Management of Acid Sulfate Soils in Wetlands between Blanchetown and Wellington

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Contents

1 Introduction

1.1 Project overview

On behalf of the South Australian Government, the South Australian Murray-Darling Basin Natural Resource Management Board (SA MDB NRM Board) has investigated management options for acid sulfate soils in the wetlands between Lock 1 and Wellington.

The changing conditions from drought to flood in the Murray Darling Basin have influenced the focus and direction of the project. However, it always remained the intention to ensure management options mitigated the risks posed by acid sulfate soils without adversely impacting the ecology and structure of the wetlands.

1.2 Background

1.2.1 Drought

Severe drought from 2006 to 2010 and continued use of water resources decreased River Murray flows into South Australia. As a consequence, water levels in the River Murray below Lock 1 declined such that the majority of the wetlands between Blanchetown (Lock 1) and Wellington permanently inundated at the previous pool level of 0.75 m AHD (Australian Height Datum) were disconnected and dry. Lakes Alexandrina and Albert downstream of Wellington experienced reduced inflows resulting in water level decline, increases in salinity and decreases in water quality.

Acid Sulfate Soils were found to be present in many of the wetlands below Lock 1 as well as Lakes Alexandrina, Albert and their surrounding wetlands. The reduction in water levels exposed these soils to the atmosphere allowing them to oxidise and turn sulfuric. Upon the return of water these sulfuric soils had the potential to acidify the water column and mobilise metals and metalloids from the sediments which could increase concentrations to unsafe levels. If the drought continued and water levels declined further, the severity of the impacts was expected to increase. Some models suggested that at a water level of -1.5 m AHD Lake Alexandrina would acidify. Should this have happened, there was a risk that water driven back up the river channel through wind seiche would not only impact the river but supply poor quality water to South Australian water off takes. This scenario prompted the Government of South Australia to investigate the installation of a temporary weir at Wellington to create a new weir pool to raise water levels between Lock 1 and Wellington and prevent water from Lakes Alexandrina and Albert seiching upstream.

The creation of a new weir pool between Lock 1 and Wellington was complicated further with the exposure of acid sulfate soils in the wetlands along that stretch of the river. There was potential for acidic water, mobilised metals and metalloids from the wetlands to enter the newly created weir pool, impacting the river channel and off-takes. As a consequence, on behalf on the Government of South Australia, the SA MDB NRM board began investigations into management options for acid sulfate soils in the wetlands between Lock 1 and Wellington. Modelling based on worst case scenarios for evaporation and rainfall indicated that water levels would drop to -1.5 m AHD by late 2009, early 2010 and construction of a weir would need to begin by mid-2009.

SA Water Commence to Flow Project

SA water video viewing undertaken on the 22 August 2007 indicated that 25 of the 80 wetlands between Lock 1 and Wellington were still connected to the main river channel at a river level of approximately 0.2 m AHD. Further work identified that these 25 wetlands would be inundated if the proposed weir at Pomanda Island was constructed and operated at a weir pool level of approximately 0.1 m AHD.

SA MDB NRM board commissioned field surveys to measure the cross-sectional and longitudinal sections of the inlets of each of the 25 wetlands to determine the commence-to-flow levels and their connections to the main river channel. The 25 wetlands identified are included in Table 1.1 and are ordered from first to connect to last.

Table 1.1 25 wetlands identified to be reconnect at a river level of 0.1 m AHD

Wetland	Primary Threshold Commence to flow (m AHD)
Wellington Marina	Unknown, remained submerged during drought
Priess Landing	- 0.69
Younghusband West	- 0.62
Lake Carlet	- 0.65
Tailem Bend	- 0.57
Riverglades	- 0.51
Mason Rock	- 0.46
Wongulla Lagoon	- 0.46
Coolcha Lagoon	- 0.45
Devon Downs North	- 0.40
Mannum Swamps	- 0.35
Bow Hill	- 0.33
Henley Park	- 0.27
Salt Bush Flat	- 0.25
Forster Lagoon	- 0.22
Caurnamont	- 0.21
Teal Flat Hut	- 0.19
Lake Bywaters	- 0.17
Teal Flat	- 0.11
Walker Flat South Lagoon	- 0.10
Younghusband	- 0.10
Wellington North	- 0.10
Reedy Creek	- 0.04
Craignook	- 0.02

Murray-Darling Basin acid sulfate soils risk assessment project

In March 2008, the Murray-Darling Basin Ministerial Council agreed to an urgent assessment of acid sulfate soils in key wetlands in the Basin. As a result the Murray Darling Basin Authority undertook the *Murray-Darling Basin Acid Sulfate Soils Risk Assessment* Project to assess the spatial extent of, and risk posed by, acid sulfate soils at priority wetlands in the Murray River system, Ramsar wetlands and other key environmental sites. As part of this project, all wetlands between Lock 1 and Wellington were identified as priority sites that would require detailed acid sulfate soil assessment to be undertaken by CSIRO and Southern Cross University.

A detailed acid sulfate soil assessment involves comprehensive sampling and analysis to assess the extent of acid sulfate soils and any associated risks, including the potential for acidification, deoxygenation, production of gases and metal mobilisation.

There were two phases to the soil analysis, phase 1 identified the acid sulfate soil hazard and phase 2 analysed the metal mobilization and de-oxygenation potential within the soils of the wetlands. This information was used to determine which wetlands required specific water quality monitoring and preparation for management.

1.2.2 Floods in New South Wales and Queensland 2009/2010

In late 2009 the decision on construction of the temporary weir was delayed due to better than worst case scenario winter rainfall and evaporation figures. Modelling at that stage indicated that water levels may fall to -1.5 m AHD in Lake Alexandrina by the end of 2011. However, between November 2009 to February 2010 floods occurred in South Western Queensland and Northern New South Wales. While these floods were expected to fill upstream storages and re-wet the landscape, they were not expected to significantly increase River Murray flows into South Australia. The State Government of South Australia secured some water for environmental flows however and it was expected that 168.3 GL from the northern New South Wales floods would be delivered before the end of June 2010 and an additional flow of up to 400 GL would be delivered from the South Western Queensland floods later on in 2010.

It was predicted that river levels would gradually rise approximately 300 to 500 mm by the end of June 2010, when all of the additional water was delivered. This increase in river levels dictated that acid sulfate soil management options had to be in place for imminent rewetting of some of the wetlands. Assessments on which wetlands would re-wet were made on the assumption of a 300 to 500 mm rise in river levels as well as a seiche height of up to 400 mm, would increase river levels to a maximum of 0 m AHD.

1.2.3 Management options for imminent re-wetting

Based on work already completed on “commence to flow elevations” (AWE, 2009) for the 25 lowest lying wetlands below Lock 1, a list of wetlands was created to show which wetlands would re-wet first with increasing river levels. Up to 25 wetlands were predicted to re-wet in the following order:

- 300 mm rise in river levels to -0.6 m AHD:
    - Wellington Marina (did not dry)
    - Priess Landing (some portions were already wet with no acidification)
    - Younghusband West
    - Lake Carlet
    - Tailem Bend
    - Marks Landing
- 400 mm rise in river levels to -0.5 m AHD:
    - Riverglades
- 500 mm rise in river levels to -0.4 m AHD:
    - Mason Rock
    - Wongalla
    - Coolcha Lagoon
    - Devon Downs North
- 600 mm rise in river levels to -0.3 m AHD:
    - Mannum Swamps
    - Bow Hill

  - Henley Park
- 700 mm rise in river levels to -0.2 m AHD:
  - Saltbush Flat
  - Caurnamont
  - Forster Lagoon
  - Teal Flat Hut
  - Lake Bywaters
- 800 mm rise in river levels to -0.1 m AHD:
  - Teal Flat
  - Walker Flat South Lagoon
  - Younghusband
  - Wellington North
- 900 mm rise in river levels to 0 m AHD:
  - Reedy Creek
  - Craignook

Using bathymetry created from surveys undertaken while wetlands were dry, surface areas and volumes were calculated for various river levels. Table 1.2 summarises estimated volumes and surface areas of water present in the wetlands at various river levels and compares those to the volumes and surface areas within the river and floodplain. It demonstrated:

- With exception of Lake Carlet, very few wetlands would have a significant volume of water enter with a 300 mm rise in river levels to -0.6 m AHD
- Even at higher river levels, the volume of water contained within the re-wet wetlands would be significantly less than that contained within the river channel, less than 1% in most instances
- The effects of wind seiche might be more pronounced with some wetlands receiving over 100 ML of water during a seiche of 400 mm increasing river levels to 0 m AHD.

It was estimated that with predicted river levels, many of the wetlands would only experience small volumes spread over small to moderate areas of wetland. It was likely to leave them with mud flats and disconnected pools of water. This was potentially a worst case scenario for individual wetlands; not enough water to inundate the soils completely and stop oxidation, but enough to produce acidic water and mud.

There was also concern over seiche events. The “ebb and flow” of seiching events exchanging 100 ML or more of water between the river and wetland had the potential to introduce acidic water and mobilised metals into the river channel. Considering the strong flow velocities likely within the river channel during the delivery of additional water, it was thought unlikely that these wetlands contained enough water to impact water quality in the river channel. Mixing, dilution and neutralisation was likely to occur rapidly as the water from the wetland entered the river channel. Should a wetland acidify, it was likely that pH and concentrations of metals would exceed water quality guidelines for freshwater ecosystems within the wetland itself, but would be quickly neutralised with mobilised metals precipitated out as the wetland water entered the river channel. The fate of precipitated metals was uncertain as they may still be bio-available once released from the soil matrix and precipitated, particularly to benthic organisms living and feeding amongst the precipitates.

