Upstream Treatment Trial Plan

Boundary Creek, Big Swamp and Surrounding Environment – Remediation and Environmental Protection Plan

January 2022

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Introduction

Background

In June 2017, Barwon Water acknowledged that historic management of groundwater pumping had an environmentally significant impact in the Boundary Creek catchment. Reductions in flows caused by groundwater extraction coupled with a drier climate and supplementary flows not reaching the intended area, all contributed to the drying out of Big Swamp. This resulted in the activation of acid sulfate soils and ongoing release of acidic water to the lower reach of Boundary Creek.

In May 2018, Barwon Water established a community and stakeholder working group to participate in the design of a remediation plan for Boundary Creek and Big Swamp. As part of this process, Barwon Water invited the working group to nominate their own technical experts to help support them in their discussions to shape the remediation plan.

In September 2018 Barwon Water's commitment to undertake remedial works was legally strengthened through the issuing of a Ministerial Notice under section 78 of the Water Act, 1989. This notice mandated the development and implementation of the Boundary Creek, Big Swamp and surrounding environment – Remediation and Environmental Protection Plan (REPP) by 1 March 2020.

The section 78 notice defined remediation to be the controls and actions that could be practicably carried out to achieve improved environmental outcomes. In order to align this with an accepted scientific definition for remediation, the REPP further expanded the definition to be "the controls and actions that could be practicably carried out to improve the ecological condition and function of areas confirmed to have been impacted by historical management of groundwater pumping at Barwon Downs, noting that this is likely to be different to the original condition due to the extent of change since European settlement."

In February 2020, Southern Rural Water (SRW) accepted Barwon Water's REPP, which will be delivered under two parallel work packages:

- The Boundary Creek and Big Swamp Remediation Plan to address remediation of confirmed impact in the Boundary Creek catchment resulting from historical management of groundwater extraction.
- The Surrounding Environment Investigation to investigate whether other areas within the regional groundwater system have been impacted by historical management of groundwater extraction.

While the primary remedial strategy for Boundary Creek and Big Swamp is to allow groundwater level recovery and maintain saturation of the Acid Sulfate Soils (ASS) within the swamp, the REPP also outlined that additional contingency measures may be required to manage the risks associated with low pH and acidity loads while the re-wetting strategy takes effect.

To date, contingency measures have focused on downstream treatment options, such as the use of a sodium hydroxide dosing plant, to mitigate the risks to downstream reaches of Boundary Creek and the Barwon River. However, as previously reported in the Hydro-Geochemical Modelling report (Barwon Water, 2021), on 17 June 2021 Barwon Water received feedback from Southern Rural Water's Independent Technical Review Panel (ITRP) that recommended further investigation of a novel upstream treatment system to manage the metal and acidity loads.

Following receipt of these recommendations, Barwon Water has engaged Earth Systems Consulting Pty Ltd. (Earth Systems) to assist in conducting the upstream treatment trial investigation. In addition to this, Barwon Water has also engaged CDM Smith to conduct an Ecological Risk Assessment of the upstream treatment trial to identify potential risks associated with the trial and the need for any risk mitigation measures to prevent unanticipated impacts from occurring in Big Swamp, Boundary Creek and the receiving waterways (i.e. Barwon River).

What has informed this Process?

The Big Swamp Upstream Treatment Trial Plan has been informed by:

- The Boundary Creek, Big Swamp and Surrounding Environment Remediation & Environmental Protection Plan (REPP)
- The environmental monitoring data collected since acceptance of the REPP in February 2020
- Barwon Water's Hydro-Geochemical Modelling Report – Design of Contingency Measure completed in July 2021
- GHD's Big Swamp Integrated Groundwater-Surface Water Modelling for Detailed Design completed in April 2021
- Feedback received from our Remediation Reference Group (RRG) and their nominated experts regarding the detailed design of hydraulic barriers, review of remediation success targets, hydro-geochemical modelling, Barwon Water's high level program outline for upstream treatment and the proposed upstream treatment trial approach
- Feedback received from the Independent Technical Review Panel (ITRP) and SRW regarding the detailed design of hydraulic barriers, review of remediation success targets, hydro-geochemical modelling and Barwon Waters outline program for upstream treatment trial

Upstream Treatment Trial

Overview

The upstream treatment system was initially postulated by Jeff Taylor of Earth Systems during his time on the ITRP, who suggested that the use of a semi-passive upstream treatment system may provide a means of treating the acidity loads both within and downstream of the swamp. Therefore reducing risks to downstream reaches of Boundary Creek and the Barwon River while the system recovers. In addition to this, treating the acidity at the source may prevent the need for the proposed caustic soda dosing plant downstream of the swamp, which has caused concern due to the potential to overshoot the desired target pH (i.e. <8) and the sodium/salinity issues that may result from the use of caustic soda.

At a high level, the proposed potential semi-passive treatment system would implement a novel treatment approach, which uses caustic magnesia rock (MgO) to increase the soluble alkalinity of the water thus, raising the pH and reducing the metal and acidity loads. Given the novelty of this treatment methodology, a staged approach has been adopted with various hold points for review and evaluation. However, while the current stage is focused on the development of this Trial Plan, further information is required from the laboratory trials to better inform the proposed small-scale field trial and associated risks.

Should the upstream treatment trial investigations reveal that the proposed semi-passive treatment system is no longer viable at any phase of the project and/or approval is not received from SRW, the focus will shift to the use of conventional treatment technologies. This will include the downstream caustic soda (NaOH) pH adjustment – flow plant recommended by Jacobs (Jacobs, 2021) or an alternate approach such as the upstream dosing system outlined in Appendix A.

Upstream Treatment Trial Roadmap

Given the novel nature of the proposed treatment method and the go/no go decisions that will need to be made along the way to ensure that this method remains a viable option, the upstream treatment trial has been broken into four phases, as shown in Figure 1.

