materials) were processed in

an identical manner to the samples. Precision was excellent with the coefficient of variation (standard deviation/mean*100) typically being in the range < 1 to 2 %.

3. RESULTS AND DISCUSSION

3.1. Summary of soil laboratory results

3.1.1. Reactive metals data

The data are presented on a dry weight basis (mg kg^{-1}) and shown in Table 3-1. The 24 hour reactive metals studies provide an indication of those metals and metalloids which are more strongly bound to minerals (or weakly soluble with an acid extraction) than would be soluble with a water extraction, and thus have the potential to be released. The use of a moderately strong acid (0.1 M HCl) should provide an indication of “stored metals” and metalloids associated with iron (Fe) and manganese (Mn) oxides and organic materials as well as acid soluble minerals. It is commonly found that the concentrations of metals and metalloids released using extractions are much higher than those found in solution (Goody *et al.* 1995). Although guideline values exist for soils and sediments, these are generally for total soil concentrations, and therefore, are not directly appropriate for the data from metal mobilisation studies. Nevertheless, they provide a basis for comparison; and concentrations close to or above guideline values indicate an elevated hazard.

The concentrations of metals and metalloids were generally below sediment quality guideline (SQG) values and soil ecological investigation levels (EIL) (Table 3-1). The exception was manganese (Mn), which was above the soil ecological investigation level (EIL) in three samples. Aluminium (Al) and iron (Fe) are also considered high.

Table 3-1 Ramco Lagoon (12046) reactive metals data.

Concentrations in mg kg^{-1} , and $\mu\text{g kg}^{-1}$ as indicated by asterisk.

Sample	Ag*	Al	As	Cd*	Co	Cr*	Cu	Fe	Mn	Ni	Pb	Sb*	Se*	V	Zn
12046_6.1	6.5	405	2.4	97	1.4	349	2.7	826	498	2.1	2.9	< 19	99	6.8	4.5
12046_6.2	11	481	3.9	167	2.5	276	3.4	1430	766	3.8	1.9	< 21	67	8.3	4.4
12046_8.1	1.4	288	0.52	23	3.1	187	2.5	469	1834	2.9	1.8	< 21	66	3.5	3.1
12046_8.2	1.1	428	2.3	25	3.3	190	2.2	1118	744	2.7	4.2	< 22	39	9.3	3.8
¹ SQG	1000	-	20	1500	-	80000	65	-	-	21	50	2000	-	-	200
² Soil EIL	-	-	20	3000	-	-	100	-	500	60	600	-	-	50	200

* Units are in $\mu\text{g kg}^{-1}$

< value is below detection limit

¹SQG: Sediment Quality Guideline Value (Australian and New Zealand Guidelines for Fresh and Marine Water Quality 2000)

²Soil EIL: Soil – Ecological Investigation Level (NEPC 1999)

3.1.2. Contaminant and metalloid dynamics data

The contaminant and metalloid dynamics data for the four Ramco Lagoon (12046) soil materials examined are presented in Appendix 2, summarised in Table 3-2 and plotted against time in Figure 3-1 to Figure 3-3. Table 3-2 also compares the pore-water metal contents to the relevant national water quality guideline for environmental protection (ANZECC/ARMCANZ 2000). Due to the high SEC in some samples, dilutions were required prior to metal analysis. As a result, for a number of elements the detection limits were higher than ANZECC/ARMCANZ environmental guideline values.

Table 3-2 Summary of contaminant and metalloid dynamics data

Parameter	units	ANZECC Guidelines	Ramco Lagoon		
			Min.	Median	Max.
pH		6.5-8.0	5.1	6.7	7.6
EC*	$\mu\text{S cm}^{-1}$	2200	3365	5700	9865
Eh	mV	-	54	277	344
Ag	$\mu\text{g l}^{-1}$	0.05	<0.01	<0.02	<0.08
Al ^A	mg l^{-1}	0.055	<0.05	<0.25	<0.25
As ^B	$\mu\text{g l}^{-1}$	13	<2	<6	31
Cd	$\mu\text{g l}^{-1}$	0.2	<0.02	<0.5	<0.60
Co	$\mu\text{g l}^{-1}$	2.8	<0.02	<0.1	0.36
Cr ^C	$\mu\text{g l}^{-1}$	1	0.20	0.75	2.0
Cu ^H	$\mu\text{g l}^{-1}$	1.4	<1.0	<2.0	6.0
Fe ^I	mg l^{-1}	0.3	<0.10	<0.50	<0.50
Mn	$\mu\text{g l}^{-1}$	1700	<2	12	1896
Ni ^H	$\mu\text{g l}^{-1}$	11	0.40	0.71	1.8
Pb ^H	$\mu\text{g l}^{-1}$	3.4	<0.06	<8.0	<8.0
Sb	$\mu\text{g l}^{-1}$	9	<1.0	<7.0	<40
Se	$\mu\text{g l}^{-1}$	11	<0.3	0.73	1.8
V	$\mu\text{g l}^{-1}$	6	<0.35	3.0	13
Zn ^H	$\mu\text{g l}^{-1}$	8	<0.80	3.0	13

Exceeded ANZECC Guideline (x1)

Exceeded ANZECC Guideline (x10)

Exceeded ANZECC Guideline (x100)

Notes.

The ANZECC guideline values for toxicants refer to the Ecosystem Protection – Freshwater Guideline for protection of 95% of biota in 'slightly-moderately disturbed' systems, as outlined in the Australian Water Quality Guidelines for Fresh and Marine Water Quality (ANZECC/ARMCANZ 2000).

* ANZECC water quality upper guideline ($125\text{-}2200 \mu\text{S cm}^{-1}$) for freshwater lowland rivers in South-east Australia is provided for salinity (there are currently no trigger values defined for 'Wetlands').

^A Guideline is for Aluminium in freshwater where pH > 6.5.

^B Guideline assumes As in solution as Arsenic (AsV).

^C Guideline is for Chromium is applicable to Chromium (CrVI) only.

^H Hardness affected (refer to Guidelines).

^I Fe Guideline for recreational purposes

The pH of the soil materials were very similar, and were slightly acidic to neutral on day 1 and all were circumneutral by day 35 (Figure 3-1). One sample decreased in pH on day 7, before increasing again up to day 35 (Figure 3-1).

The Eh generally showed a decrease over the day 35 period in all samples, from relatively oxidising initially on day one (Figure 3-1). The decrease in Eh was different for the samples from the two profiles, with profile 8 becoming more reducing than profile 6. The Eh values in both, however, are such that iron (Fe) is not soluble. Salinities, as indicated by the SEC, were variable but moderately high and all were above the upper limit for upper ANZECC/ARMCANZ environmental protection guideline ($125\text{-}2200 \mu\text{S cm}^{-1}$) for freshwater lowland rivers in south-east Australia. The highest SEC values were in the surface layers (Figure 3-1).

Iron (Fe) was below detection limit in all samples. The detection limits were relatively high ($<0.5 \text{ mg l}^{-1}$) for some samples, and above the ANZECC/ARMCANZ environmental protection guideline value of 0.3 mg l^{-1} . Manganese (Mn) concentrations were generally low, but above the ANZECC/ARMCANZ environmental protection guideline value for the most reducing sample 12046_8.1 (Figure 3-2). The data for manganese (Mn) and iron (Fe) are consistent with the slightly oxidising to slightly reducing conditions.