Table 1.2 Summary of estimated surface areas and volumes of water within wetlands at various river levels

Wellington to Murray Bridge

River & floodplain			Wellington North*		Tailem Bend (-0.57)			Mason Rock (-0.46)*		Wetlands		Ratio	
River Level (m AHD)	Area (Ha)	Volume (ML)	Area (Ha)	Vol (ML)	Area (Ha)	Vol (ML)	Depth (m)	Area (Ha)	Vol (ML)	Total Area (Ha)	Total Vol (ML)	Surface Area (%)	Volume (%)
-0.6	843.45	69523.94	0.03	0.10	13.30	15.00	0.34	0.13	0.49	13.46	15.59	1.60	0.02
-0.5	846.12	70368.66	0.03	0.13	21.83	32.00	0.44	0.13	0.62	22.00	32.76	2.60	0.05
-0.4	848.88	71216.17	0.03	0.17	31.75	59.00	0.54	0.14	0.76	31.92	59.93	3.76	0.08
-0.3	851.77	72066.61	0.03	0.20	40.12	95.00	0.64	0.15	0.90	40.30	96.10	4.73	0.13
-0.2	857.92	72920.91	0.04	0.24	47.45	139.00	0.74	0.68	1.31	48.17	140.55	5.61	0.19
-0.1	861.48	73780.66	0.04	0.27	52.58	189.00	0.84	0.79	2.05	53.41	191.32	6.20	0.26
0	865.62	74644.24	0.04	0.31	56.45	244.00	0.94	0.90	2.89	57.39	247.21	6.63	0.33
0.1	873.53	75513.74	0.04	0.36	59.92	302.00	1.04	1.04	3.86	61.00	306.22	6.98	0.41

Murray Bridge to Mannum

River & floodplain			Riverglades (-0.51)*		Reedy Creek (-0.04)*		Wetlands		Ratio	
River Level (m AHD)	Area (Ha)	Volume (ML)	Area (Ha)	Vol (ML)	Area (Ha)	Vol (ML)	Total Area (Ha)	Total Vol (ML)	Surface Area (%)	Volume (%)
-0.6	646.96	52947.94					0.00	0.00	0.00	0.00
-0.5	648.39	53595.39					0.00	0.00	0.00	0.00
-0.4	649.89	54244.39					0.00	0.00	0.00	0.00
-0.3	651.46	54894.89					0.00	0.00	0.00	0.00
-0.2	653.15	55547.03	0.00	0.00			0.00	0.00	0.00	0.00
-0.1	655.01	56200.99	0.14	0.07			0.15	0.08	0.02	0.00
0	657.43	56857.03	4.44	2.37	0.01	0.01	4.45	2.38	0.68	0.00
0.1	660.99	57515.88	13.48	11.33	0.13	0.08	13.61	11.41	2.06	0.02

Mannum to Walker's Flat

River & floodplain			Mannum Swamps (-0.35)			Younghusband West (-0.62)			Younghusband (-0.10)			Teal Flat (-0.11)*		Teal Flat Hut (-0.19)*		Lake Carlet (-0.65)^		Coolcha Lagoon (-0.45)			Bow Hill (-0.33) *		Craignook (-0.02)*		Saltbush Flat (-0.25)*		Caurnamont (-0.21)*		Walker Flat South (-0.10)			Wetlands	
River Level (m AHD)	Area (Ha)	Volume (ML)	Area (Ha)	Vol (ML)	Depth (m)	Area (Ha)	Vol (ML)	Depth (m)	Area (Ha)	Vol (ML)	Depth (m)	Area (Ha)	Vol (ML)	Area (Ha)	Vol (ML)	Area (Ha)	Vol (ML)	Area (Ha)	Vol (ML)	Depth (m)	Area (Ha)	Vol (ML)	Area (Ha)	Vol (ML)	Area (Ha)	Vol (ML)	Area (Ha)	Vol (ML)	Area (Ha)	Vol (ML)	Depth (m)	Total Area (Ha)	Total Vol (ML)
-0.60	901.57	59464.63	15.90	19.49	0.26	4.30	2.49	0.58																0.32	0.35	0.06	0.04			0.01	0.00	0.01	20.60	22.36
-0.50	903.73	60367.03	24.40	39.00	0.36	12.80	10.00	0.68	0.04	0.01	0.04					194.76	355.08						3.31	2.17	0.21	0.18			1.90	0.68	0.11	42.66	52.03
-0.40	905.97	61271.64	34.20	68.00	0.46	25.70	30.00	0.78	0.30	0.18	0.14							0.07	0.00	0.05			7.71	7.67	0.46	0.51	0.13	0.13	5.80	4.45	0.21	74.37	110.94
-0.30	908.31	62178.63	46.90	109.00	0.56	39.30	62.00	0.88	0.50	0.58	0.24							8.82	3.20	0.15			9.40	16.23	0.87	1.18	18.02	1.09	9.40	12.00	0.31	133.23	205.28
-0.20	910.79	63087.93	63.80	164.00	0.66	51.20	108.00	0.98	0.74	1.19	0.34	0.04	0.03	0.01	0.01			30.05	23.00	0.25			10.95	26.41	1.28	2.26	67.17	5.35	14.50	24.00	0.41	239.87	354.35
-0.10	913.49	63999.86	91.30	240.00	0.76	60.80	164.00	1.08	1.10	2.09	0.44	1.16	0.63	0.06	0.04			42.10	59.00	0.35			12.90	38.34	1.77	3.78	18.23	17.83	26.70	44.00	0.51	256.69	570.16
0.00	916.72	64914.68	127.80	349.00	0.86	71.50	230.00	1.18	1.70	3.43	0.54	11.36	6.89	0.14	0.14			58.58	110.00	0.45	0.97	1.16	15.05	52.32	2.55	5.94	28.66	41.27	41.60	78.00	0.61	361.93	879.89
0.10	921.20	65833.30	152.40	492.00	0.96	84.10	307.00	1.28	2.90	5.65	0.64	32.94	29.04	0.70	0.56	270.50	1685.80	78.90	178.00	0.55	8.46	5.88	17.93	68.81	4.42	9.43	37.99	74.60	54.20	126.00	0.71	480.78	1302.62

Walker's Flat to Swan Reach

River & floodplain			Lake Bywaters (-0.17)			Forster Lagoon (-0.22)			Wongulla (-0.46)			Devon Downs North (-0.40)*		Priess Landing (-0.69)			Henley Park (-0.27)			Marks Landing (-0.60)			Wetlands		Ratio	
River Level (m AHD)	Area (Ha)	Volume (ML)	Area (Ha)	Vol (ML)	Depth m	Area (Ha)	Vol (ML)	Depth m	Area (Ha)	Vol (ML)	Depth (m)	Area (Ha)	Vol (ML)	Area (Ha)	Vol (ML)	Depth (m)	Area (Ha)	Vol (ML)	Depth (m)	Area (Ha)	Vol (ML)	Depth (m)	Total Area (Ha)	Total Vol (ML)	Surface Area (%)	Volume (%)
-0.6	619.67	25969.83	0.01	0.01	0.17	13.30	15.00	0.34	0.08	0.04	0.14			0.50	0.74	0.32	2.50	2.00	0.39	3.20	1.01	0.25	19.59	18.80	3.16	0.07
-0.5	621.32	26590.11	0.03	0.03	0.27	21.80	32.00	0.44	0.21	0.18	0.24			0.70	1.34	0.42	4.40	5.00	0.49	15.30	9.76	0.35	42.44	48.31	6.83	0.18
-0.4	623.03	27212.13	0.06	0.08	0.37	31.70	59.00	0.54	0.41	0.48	0.34			1.00	2.23	0.52	7.40	11.00	0.59	40.80	38.00	0.45	81.37	110.79	13.06	0.41
-0.3	624.82	27835.83	0.12	0.16	0.47	40.10	95.00	0.64	0.77	1.00	0.44	0.81	2.40	1.30	3.38	0.62	9.60	20.00	0.69	64.10	91.00	0.55	116.80	212.94	18.69	0.76
-0.2	626.80	28461.44	13.90	5.88	0.57	47.50	139.00	0.74	1.48	2.10	0.54	1.24	3.43	1.50	5.00	0.72	11.60	30.00	0.79	82.40	164.00	0.65	159.62	349.41	25.47	1.23
-0.1	628.92	29089.14	27.00	24.00	0.67	52.60	189.00	0.84	6.60	5.80	0.64	2.04	5.07	1.80	6.00	0.82	13.60	43.00	0.89	98.60	255.00	0.75	202.24	527.87	32.16	1.81
0	631.28	29719.02	27.60	49.00	0.77	56.50	244.00	0.94	18.38	16.00	0.74	5.10	8.64	2.10	8.00	0.92	15.20	57.00	0.99	115.80	362.00	0.85	240.68	744.64	38.13	2.51
0.1	634.31	30351.59	31.20	79.00	0.87	59.90	302.00	1.04	32.96	40.00	0.84	36.96	29.67	2.40	11.00	1.02	16.60	73.00	1.09	133.20	487.00	0.95	313.22	1021.67	49.38	3.37

The 25 wetlands were put through a risk matrix to help decide which wetlands were at the greatest risk (Table 1.3). When considering the information presented in both Table 1.2 and Table 1.3, it was decided to monitor six wetlands containing significant acid sulfate soil hazards and volumes of water. Should these wetlands significantly acidify and deteriorate water quality or influence the water quality within the river channel then management actions would be undertaken. Based on the experience from these six wetlands, more informed decisions could be made in regards to the management of the remaining wetlands between Lock 1 and Wellington.