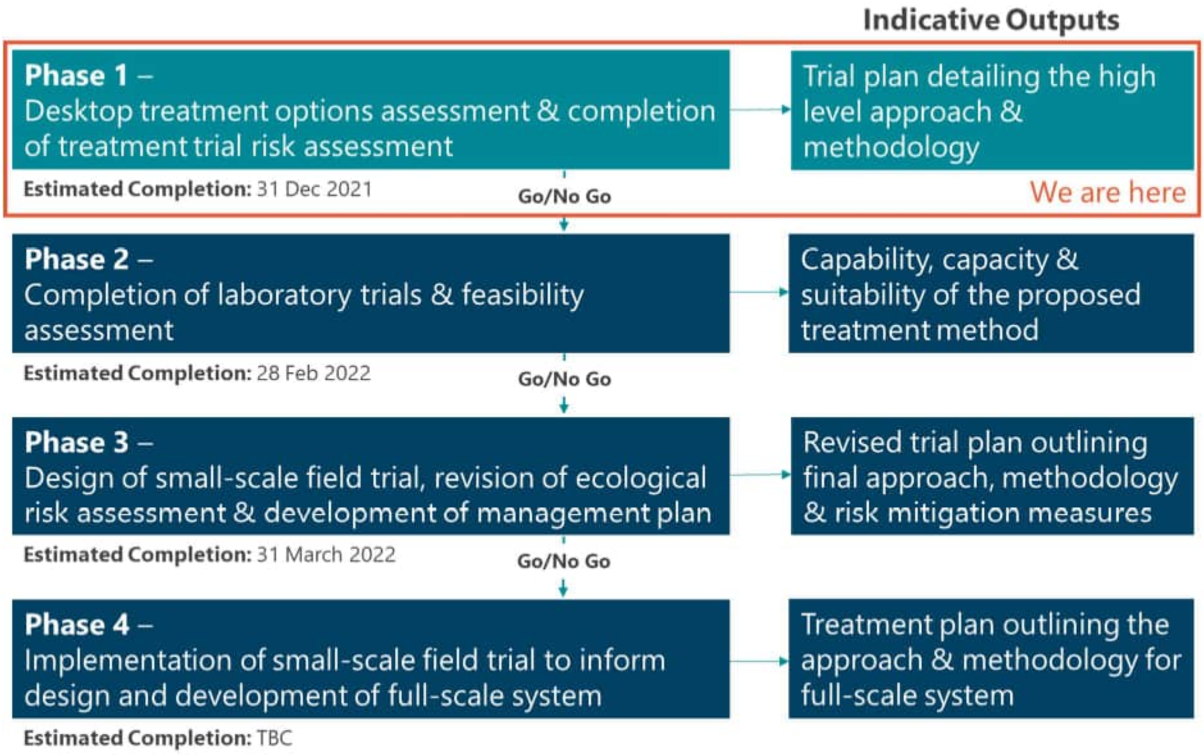

Figure 1 Treatment Trial Roadmap

This Trial Plan outlines the findings from Phase 1 works and presents the initial conceptual design that will be refined based on the outcomes of subsequent phases. It is important to note that this Trial Plan does not aim to present the detailed design of the trial nor the potential full-scale system as these will be informed by the subsequent phases.

Objectives of the Upstream Treatment Trial

The objectives of the upstream treatment trial are:

1. To investigate the potential application of caustic magnesia (MgO) in neutralising acidity-affected portions of the swamp and assess any potential ecological risks associated with this approach
2. Quantify the benefits and clarify the capital and operating costs of the proposed semi-passive treatment system
3. Assess the chemical interaction between the source water and the caustic magnesia under a range of scenarios using a small-scale system, and
4. Inform assessment of the feasibility of implementing the proposed upstream treatment method and development of a potential full-scale system.

It is noted that given the small-scale of the treatment trial system, the trial itself it is not aimed at materially improving the water quality within Big Swamp and/or Boundary Creek. This will instead be to inform subsequent phases of the project and identify knowledge gaps that will need to be addressed prior to implementing any potential full-scale system.

Desktop Treatment Options Assessment

As outlined in the desktop treatment options assessment provided in Appendix A, the metal and acidity loads within Big Swamp impose clear constraints of suitable treatment technologies (Earth Systems, 2022). Based on the average daily acidity loads of between 200-400 kg $CaCO_3$/day and the economic and environmental drivers, two potential upstream treatment options have been proposed as part of this assessment:

1. Active treatment with Caustic Soda, or
2. Semi-passive treatment with Caustic Magnesia

It is noted that these are alternate options to the initial downstream treatment contingency measure, consisting of a caustic soda (NaOH) dosing system.

Refer to Appendix A for a full review of potential treatment technologies and limitations.

Treatment Trial Overview

At a conceptual level, the treatment trial would span a period of 4-6 weeks and involve passing water from Reach 2 of Boundary Creek (i.e. upstream of Big Swamp) via an off-take pipeline through a reaction vessel of approximately 1-2 m^3 filled with caustic magnesia rock (MgO). As the water passes through the reaction vessel the water would react with the caustic magnesia rock increasing the soluble alkalinity of the water. This water would then be piped and mixed with the acidic swamp water in-situ, thus marginally increasing the pH and partially neutralising dissolved acidity within the water flowing through the swamp, as shown in Figure 2. It is noted that the small-scale field trial will only treat a small proportion of the total acidity and as such is not aimed at treating the swamp in the same manner as the potential full-scale system.

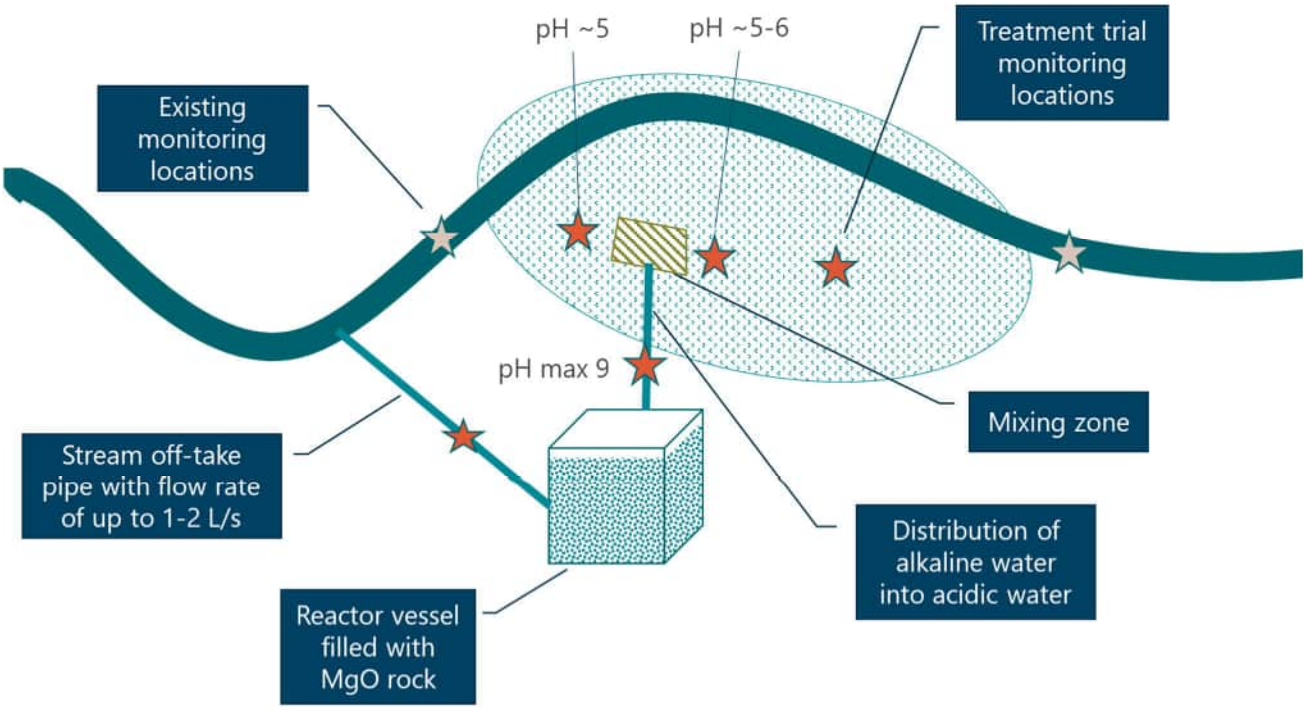

Figure 2 Conceptual Treatment Trial Schematic

Once established, the flow rate through the reactor vessel and the reagent will be varied to determine the relationship between flow and alkalinity output to inform the design of a potential full-scale system.

Further information regarding the proposed small-scale field trial is provided in Appendix A.

Potential Siting of the Treatment Trial

Following completion of a site visit with Barwon Water and Earth Systems, the current preferred siting option is to place the reaction vessel on existing cleared ground within the western portion of the swamp adjacent to acidic portions of the swamp. The stream off-take pipe, consisting of 2” pressure High Density Poly Ethylene (HDPE) would then be laid along the existing tracks between this location and stream gauge 233275A.

It is noted that the stream off-take pipe would only divert a small portion of water from the overall flows to maintain stream flows through Boundary Creek and Big Swamp.