Aluminium (Al) concentrations were below detection limit in all samples, although the detection limit was high ($<0.25 \text{ mg l}^{-1}$) for most samples (Figure 3-1). Arsenic (As) displayed a clear increase in concentrations over time in all samples (Figure 3-1). For three samples, the concentrations remained below the ANZECC/ARMCANZ environmental protection guideline value, with the rate of increase falling after day 14. Arsenic (As) increased above the ANZECC/ARMCANZ environmental protection guideline value in the sub-surface soil sample 12046_8.2 on day 35 (Figure 3-1).

Cobalt (Co), nickel (Ni) and selenium (Se) were less than the ANZECC/ARMCANZ environmental protection guideline values (Figure 3-2 and Figure 3-3). Vanadium was below the ANZECC/ARMCANZ environmental protection guideline value in one profile (12046_8), and higher in the second (12046_6), mainly after day 14. Most other metals were present at very low concentrations (Figure 3-2 and Figure 3-3), although for a number of these, detection limits were slightly above the ANZECC/ARMCANZ environmental protection guideline value, due to a requirement to dilute samples prior to analysis. The latter included silver (Ag), aluminium (Al), cadmium (Cd), iron (Fe), lead (Pb) and antimony (Sb).

The magnitude of metal mobilisation is affected by many factors that include but are not exclusive to: 1) the abundance and form of metal and metalloid contaminants; 2) the abundance and lability of organic matter; 3) the abundance and reactivity of iron minerals; 4) availability of sulfate; 5) acid/alkalinity buffering capacity; 6) pH; 7) EC; 8) clay content; 9) microbial activity; 10) temperature; and 11) porosity (MDBA 2010). The relationship with pH for metals and metalloids showed no consistent behaviour due largely to the very low concentrations. However, there was a tendency for higher concentrations at high pH.

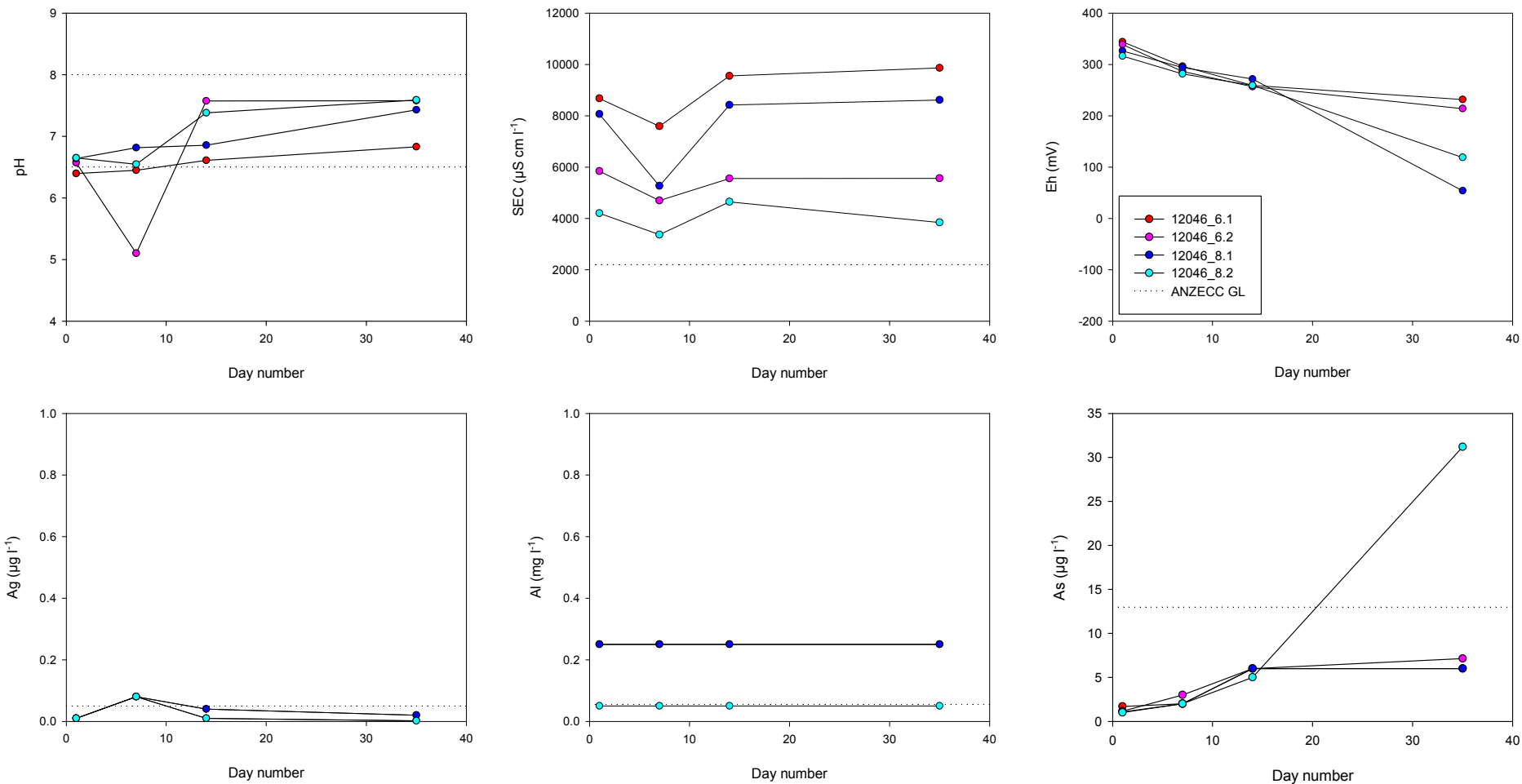


Figure 3-1 Contaminant and metalloid dynamics results for Ramco Lagoon (12046) soil materials for pH, SEC, Eh, silver (Ag), aluminium (Al) and arsenic (As).

Note: silver (Ag) and aluminium (Al) were all < detection limit, data represent detection limits which vary according to required dilutions.