Table 1.3 Risk matrix of wetlands that would re-wet with imminent river level rises

Wetland	Acid sulfate soil hazard 0=none 1=low 2=low-moderate 3 =moderate-low 4=moderate 5=moderate-high 6=high-moderate 7=high	Water volume commence to flow 0=<20ML 2=20-70ML 3=70-120ML 4=>120ML	Water volume difference with seiching (potential for exchange with the river) 0=<20ML 2=20-100ML 3=100-300-ML 4=>300ML	Score 15= highest risk 0= lowest risk	Risk Low=0-4 Moderate=5-8 High=9-12 Very High=13-15
Wellington Marina	0			0	Low
Priess Landing	2	0	0	2	Low
Lake Carlet	7	4	4	15	very high
Younghusband West	6	0	4	10	high
Marks Landing	2	0	4	6	moderate
Tailem Bend	6	2	3	11	high
Riverglades	7	0	0	7	moderate
Mason Rock	4	0	0	4	Low
Wongalla Lagoon	1	0	2	3	Low
Coolcha Lagoon	5	0	3	8	moderate
Devon Downs North	6	0	2	8	moderate
Mannum Swamps	4	3	4	11	high
Bow Hill	2	0	0	2	Low
Henley Park	2	2	2	6	moderate
Salt Bush Flat	4	0	0	4	Low
Forster Lagoon	2	4		6	moderate
Caurnamont	2	0	2	4	Low
Teal Flat Hut	7	0	0	7	moderate
Lake Bywaters	4	0		4	Low
Teal Flat	2	0	2	4	Low
Walker Flat South Lagoon	7	2	2	11	high
Younghusband	6	0	0	6	moderate
Wellington North	7	0	0	7	moderate
Reedy Creek	1	0	0	1	Low
Craignook	4	3	0	7	moderate

The six wetlands chosen to be monitored were:

- Lake Carlet

- Younghusband West
- Tailem Bend
- Riverglades Unmanaged
- Coolcha Lagoon
- Devon Downs North.

These six wetlands were predicted to be some of the first to re-wet, were calculated to have significant volumes of water at predicted river levels and had significant acid sulfate soil hazards present. During the monitoring, should the acid sulfate soils hazards be proven to have a significant impact, then further funding would be sought for management of other high risk wetlands. Those additional wetlands of concern were:

- Mannum Swamps
- Teal Flat Hut
- Walker Flat South
- Wellington North.

1.2.4 Additional increases in flow during 2010

Following the floods in New South Wales and Queensland at the end of 2009 and beginning of 2010, South Australia had a cooler and wetter than average winter followed by the wettest spring on record. Some locations experienced record spring rainfall while maximum temperatures were the third lowest on record for the state (BOM 2011a). This translated to lower evaporation, more water input into the reservoir catchments, reducing the volume pumped from the River Murray to the reservoirs and increased local inputs into the River Murray and Lakes Alexandrina and Albert. This decreased the likelihood of Lake Alexandrina levels falling to the critical -1.5 m AHD with rive levels increasing more than the earlier predictions.

Floods in Victoria during September 2010 and in New South Wales around Wagga Wagga in December 2010 plus significant snow and rainfall in the highlands for both states meant that flows into South Australia increased significantly. Water levels below Lock 1 began to rise well beyond the earlier predictions. A return to pre drought pool levels occurred in late September 2010 and by December 2010 strong seiche events had driven river levels as high as 1.1 m AHD.

2 Overview of acid sulfate soils

Acid sulfate soils are soils and sediments containing iron sulfides, the most common being pyrite (FeS^2). When under anaerobic conditions, these soils are stable and are known as sulfidic soils. If they are exposed to oxygen, either through disturbance or drainage, the iron sulfides in the soil react with oxygen and water to produce a variety of iron compounds and sulfuric acid with potential impacts to water quality and ecology. At this stage they are known as sulfuric soils (QNRM, 2009).

2.1 Formation

Acid sulfate soils have been a natural part of many aquatic environments such as coastal lakes and estuaries for millions of years and are still being formed in similar environments today. Conditions suitable to the formation of acid sulfate soils include:

- A supply of sulfur (via seawater, saline groundwater or geology with ancient marine minerals). Sulfur is a natural part of salt, and so saline water sources are often a source of sulfur
- A supply of iron oxides (often in land sediments)
- Anaerobic conditions that create a reducing environment in which chemical reactions can produce iron sulfides and sulfate reducing bacteria can survive, which also produce iron sulfides
- Organic matter to act as a supply of energy for sulfate reducing bacteria
- Low energy conditions to allow the accumulation of sediments
- Temperatures greater that 10°C.
  (QNRM, 2009)

Acid sulfate soils are also a natural part of the River Murray, and have a wide distribution throughout the Murray-Darling Basin. Before European settlement, the natural wetting and drying cycles of the River Murray oxidised smaller quantities of acid sulfate soils during low flow events and then flushed them from the system during high flow events. This prevented the accumulation of large volumes of acid sulfate soils, reducing the risk to the environment posed by acidification. After more than 80 years of river regulation, particularly within the Lower Murray with the permanent inundation of wetlands and river banks, the suppression of this natural wetting/drying cycle has accumulated a significant volume of acid sulfate soils in the river system.

2.2 Acidification

Under anaerobic reducing conditions such as inundation with ground or surface waters, the iron sulfides within sulfidic soils are stable and the surrounding soil pH is often weakly acid to weakly alkaline. Sulfidic soils:

- Often have a pH close to neutral (6.5–7.5)
- Contain un-oxidised iron sulfides such as pyrite
- Are usually saturated with water
- Can be soft, sticky and gel like, but can also be sands and gravels
- Have the potential to produce acid if exposed to oxygen.

(QNRM, 2009)

When sulfidic soils are disturbed or exposed to oxygen, the iron sulfides are oxidised to sulfuric acid and the soil becomes strongly acidic (pH <4). Pyrite is the most common form of iron sulfide present in acid sulfate soils and due to its structure, has a large surface area and thus reacts rapidly with oxygen (QNRM, 2009). Earth Systems (2008) describes the series of reactions where by sulfidic material is exposed to oxygen and results in the production of:

- Acid
- Ferrous and ferric iron
- Ferric hydroxide

These reactions can been summarised by:

Equation 1 Summary of reactions for the oxidation of pyrite

FeS_2 +	15/4 0_2 +	7/2H_2O →	2 $SO4^{2-}$	+	$4H^+$ +	$Fe(OH)^3$
pyrite	oxygen	water	sulfate		acid	ferric hydroxide

Some points about the series of reactions to note are:

- The initial reaction produces ferrous iron, which can then be further oxidised to ferric iron, reducing the amount of acid present
- Ferric iron then reacts with water to produce ferric hydroxide and acid
- The ferric hydroxide precipitates out of solution and forms the orange precipitate often seen in acid water bodies and soil
- Ferric oxide can accelerate the oxidation of pyrite, producing more acid
- 4 moles of acid are produced when 1 mole pyrite is oxidised
- 16 moles of acid are produced when 1 mole of pyrite is oxidised in the presence of ferric iron.

Sulfuric soils:

- Have a pH of less than 4
- Contain oxidised iron sulfides
- Vary in texture
- Often, a sulfur mineral called jarosite ($KFe_3(SO4)_2(OH)_6$), is present at the surface and exposed faces of acid sulfate soils and is an indicator that the iron sulfides in the soil are oxidising and producing sulfuric acid
- One tonne of iron sulfides can produce about 1.5 tonnes of sulphuric acid when oxidised.

(DPI NSW, 2009)

The pH scale is a logarithmic scale ranging from 0 (strongly acidic) to 14 (strongly alkaline). Neutral solutions are pH 7. Because it is a logarithmic scale, a soil with a pH of 4 is 10 times more acidic than a pH 5 soil and 1000 times more acidic than a pH 7 soil (QNRM, 2009).

2.3 Monosulfidic black oozes

Monosulfidic black oozes (MBO) are the accumulation of thick layers of organic materials enriched in iron monosulfides in locations impacted by acid sulfate soils. Research and real world examples from around Australia have demonstrated that MBO can react rapidly when suspended in the water column and can completely consume dissolved oxygen, with extreme deoxygenation resulting in fish kill events (Bush *et al*., 2004)

Earth Systems (2008) state that the oxidation of MBO does not generate acid, but it is acidity generating. Once MBO is oxidised it can then follow a similar series of reactions as in the oxidation of pyrite:

- Produce ferrous iron
- Ferrous iron can then be oxidised to ferric iron
- Ferric iron eventually can precipitate as ferric hydroxide

Equation 2 Simple equation for the oxidation of monosulfidic black oozes

$$FeS + 2O_2 \rightarrow Fe^{2+} + SO_4^{2-}$$

monosulfide oxygenferrous iron Sulfate

MBO firstly generate acidity through the oxidation of sulfur, and then they can generate further acidity through the precipitation of metal hydroxides such as ferric hydroxide ($Fe(OH)_3$), aluminium hydroxide ($Al(OH)_3$) or manganese hydroxide ($Mn(OH)_4$). The acidity generated is dependent on the metals present and their solubility (Earth Systems, 2008).

2.4 Potential ecological impacts of acid sulfate soils

The acid produced by sulfuric soils can severely impact the water quality and ecology of a wetland and connected river channel. Sulfuric acid has the potential to strip the soil of metals such as iron, aluminium and manganese and mobilise heavy metals into the water column. This can be harmful to the fauna present and limit the productivity of flora.

Typically, the re-wetting of acid sulfate soils triggers production of sulfuric acid and mobilisation of metals and metalloids. After long dry periods, the trigger can be high intensity local rainfall or re-flooding of a floodplain or wetland.

In aquatic environments, such as the River Murray wetlands between Lock 1 and Wellington, the mobilisation of acids and metals may:

- Have detrimental impacts that could potentially cause death events for:
  - Fish
  - Crustaceans
  - Annelid worms
  - Shellfish
  - Oysters
  - Microscopic organisms
- Cause fish diseases
- Alter the structure of aquatic plant communities by favouring acidic tolerant species
- Increased light penetration due to water clarity
- Cause the destruction of fish eggs
- Introduce metals into the food chain
- Reduce the availability some nutrients due to low pH.

(QNRM, 2009 & DPI NSW, 2009)

The main ecological effects of acid sulfate soils are habitat degradation and poor plant productivity (QNRM, 2009).

Habitat degradation

In aquatic environments, acidic drainage from sulfuric soils can cause a number of negative impacts on habitats and biota such as:

- Destroy food resources
- Displace biota
- Precipitate iron that in turn can smother vegetation and microhabitat
- Alter the chemical and physical properties of the water
- Degrade spawning and nursery grounds.

Poor plant productivity

The optimal pH for plant growth is between a pH of 5 and 7. Poor plant productivity and stunted growth can occur at low soil pH, which can be caused by:

- Toxic effects of aluminium, iron and manganese that are mobilised by acidic water
- A deficiency in plant base minerals such as calcium, magnesium and potassium
- Low availability of some nutrients at low pH
- Increased attacks by plant pathogens
- Decrease in soil microbes, particularly those responsible for nitrogen fixation
- Stunting of roots producing water stress.