Further information regarding the proposed arrangement of the small-scale field trial is provided in Appendix A.

Water Quality Simulations

Given the potential changes in water quality/chemistry following mixing with the treated water - with an upper pH threshold of 9 pH units, hydro-geochemical modelling was undertaken using PHREEQC to determine the potential water chemistry both within the mixing zone and downstream of the proposed treatment trial location, as shown in Table 1.

To do this, the pH fix function was used in PHREEQC to a pH end point of 9 using caustic magnesia (MgO) at the proposed treatment location prior to running a mixing simulation. This simulation assumed that the water composition at the mixing point comprised of 30% treated effluent and 70% native swamp water. Given the potential impacts associated with the input of highly alkaline water (pH >9), fail safe measures will be put in place to halt the input of treated effluent if a pH value >9 is observed immediately downstream of the treatment location. It is noted that while the theoretical saturation pH of caustic magnesia (MgO) is between 9.5 and 10.8, the effective pH is between 9 and 10 (Earth Systems, 2022). As such, upon mixing, the pH within the mixing zone is expected to remain < 9.

The remaining assumptions during modelling reflect those used during previous hydrogeochemical modelling, including:

- Full atmospheric equilibrium is achieved with O_2 and CO_2
- The dominant mineral phases involved in precipitation reactions include amorphous aluminium, iron and manganese hydroxides including $Al(OH)_3$(am), $Fe(OH)_3$(a) and Pyrolusite.

Table 1 Modelled water chemistry prior to intervention and following dosing with treated effluent (all units mg/L except pH) and indicative toxicity assessment based on information presented in the Ecological Risk Assessment (CDM Smith, 2021)

Analyte	Current Conditions		During Treatment Trial		
	Indicative water chemistry at the proposed trial location	Indicative water chemistry in Barwon River downstream of confluence	Indicative water chemistry at dosing point (i.e. within mixing zone)	Indicative water chemistry downstream of Big Swamp	Indicative water chemistry in Barwon River downstream of confluence
Alkalinity	8.3	-0.1	415.2	5.2	7.4
Aluminium	2.7	1.4	2.7	7.2	0.6
Ammonia	0.3	<0.001	<0.001	<0.001	<0.001
Antimony	0.0005	0.0009	0.0005	0.0005	0.0009
Arsenic	0.002	0.001	<0.001	<0.001	<0.001
Barium	0.016	0.02	0.016	0.0216	0.02
Beryllium	0.001	0.001	<0.001	<0.001	<0.001
Boron	0.01	0.02	0.01	0.01	0.02
Cadmium	0.0001	0.0005	0.0001	0.0001	0.0002
Calcium	4.3	5.9	4.3	3.7	5.9
Chloride	83.0	102.0	83.0	109.0	100.4
Chromium	0.0005	0.0009	0.0002	0.0001	0.0004
Cobalt	0.0033	0.002	0.003	0.007	0.001
Copper	0.0005	0.0009	0.0002	0.0003	0.00003
Iron	30.0	13.9	<0.1	15.0	0.3
Lead	0.0005	0.0009	0.0002	0.0004	0.00007
Lithium	<0.001	<0.001	<0.001	<0.001	<0.001

Analyte	Current Conditions		During Treatment Trial		
	Indicative water chemistry at the proposed trial location	Indicative water chemistry in Barwon River downstream of confluence	Indicative water chemistry at dosing point (i.e. within mixing zone)	Indicative water chemistry downstream of Big Swamp	Indicative water chemistry in Barwon River downstream of confluence
Magnesium	6.4	8.7	117.6	39.5	13.4
Manganese	0.02	<0.001	<0.001	<0.001	<0.001
Mercury	<0.001	<0.001	<0.001	<0.001	<0.001
Molybdenum	0.0005	0.0009	0.0005	0.0001	0.0008
Nickel	0.02	0.01	0.02	0.06	0.009
Nitrate	0.2	0.5	1.3	4.2	0.6
pH	5.7	4.8	9.0	5.1	7.1
Potassium	2.4	2.9	2.4	2.8	2.9
Selenium	0.002	0.001	0.002	0.003	0.001
Silver	0.001	0.001	0.001	0.001	0.001
Sodium	42.3	53.9	42.3	54.0	53.2
Strontium	0.06	0.06	0.06	0.05	0.06
Sulfate as SO_4	64.0	44.9	64.0	159.0	38.0
Thallium	0.0005	0.0009	0.0005	0.0005	0.0009
Tin	0.0005	0.0009	0.0005	0.0005	0.0009
Vanadium	0.0005	0.0009	<0.001	0.0004	0.000008
Zinc	0.07	0.03	0.05	0.18	0.03

Indicative toxicity assessment against key receptors
Stock and Domestic Water Use
Terrestrial Vegetation
Macroinvertebrate Community
Fauna

As shown in Table 1, the upstream treatment trial is not anticipated to lead to a marked change in water quality in Boundary Creek or the Barwon River. Instead, the primary change in water quality will occur in the mixing zone adjacent to the dosing point where the alkaline water (with a maximum pH of 9) mixes with the acidic water within the swamp. It is envisaged that this mixing zone will be around 1-2 m in length, with minimal changes to water chemistry downstream of this zone. However, based on the indicative water chemistry, the increase in pH is also likely to lead to iron, aluminium and manganese hydroxides becoming saturated, thus leading to precipitate formation which may flow downstream.

The mass of precipitate formation during the trial can be estimated via a mass balance. However, given the preliminary nature of this work, this has not been calculated as part of this assessment and will be assessed during the detailed design phase once the exact approach and methodology has been established.

Ecological Risk Assessment

To assess the potential risks associated with the completion of the upstream treatment trial, CDM Smith was engaged to to assess the potential impacts of the treatment trial on the ecological values of the swamp and its downstream waterways (Boundary Creek and Barwon River) and characterise the level of risk associated with the trial.

This Ecological Risk Assessment Framework adopted for this assessment was based on a conceptual risk model that includes an assessment of the sources, pathways and receptors (refer Figure 4) (CDM Smith, 2021). Following identification, these risks were characterised based on their likelihood and consequence to determine the risk ranking for each scenario in accordance with EPA guidelines.

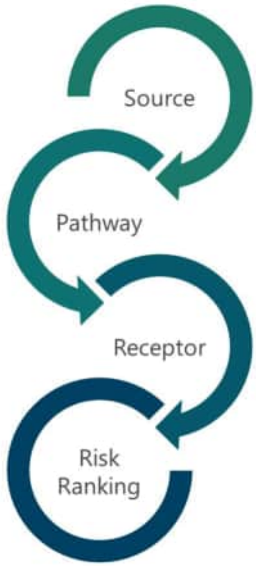

Figure 3 Source, pathway and receptor relationship

Refer to Appendix B for the Ecological Risk Assessment report and the key findings and recommendations that will be used to inform subsequent phases of the project.

At a high level the key changes in risk profile associated with undertaking the trial relate to:

- Reduced flows/water levels in the western portion of the swamp through diversion of the water for treatment
- Increased pH and potential for alkaline waters in the mixing zone
- Potential for spillage of treatment reagent (i.e. caustic magnesia (MgO) or fuel from the use of pumps at the treatment site

However, as detailed in the ecological risk assessment these can be mitigated via the use of supplementary flows, shut-off criteria and placement of the treatment infrastructure, which will need to be detailed in a Treatment Trial Management Plan following completion of the laboratory trials and the detailed design phase.