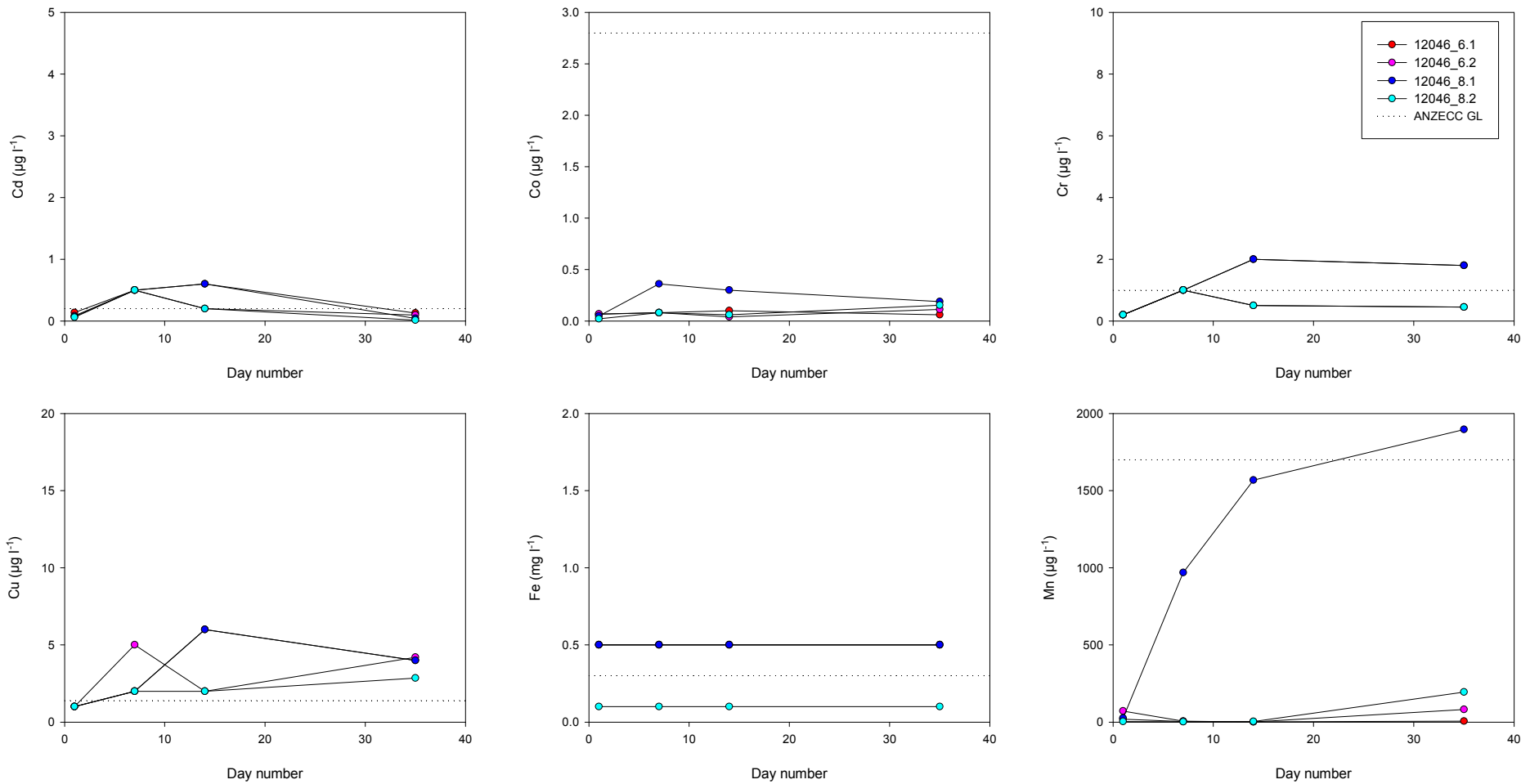


Figure 3-2 Contaminant and metalloid dynamics results for Ramco Lagoon (12046) soil materials for cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe) and manganese (Mn).

Note: cadmium (Cd) and iron (Fe) were all < detection limit, data represent detection limits which vary according to required dilutions.

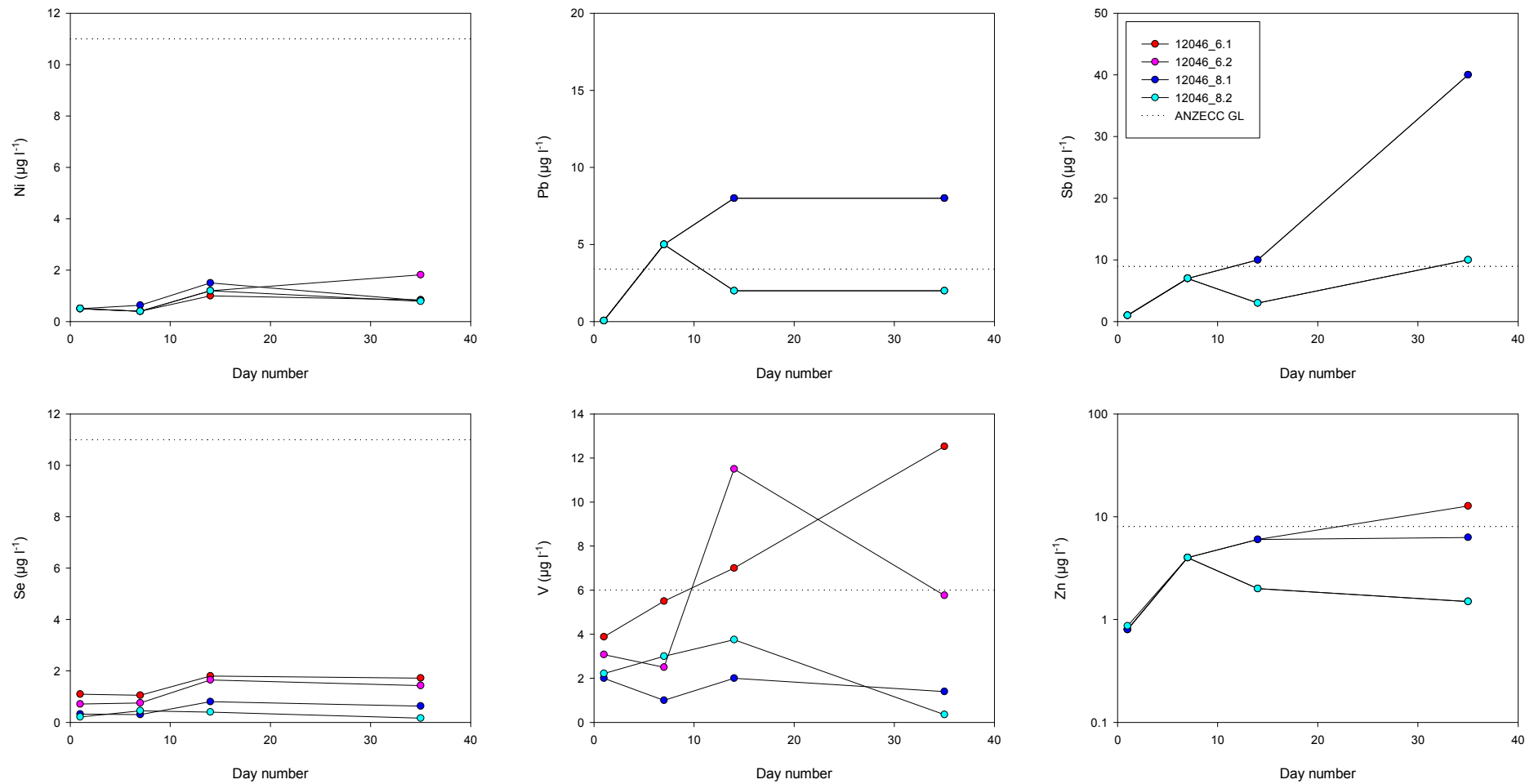


Figure 3-3 Contaminant and metalloid dynamics results for Ramco Lagoon (12046) soil materials for nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), vanadium (V) and zinc (Zn).

Note: lead (Pb) and antimony (Sb) were all < detection limit, data represent detection limits which vary according to required dilutions.