(QNRM, 2009)

Human health impacts

The impacts of sulfuric soils are aesthetically unpleasing and have the potential for human health impact. The mobilisation and precipitation of metals can enter the food chain through benthic organisms and aquatic flora and fauna, which in the long term can impact human health. Noxious odours are produced when volatile sulfur compounds are released during disturbance of sediments. These compounds have the potential to also impact human health (Baldwin & Fraser, 2008).

2.5 Acid sulfate soil considerations

It is difficult to predict if a wetland will acidify its body of water, to what extent and how it will recover. Some general observations can be made which add some context to the risks for acidification and management options for the wetlands between Lock 1 and Wellington.

2.5.1 Causes and symptoms

Baldwin and Fraser (2009) suggested that the principle difference between inland water ways and other areas with acid sulfate soil problems such as mines and coastal wetlands is age of formation. Coastal sediments and mine locations are in areas with ancient reduced sulfur and they have been disturbed by human activities, creating acidification problems. These can quite often be managed by not disturbing the areas. In contrast, inland systems such as the Murray-Darling Basin have accumulated reduced sulfur over a relatively short period and are a sign of a system under stress due to salinity increases through poor water usage and unnaturally long periods of inundation with dams and weirs. As a consequence acid sulfate soils in the Murray-Darling basin are a symptom of problems within the system. Baldwin and Fraser (2009) stress the need to not only address the symptoms but also to invest substantial effort to address causes otherwise problem will continue to re-occur during future drying events.

Simply “treating the symptoms rather than the disease” is a consideration when looking at remediation options. The use of bioremediation which is the addition or organic matter to create anoxic conditions and then supply organic carbon to sulfate reducing bacteria is potentially most significant. Sulfate reducing bacteria are what created the acid sulfate soils in the first place and using them in bioremediation to reduce oxidised sulfate and iron back to a reduced state will simply reset the system to a similar state as before drying. Hence, bioremediation is likely to be only a stop gap; if water levels drop in the future then the same problem will occur again, unless the sources of the sulfur within the system can be limited.

2.5.2 The rate of oxidation

The oxidation rate of the sulfidic soils governs the speed at which a wetland may acidify. A slow oxidation rate may allow more buffering capacity to be introduced in the form of river flow, physical intervention with neutralising agents or buffering from the alkalinity within the soil matrix. This reduces the risk of acidification of the water body. Reid (2009) suggested the significant variables governing the oxidation rate and the quantity of acid produced are:

- *Time of exposure*, based on observations that submerged soils have low oxygenation or are anoxic
- *Degree of hydration*, based on dry soils have little or no water available
- *Surface area of the soils*, based on a study showing after aging, surface soils to 1mm were completely oxidised but at 3 to 7 mm less than 20% had oxidised

As a result, soils that are totally submerged and/or totally dry have the slowest oxidation rates and any soils with conditions in between these have the highest oxidation rates. In areas where soils experience both rising and falling water levels, such as the shore of a water body are most likely to have the maximum amount of water and oxygen to convert to oxidise the iron sulfides and then react to sulfuric acid.

2.5.3 Drying, cracking and rewetting

As a wetland dries, sediments are exposed to oxygen with a retreating water line. Reid (2009) observed that in this initial stage of drying only the surface of the drying soil is exposed to oxygen. As the soil dries further, shrink swell properties, particularly in the clays of the wetlands create cracks. These cracks significantly increase the surface area of the soils and expose deeper horizons in the profile. Further drying of the soils dehydrates them, which at this stage, Reid (2009) highlights very little oxidation is occurring due to the lack of moisture. Cracks become deeper and wider due to desiccation of the soils.

Upon rewetting of these heavily cracked and desiccated soils, oxidation increases due to the supply of water and the large surface area of soils exposed. Swelling of the clays will narrow the cracks however due to the desiccation, the majority stay open. Some evidence has seen that the top of the soil peds slake and crumble and cracks are simply filled in over time (pers comm., CSIRO). This indicates that the surface area of the soils remains greater for a longer period of time after re-wetting than if the cracks in the soils were simply shrink swell.

Reid (2009) states that plants have an influence on soil moisture and structure as they can hasten the drying of soils through water usage but can regulate transpiration to suit availability, possibly stabilising soil moisture. Additionally they provide organic litter that can serve to buffer changes in moisture by acting as mulch to minimise evaporation. Roots stabilise soil structure binding soil particles together which is important once water has retreated, as in the case of Lake Alexandrina where vast quantities of sand were being transported across the lakes by the prevailing winds, smothering vegetation and creating dust storms over nearby towns.

Common Reed (*Phragmites australis)* is one of the dominant species of vegetation across the wetlands. It is well adapted to grow in anaerobic soils, can tolerate saline conditions and periods of drying. Reid (2009) states that macrophytes can adapt to varying conditions by slowing growth during drying and survive extended periods of dry in root rhizomes under the soil. In contrast, few terrestrial plants can survive periods of inundation and aquatic plants cannot survive periods of drying.

Phragmites can build up a thick organic layer that eventually is incorporated into the soils structure. It can extract water from deep in the soil profile and Reid (2009) states that a $500m^2$ of Common Reed could evaporate 1000 litres of water per day, approximately the same average evaporation rate for the same area of Lake Alexandrina.

The dense matt of organic matter associated with Common Reed could act to regulate moisture in the soils, however its deep extraction and high water consumption could dehydrate soil rapidly and deeply, exacerbating soil cracking, particularly in adjacent bare areas where the combination of evaporation and Phragmites water consumption could dry the soil out rapidly. Reid (2009) also highlights that large quantities of organic matter from common reed could also form MBO.

Pale Knotweed (*Persicaria lapathifolia*) had colonised many formally open water areas within the wetlands. This is a semi aquatic plant that may be native to Australia, although its origin is unknown. While it appears to have died due to lack of water however it managed to form dense stands before doing so. Based on the assumption of high water use due to its preferences for growth along the margins of water bodies, it is likely to have dried the wetland soils rapidly, exacerbating cracking and dehydration of the soils.

2.5.4 Understanding the potential for acidification

There are several sets of laboratory data that can indicate the presence of and the severity of acid sulfate soil materials. The following set of criteria has been established to identify soil materials of concern in the wetlands:

- All sulfuric materials where at the time of sampling $pH_{water} < 4$ (occasionally field identification key minerals such as Jarosite were also used).
- All hypersulfidic materials were recognised by either
  - 1) $pH_{incubation}$ where pH decreases from a value >4 to a value <4 on ageing for 8 weeks, or
  - 2) a positive net acidity result (calculated with a fineness factor of 1.5)
- All hyposulfidic materials with chromium reducible sulfur contents ≥ 0.10%S.
- All surface soil materials (i.e. within 0-20 cm) with water soluble sulfate (1:5 soil:water) contents >100 mgSO4/L.
- All monosulfidic materials identified by field observation.

Acid sulfate soils are considered to be a hazard when the above criteria are triggered. However, to determine if an area or wetland has an acid sulfate soil problem of concern other factors are taken into consideration. These include:

- The depth of the soil material from the soil surface and if cracks into the subsoil are present
- The thickness of the acid sulfate soil layer

- The predicted distribution of the soil material as a proportion throughout the area and the wetland
- The location of the acid sulfate soil material within the wetland, such as proximity to the inlet, connection to receiving water, elevation within the wetland topography.

It is not a straightforward quantitative decision making process to determine if a wetland or a section of the wetland has acid sulfate soil materials of concern, professional judgement is required. This is necessary because

i) Laboratory results for a soil sample have been shown to not necessarily correlate in the identification of an acid sulfate soil material and
ii) Laboratory results need to be considered while also taking into account the understanding of soil material distribution throughout the wetland.

3 Associated Reports and Data

Considerable data sets have been gathered during the investigation of management options for acid sulfate soils in wetlands between Blanchetown and Wellington. This section summarises each of the associated projects, data available and outcomes relevant to devising management options.

3.1 SA Water video review of wetlands between Lock 1 and Wellington

SA Water undertook video viewing of the River Murray between Lock 1 and Wellington on 22 August 2007. They used video footage recorded from air flights on 14 and 15 June 2007 when the river level was approximately 0.2 m AHD.

The aim was to identify which wetlands would be connected to the river channel at a river level of 0.1 m AHD by observing which wetlands contained water on the video footage. Wetlands containing water were identified for further survey work on inlets to establish detailed commence to flow elevations for each inlet.

SA Water provided the SA MDB NRM board with a word document containing 73 wetlands with each wetland identified as being either wet or dry, if it appeared there was still connectivity with the river channel and if more sill level work was required.

It identified 25 wetlands as wet and 21 wetlands needing further sill work to establish commence to flow elevations.

The document can be found in the folder "**01 SA Water video review**"

3.2 Estimates on water volumes and surface areas using LiDAR

The consultancy WBM was commissioned by SA MDB NRM board to undertake modelling of surface areas and volumes based on bathymetry created by Light detection and Ranging technology (LiDAR).

The LiDAR was taken at a river level of 0.2 m AHD making bathymetry below that unknown however WBM used bathymetry data from additional sources (where available) to estimate the volumes and surface areas.

The project resulted in a spreadsheet containing a summary of surface areas and volumes at various river levels in 0.1 m increments. Graphs of surface area and volume relationships were also presented. This enabled the SA MDB NRM board to highlight wetlands with shallow water bodies over large surface areas, which at that stage were thought to be the wetlands most likely to suffer acidification.

GIS layers were also presented allowing the SA MDB NRM board to create bathymetry maps highlighting areas at most risk and where water was likely to be located in wetlands at various river levels.

The data can be found in the folder "**02 Volume and Surface Areas 25 wetlands**".

3.3 Survey of inlets and detailed bathymetry for 24 lowest lying wetlands

Australian Water Environments (AWE) was commissioned to undertake surveys of inlets at the 24 lowest lying wetlands between Lock 1 and Wellington. Additionally they were commissioned later in the project to undertake a survey to create detailed bathymetry of 13 high risk wetlands that did not have sufficient detail below 0.2 m AHD.