This Treatment Trial Plan will include:

- An overview of the risk mitigation measures adopted to manage the potential risks, and
- The adopted shut-off triggers should the system experience any malfunctions or if the pH exceeds 9 pH units

Environmental Monitoring Program

In order to assess the potential impacts and improvements associated with the treatment trial and manage the risks associated with dosing the swamp with alkaline water, an environment monitoring program has been established, as outlined in Appendix A.

This will include the collection of:

- Field parameters at regular intervals throughout conducting the trial, including:
    - pH
    - Electrical Conductivity (EC)
    - Temperature
    - Oxidation Reduction Potential (ORP)
    - Total Suspended Solids (TSS)
    - Alkalinity if pH>6 or acidity if pH<6, and
    - Major cations (Ca and Mg)
- Daily grab water quality samples from the monitoring locations outlined in Appendix A throughout conducting the trial. These samples will be collected in laboratory supplied sample bottles and be submitted to a NATA accredited laboratory for the following analysis at a minimum
    - pH
    - Electrical Conductivity (EC)
    - Total Suspended Solids (TSS)
    - Alkalinity if pH>6 or acidity if pH<6
    - Major cations and anions (Ca, Mg, Na, K, HCO_3, SO_4, Cl)
    - Nutrients (total N and total P), and
    - Total and dissolved trace elements (Al, As, Cd, Co, Cu, Fe, Mn, Ni and Zn)

The field parameters will be used to identify changes beyond those forecast in this assessment and act as a shut-off trigger should the pH downstream of the mixing zone rise above 9 pH units. The laboratory analytical results will be used to inform the ecological risk assessment and detailed design of the potential full-scale system and whether any additional monitoring would be required to monitor and manage risks associated with a potential full-scale system.

Next Steps

In order to inform the next phases of the project, as outlined in Figure 1, laboratory trials of commercially available caustic magnesia (MgO) are required to determine the potential soluble alkalinity that can be generated from this treatment methodology to inform the detailed design.

This along with the outputs from Phase 1, will inform the overall feasibility assessment of undertaking the upstream treatment trial and ensure the treatment methodology does not lead to any undue environmental impacts.

The overall feasibility assessment will incorporate a quadruple bottom line assessment that considers cultural, economic, environmental and social aspects and will help determine whether Barwon Water progresses to the detailed design phase.

Should the upstream treatment trial remain feasible, Barwon Water will progress to Phase 3 - design of small-scale field trial, revision of ecological risk assessment & development of treatment trial management plan, which will need to be approved by SRW prior to implementing the small-scale field trial. Should the upstream treatment trial investigations reveal that the proposed semi-passive treatment system is not viable and/or approval is not received from SRW, Barwon Water will explore the alternate treatment option outlined in Appendix A and/or whether the downstream caustic soda (NaOH) pH adjustment – flow plant recommended by Jacobs (Jacobs, 2021) remains the most suitable option. It is noted that the implementation of the small-scale field trial will also require the submission of EPA Victoria's form F1021: Permission Pathway Form, to determine which permission pathway is most suitable and the type of permission required. A similar process is likely required for any potential future full-scale system. In addition to this, a Works on Waterways Application through the Corangamite Catchment Management Authority may also be required. This will be explored in greater detail following the feasibility assessment.

Implications for Full-Scale System

Following completion of the small-scale field trial, the data obtained as part of this investigation will be used to determine the feasibility of implementing a full-scale system and inform the detailed design of the potential full-scale system.

It is noted that given the full-scale system would be approximately 10 times larger than the field trial, this will require a more detailed risk assessment to be completed. It is also noted that given the flow rates would also increase by a factor of 10 (max 20 L/s), that the water to be treated would come from a temporary pipeline connected to the water main located approximately 1,300 m to the south west of the swamp rather than a stream off-take pipe to prevent impacts associated with reduced water flows through the upper and western portions of the swamp.

In addition to this, the treated water from the reactor vessel could then be piped to multiple portions of the swamp, targeting the acidity and preventing large-scale water quality changes at a single location. This would enable the system to be adaptive to changing conditions and manage the acidity until the system sufficiently recovers.

It is noted that the proposed treatment technology will not neutralise the natural occurring Acid Sulfate Soils (ASS), rather this is aimed at treating the acidic water resulting from the oxidation of ASS. The oxidation of ASS is being addressed via the cessation of groundwater pumping activities and commitment to no further groundwater extraction from Barwon Downs, and the use of supplementary flows to maintain saturation of these soils and prevent wet-dry cycling.

Appendix A – Desktop Assessment of Upstream Treatment Trial (Earth Systems, 2022)

Semi-Passive Treatment of Big Swamp

Desktop Review and Trial Treatment Plan

prepared for

Barwon Water

by

Earth Systems

BARW2346.07.Rev1

14 January 2022

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EXECUTIVE SUMMARY

Barwon Water engaged Earth Systems to assess the benefit of conducting laboratory testwork and a small-scale field trial of a novel water treatment technology to assist in safely and cost effectively managing the water quality in Big Swamp (Boundary Creek) near Yeodene, Southwestern Victoria. This report provides a desktop review of current active and passive treatment systems and pH control treatment technologies and outlines the rationale for developing the proposed innovative semi-passive water treatment technology.

The oxidation of naturally occurring acid sulfate soils (ASS) within Big Swamp has led to the acidification and discharge of water with elevated acidity (acid + metal) values ranging between 30 and 300 mg/L $CaCO_3$. Flow rates from the swamp display significant seasonal variations, commonly varying from 5 to ~1300 L/s. Based on these physicochemical characteristics, acidity loads from Big Swamp likely average 300-400 kg $CaCO_3$/day, with substantially high peak values. A water treatment system is required to manage these high acidity loads.

At acidity loads >150 kg $CaCO_3$/day, no passive treatment systems are likely to be appropriate for treating the water in Big Swamp. On the other hand, active treatment systems could readily be designed to easily handle the acidity loads from the swamp. Jacobs in Barwon Water (2021) proposed a conventional active treatment system downstream of the swamp that is likely to be chemically successful. If this becomes the preferred treatment method, some improvements on this approach are suggested.

Knowledge of the physical and chemical characteristics of caustic magnesia indicate that a hybrid semi-passive treatment plant based on the passive dissolution of caustic magnesia could substantially lower the capital and operating cost of a treatment system in Big Swamp, as well as significantly lowering the environmental and OH&S risks related to its operation. This novel approach involves the passive dissolution of an alkaline reagent (caustic magnesia) using clean catchment water to produce and deliver an alkalinity enriched solution into acid water flows in Big Swamp. By treating the acid water at the source, this optimises the protection of Big Swamp. This approach is also expected to be a much lower capital and operating treatment cost option, and represents a substantially lower environmental and OH&S risk method. At present this novel but unproven method is the current preferred treatment strategy for Big Swamp.

In order to confirm the benefits of using a semi-passive caustic magnesia treatment approach at Big Swamp, we need to clarify the dissolution behaviour of aggregate caustic magnesia in distilled water. A series of laboratory tests have been designed to achieve this. If the outcomes of the laboratory testwork identify that appropriate alkalinity loads can be released from commercial caustic magnesia, then we propose to conduct a series of small-scale field trials using water from Boundary Creek upstream of Big Swamp to confirm the performance of the caustic magnesia in a natural setting. A list of equipment and the general layout of the trials in Big Swamp, along with the proposed water quality monitoring locations and parameters, is documented.