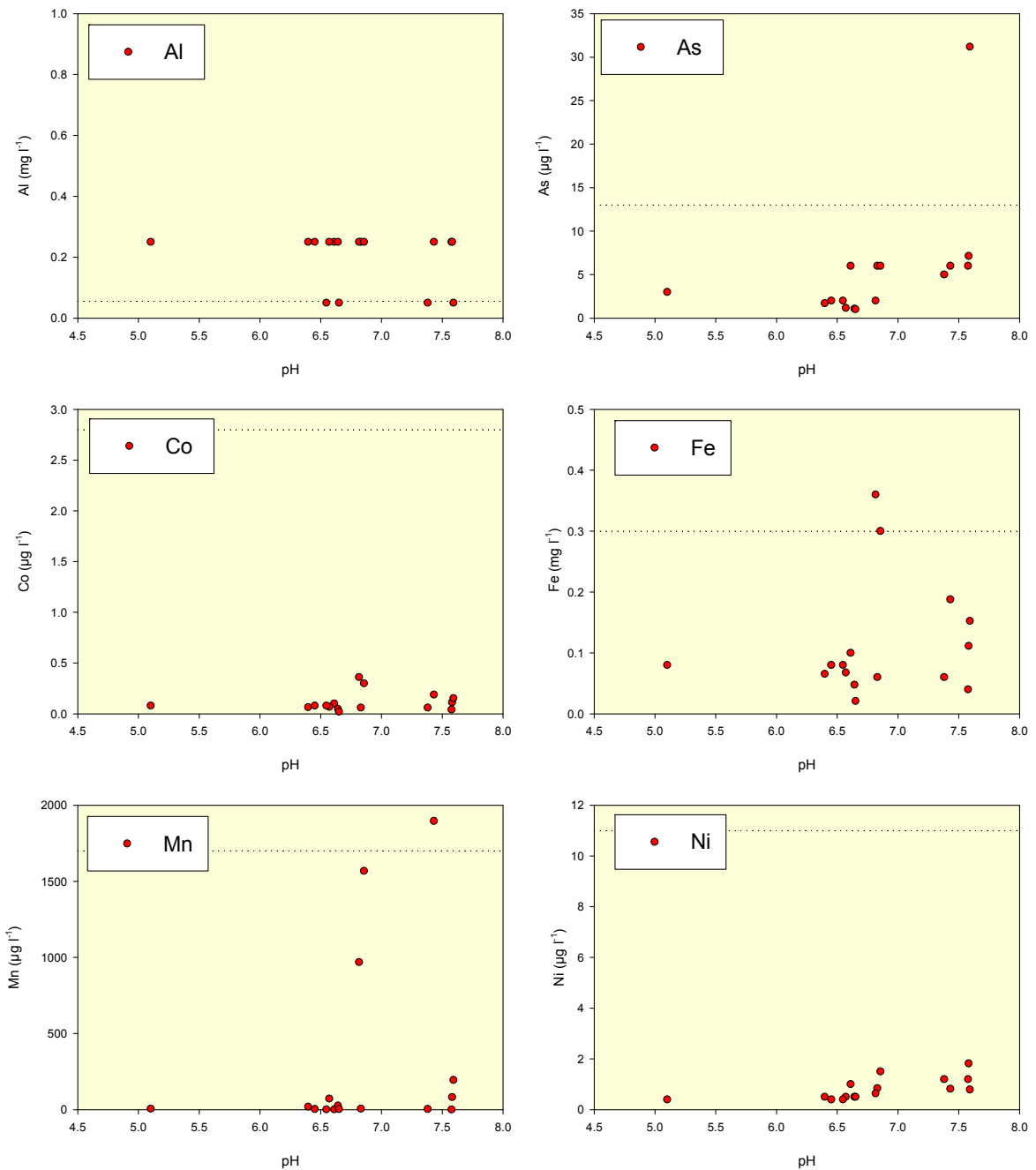


Figure 3-4 Selected trace elements plotted against pH.

3.1.3. Monosulfide formation potential data

No samples were selected from this wetland for monosulfide formation potential studies, as monosulfidic black ooze was identified previously at this site. As the wetland was drier than previous visits, monosulfidic black ooze was not as extensive, but formed a very thin layer beneath algal mats in some areas.

3.1.4. Mineral identification by x-ray diffraction

No surface mineral efflorescences were identified or sampled at this wetland during the Phase 1 field survey.

3.2. Interpretation and discussion of results

The reactive metals and contaminant and metalloid dynamics tests undertaken as part of this Phase 2 assessment assist in determining the impacts on water quality by simulating the release of metal and metalloid concentrations that may occur under saturated conditions.

The 24 hour **reactive metals** studies provide an indication of those metals and metalloids which are more strongly bound to minerals (or weakly soluble with an acid extraction), and thus have the potential to be released. The use of a moderately strong acid (HCl) should provide an indication of “stored metals” and metalloids associated with iron (Fe) and manganese (Mn) oxides and organic materials as well as acid soluble minerals. It is commonly found that the concentrations of metals and metalloids released using extractions are much higher than those found in solution (Goody *et al.* 1995). Although guideline values exist for soils and sediments, these are generally for total soil concentrations, and therefore, are not directly appropriate for the data from metal mobilisation studies. Nevertheless, they provide a basis for comparison; and concentrations close to or above guideline values indicate an elevated hazard.

The metal and metalloid concentrations, except for manganese (Mn), were below sediment quality guidelines and soil ecological investigation level values (Table 3-1). Concentrations, for which guideline values are available, were all below sediment quality guidelines and ecological investigation levels (EIL) for the other elements. Nevertheless, the concentrations of many metals are sufficiently high (mg kg^{-1}) compared to water quality guidelines (generally $\mu\text{g kg}^{-1}$) that significant release could pose a hazard to soil and surface water quality.

The **contaminant and metalloid dynamics** test was designed to determine the release of metals and metalloids in soils. The data represent the availability of metals and metalloids from a weak extraction (water, and thus easily bioavailable) of saturated soils, and for dry wetland soils (especially below Lock 1), those easily mobilised from mineral surfaces and readily soluble mineral phases (such as salts). The exercise was undertaken in a batch process for time periods of 1 day, 7 days, 14 days and 35 days. This approach was aimed at understanding changes in concentrations over time. This is particularly important for dried soils which have been in contact with the atmosphere. The soil materials and the release/uptake of metals/metalloids are expected to change as the chemical environment changes from oxidising to reducing. Typical changes would be a reduction in redox potential (Eh), providing sufficient organic matter or other reducing agents are present, and an increase in pH (providing the soils contain or have the capacity to generate acid neutralising agents). The data can be compared to existing water quality guidelines, although care should be taken when extrapolating to surface waters without knowledge of hydrological conditions and natural chemical barriers. The impact on surface waters will be governed by the upward chemical flux which is a function of soil type, water flow, diffusion and the chemistry of the soils near the sediment-water interface. The mobility of most metals is commonly related to the stability of iron (Fe) and manganese (Mn) minerals. Under oxidising conditions iron (Fe) and manganese (Mn) oxide minerals are important sorbents for trace metals, whilst under very reducing conditions they may be incorporated into sulfide minerals. However, under moderately reducing conditions i.e. during the transition (suboxic) from oxidising to reducing conditions, iron (Fe) and manganese (Mn) are soluble and this is the period where metals may be released into solution and pose the greatest hazard.

The soils had a slightly acidic to circumneutral pH on day one of the contaminant and metalloid dynamics tests, and by day 35 the pH was within the ANZECC/ARMCANZ environmental protection guideline values for all samples. For one sample, there was a

decrease in pH (to pH 5.47) on day 7 of the tests (Figure 3-1). However, this was only seen in one of the two duplicates and may be due to sample heterogeneity e.g. a localised enrichment in sulfide. The samples are generally very well buffered with high ANC (Grealish *et al.* 2010). It appears that the pH was not low enough to allow iron (Fe) to become soluble due to high Eh. The limited change in Eh towards more reducing conditions in most samples may be related to insufficient organic matter, but there is insufficient data to test this. Only one sample decreased sufficiently to allow manganese (Mn) to become soluble, but not sufficient for iron (Fe) to increase. The indications from the reactive metals data is that there is sufficient iron (Fe) and manganese (Mn) available for dissolution under the right pH-Eh conditions. The hazards from metal and metalloids may thus not yet be apparent in these soils with a 35 day test. Nevertheless, the concentrations of most metals were low. The main hazards appear to be for arsenic (As) and manganese (Mn).