A final report presents all data including:

- Commence to flow elevations for all inlets
- Slopes and cross sections for all inlets
- Photographs and detail in regards to structures and pipes within inlets
- Detailed bathymetry
- Maps highlighting inlets and major points of interest
- Accessibility to the wetland.

Excel spreadsheets containing cross sections and slopes for each inlet plus GIS layers of bathymetry and spot elevations were also included as part of the project output.

The report and data can be found in the folder "**03 Survey of 24 wetland Inlets and 13 with detailed bathymetry**"

3.4 Assessment of nine wetlands below Lock 1

The project was undertaken by CSIRO in conjunction with AWE and included an acid sulfate soil baseline assessment and development of a monitoring program for vegetation, including a baseline assessment.

The acid sulfate soil assessment can be summarised in the following table extracted from the report.

Table 3.1 Summary of acid sulfate soil assessments (Fitzpatrick et al., 2008)

[1]ASS Risk	Wetland	[1]Dominant Acid Sulfate Soil (ASS)	
		Material	[1]Classification (ASS subtypes)
Extremely High	**Ukee and Swanport**	**Sulfuric**	**[2]Sulfuric cracking clay soil**
High	Murrundi (North Wellington) Lake Carlet	Sulfidic	[2]Sulfuric organic soil [3]Sulfidic subaqueous clayey soil
High to Moderate	Kroehns Landing Devon Downs North	Sulfidic	[4]Sulfidic cracking clay soils
Moderate to High	Noonawirra North Purnong	Sulfidic	[4]Sulfidic cracking clay soils
Moderate	Devon Downs South	Hypo-Sulfidic	[5]Cracking clay soil containing some sulfides

The field work and laboratory analysis undertaken during this project was used in later reports for acid sulfate soils between Lock 1 and Wellington.

The report can be found in the folder "**04 Nine wetlands below Lock 1**".

3.5 Assessment of acid sulfate soils in five wetlands below Lock 1

CSIRO was commissioned by SA MDB NRM board to undertake an acid sulfate soil assessment of five wetlands below Lock 1 including:

- Morgans Wetland
- Paiwalla Wetland
- Jury Swamp
- Riverglades Wetland
- Swanport Wetland

The aim of this investigation was to quantify the impact of rewetting on acid sulfate soils and water processes to better evaluate management options.

The report found the following acidifications risks:

- Swanport Wetland - high to very high
- Riverglades Wetland - high
- Jury Swamp - very high
- Paiwalla Wetland - low to medium
- Morgans Wetland - medium to high.

The investigation concluded that the greatest risk of profile acidification will occur in High risk environments and will require active management should river water levels continue to recede or when they are re-flooded.

The report can be found in the folder "**05 five wetlands below Lock 1**"

3.6 Assessment of acid sulfate soils in disconnected wetlands between Locks 1 and 5, River Murray South Australia

CSIRO was commissioned by SA MDB NRM board to undertake acid sulfate soil assessments in eight wetlands located between Lock 1 (Blanchetown) and Lock 5 (Renmark). Sampling and analysis was undertaken to determine the presence of sulfidic materials and the actual and potential development of sulfuric soil materials. Two wetlands (Donald Flat and Tanyaca Creek) were not disconnected from the river channel and were selected as control wetlands. Results are summarised in Table 3.2

Table 3.2 Summary of the acid sulfate soil hazards for each wetland (Shand et al., 2009)

Hazard Wetland	Soil acidification	Water acidification	Metal mobilisation	Deoxygenation	Malodours
Tanyaca	moderate-high	moderate-high	moderate-high	low	low
Donald Flat	Low	low	low	low	low
Murbko South	Moderate	moderate	moderate	low	low
Ross Lagoon	Moderate	low-moderate	moderate-high	high	high
Jaeschke Lagoon	High	moderate	moderate	low	low
Lake Bonney	Low	low	moderate	low	low
Yatco North	Low	low	low	low	low
Yatco South	low-moderate	low-moderate	low-moderate	low	low
Nelwart Lagoon	High	high	high	low-moderate	low-moderate

The report is located in the folder "**06 eight wetlands between lock 1 and 5**"

3.7 Study of Nelwart Swamp re-wetting

CSIRO was commissioned by the SA MDB NRM board to undertake detailed monitoring of Nelwart Swamp for a year following re-wetting. There were four progress reports and a final report presented to the SA MDB NRM board.

The monitoring involved detailed water analysis including water chemistry, metals and nutrients, sediment sampling and analysis, a logger continuously recording redox data at various depths in the soil profile and shallow groundwater sampling and analysis.

Upon re-wetting Nelwart Swamp acidified and to ensure minimal impact to the river channel it was kept separated. The wetland remained acidic for approximately 8 months until a top up of water in December 2010 neutralised the water column and began the recovery of the wetland. Nelwart Swamp represented the projects best opportunity to assess the real world consequences of acidification and the mechanics of the recovery as well as the fate of mobilised metals and the potential uptake in biota.

The progress and final reports can be found in folder “**07 Re-wetting of Nelwart Swamp**”

3.8 Assessment of acid sulfate soils in wetlands below Lock 1

The project was instigated by the Murray-Darling Basin Catchment Authority and managed by the South Australian Murray-Darling Basin Natural Resources Management Board (MDB NRM Board).

The aim of the investigation was to determine the presence or not of acid sulfate soil materials in wetlands between Lock 1 and Wellington. The study was known as a phase 1 assessment and those wetlands identified as high risk would then undergo more detailed Phase 2 assessment including laboratory analysis.

A total of 62 wetlands were visited between August and October 2008 with 198 soil profiles described and sampled. Two additional wetlands, Pomanda Bay and Wellington Marina were surveyed in January 2010 adding a further 15 soil profiles.

A comprehensive database consisting of site and profile descriptions and laboratory data was compiled, along with a library of photographs showing wetlands, sites, soil profiles and chip-tray samples.

At the time of this report, a final report had not been released by the MDBA however; draft reports and data are included in the folder “**08 Assessment of acid sulfate soils below Lock 1**”.

3.9 Assessment of acid sulfate soils in wetlands above Lock 1

CSIRO and SA MDB NRM board successfully tendered to undertake acid sulfate soil assessments of wetlands between Locks 1 and Lock 5 in South Australia. This work followed the rapid assessment previously undertaken to identify acid sulfate soils in wetlands.

At the time of this report, a final report had not been released by the MDBA however; draft reports and data are included in the folder “**09 Assessment of acid sulfate soils above Lock 1**”

3.10 Aerial Photographs of Lock 1 to Wellington

Since 2007, as part of a project to identify algal blooms and indicators of poor water quality, SA water had regularly taken aerial photographs of the river and adjacent wetlands below Lock 1. SA Water shared copies of the images for selected months with the SA MDB NRM board, including:

- 2007: April, August, November
- 2008: January , April, August, November
- 2009: January, April.

Each month comprised of up to 500 individual photographs which were between 30MB and 60MB each. This made the use of these photos and quick comparisons between years extremely difficult and as such they would serve the process better if they were stitched together and rectified so they can be used as GIS layers. This would make finding wetlands and comparing months extremely quick.

SAMRIC were commissioned to undertake stitching and rectification for photos from April of each year (07, 08 and 09). This gave a good spread of different river levels at a similar time of year for a direct comparison.

Original photos, stitched and rectified photos and contracts with SAMRIC can be found in folder "**10 Aerial Photos of Lock1 to Wellington**"

3.11 Dry wetlands report

At the beginning of 2010 forecasts for water levels in Lake Alexandrina to drop to -1.5 m AHD, the critical threshold for acidification of the lake, had been extended further. It appeared that the temporary weir at Pomanda Island may not be constructed, but water levels would remain low, keeping wetlands between Lock 1 and Wellington disconnected and dry for an extended period.

This pending scenario prompted a request for a briefing paper to outline the implications of keeping wetlands between Lock 1 and Wellington dry for an extended period (years) and what this would mean for acid sulfate soils risks, ecology and some potential impacts to the surrounding communities. It discussed the advantages and disadvantages of the possible management options and the present knowledge gaps. A way forward was also presented indicating investigations and management options that should be undertaken.

The report concluded that there were 77 wetlands between Lock 1 and Wellington, of which 67 are considered permanent wetlands, 49 of which were likely to have or may have acid sulfate soils of concern. In many of these wetlands, precipitation of toxic salts on the soil surface and extensive cracking of the soils was observed.

The structure of the wetlands was changing with significant colonisation of weeds and terrestrial species of vegetation including river Red Gums (*Eucalyptus camaldulensis*). Those wetlands that had not been colonised by vegetation and remained bare were becoming sources of dust, impacting surrounding residents. Native fish and water birds had fled the wetlands, with signs that the river channel was not acting as a suitable replacement for wetland habitat.

The river channel banks were also showing signs of oxidised acid sulfate soils. There were toxic salts precipitating on the surface of the sediments and small pools of acidic water trapped along the banks due to the variation in water levels.

If dry conditions continued for an extended period, it was likely that cracking in the wetlands would increase. This would have oxidised more acid sulfate soils, potentially creating even more acid upon re-wetting. Soil structure would continue to breakdown with disassociation of clay particles. This would have made it difficult for plants to grow and may have increased the potential for wind and water erosion, the former impacting surrounding communities. Seed banks within the wetland soils were at risk of becoming unviable with such an extended dry period, potentially unlike any other within the recent geological history of the river system. Native species of fish that were hiding in the river channel were open to more predation and some species were heavily dependent on the wetland structure in order to reproduce. They may have had a life cycle shorter than the period of time the wetlands had been dry, creating the potential for these species to become locally extinct.

The report can be found in folder “**11 Dry wetlands report**”.

3.12 Lower Murray Inlet Management review of technology and concepts

In preparation for the return of water to some wetlands at the beginning of 2010, the feasibility of some management concepts needed to be investigated. A major part of any management strategy was to ensure poor quality acidic water was not allowed to flow into the river form the wetland.