1. INTRODUCTION

Barwon Water has engaged Earth Systems to assess the benefit of conducting a small-scale field trial of a novel water treatment technology to assist in safely managing the acidity loads (acid and metals) emanating from acid sulfate soils (ASS) in Big Swamp (Boundary Creek) near Yeodene, Southwestern Victoria. As part of the scope of works for this proposed small scale treatment trial, this report provides a desktop review of current active and passive treatment systems and technologies and outlines the rationale for developing the proposed innovative semi-passive water treatment technology. A trial treatment plan is also developed and documented to outline how the trial is to be implemented as part of the remediation strategy for Big Swamp.

ASS are naturally occurring sediments and soils that contain iron sulfides, predominantly pyrite (FeS_2) (Sullivan et al. 2018). These soils are commonly found in low-lying coastal and estuarine areas (often Holocene in age), as well as certain inland settings and some artesian freshwater wetlands. While these soils are water saturated, they are relatively benign. Exposure of these sulfidic soils to atmospheric oxygen, either by disturbance, excavation, or lowering of the water table, can result in the production of low pH (acid) water with elevated dissolved metal(oid)s (eg. Fe, Al, Mn, As, Zn, Ni and Cu).

The production of low pH and high metal concentrations are the result of a series of complex oxidation, hydrolysis and precipitation reactions beginning with pyrite oxidation that can be simplified by Reaction 1.

$$FeS_2(s) + 3.75\ O_2 + 3.5\ H_2O \Leftrightarrow Fe(OH)_3(s) + 2\ SO_4^{-2} + 4\ H^+ \qquad \text{(Reaction 1)}$$

The acid (H^+) produced is measured by pH (ie. pH=-$\log_{10}[H^+]$), the generation of which will continue until all available iron sulfides are oxidised, or atmospheric oxygen is excluded from the system, generally via permanent flooding or increases in groundwater levels. Elevated dissolved sulfate concentrations also result from the overall process (Equation 1).

Acid released by this process is available to react with other minerals and compounds in the soil, resulting in the production of dissolved metals. This dissolution process consumes acid, but some of these dissolve metals have the potential to regenerate acid (H^+) from the hydrolysis and precipitation of their respective metal hydroxides (Reactions 2a & 2b).

$$M^{+2} + 2\ H_2O \Leftrightarrow M(OH)_2\ (s) + 2\ H^+ \quad \text{(where } M^{+2} = Cu^{+2}, Ni^{+2}, Pb^{+2}, Mn^{+2}, Zn^{+2}\text{)} \qquad \text{(Reaction 2a)}$$

$$M^{+3} + 3\ H_2O \Leftrightarrow M(OH)_3\ (s) + 3\ H^+ \quad \text{(where } M^{+3} = Al^{+3}, Fe^{+3}\text{)} \qquad \text{(Reaction 2b)}$$

The potential for these dissolved metals to regenerate acid by this process is known as *latent* or *metal acidity*. It is important to understand that this metal acidity is dependent on which metals are present in solution, and that changes in pH influence which metal hydroxides precipitate.

Net or *Total Acidity* refers to the combined concentrations of H^+ (acid) measured by pH, and the potential H^+ generated from the precipitation of the metal hydroxides. Total acidity is often reported in milligrams of calcium carbonate ($CaCO_3$) equivalent per litre (mg $CaCO_3$/L), as this provides an indication of how much base, or alkalinity, is required to neutralise the waters' acidity. Total acidity can also be reported in mg H_2SO_4/L. This provides an indication of how much acid needs to be neutralised. Both units are essentially equivalent as the atomic weights of $CaCO_3$ and H_2SO_4 are very similar. Acidity is effectively a measure of how much treatment the water requires to raise 1 litre to a pH to 8.3 (by convention). The product of total acidity and flow rate (eg. acidity concentration (mg $CaCO_3$/L) x flow rate (litres per unit time)), is known as the *acidity load*. Acidity loads are normally reported in kg of H_2SO_4 (acid) or kg of $CaCO_3$ (base) per unit time (eg. day /year). These values are essentially a measure of treatment reagent requirements.

Any treatment of ASS impacted water from Big Swamp will need to produce sufficient alkalinity to neutralise acidity from the sulfide oxidation. Limited available data suggests that acidity concentrations from Big Swamp can be as high as 300 mg $CaCO_3$/L with average daily acidity loads of 200-400 kg $CaCO_3$/day, and peak values of at least twice this.

The process responsible for acidity generation in ASS is referred to as acid and metalliferous drainage (AMD) or sometimes as acid rock drainage (ARD). This process is also a common issue impacting water quality at mine sites globally. Extensive research has been conducted into identifying the optimum technologies to treat the acidity loads generated from sulfide oxidation associated with AMD/ARD. Such technologies vary from high-cost, highly engineered water treatment plants using manufactured chemical reagents to lower cost systems using naturally occurring materials placed within drainage pathways. The wide range of technologies reflects the variable physical and chemical nature of water affected by AMD/ARD processes.

This desktop review of treatment technologies provides and overview of the range of technologies and the reagents they employ, along with the benefits and limitations of the methods and reagents, and their application to the treatment of water quality being generated and discharged from Big Swamp.

The relative benefits and limitations of passive and active treatment systems are briefly assessed. A new hybrid, semi-passive treatment system is identified and described.

Earth Systems proposes to conduct further testwork on the new hybrid treatment system.

Once the rationale for the passive application of caustic magnesia at Big Swamp has been developed, the proposed treatment plan and related monitoring strategy is documented.

2. ACTIVE AND PASSIVE WATER TREATMENT SYSTEMS

2.1 Overview

Current water treatment technologies can be categorised as either 'active' or 'passive', with both potentially combining physical, biological, and chemical approaches. The principal aim of both types of treatment is to lower total acidity, meaning raising the pH and lowering dissolved metal concentrations. Some treatment methods and reagents also permit a decrease in sulfate salinity. A broad range of treatment approaches are available for dealing with acid and metal discharges associated with sulfide oxidation (ie. ASS or AMD related to mining scenarios). The most common treatment mechanisms related to these systems are listed in Table 2-1.

Table 2-1: Chemical, physical and biological mechanisms for the treatment of AMD/ASS.

Treatment Mechanisms	
pH control	Oxidation / reduction (± lime)
Adsorption / absorption	Electrochemistry
Complexation	Sedimentation
Chelation	Flocculation-filtration-settling (+ lime)
Natural Biological Mediation (eg. wetlands)	Ion Exchange (+ lime)
Engineered Biological Mediation	Crystallisation
Reverse Osmosis (± lime)	Controlled evaporation

The single most common treatment mechanism for managing acid and metal discharge is pH control, but both redox and biological aspects are often used in parallel. The following sections focus largely on systems that facilitate pH control and associated metal removal.

For the purposes of water treatment at Big Swamp, the primary treatment objective would be to lower acidity concentrations from approximately 300 mg $CaCO_3$/L to less than 20 mg $CaCO_3$/L and maintain baseline pH values between 6 and 9. Key physicochemical aspects of Big Swamp drainage that will influence suitable treatment technologies include:

- Highly variable seasonal flow rates (eg. 5 L/s to 1200 L/s);
- Relatively high acidity values (30-300 $CaCO_3$/L);
- Relatively high and seasonally highly variable acidity loads (eg. averaging 300-400 kg $CaCO_3$/day, and occasionally rising to a maximum of at least 700 kg $CaCO_3$/day);
- Relatively high soluble Al concentrations (eg. 10-30 mg/L) that severely limit many passive treatment approaches due to reagent passivation by treatment precipitates.