The degree to which samples exceed guideline concentrations has been used to assign a degree of hazard (Table 3-3). The data are consistent with the generally low (and often negative) net acidities noted by Grealish *et al.* (2011) which suggest that these shallow soils will take little time to recover in terms of any acidification. This appears to be largely confirmed in the contaminant and metalloid dynamics experiments where most samples reached circumneutral to slightly alkaline pH during the experiments (Figure 3-1). The higher pH will limit the solubilities of most trace metals, and the concentrations in this study suggest that mobilisation will be limited and of short duration at the circumneutral pH of most samples. The main risk will be related to how quickly reducing conditions are achieved and maintained in the soils. Manganese (Mn) was above the ANZECC/ARMCANZ environmental protection guideline value on days 7-35 in the most reducing sample, but iron (Fe) remained below detection limit, therefore continued reducing conditions may lead to further release of a number of metals and metalloids to solution. At higher pH, the metalloids identified as a hazard in this study (arsenic and vanadium) may be stable due to limited adsorption of oxyanions at high pH. These metalloids may dissolve over longer timescales, at least until very reducing conditions in the field of iron sulfide stability, in which case they may be scavenged by precipitating iron (Fe) sulfides.

Table 3-3 Summary of the degree of hazard associated with the measured contaminant and metalloid concentrations in Ramco Lagoon (12046).

Degree of Hazard	Guideline Threshold	Metal/Metalloid
No Hazard	Value below ANZECC/ARMCANZ guideline threshold	Co, Ni, Se
Low Hazard	Value exceeds ANZECC/ARMCANZ guideline threshold, but is less than 10x exceedance	As, Cr, Cu, Mn, V, Zn
Moderate Hazard	Value exceeds ANZECC/ARMCANZ guideline threshold by 10x or more, but is less than 100x exceedance	
High Hazard	Value exceeds ANZECC/ARMCANZ guideline threshold by 100x or more	

Note: Ag, Al, Cd, Fe, Pb and Sb were all below detection limits due to dilutions, and are therefore likely to be in the low or no hazard classification.

The monosulfide formation potential test assists in determining the propensity for monosulfides to form during future inundation. Water soluble sulfate concentrations were high in the wetland (596 to 41849 mg kg⁻¹). Monosulfidic black ooze was identified in the wetland in the past under more saturated conditions, and as a very thin layer (not analysed) beneath algal mats in Phase 1 of the project for Ramco Lagoon (12046), and therefore, the tests were not required to be completed during Phase 2. There are no acid volatile sulfide analyses available hence it was not possible to determine a hazard (

Table 3-4).

Table 3-4 Guideline thresholds for the degree of hazard associated with acid volatile sulfide (S_{AV}) concentrations.

Degree of Hazard	Guideline Threshold
No Hazard	< 0.01 % S_{AV}
Low Hazard	0.01 % S_{AV}
Moderate Hazard	>0.01 – 0.05 % S_{AV}
High Hazard	> 0.05 % S_{AV}

4. RISK ASSESSMENT

4.1. Risk assessment framework

Risk is a measure of both the consequences of a hazard occurring, and the likelihood of its occurrence (MDBA 2011). According to the National Environment Protection Measures (NEPM), risk is defined as "*the probability in a certain timeframe that an adverse outcome will occur in a person, a group of people, plants, animals and/or the ecology of a specified area that is exposed to a particular dose or concentration of a hazardous agent, i.e. it depends on both the level of toxicity of hazardous agent and the level of exposure*" (NEPC 1999).

The MDB Acid Sulfate Soils Risk Assessment Project developed a framework for determining risks to wetland values from acid sulfate soil hazards (MDBA 2011). The risk assessment framework has been applied in this study to determine the specific risks associated with acidification, contaminant mobilisation and de-oxygenation. In this risk assessment framework, a series of standardised tables are used to define and assess risk (MDBA 2011). The tables determine the consequence of a hazard occurring (Table 4-1), and a likelihood rating for the disturbance scenario for each hazard (Table 4-2). These two factors are then combined in a risk assessment matrix to determine the level of risk (Table 4-3).

Table 4-1 determines the level of consequence of a hazard occurring, ranging from insignificant to extreme, and primarily takes account of the environmental and water quality impacts, to the wetland values and/or adjacent waters.

Table 4-1 Standardised table used to determine the consequences of a hazard occurring, from MDBA (2011).

Descriptor	Definition
Extreme	Irreversible damage to wetland environmental values and/or adjacent waters; localised species extinction; permanent loss of drinking water (including stock and domestic) supplies.
Major	Long-term damage to wetland environmental values and/or adjacent waters; significant impacts on listed species; significant impacts on drinking water (including stock and domestic) supplies.
Moderate	Short-term damage to wetland environmental values and/or adjacent waters; short-term impacts on species and/or drinking water (including stock and domestic) supplies.
Minor	Localised short-term damage to wetland environmental values and/or adjacent waters; temporary loss of drinking water (including stock and domestic) supplies.
Insignificant	Negligible impact on wetland environmental values and/or adjacent waters; no detectable impacts on species.

Table 4-2 determines the likelihood (i.e. probability) of disturbance for each hazard, ranging from rare to almost certain. This requires an understanding of the nature and severity of the materials (including the extent of acid sulfate soil materials, the acid generating potential and the buffering capacity of wetland soil materials) as well as contributing factors influencing the risk (MDBA 2011). Examples of disturbance include: (i) rewetting of acid sulfate soil materials

after oxidation, (ii) acid sulfate soil materials that are currently inundated and may be oxidised, or (iii) acid sulfate soil materials that are currently inundated and may be dispersed by flushing (e.g. scouring flows) (MDBA 2011). As mentioned previously, the consequence of a hazard occurring and the likelihood rating for the disturbance scenario for each hazard are then ranked using a standardised risk assessment matrix (Table 4-3).

Table 4-2 Likelihood ratings for the disturbance scenario, from MDBA (2011).

Descriptor	Definition
Almost certain	Disturbance is expected to occur in most circumstances
Likely	Disturbance will probably occur in most circumstances
Possible	Disturbance might occur at some time
Unlikely	Disturbance could occur at some time
Rare	Disturbance may occur only in exceptional circumstances

Table 4-3 Risk assessment matrix, adapted from Standards Australia & Standards New Zealand (2004).

Likelihood category	Consequences category				
	Extreme	Major	Moderate	Minor	Insignificant
Almost certain	Very High	Very High	High	Medium	Low
Likely	Very High	High	Medium	Medium	Low
Possible	High	High	Medium	Low	Low
Unlikely	High	Medium	Medium	Low	Very low
Rare	High	Medium	Low	Very low	Very low

It is suggested that:

- For very high risk immediate action is recommended.
- For high risk senior management attention is probably needed.
- Where a medium risk is identified management action may be recommended.
- Where the risk is low or very low, routine condition monitoring is suggested.

These categories of management responses have been kept quite broad to acknowledge that jurisdictional authorities and wetland managers may choose to adopt different approaches in dealing with acid sulfate soils. The imprecise nature of these management responses is intended to provide flexibility in jurisdictional and wetland manager responses to the risk ratings associated with the acid sulfate soil hazards (MDBA 2011).