It was the aim of the SA MDB NRM board to ensure management options undertaken had minimal impact on the structure or ecology of the wetland. As such it was thought the best technique to separate wetlands from the river channel was to use sandbags filled with crushed limestone to act as temporary control structures that could be removed once water quality recovered.

SA MDB NRM board commissioned Australian Water Environments (AWE) to investigate the feasibility of using sandbags filled with limestone as temporary control structures. There were several aims for the project:

1. To assess the feasibility of using sandbags filled with crushed limestone as temporary structures at inlets of 20 wetlands between Lock 1 and Wellington. The feasibility was assessed under three scenarios where the aim would be to:
    - Remain water tight and prevent water from entering wetland at a river level of 0.1 to 0.4 m AHD
    - Remain water tight and prevent water from entering wetland at a river level of 0.7 to 0.9 m AHD
    - Act as a hydrological barrier, but did not have to be water tight when water in the wetland was at a similar height to the river.

2. If sandbags were feasible then the project also aimed to understand the best way to fill and distribute the sand bags. A configuration for each inlet and how to install and remove the sandbags required; all with associated costs.

3. Suggest other options or technologies for water control using temporary structures as an alternative, particularly if they were less intrusive, more cost effective or more feasible.

The first phase of the investigation concluded sandbags were not suitable due to:

- Labour intensive nature to install the sandbags
- The difficulty in removing the structure, this included other flood mitigation technologies. All were designed to be built and removed in dry conditions. Under this scenario, they would need to be removed from under water
- The durability of the sandbags could not be relied upon to cover some of the periods they would potentially need to be in place.

The recommendation from AWE was to install conventional earth banks with a 4 m wide top to allow for easier removal. AWE felt this was the most cost effective method with the best chance of removal. AWE then proceeded to phase 2 of the investigation, producing concept designs and costs for the installation of conventional banks for six of the highest risk wetlands predicted to re-wet.

Costs were extremely expensive at some wetlands such as Riverglades and Younghusband West and were related to the width of the inlets and difficulty in accessing them. The installation of blocking banks at all wetlands was highly undesirable due to the impact they would have on the wetland, the high cost and quantity of resources used creating them. The total was $3,500,000 for only six wetlands and with such a cost and impact to the wetlands, it was unlikely to be a realistic management option.

AWE reports and contract documents and tender details can be found in folder "**12 Wetlands structures using sandbags**".

3.13 Assessment of acid sulfate soils in river banks sediments between Lock 1 and Wellington

During field trips to wetlands, the staff from both the SA MDB NRM board and CSIRO observed an increasing quantity of colouration and precipitates on the surface of the exposed banks. Often these were orange, bright yellow, cream and brown, which can be indicators of oxidation and the precipitates are minerals and metal oxides produced by acidification.

Based on these observations, the SA MDB NRM board and CSIRO were commissioned by the Murray-Darling Basin Authority (MDBA) to undertake an assessment of the potential extent and distribution of acid sulfate soil materials along the banks of the River Murray between Blanchetown (Lock 1) and Wellington, South Australia.

Field work was conducted over a three week period, in September 2009, using a four wheel drive vehicle and a boat, and comprised:

- Rapid assessment every five kilometres on both banks of the river channel
- Morphological observations every one kilometre on both banks of the river channel
- Visual observations along the length of the river channel.

The results indicated that a significant proportion of the river channel banks contained acid sulfate soils, some were already acidic and many more had the potential to acidify with further exposure.

A presentation was made to the water security technical group (WSTG) to request funding for further investigations however the risk to human health was considered low by the WSTG. The issue was referred to the Lower Murray Coordinating Committee who appointed DEH as the lead agency for the matter.

Documents can be found in folder “**13 ASS in banks of river channel**”.

3.14 Draft Management report in preparation for the Wellington Weir

This draft report was prepared when the weir at Pomanda Island was expected to be the constructed. It contains considerable work with hydrological maps of wetlands and a presentation of potential management options.

The increase in river levels and subsequent monitoring changed the focus of the management report and so this draft report was not completed.

The report and associated data can be found in folder “**14 Draft management report in preparation for the wellington weir**”.

3.15 Re-wetting soils in buckets

Sediments were retrieved from wetlands that were about to re-wet with rising river levels. Measured quantities of sediment were placed in buckets and re-flooded with river water to ascertain the length of time and severity of acidification.

The study was cut short due to time constraints with rapidly rising river levels however, it did indicate that sediments re-wet in this manner could be used as a good predictive tool for future re-wetting events.

Report and data can be found in folder “**15 Re-wetting soils in buckets**”.

3.16 Report on metals uptake in biota at Nelwart Swamp

Nelwart Swamp is a small wetland near Renmark in South Australia that was disconnected from the river channel for water savings during the drought. The wetland was re-wet but kept disconnected from the river channel and the water body acidified rapidly. It remained acidic for approximately eight months until it was topped up with water in December 2010. This additional influx of river water neutralised the water body. The wetland was kept disconnected from the river channel however, fauna that entered during the top up was able to survive and reproduce. This represented an ideal opportunity to see if there were signs of metal uptake following this acidification and neutralisation of the wetland. Samples of biota were taken from Nelwart Swamp and Paringa Paddock, a wetland nearby that did not suffer acidification.

The study did not find substantial differences in metal concentrations between tissue from fauna specimens collected at Nelwart Swamp and Paringa Paddock. Concentrations in Yabbies were consistently higher than other species while freshwater shrimp were abundant and had concentrations higher than fish specimens.

There were no trends evident between wetlands for flora specimens although Nelwart Swamp did display some increasing trends in metals for sites further from the river channel. Overall concentrations for many metals were similar to those found in specimens from polluted sites in other studies, suggesting that both wetlands had elevated concentrations in flora, potentially as a result of contamination from other sources.

Results indicated that there may be potential to harvest wetland plants to remove metals from a wetland. This has the potential to assist in removal of metals from the system should a species be identified that can accumulate significant concentrations in its leaves as roots will be too difficult to harvest.

The report and data can be found in folder “**16 Metal uptake by biota in Nelwart Swamp**”

3.17 Report on six wetlands intensely monitored

The imminent re-wetting of up to 25 wetlands during 2010 prompted the project to undertake intensive monitoring of six high risk wetlands. This monitoring would identify hazards quickly, allowing time to seek funding for management actions. The data collected would also inform the project as to the real hazards presented by acid sulfate soils, testing the hazard assessments produced by CSIRO.

The report concluded that significant bodies of water were not acidified and impacts to the river channel were minimal with only minor fluctuations evident in results. There were elevated concentrations of metals and nutrients within the wetlands and differences in water chemistry to suggest influences from acid sulfate soils did occur. Changes to river channel water quality and chemistry were detected however the severity and duration of these events were minor.

The hazard assessments for acidification of the water column and metal mobilisation were accurate for four of the six wetlands. What the hazard assessments could not consider were the changes to the wetlands during drought or the manner in which the re-wetting occurred.
The floods preceding the increase in river levels below Lock 1 were so significant that river levels increased well beyond predictions. River level increases were relatively quick, re-wetting wetlands quickly enough to minimise the length of time disconnected water bodies, mud flats and shallow water bodies were present. Flow in the river channel was as high as 41100 ML/day assisting to quickly mix dilute and disperse water exiting wetlands.

Characteristics of the wetlands such as local sources of alkalinity, bathymetry, vegetation and connectivity to the river channel assisted to mitigate impacts. Local sources of alkalinity helped neutralise acid on re-wetting, deep cracks and basin areas within wetlands helped to retain the most saline water, which in most cases was acidic. Vegetation such as reeds assisted in providing connectivity but slowing flow while wide inlets allowed large volumes of water to exchange between the river and the wetland without high velocity flows. This assisted in keeping the neutralisation boundary within the wetland.

The report suggested that an ideal wetland would be one with a continuous inlet and no separation from the river channel. It would also have a lip along the bank of the river creating a basin effect in the wetland. More dense saline water at the bottom would then stay in the wetland with fresher water exiting of the top. Fluctuations in river levels would present a more gentle ingress and exit of water, allowing the neutralisation and mixing boundaries to remain within the wetland.

Recommendations for the management of acid sulfate soils in wetlands below Lock 1 were:

- Consider hazard assessments for acidification and metal mobilisation to be accurate but do not base management entirely on this hazard rating. Understand the other influencing factors better before making an assessment:
    - Type of inlets connecting to the river channel
    - Species and density of vegetation present
    - Bathymetry of the wetland
    - Sources of alkalinity such as windswept sediments, eroded cliffs and banks and manmade structures such as limestone causeways
    - Groundwater seeps present in the wetland
    - Timeframe in which re-wetting will occur and to what depth.
- Do not allow wetlands to completely dry for the length of time that occurred during the drought. The longer the wetland is dry, the deeper the profile dries and potentially acidifies. Under shallow water levels the acidity at depth could diffuse into the water column
- If wetting and drying wetlands via management structures, do not undertake this at many wetlands at the same time, the accumulative effect from multiple wetlands may impact the river channel if flows are slow enough
- Increase the width of inlets. This allows a greater surface area for water to exchange between the wetland and river channel, slows flow and increases the area which precipitation of mobilised metals will occur. This in turn reduces the concentration of precipitates on the wetland bed, reducing the risk to benthic fauna
- Prevent landowners from excavating deep narrow channels. These channels are the most likely source of impacts to water quality in the river channel as they have higher flow velocities. Also excavation often reaches groundwater, changing the way it interacts with the wetland
- Encourage the removal of willows. As they grow along the river bank in front of the wetland, the root system catches sediments and organic matter. This creates a leaky levee that doesn’t hold water in the wetland or prevent it from re-wetting but slows water too much, reducing connectivity. As a consequence of this growth, water is concentrated through increasingly narrower inlets, increasing flow velocities, thus risks to the river channel as water is pushed into the channel before it is mixed, diluted and neutralised. Additionally the increased velocity scours the inlet, increasing depth and removing a

natural lip that would create a saucer like effect in the wetland which enables it to hold the most saline water

- Partial removal of levees. Any levees between the river channel and wetland should be reduced in height to allow connectivity along the entire front of the wetland. By leaving the lower portion of the levee, a saucer effect is created in the wetland allowing it to keep the most saline water
- Encourage the growth of reeds along the bank between the river channel and wetland and across inlets. Reeds will assist in slowing water sufficiently to allow better mixing before the water enters the river channel
- Do not build control structures at wetlands as this process requires the wetland to be separated from the river and connections are then only through narrow inlets
- Vary the weir pool more significantly to oxidise more acid sulfate soils regularly in small quantities, which will prevent the build-up of the amounts that were exposed during the drought
- Although no deaths or injury were observed as a result of acidification and metal mobilisation, the concentrations of mobilised metals that would have precipitated within the wetland warrant further investigation into their fate and impact to the food chain
- Continue to gather data on wetland water quality, sediments and structure. This monitoring program covered only six wetlands and contained limited sample points for 20 weeks. Some monitoring locations may have not been representative of the wetland or river channel the entire monitoring period due to influences from local factors. Sediment samples were not taken, leaving a gap in knowledge as to what was happening beneath the surface. A sustained accumulation of data across many wetlands including better monitoring location selection, sediment monitoring and fauna/flora monitoring will prepare for the next drought to inform hazard assessments more thoroughly.