One of the key chemical parameters that helps to define whether an active or passive treatment system is most appropriate for a specific treatment task is acidity load. In general terms, if the daily acidity load from a pollution source is <150 kg $CaCO_3$/day, then it is logical to consider the deployment of a passive treatment system. Other features of the site or water chemistry may preclude the use of passive systems, but a good initial filter is the 150 kg $CaCO_3$/day acidity load cutoff value. Under most circumstances, daily acidity load values greater than 150 kg $CaCO_3$/day would strongly recommend that active treatment systems are more likely to succeed than a passive approach (refer to Figure 2-1).

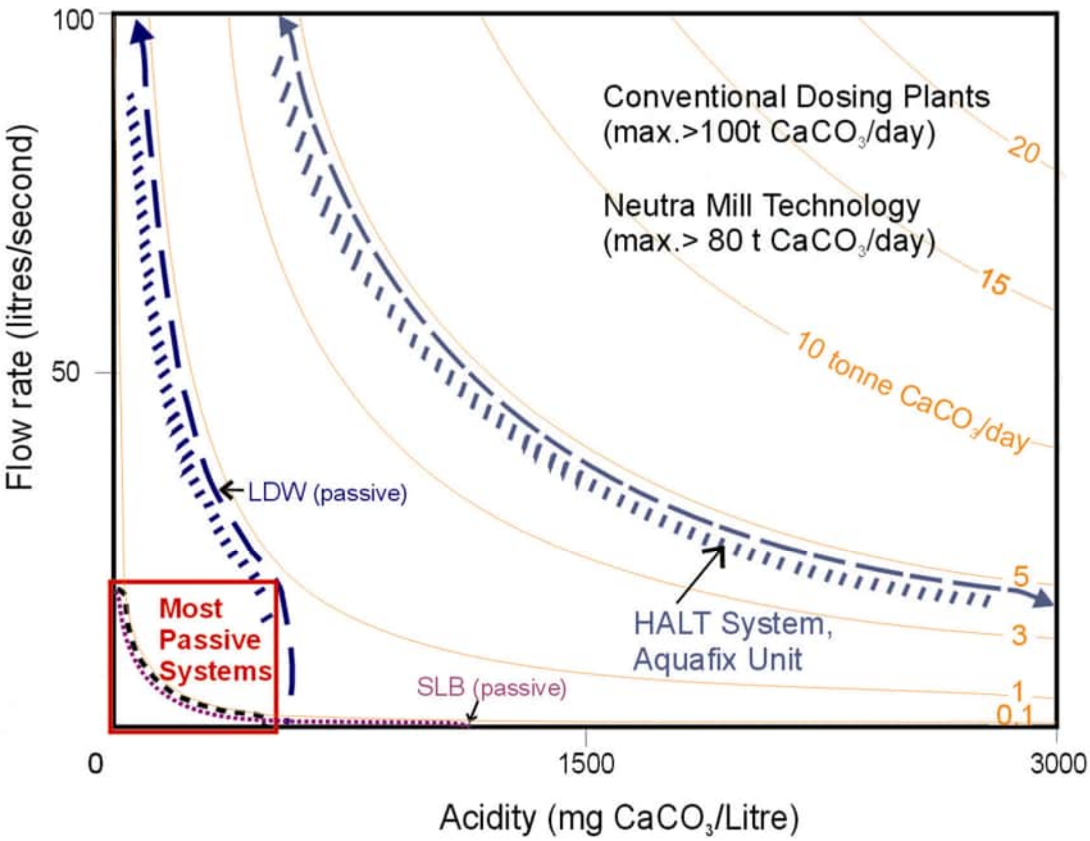

Figure 2-1: Acidity load guidelines for selecting effective active and passive treatment systems. Contours shown are for acidity loads in tonnes $CaCO_3$/day (see text for abbreviations). The acidity load field for passive systems (red box) has been expanded in Figure 2-3. (Taylor and Waters, 2003).

2.2 Active Treatment Systems

Active treatment systems by definition require:

- A fully engineered and largely automated fixed plant system;
- External electrical power source;
- Routine reagent addition (eg. continuous);
- Daily operational overview and routine maintenance;
- A generally high capital cost (>>$1 million);
- A generally very high operating cost (>>$2,000/day).

Active treatment approaches fall into two main categories: (i) fixed plant and (ii) in-situ. The first category comprises conventional active treatment plants that are fixed in location and typically require pumping of AMD to the plant (Figure 2-2).

The key components of most pH control based active treatment systems comprise:

- Acid water collection and storage system;
- Infrastructure to deliver acid water to the treatment plant;
- Neutralant storage system (eg. hydrated lime silos);
- Neutralant mixing and delivery system;

- Multiple acid-base reactor / neutralisation / aeration tanks;
- Flocculation mixing, storage and dosing system;
- Sludge settling and clarification system;
- Sludge dewatering / storage / disposal system.

The main benefit of fixed plant active treatment systems is they can be designed to:

- Treat essentially any flow rate (eg. 5 m^3/second);
- Treat almost any acidity load (eg. 200 tonnes $CaCO_3$/day);
- Achieve virtually any water quality targets.

In-situ active treatment approaches use portable land-based or water-based systems to conduct treatment within or adjacent to an affected water body (eg. swamp) or stream. Hence, reagents are mixed into the water body or flow, rather than the flow being directed into a fixed plant and then dosed. In situ treatment systems often avoid the need to manage treatment precipitates (ie. sludge).

Active treatment systems (fixed plant or in-situ) could be successfully applied to deal with drainage from the Big Swamp. Systems could be deployed at multiple locations and there are a range of potentially suitable neutralising reagents. Key drawbacks for either type of active system include very high capital and operating costs. Any active treatment system installation in or near Big Swamp would be disruptive and carry the risk of environmental spills of fuel and/or reagent.

Figure 2-2: Typical fixed plant, hydrated lime dosing treatment (high density sludge) system for acid and metalliferous drainage.

2.3 Passive Treatment Systems

Passive treatment systems use natural biological and geochemical processes to improve water quality (Skousen et al 2017). There are a broad variety of passive treatment systems available, but they operate on broadly similar principles: passive flow-through natural reactive substrates to assist with acid neutralisation and metal precipitation, sometimes employing bacterial activity to enhance alkalinity generation. A range of common systems are listed in Table 2-2 and summarised in Attachment A.

Table 2-2: Passive treatment systems.

Biological Systems	Geochemical Systems
Aerobic/ Anerobic Wetlands	Anoxic Limestone Drains (ALD)
Vertical Flow Wetlands	Open Limestone Channels (OLD)
Bioreactors (RAPS and SAPS)	Alkaline Leach Beds (SLB)
Permeable Reactive Barriers (PRB)	Limestone Diversion Wells (LDW)

Passive treatment systems, by definition, display the following characteristics:

- One-off installation of largely in-ground, passive flow-through systems;
- Most commonly based on installation of aggregate-carbonate based reactive media, with or without the inclusion of organic matter;
- No external power or complex pumping or piping infrastructure employed;
- Often designed with sufficient carbonate and/or organic matter to treat the influent water chemistry for 10-30 years of operational life;
- Largely maintenance free;
- No ongoing reagent addition required during design life;
- Minimal routine monitoring necessary;
- Unsuitable for high flow or high variability flow scenarios;
- Unsuitable for very low pH water;
- Not suited to high acidity water or highly variable acidity scenarios;
- Largely limited to acidity loads of <150 kg $CaCO_3$/day (refer to Figure 2-3);
- Inappropriate for waters with soluble aluminium concentrations in excess of ~2-3 mg/L.
- Only applicable to water chemistry where metal concentrations respond to pH change or sulfide precipitation;
- Will cease to be chemically effective at the end of their design life;
- Often requires disposal of sulfidic or precipitate rich substrates at the end of their operational life;
- Generally a moderate capital cost (~$500,000-$2 million);
- Generally a very low operating cost (~$5,000/year).