4.2. Assessment of risks

Realisation of the main risks associated with acid sulfate soil hazards (acidification, contaminant mobilisation and deoxygenation) is highly dependent on transport and therefore on the surface and sub-surface hydrology. The risks are thus scenario dependent, and difficult to quantify without predicted changes of water flows and inputs and hydrogeological controls.

The consequences of a hazard, as outlined in Table 4-1, relate to reversible or irreversible damage to wetland values. Few studies have documented in sufficient detail the short or long term damage to inland wetland ecosystems and values caused by acid sulfate soil hazards, but short term consequences have been clearly illustrated e.g. for water quality and ecosystem impacts (McCarthy *et al.* 2006; Shand *et al.* 2010). Irreversible damage is difficult to assess due to lack of sufficient data over longer timescales and lack of knowledge, for example, on sub-surface soil recovery and metal mobilisation impacts on benthic organisms. Nevertheless, the following sections detail the hazards and likelihood of a number of scenarios and discuss consequences based on limited previous work (e.g. McCarthy *et al.* 2006; Shand *et al.* 2010). The risks to soil water quality and surface water quality are necessarily different. The risks to soil water quality in terms of acidification and contaminant release are easier to assess from the tests carried out in this study than the risks posed to surface water quality. The impacts on surface water quality will be largely controlled by upward flux of acidity and metals from the soils and sediments into the water column. This will be controlled by *inter alia* surface water volume and groundwater connectivity and level, soil type, hydraulic conductivity and degree and depth of soil cracking.

Ramco Lagoon (12046) has been classified as high conservation status by the SA Murray-Darling Basin Natural Resources Management Board (Miles *et al.* 2010).

4.2.1. Risks associated with acidification

The variable net acidities in the shallow samples from Ramco Lagoon (12046) studied here (-1360 to -316 mol H⁺/tonne) and overall in the wetland (-2280 to 99 mol H⁺/tonne; Grealish *et al.* 2010) suggest that the overall acidification hazard is likely to be minimal. Furthermore, the ageing of soils during Phase 1 showed that the all soil materials showed little change in pH (8 week incubation range was pH 5.27 to 8.26), and only two samples were less than pH 6. The acidification hazard is therefore, considered to be very low.

The wetland was largely dry when the samples were collected, with very shallow pools in the deepest part of the wetland. The wetland is close to the river, separated by shallow banks and an inlet at the north which allows refilling at high river flows. The wetland is managed with structures to control flow. Local rainfall events may also cause local flows of surface water, as indicated by the small pools noted during sampling. The likelihood of disturbance is therefore considered **likely**. The consequences for soil ecology are likely to be minor in the soil layers although the timescale for soil recovery in the surface soils from acidification will probably be quite rapid as indicated in the contaminant and metalloid dynamics experiments. The small changes in pH for most samples noted in the contaminant and metalloid dynamics tests suggests that an **insignificant** rating is best applied for consequence as short-term damage to soil water chemistry is considered likely. Localised decreases in pH may occur in some deeper soils layers, but these are likely to be neutralised by the large store of alkalinity in the wetland soils. This provides a *risk rating for soil acidification* of **low**. A rating for surface water acidification will depend on surface and sub-surface hydrology. The highest risk for acidic soils is likely to be during low flows where the soil to water ratio is high: acidity will be most concentrated. The risk to surface water acidification is considered lowest where high flows are available to both dilute acidity and transport acidity downwards in the soil profile. Surface water acidification is likely to be lower than soil acidification, due to limited transport and buffering reactions at the soil/water interface. In the case of Ramco Lagoon (12046), acidification of surface water is very unlikely, therefore an **insignificant** categorisation is

given for consequence. The *risk to surface water acidification* is therefore likely to range from **low**.

4.2.2. Risks associated with contaminant mobilisation

The risks of metal and metalloid mobilisation are controlled primarily by metal abundance and availability, geochemical controls on speciation and transport mechanisms. The master variables pH and Eh exert a direct major influence on the solubility of individual metals and metalloids and minerals such as iron (Fe), iron (Fe) and manganese (Mn) oxides and hydroxides which are important sorbents of metal and metalloid species. The low acidification hazard due to the oxidation of sulfide minerals means that metals and metalloids are not likely to be present at high concentrations. Reduction processes may lead to reincorporation of metals and metalloids into sulfide minerals (following sulfate reduction), but at intermediate redox potentials mobility may be high where iron (Fe) and manganese (Mn) are soluble. The reactive metals results attest to the limited availability and mobility of a number of metals, the exceptions being manganese (Mn) and to a lesser degree aluminium (Al) and iron (Fe). The concentrations of most metals and metalloids were generally low and below ANZECC/ARMCANZ environmental protection guidelines, an exception being vanadium (V). The oxyanion vanadium (V) increased in some samples throughout the 35 day experiments and should be considered a future hazard. Arsenic (As) and copper (Cu) also increased with time and should be considered for hazards associated with longer timescales. It is not known how long the Eh would continue to decrease, but further decreases would allow the reductive dissolution of iron (Fe) and manganese (Mn) oxyhydroxides and any associated adsorbed metals and metalloids.

Although the timescales cannot be assessed with existing information, the data suggest that metal availability is significant for only a few metals. Comparisons with other studies (e.g. Nelwart Lagoon, Shand *et al.* 2010), suggest that at the pH levels of the surface layers after 35 days of the contaminant and metalloid mobilisation tests, reductive processes may occur rapidly once initiated if there is sufficient organic matter available, and soil recovery may be rapid. The results for Ramco Lagoon (12046), however, indicate that reductive processes are less rapid in comparison with other wetlands with high pH, possibly due to limited organic matter in the samples studied. The main solutes likely to present a hazard are manganese (Mn) and the oxyanion forming metalloids arsenic (As) and vanadium (V). Taking into account the metal and metalloid mobility assessed, a **minor** rating is applied for consequence, due to increasing manganese (Mn) and the oxyanions. Mobilisation of those metals, which typically form cations is likely to be minimal. The minor rating is also partly due to the limited change to reducing conditions in the contaminant and metalloid dynamics experiments as this may be due to the short timescale over which experiments were conducted e.g. slow kinetics, lack of organic matter. This provides a risk rating for contaminant mobilisation in soils of **medium** (Table 4-4).

A rating for surface water impacts from metals and metalloids will depend on surface and sub-surface hydrology. The circumneutral pH values by day 35 in the contaminant and metalloid dynamics tests undertaken in this study, however, means that longer term impacts are unlikely. As with the soil pore-water risks, those for surface waters are likely to relate to the oxyanions arsenic (As) and vanadium (V), and also manganese (Mn). Chemical reactions with soils and interactions at the soil/water interface are likely to diminish hazards from upward soil metal flux. The highest risk is likely to be during low flows where the soil to water ratio is high: metals will be most concentrated. The risk to surface metal and metalloid flux is considered lowest where high flows are available to both dilute metal and metalloid concentrations and transport these downwards in the soil profile. Due to enhanced mobility of metalloids at higher pH, the hazard cannot be assumed to be insignificant with the limited time series data available in this study, hence a **minor** rating for consequence is applied. The risk to surface waters from metal mobilisation is therefore considered to be **medium** (Table 4-4). The Phase 1 study sampled two soil pit-waters and noted high concentrations above ANZECC/ARMCANZ environmental protection guidelines for the nutrients ammonium (NH₄) and phosphate (PO₄) as well as high manganese (Mn), cobalt (Co) and zinc (Zn).