The report and monitoring data can be found in folder “**17 Water Quality Monitoring in six wetlands re-wetting following drought**”

3.18 Report on extra wetlands monitored

As river levels increased well beyond predictions, other wetlands were visited to take water quality measurements. The number of visits to most wetlands was very low however in most cases the data gives an indication if acidification was occurring. Comparing these results to the hazard assessments allowed conclusions to be made on the risks presented by acid sulfate soils.

The report concluded that the hazard ratings for acidification were accurate. Wetlands with a low hazard rating were most reliable while some of the high and very high ratings did not translate to severe acidification. This was likely to the manner in which re-wetting occurred and the connectivity of the wetlands themselves.

It was difficult to make comment of metal mobilisation hazards with so few wetlands having analysis undertaken. De-oxygenation hazards appeared to be too high however it may be too early for monosulfides to have formed to be a threat at this stage. Based on field observations when the wetlands were dry however, very little dried monosulfides were observed, suggesting that the hazards may be too high.

The report and associated data can be found in folder "**18 Additional wetlands visited during re-wetting**".

3.19 Re-opening of Riverglades Managed Wetland

Riverglades managed wetland has closable structures across each of its three inlets. These remained closed during the re-wetting however, the levee separating the wetland from the river channel is composed if willows and as such was not water tight. It leaked as river levels increased and the water column within the wetland acidified.

Based on the monitoring undertaken in Riverglades unmanaged wetland it was thought the best management option would be to open the wetland and allow additional river water in. During the discussion and investigation as to the risk posed by opening the wetland, river levels increased further until the water column within the wetland was neutralised.

A project was undertaken in conjunction with SA Water to closely monitor the wetland on re-opening as the water column still had elevated concentrations of manganese and was saline. The SA Water River Murray off take is located directly opposite the river channel and so it was important to ensure saline water from the wetland did not reach the off take.

The report found that water from Riverglades did not impact the off take and that turnover from water was slow with changes in river levels the only effective driver for exchanging water with the river channel.

The report and associated data can be found in folder "**19 Re-opening of Riverglades Managed Wetland**"

3.20 Field Photographs during the drought and re-wetting

Photographs taken during field trips during the drought and subsequent re-wetting are in the folder "**20 Field Photos during drought and re-wetting**". They are arranged in subfolders names on the date they were taken YYMMDD. Subfolders are the individual wetland if more than one wetland was visited on that day.

3.21 Additional reports outside of this project

Literature used during the project is in the folder "**21 Additional literature**". This folder contains many of the papers referred to by other reports presented in this section.

4 Discussion

This project has undergone distinct changes in direction in order to keep pace with developing conditions. Each change has attempted to focus on answering questions surrounding acid sulfate soils to better inform management options. It has always been the intention of the project to formulate management options that are practical and specific to the wetlands between Lock 1 and Wellington with minimal impact to the ecology and structure.

A significant data set has been accumulated on the structure of the wetlands with surveys of every inlet and bathymetry for each of the first 25 wetlands to re-wet. Aerial photographs are available for the entire stretch between Lock 1 and Wellington for 2007 to 2009, particularly helpful for revealing the vegetation and structure of the wetlands. In addition, a comprehensive data set has been assembled containing the acid sulfate soil status in every wetland between Lock 1 and Wellington with a hazard ratings outlined for acidification, metal mobilisation and deoxygenation.

The return of water to the wetlands has enabled validation of acid sulfate soil hazards and given an insight to some of the factors influencing the impact from acid sulfate soils present. Field work undertaken before the return of water has enabled us to summarise some of the changes to the wetlands during the drought which in combination with the detailed monitoring undertaken during the re-wetting gives an insight to conditions that have influenced the impact from acid sulfate soils.

Investigations into possible management options revealed just how few there are to manage acid sulfate soils in wetlands. Many neutralising agents are unsuitable leaving ultrafine crushed agricultural limestone (aglime) as the only choice for neutralising acidic water. Aglime will not overcorrect pH, ensuring an over application will result in undissolved limestone rather than a pH above 10. It is safe to handle, relatively cheap and has a range of distribution methods. Investigations into the toxicity revealed that it is unlikely to impact fauna, when tested on two species of Hardyhead (Gillanders et al., 2011). The study did not address the bioavailability of metals mobilised during acidification and precipitated during neutralisation and it highlighted there is much more work to be done testing other species of fauna as well as field trials and further work into metal complexes created, particularly aluminium.

A study on the uptake of metals by biota at Nelwart Swamp was undertaken and concluded that there were no trends to indicate increased concentrations in biota from Nelwart Swamp compared to the biota from the control wetland Paringa Paddock. There was an increasing trend in concentrations further from the river channel within Nelwart Swamp. The most notable conclusion was from the comparison of concentrations found in similar species from other studies. It was concluded that concentrations were greater than other non-polluted sites and similar to polluted sites but less than substantially polluted sites. There was also potential that species of vegetation may function to uptake metals into their roots and leaves. Should a species be found that can be easily harvested, it may form part of management to remove metals from the wetland.

Investigations into alternative materials and technologies to block wetland inlets, in particular sandbags filled with limestone, revealed that the best way was with traditional earthen bank structures. If constructed with a 4 metre wide flat top, these structures could be crossed by machinery during installation and removal. All other technologies were developed for floodwaters where installation and removal is undertaken in dry conditions and one side of the barrier was intended to remain dry. Sandbags were considered too labour intensive and the life of the structure could not be reliably predicted, putting safety at risk. When estimating the costs for earthen banks and forming preliminary designs it was found costs were extremely high. The impacts to the wetland and surrounding environment were considered excessive with large amounts of material required with access roads, stockpile areas and clearance required around each inlet in order to install and remove them. It is highly likely that removal would create a significant amount of turbidity in both the wetland and river channel. As such, blocking wetland inlets was considered an unrealistic option.

Sediment samples were collected from high risk wetlands that would re-wet first. These were placed in known quantities in buckets and re-wet with measured volumes of river water and water quality was monitored. This showed that Riverglades acidified rapidly and severely while Lake Carlet and Devon Downs North acidified more slowly but still severely. The remaining three wetlands, Coolcha Lagoon, Tailem Bend and Younghusband West did not acidify to any significant extent. Stage two of this project was to then undertake the addition of ultra-fine crushed limestone to assess the dry application of neutralising agent and to the water column. The rapid increases in river levels terminated this project early however it did show there is scope for using this method to predict acidification severity.

Leading up to the re-wetting of wetlands, the severity of potential impacts to the river channel water quality was put into context with some comparisons of water volume. Using bathymetry of the river channel and wetlands it was calculated that at a river level of 0.1 m AHD the wetlands would contain 4.5 GL of water compared to 248.2 GL in the river channel. This meant that 1.8% of the water between Lock 1 and Wellington would be contained in the wetlands. Considering the predicted flow velocities it was likely that water exiting wetlands would be rapidly mixed and diluted, reducing the risk to water off takes and ecology in the river channel. It was only the severity of the acidification of the wetlands that was unknown, but this could be addressed on an individual wetland basis as problems emerged. Based on this, intensive monitoring of six wetlands was planned, which would detect severe acidification and any impacts to the river channel. Any areas that required management would be addressed as the problem presented itself and the data collected would help inform future management decisions.

Upon re-wetting some wetlands did acidify and there were some minor impacts to river channel water quality however they were localised and short in duration. Sample points furthest from the river channel were most at risk of acidification and had the poorest quality water while wetlands with narrow inlets were most at risk of pushing poor quality water into the river channel.

There were several wetlands that could be compared to assess the differences in the severity and duration of acidification. Riverglades managed and unmanaged wetlands acidified, however their connectivity and manner in which they re-wet were quite different. This was reflected in the severity and extent of acidification. Additionally both Jury Swamp and Swanport wetlands were rated as having a very high acidification hazard and they did acidify the water column on re-wetting. Once again there were differences in the severity and duration of acidification which were reflective of the connectivity of each wetland.

Differences in colour, turbidity and salinity allowed easy identification where wetland water met river water. Wetlands such as Devon Downs North and Lake Carlet had narrow inlets that channelled water in and out of the wetlands at higher velocities than wetlands such as Coolcha Lagoon which had multiple wide inlets. Wetlands with narrow inlets had a highly mobile interface between water bodies with the interface moving up to hundreds of meters in the direction of flow. Water rushing out of wetlands with narrow inlets tended to have the boundary between water bodies on the edge of the river channel rather than within the wetland. River level changes driven by wind seiche appear to be the main driver of turnover of water within wetlands, thus connectivity to the river channel has a significant influence on water quality within the wetland and severity of impact from acid sulfate soils.

The CSIRO hazard assessments for acidification on the whole appeared accurate. The most accurate were those with a low hazard rating. This makes sense as the lack of acid sulfate soils present ensured there was no facility to produce acid. Other wetlands with higher hazard ratings such as moderate, high and very high were also accurate but on many occasions were lower than expected. This is likely due to the manner of re-wetting with such a significant increase in river levels in a short period of time to levels above the old pool level of 0.75 m AHD.