The design of passive systems should:

- Accommodate slow reaction rates and high residence times for water-carbonate reactions;
- Attempt to minimise precipitate armouring or at least accommodate precipitate accumulation (ie. provide sufficient porosity to avoid permeability reduction);
- Provide sufficient carbonate and/or organic matter substrate to manage the influent sulfate and metal loads over the design life of the system;
- Consider the importance of high-flow bypass systems;
- Appreciate the chemical limitations of passive systems (eg. poor manganese removal).

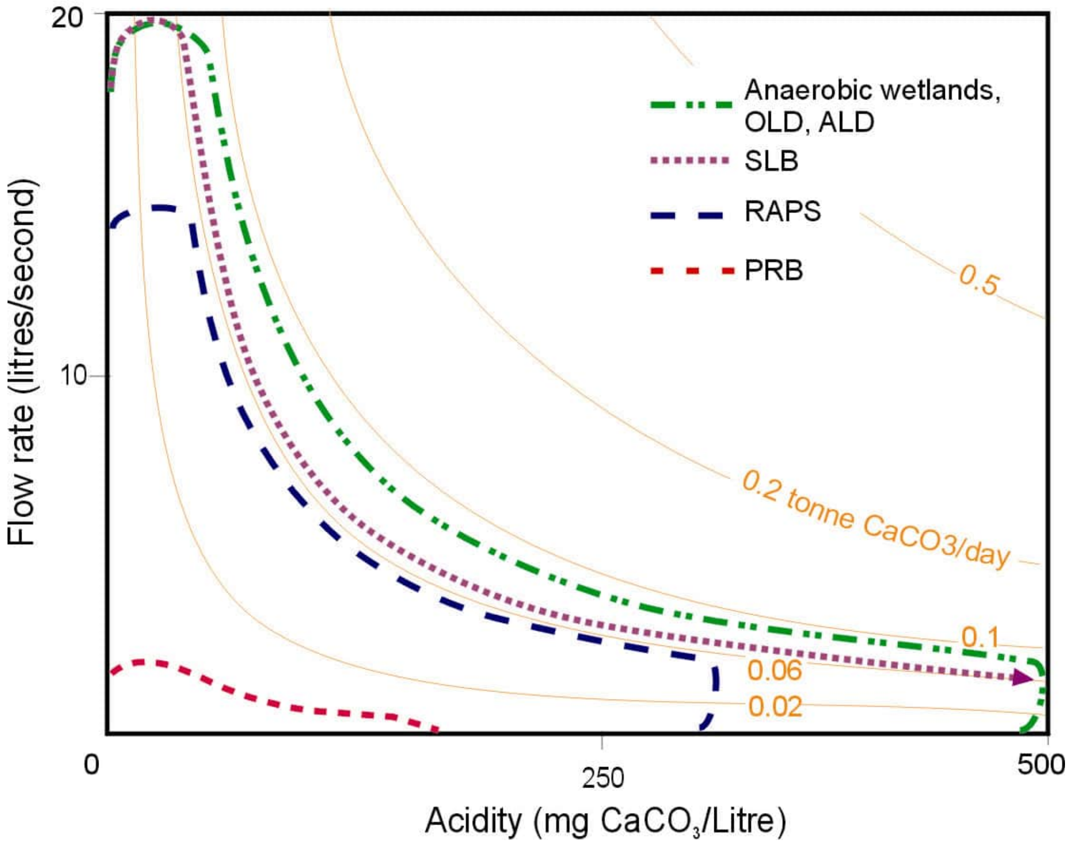

Figure 2-3: Acidity load guidelines for selecting effective passive treatment systems. Contours shown are for acidity loads in tonnes $CaCO_3$/day (see Table 2-2 for abbreviations). (Taylor and Waters, 2003).

Based on the typical characteristics and performance of passive treatment systems, it is clear that they have limited application to the treatment of water in Big Swamp. Key limitations include:

- Current knowledge of acidity loads (acidity x flow rate) at Big Swamp indicate that they are too high for effective treatment under most flow scenarios.
- Very large areas of land would need to be set aside to install a passive system based on the current acidity loads (eg. ~12 Ha).
- Limited data on water quality suggests that armouring of limestone with soluble aluminium may be an issue.
- High flows and highly variable flows in Big Swamp are not ideal for most passive treatment systems.

3. CHEMICAL REAGENTS USED FOR pH CONTROL

Most pH control treatment technologies, whether active of passive, require the use of an alkaline chemical reagent to raise the pH of the water and effect metal precipitation. The most common neutralising reagents are solid calcium-based reagents due to their widespread availability (worldwide), low cost, neutralisation efficiency and relative ease of use. Another benefit is that some Ca-based reagents can facilitate salinity management by lowering soluble sulfate in some waters by precipitating gypsum. Other alkaline reagents, both in solid and/or liquid form, are available and are used selectively depending on their availability and application.

Commonly used reagents along with their chemical properties are summarised in Table 3-1.

Table 3-1: General chemical properties (saturation pH and typical solubility) and cost per tonne of acid neutralised associated with some commonly used neutralisation materials (adapted from Taylor et al. 2005).

Neutralisation material	Saturation pH	Solubility in neutral water @ ~25•C	Cost / Tonne Acid Neutralised
Quicklime (CaO)	12.4	1,300-1,850 mg/L	$ 180-300
Hydrated lime ($Ca(OH)_2$)	12.4	1,300-1,850 mg/L	$ 300-400
Limestone ($CaCO_3$)	8-9.3	15-30 mg/L (effective)	$ 40-80
Dolomite ($CaMg(CO_3)_2$)	8-9.5	10-30 mg/L (effective)	$ 40-80
Magnesite ($MgCO_3$)	9.5-10	10-50 mg/L (effective)	$ 50-100
Caustic magnesia (MgO)	9.5-10.8	1-200 mg/L	$ 330-450
Mg Hydroxide ($Mg(OH)_2$)	9.5-10.8	1-200 mg/L	$ 330-450
Soda Ash (Na_2CO_3)	10.9-11.6	340 g/L	$ 530-700
Caustic Soda ($NaOH$)	14	1,000 g/L	$ 1,500-2,000
Ammonia (NH_4OH)	11-12	310 g/L	?

The key factors controlling reagent and equipment selection for chemical neutralisation are listed in Table 3-2.

Table 3-2: Chemical neutralisation issues for active treatment systems.

Issue	Comment
Reagent availability and cost	Important in determining the most suitable reagent for the treatment system.
Reagent purity	Critical to system operation as impurities can alter chemical processes / conditions, leading to ineffective or incomplete treatment.
Reagent reactivity	Solubility and dissolution kinetics must be suited to site-specific AMD generation rates and resulting acidity Loads.
Acidity loads	The total mass of reagent to be supplied per unit time, corresponding to the acid and metal loads of a water, affects the choice of reagent and equipment.
Reagent supply, storage, delivery and dispensing techniques (materials handling)	Availability, cost and properties of treatment reagents and associated handling equipment can influence selection of AMD treatment technologies.
Occupational health and safety	Some reagents (eg. quicklime) have significant health and safety risks during storage and handling. Careful handling may be required to avoid burns, dust production, etc.
Adequate mixing / reactions times / aeration techniques	Effective treatment requires sufficient aeration, mixing and reaction times to enable complete neutralisation of AMD.