4.2.3. Risks associated with de-oxygenation

Monosulfidic materials are considered the main cause of deoxygenation risk in acid sulfate soils. The water soluble sulfate concentrations in the sample were high and above the trigger value for monosulfidic black ooze formation (MDBA 2010). A monosulfide formation potential test was not undertaken for Ramco Lagoon (12046) as monosulfidic black ooze had been identified during the earlier Phase 1 assessments.

The risk of deoxygenation is most significant if the surface soils are disturbed and the soils have a consistency that will allow rapid movement and transport to areas of high value. Ramco Lagoon (12046) is separated from the River Murray in places by a shallow bank and any risks are therefore not limited to the wetland itself, but also to the river channel. However, the wetland is managed and this may lessen the risks if the banks are not overtopped during large floods. The consequence of deoxygenation is considered to be **moderate** as disturbance may lead to short term deoxygenation, particularly if the low density surface monosulfidic soils can be mobilised easily. There may also be a risk during periods of flood to the adjacent river. Taking into account the **likely** likelihood of disturbance and the **moderate** consequence, a risk rating of **medium** is attributed for deoxygenation potential.

Table 4-4 Summary of risks associated with acid sulfate soil materials in Ramco Lagoon (12046).

Acidification Risk		Contaminant mobilisation		Deoxygenation
<i>Soil</i>	<i>Water</i>	<i>Soil</i>	<i>Water</i>	
Low	Low	Medium	Medium	Medium

5. BROAD ACID SULFATE SOIL MANAGEMENT OPTIONS

The options available for rehabilitation of inland waterways containing acid sulfate soils has recently been reviewed (Baldwin & Fraser 2009) and incorporated into the *National guidance on managing acid sulfate soils in inland aquatic ecosystems* (EPHC & NRMMC 2011; see Table 5-1). The national guidance document provides a hierarchy of management options for managing acid sulfate soils in inland aquatic ecosystems including:

1. *Minimising the formation of acid sulfate soils in inland aquatic ecosystems.*
2. *Preventing oxidation of acid sulfate soils, if they are already present in quantities of concern or controlled oxidation to remove acid sulfate soils if levels are a concern but the water and soil has adequate neutralising capacity.*
3. *Controlling or treating acidification if oxidation of acid sulfate soils does occur.*
4. *Protecting connected aquatic ecosystems/other parts of the environment if treatment of the directly affected aquatic ecosystem is not feasible.*
5. *Limited further intervention.*

In designing a management strategy for dealing with acid sulfate soils in affected inland wetlands, other values and uses of a wetland need to be taken into account to ensure that any intervention is compatible with other management plans and objectives for the wetland. The high conservation status for this wetland suggests that the management responses required should align with those suggested following the risk assessment ratings (Table 4-3).

A number of options for treating acid sulfate soils in inland wetlands have been identified (see Table 5-1). By far the best option is not to allow acid sulfate soils to build up in the first instance. This requires removing the source of sulfate from the wetland, for example, by lowering saline water tables and/or introducing frequent wetting and drying cycles to the wetland so that the amount of sulfidic material that can build up in the sediments during wet phases is limited, hence reducing the likely environmental damage (acidification, metal release or deoxygenation) that would occur as a consequence of drying.

If acid sulfate soils have formed, prevention of oxidation, usually by keeping the sediments inundated to sufficient depth, is a potential strategy. If oxidation of acid sulfate soils occurs and the sediment and/or water column acidifies, neutralisation may be necessary.

The medium risks identified in this study are due to contaminant mobilisation and deoxygenation respectively. The likelihood of water refilling the wetland is high as flows return to normal levels. The limited number of case studies on refilling wetlands makes prediction of risk difficult in terms of determining whether reversible or irreversible damage is likely to occur. However, at the pH's observed, the increase in pH over the 35 day period and limited metal mobilisation imply that any risks are likely to be localised in nature. The main risks are associated with the metalloids arsenic (As) and vanadium (V), and also manganese (Mn). However, if more reducing conditions are established in the wetland soils, a number of other metals may be mobilised such as cobalt (Co) and nickel (Ni). The risks are likely to be lower than an unmanaged wetland as control structures are present to help manage any acid sulfate soil associated impacts.

As the wetland had previously dried and undergone oxidation, management options 1 and 2 in Table 5-1 are not relevant to the current study, although minimising further oxidation could have been an option prior to recent high flows down the River Murray. Treatment options currently remain a viable option should water quality impacts involving acidification of surface water and metals seen. The risks with the metalloid oxyanions are more difficult to deal with as they are mobile at high pH. Since the risks are scenario dependent, it is recommended

that surface water monitoring be undertaken at this wetland, particularly because a number of metals and metalloids (arsenic and vanadium) were increasing over the 35 days of the contaminant and metalloid dynamics experiments, and also because the Eh may reduce further with time allowing the reductive dissolution of iron (Fe) and manganese (Mn) oxides/oxyhydroxides and their associated adsorbed metals and metalloids. Based on the data from this study and elsewhere (Shand *et al.* 2010), it is likely that soil recovery from any localised acidification will be relatively rapid as pH is relatively high and increased in experiments in this study over time. The impacts on surface and sub-surface ecosystems are not well understood and are worthy of further work, particularly long term impacts on ecosystem functionality and diversity.

Table 5-1 Summary of management options and possible activities, from EPHC & NRMCC (2011).

Management Objective	Activities
1. Minimising the formation of acid sulfate soils in inland aquatic ecosystems	<p>Reduce secondary salinisation through:</p> <ul style="list-style-type: none"> • Lowering saline water tables • Maintaining the freshwater lens between saline groundwater and the aquatic ecosystem • Stopping the delivery of irrigation return water • Incorporating a more natural flow regime.
2. Preventing oxidation of acid sulfate soils or controlled oxidation to remove acid sulfate soils	<p>Preventing oxidation:</p> <ul style="list-style-type: none"> • Keep the sediments covered by water • Avoid flow regimes that could re-suspend sediments. <p>Controlled oxidation:</p> <ul style="list-style-type: none"> • Assess whether neutralising capacity of the sediments and water far exceeds the acidity produced by oxidation • Assess the risk of deoxygenation and metal release. Monitor intervention and have a contingency plan to ensure avoidance of these risks.
3. Controlling or treating acidification	<ul style="list-style-type: none"> • Neutralise water column and/or sediments by adding chemical ameliorants • Add organic matter to promote bioremediation by micro-organisms • Use stored alkalinity in the ecosystem.
4. Protecting adjacent or downstream environments if treatment of the affected aquatic ecosystem is not feasible	<ul style="list-style-type: none"> • Isolate the site • Neutralise and dilute surface water • Treat discharge waters by neutralisation or biological treatment.
5. Limited further intervention	<ul style="list-style-type: none"> • Assess risk • Communicate with stakeholders • Undertake monitoring • Assess responsibilities and obligations and take action as required.