In addition to the manner in which re-wetting occurred and the connectivity of wetlands with the river channel other factors influenced the severity of acidification. Density driven stratification was observed with saline wetland water siting under fresh river water. As a consequence, the most acidic metal laden water was also saline and sat deep below the surface water between cracks or on the wetland bed. Wetlands with a dish shaped bathymetry or lip at the inlets were able to retain some of the poorest quality water. This kept it out of the river channel and turbulence and diffusion allowed the water body to become more uniform over time. This ability to retain the poorest quality water and gradually dilute and mix it over time helped to buffer the impacts to the river channel.

During the drought wetlands such as Lake Carlet, Coolcha Lagoon and Devon Downs North accumulated large quantities of wind swept materials. These materials proved to be calcareous upon re-wetting and were a source of additional alkalinity. Lake Carlet had alkalinity concentrations higher than the river channel on initial re-wetting as water passed through sand dunes that had accumulated at the upstream inlet during the drought. Additional sources of alkalinity such as groundwater seeps, material fallen at the base of cliffs, hill slopes and some man made causeways were all additional sources of alkalinity.

Vegetation that grew during the drought broke down at different rates, depending on the species tolerance to inundation. As a consequence there was a regular supply of carbon to the system, a source of energy for sulfate reducing bacteria to reduce sulfates back to sulfides however there did not appear to be a pulse of decayed vegetation. Vegetation such as reeds, rushes and sedges allowed connectivity and water flow, but at a reduced velocity, likely in combination with uptake of metals and nutrients.

Although impacts to the river channel and wetlands appeared to be minimal, acidification was observed at enough wetlands to confirm that the hazard assessments should be considered in future management plans for wetlands. Additionally, concentrations of metals and their potential entry into the food chain should be investigated further in order to identify sensitive receptors that would justify more aggressive management as well as identify species of vegetation that could be harvested to removed metals from the wetland altogether.

Wetland characteristics changed during the drought, some of which assisted the wetland on re-wetting. Any future droughts should re-assess the condition of the wetlands before re-wetting to identify characteristics both helpful and unhelpful to management.

5 Management Recommendations

Recommendations for the management of acid sulfate soils in wetlands between Lock 1 and Wellington are based on the accumulation of knowledge during this project, including the observations from re-wetting. The outcomes of the project now have a different focus, instead of preparing for river levels to increase to 0.1 m AHD following the installation of the temporary weir at Pomanda Island we now know what happened to a significant number of wetlands following rapid re-wetting. As a result, the bigger picture can be considered as well as specific management options for this stretch of the River Murray.

The publication “National guidance for the management of acid sulfate soils in inland aquatic ecosystems” (Baldwin, 2010) should be considered to be the primary guidance. It states that the formation of acid sulfate soils is a secondary symptom of a system already under stress. The main drivers for this stress are elevated sulfate concentrations, primarily through salinisation from elevated groundwater and extended periods of inundation outside the natural hydrological regime (Baldwin, 2010). These two drivers are observed across the Murray Darling Basin with irrigation elevating saline groundwater surrounding the river valley and the series of weir pools elevating the river and wetlands to stable abnormally high water levels.

Reducing salinisation and weir pool variation are not new concepts and have been highlighted as the main drivers to other problems across the Murray Darling basin. Table 5.1 has been extracted from Baldwin (2010) and summarises the management objectives and possible activities to achieve them. The table suggests:

- Reducing salinisation with better management of irrigation and allowing a more natural flow regime.
- Preventing oxidation of acid sulfate soils either by retaining inundation or undertaking controlled oxidation to reduce the build-up of acid sulfate soils. Should there already be a significant accumulation of acid sulfate soils then inundation may be the only safe option
- Either using a neutralisation agent, organic matter to encourage bioremediation or used stored alkalinity in the system to neutralise the acidification. Bioremediation will simply reset the state of the acid sulfate soils and will not reduce the acidification hazard while using the natural alkalinity in the system may mitigate impacts now, but may leave a deficit in the system for suture acidification events
- Protecting the receiving environment either through separation or neutralisation and dilution. In the experiences form this project, isolation may create more problems than it solves while neutralisation and dilution will only work when sufficient flows are available
- Assessing the risk, communicating with stakeholders, monitoring and then taking action as required. This is the philosophy undertaken during the re-wetting of this project.

These objectives provide a solid framework for management and should be followed when creating wetland management plans in the future. Management plans should consider the impacts from surrounding irrigation and methods to best vary water levels within the wetland. The only way to vary wetland water levels currently is to install structures across inlets, which is a costly and intrusive exercise. Weir pool manipulation to vary river levels would be a more cost effective method, which would benefit the entire area, including groundwater rather than a single wetland.

Table 5.1 Summary of management objectives and possible activities (Baldwin, 2010)

Management objective	Activities
Minimising the formation of ASS in inland aquatic ecosystems	Reduce secondary salinisation through: • lowering saline water tables • maintaining the freshwater lens between saline groundwater and the water body • stopping the delivery of irrigation return water • Incorporating a more natural flow regime
Preventing oxidation of ASS or controlled oxidation to remove ASS	Preventing oxidation: • Keep the sediments covered by water • Avoid flow regimes that could re-suspend sediments Controlled oxidation: • Assess whether neutralising capacity of the sediments and water are in excess of the acid that would be produced in oxidation • Monitor intervention to avoid or mitigate against perverse outcomes such as deoxygenation or metal release
Controlling or treating acidification.	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
Protecting adjacent or downstream environments if treatment of the affected aquatic ecosystem is not feasible	Isolate the site Neutralise and dilute surface water Treat discharge waters by neutralisation or biological treatment
Limited further intervention	Assess risk Communicate with stakeholders Undertake monitoring Assess responsibilities and obligations and take action as required

Note: The range of activities to be undertaken is dependent on the site and the risk it poses to the environment.

Management options presented by Baldwin (2010) are broader and not specific to the wetlands between Lock 1 and Wellington. More specific management options have been formulated based on the experience and observations from the re-wetting of the wetlands. These are:

- Remove willow forests lining the river channel that form a leaky levee along many wetlands. Wetlands such as Wellington North, Tailem Bend, Mason Rock, Jury Swamp, Swanport and Riverglades are just a few that have significant growth of Willows along the river banks for the majority of the length of the wetland. These Willow forests form a leaky levee that forces flow between the remaining openings to the river channel. Removal of these willow forests and replacement with reed beds on a submerged lip would allow exchange with the river channel, in most cases along the entire length of the wetland. This greatly increases the surface area of exchange between the wetland and river channel. The lip would keep the most saline water within the wetland, the reeds would slow flow sufficiently to stabilise the boundary between river and wetland water while still allowing significant exchange to occur

- Improving connectivity at wetlands without willow levees should also be undertaken by widening inlets, particularly natural overbank connections
- Strongly discourage excavation of deep channels across the wetland to supply irrigation infrastructure. In cases where excavation has already occurred, backfill these channels when conditions allow. This most likely could not occur until wetlands were dry, perhaps the next drought? Many excavations were carried out during the previous drought to supply irrigation infrastructure as river levels decreased. Approvals should not be given to excavation of deep inlets and channels within wetlands. Irrigators should be assisted in these circumstances to extend infrastructure to the river channel for extraction
- Promote the growth of reed beds across wetland inlets. Reeds will slow flow, but not prevent it. They will also uptake metals, nutrients and reduce turbidity and provide habitat
- Should acidification occur in the future and the water regime does not effectively mitigate it then ultrafine crushed limestone (Aglime) should be applied to the acidic water to increase pH and alkalinity. This should be undertaken as a last resort on acidic portions of the water body only. Previous examples of wetlands being neutralised have shown just how little additional alkalinity is required.

Management is not just about actions at the wetlands, it is also about better understanding. Wetlands are constantly changing as demonstrated during the drought. As such ongoing monitoring and investigations should take place, including:

- Undertake more groundwater monitoring to understand the interaction with wetlands and river channel. This will identify if groundwater is contributing contaminants, alkalinity, salinity, sulfur or is already acidic. Monitoring should periodically analyse for major ions, metals and nutrients to establish a baseline
- Continue to monitor water quality and undertake periodic laboratory analysis on metals, nutrients, major ions in wetlands and the river channel, particularly those monitored intensely during this project. This will establish a better baseline for wetlands and river channel
- Investigate metal uptake by biota in the region to determine baseline concentrations and compare with other river systems. Continue to monitor for changes in selected species to identify hazards to the food chain
- Undertake alkalinity tests with all future water quality monitoring. This is a primary indicator if acidification is occurring and if it is about to impact the pH of the water column
- Investigate species of vegetation that have strong uptake of metals into their leaf and stems and will tolerate regular harvesting. If a species can be identified and encouraged to grow in areas where large quantities of metals precipitate, then removal of metals from the wetland system can be facilitated
- Investigate the pre liming of dry wetlands just before water returns to emulate some of the natural processes during the drought when calcareous materials blew in and accumulated in the wetlands.

To summarise recommended management options for acid sulfate soils in wetlands between Lock 1 and Wellington:

- Reduce irrigation and other human activities that increase groundwater levels and mobilise saline groundwater into the river channel and wetlands
- Vary weir pool levels to emulate more natural regimes and allow acid sulfate soils to be exposed in smaller quantities for shorter periods, more regularly
- Ensure wetlands with significant volumes of acid sulfate soils do not become exposed or disturbed, particularly areas that would not have been exposed before river regulation (areas below sea level)
- Improve connectivity to wetlands by removing levees, willows and other obstructions.
- Do not allow landowners to excavate deep, narrow channels, exposing groundwater and creating inlets with high flow velocities
- Encourage natural submerged lips to wetlands preventing the most saline water entering the river channel
- Encourage reed growth across inlets to slow but not prevent flow
- Use ultrafine crushed limestone (Aglime) as a neutralisation agent in acidic water bodies that are unlikely to recover due to poor connectivity to the river channel or are having major impacts to the ecology and/or the community.

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