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APPENDICES

APPENDIX 1 REACTIVE METALS DATA

Ramco Lagoon (12046)

Sample	Depth	Analysis	Ag*	Al	As	Cd*	Co	Cr*	Cu	Fe	Mn	Ni	Pb	Sb*	Se*	V	Zn
12046_6.1	0-5	a	6.5	405	3.2	93	1.4	356	2.9	865	455	2.1	3.1	< 19	93	7.3	4.7
		b	6.5	405	1.7	101	1.4	342	2.5	787	540	2.0	2.7	< 19	105	6.3	4.4
12046_6.2	5-10	a	9.6	506	4.5	181	2.0	288	3.4	1458	440	3.3	1.6	< 21	66	8.7	4.8
		b	13	456	3.3	152	3.0	264	3.4	1402	1093	4.2	2.1	< 21	68	7.9	3.9
12046_8.1	0-5	a	0.78	282	0.62	28	3.3	186	2.2	409	2215	3.1	2.0	< 21	64	4.5	2.8
		b	2.1	293	0.43	18	2.9	187	2.9	528	1453	2.7	1.6	< 21	68	2.5	3.4
12046_8.2	5-10	a	1.9	388	2.7	31	4.0	190	3.6	1099	802	3.2	4.3	< 22	37	9.7	4.3
		b	< 0.28	468	1.9	18	2.5	190	0.69	1138	686	2.1	4.1	< 22	40	8.9	3.3

Units are mg kg⁻¹ unless indicated otherwise as below

* Units are in µg kg⁻¹

< value is below detection limit

APPENDIX 2 CONTAMINANT AND METALLOID DYNAMICS DATA

Ramco Lagoon (12046)

Sample	Day	Depth cm	Analysis	Eh mV	EC µS/cm	pH	Ag µg/L	Al mg/L	As µg/L	Cd µg/L	Co µg/L	Cr µg/L	Cu µg/L	Fe mg/L	Mn µg/L	Ni µg/L	Pb µg/L	Sb µg/L	Se µg/L	V µg/L	Zn µg/L
12046_6.1	1	0-5	a	344	8460	6.45	<0.01	<0.25	1.6	0.09	0.06	<0.2	<1	<0.5	16	<0.5	<0.06	<1	1.1	3.9	<0.8
			b	344	8890	6.34	<0.01	<0.25	1.8	0.19	0.07	<0.2	<1	<0.5	20	<0.5	<0.06	<1	1.1	3.9	<0.8
	7		a	299	6960	6.34	<0.08	<0.25	<2	<0.5	<0.08	<1	<2	<0.5	4.0	<0.4	<5	<7	0.90	4.0	<4
			b	294	8210	6.56	<0.08	<0.25	<2	<0.5	<0.08	<1	<2	<0.5	4.0	<0.4	<5	<7	1.2	7.0	<4
	14		a	254	9560	6.67	<0.04	<0.25	<6	<0.6	<0.1	<2	<6	<0.5	<2	<1	<8	<10	1.6	8.0	<6
			b	264	9550	6.55	<0.04	<0.25	<6	<0.6	<0.1	<2	<6	<0.5	<2	<1	<8	<10	2.0	6.0	<6
	35		a	229	9720	6.72	<0.02	<0.25	<6	0.14	<0.06	<1.8	<4	<0.5	3.2	0.94	<8	<40	1.5	11	19
			b	234	10010	6.94	<0.02	<0.25	<6	0.12	<0.06	<1.8	<4	<0.5	7.0	0.75	<8	<40	1.9	14	<6
12046_6.2	1	5-10	a	334	5700	6.54	<0.01	<0.25	1.0	0.07	0.06	<0.2	<1	<0.5	71	<0.5	<0.06	<1	0.76	2.5	<0.8
			b	344	5980	6.60	<0.01	<0.25	1.3	0.09	0.08	<0.2	<1	<0.5	73	<0.5	<0.06	<1	0.67	3.6	<0.8
	7		a	284	5150	6.50	<0.08	<0.25	2.0	<0.5	<0.08	<1	8.0	<0.5	10.0	<0.4	<5	<7	0.90	3.0	<4
			b	289	4240	3.70	<0.08	<0.25	4.0	<0.5	<0.08	<1	<2	<0.5	<2	<0.4	<5	<7	0.60	2.0	<4
	14		a	254	5550	7.68	<0.01	<0.25	6.0	<0.2	<0.04	<0.5	2.0	<0.5	0.80	0.90	<2	<3	1.5	11	<2
			b	259	5560	7.47	<0.01	<0.25	6.0	<0.2	<0.04	<0.5	2.0	<0.5	1.2	1.5	<2	<3	1.8	12	<2
	35		a	219	5710	7.62	0.00	<0.25	3.9	0.16	0.17	<0.45	3.5	<0.5	162	2.8	<2	<10	1.4	5.6	<1.5
			b	209	5410	7.54	<0.002	<0.25	10	0.04	0.05	<0.45	4.9	<0.5	2.0	0.86	<2	<10	1.5	5.9	<1.5
12046_8.1	1	0-5	a	329	7930	6.64	<0.01	<0.25	1.0	0.08	0.04	<0.2	<1	<0.5	18	<0.5	<0.06	<1	0.33	2.3	<0.8
			b	324	8200	6.64	<0.01	<0.25	1.1	0.06	0.05	<0.2	<1	<0.5	35	<0.5	<0.06	<1	0.31	1.8	<0.8
	7		a	294	6340	6.94	<0.08	<0.25	<2	<0.5	0.56	<1	<2	<0.5	1710	0.80	<5	<7	<0.3	<1	<4
			b	294	4200	6.69	<0.08	<0.25	<2	<0.5	0.16	<1	<2	<0.5	228	0.47	<5	<7	<0.3	<1	<4
	14		a	269	8560	7.13	<0.04	<0.25	<6	<0.6	0.30	<2	<6	<0.5	1566	1.0	<8	<10	0.80	<2	<6
			b	274	8280	6.58	<0.04	<0.25	<6	<0.6	0.30	<2	<6	<0.5	1570	2.0	<8	<10	0.80	<2	<6
	35		a	69	8940	7.39	<0.02	<0.25	<6	0.06	0.21	<1.8	<4	<0.5	2076	0.80	<8	<40	0.76	<1.4	6.6
			b	39	8290	7.47	<0.02	<0.25	<6	<0.02	0.16	<1.8	<4	<0.5	1716	0.84	<8	<40	0.50	<1.4	<6
12046_8.2	1	5-10	a	314	4230	6.70	<0.01	<0.05	1.1	0.06	0.03	<0.2	<1	<0.1	5.7	<0.5	<0.06	<1	0.24	2.5	<0.8
			b	319	4180	6.60	<0.01	<0.05	0.88	0.06	0.01	<0.2	<1	<0.1	2.4	<0.5	<0.06	<1	0.18	1.9	0.93
	7		a	279	3390	6.50	<0.08	<0.05	<2	<0.5	<0.08	<1	<2	<0.1	<2	<0.4	<5	<7	0.60	3.0	<4
			b	284	3340	6.59	<0.08	<0.05	<2	<0.5	<0.08	<1	<2	<0.1	<2	0.40	<5	<7	<0.3	3.0	<4
	14		a	259	4960	7.07	<0.01	<0.05	4.0	<0.2	0.08	<0.5	<2	<0.1	4.8	1.5	<2	<3	0.40	3.0	<2
			b	259	4340	7.69	<0.01	<0.05	6.0	<0.2	<0.04	<0.5	<2	<0.1	2.8	0.90	<2	<3	0.40	4.5	<2
	35		a	119	3690	7.57	<0.002	<0.05	39	<0.02	0.07	<0.45	<1	<0.1	135	0.48	<2	<10	0.16	<0.35	<1.5
			b	119	4000	7.61	<0.002	<0.05	23	0.03	0.23	<0.45	4.7	<0.1	255	1.1	<2	<10	0.16	<0.35	<1.5

< value is below detection limit



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