Issue	Comment
	Aeration may be needed to create appropriate redox conditions for treatment. For example, oxidised conditions may be required to convert total acidity (associated with reduced metals) into acid (H^+ ions) prior to full neutralisation of the water. Armouring of reagents can be minimised by continuous mixing and abrasion of neutralisation reagents.
Efficiency of reagent use	Reagent dosing needs to be carefully controlled to avoid saturation with respect to the neutralising reagent, and thus maximise reagent use efficiency.
Properties of reagent in water	Reagent impurities may adversely affect the treatment process, for example by affecting redox conditions or introducing new contaminants to the AMD.
Sludge / precipitate formation	The cost and logistics of sludge management are affected by the mass and volume of sludge produced, the relative proportions of solid/water, and the chemical composition and stability of treatment precipitates in the sludge. The settling, handling, storage, stability and disposal of sludge can all add significantly to the treatment costs. Reagents can be chosen to either optimise of minimise sludge formation.
Power source	Availability of a suitable power supply may influence selection of AMD treatment system and reagent, particularly for active and portable treatment systems.
End use of water / treatment targets	Treatment objectives depend on the desired end use of treated water. Objectives may be related to off-site discharge, recycling of water with the site, or infrastructure protection. Final water quality standards or beneficial uses can influence the selection of reagents and dispensing equipment. Sulfate removal specifications limit suitable reagent types, handling equipment needs or ancillary equipment requirements.

Reagents that exhibit high solubility in clean water are typically used in active treatment systems to deal (easily) with very high and highly variable acidity loads and flows. Those reagents with very low solubilities are normally only suitable for passive treatment systems where they need to be exposed directly to acid water, thereby raising their solubility to more useful levels. The downside to reacting low solubility neutralants with acid water is that treatment precipitates form directly on the reagent aggregates/particles, causing coating (passivation) of their reactive surfaces. Most reagent passivation is the result of aluminium hydroxide deposition due to its amorphous and largely impermeable nature.

3.1 Calcium-based Reagents

Calcium-based reagents are the most common pH control reagents in both active and passive treatment systems. These reagents range in their chemical properties, handling methods and associated OH&S issues, but are widely available at low to moderate cost across the world. The precipitates produced from treatment of acid water from ASS sources is generally dominated by metal(loid)s oxides and oxy-hydroxides (eg. Fe, Al, Mn, Zn, Ni, As and Cu) and commonly gypsum.

3.1.1 Quicklime

Quicklime (CaO) is a manufactured reagent (calcined from $CaCO_3$), available in powdered or aggregate form, primarily used in active treatment systems. Aggregate quicklime decomposes rapidly on contact with water to provide a solution of a slurry. It is not possible to maintain the aggregate form after contact with water. The key chemical properties of quicklime relevant to its use for neutralisation are:

- Saturation pH 12.4;
- Solubility @ 20°C, 1,300-1,850 mg/L;

- Soluble alkalinity of up to ~1,750-2,500 mg/L $CaCO_3$ equivalent in near neutral water;
- Reacts with water to produce hydrated lime, and if left to react with atmospheric CO_2 can reform $CaCO_3$ once again after weeks to months;
- The hydration process is highly exothermic and is sufficient to boil water under some circumstances, making it particularly difficult and dangerous to handle.

The range in chemical properties, including dissolution and solubility kinetics, is influenced by the grainsize of the limestone and its calcination temperature.

Due to the high treatment pH's achievable using quicklime most metals can be precipitated from solution, although at higher pH's some metals (eg. Al) may begin to redissolve (ie. exhibit amphoteric behaviour).

Being a calcium-based reagent quicklime may also result in some removal of dissolved sulfate concentrations by precipitating gypsum ($CaSO_4.2H_2O$).

Specialist storage and handling equipment is required to prevent contact with moisture and to prevent contact with skin due to its caustic and highly exothermic nature. As a result of its saturation pH and specialist handling requirements, quicklime is almost exclusively used in active treatment technologies.

3.1.2 Hydrated lime

Hydrated lime ($Ca(OH)_2$) is a manufactured dry powdered reagent that can be added as either as a controlled dispersion of powder or more commonly as a lime slurry. The key chemical properties of hydrated lime relevant to its use for neutralisation are:

- Saturation pH 12.4;
- Solubility @ 20°C, 1,300-1,850 mg/L;
- Soluble alkalinity of up to ~1,750-2,500 mg/L $CaCO_3$ equivalent in near neutral water;
- Hydrated lime can react with moisture and CO_2 in air resulting in its eventual transformation back to $CaCO_3$.

Due to the high treatment pH's achievable using quicklime most metals can be precipitated from solution, although at higher pH's some metals (eg. Al) may begin to redissolve (ie. exhibit amphoteric behaviour).

Being a calcium-based reagent hydrated lime may also result in some removal of dissolved sulfate concentrations by precipitating gypsum ($CaSO_4.2H_2O$).

Specialist storage and handling equipment is required to prevent contact with moisture and to minimise contact with skin. As a result of its saturation pH and specialist handling requirements hydrated lime is almost exclusively used in active treatment technologies.

3.1.3 Limestone / Dolomite

Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are naturally occurring rocks/minerals and display varying purity and grainsize during quarrying. Major impurities include common rock forming minerals including quartz, clay minerals and often some carbon, which effectively provide no additional neutralising capacity. The key chemical properties of limestone/dolomite relevant to its use for neutralisation are:

- Saturation pH 9.3 (theoretical), 6.5-8.0 (effective);
- Solubility @ 20°C ,15-30 mg/L;
- Alkalinity of up to 15-30 mg/L $CaCO_3$ equivalent in near neutral water.

Limestone and dolomite are both only sparingly soluble in near-neutral waters and therefore are often only used where they are in direct contact with acid waters so that their solubility is enhanced. This combined with their low cost and widespread availability is the primary reason they are used in passive treatment systems.

3.1.4 Other Ca-based Reagents

There are a few other calcium-bearing reagents that have been used for neutralisation treatment including:

- cement kiln dust, and
- lime kiln dust.

These reagents have limited use due primarily to common impurities (thallium and chromium), highly variable composition and limited availability.

While generally lower cost than pure quicklime or hydrated lime, these reagents still require relatively specialised handling and dispensing equipment.

3.2 Magnesium-based Reagents

Magnesium-based reagents are less commonly used than calcium-based reagents for pH control largely because they are less widely available and partly because they display much lower solubility in clean water than Ca-based reagents. Precipitates from the neutralisation of acid and metalliferous drainage using caustic magnesia or magnesium hydroxide will likely generate oxides and oxy-hydroxides of metal(loid)s (eg. Fe, Al, Mn, Zn, Ni, As and Cu), but no gypsum ($CaSO_4.2H_2O$) due to the lack of calcium. In many treatment scenarios, lower sludge volume is regarded as a key benefit of employing Mg-based neutralants, and in others it is regarded as a limitation in that it cannot lower sulfate concentrations via gypsum precipitation.

3.2.1 Caustic Magnesia and Magnesium Hydroxide

Caustic magnesia (MgO) is a manufactured reagent (calcined from magnesite: $MgCO_3$) available in powdered or aggregate form. When added to water it forms magnesium hydroxide. Caustic magnesia is consumed directly by humans as a pharmaceutical agent (health supplements / antacids / constipation treatment). Magnesium oxide and hydroxide also have agricultural applications, are employed in glass manufacture as a network modifier, and are used in water treatment as a source of alkalinity.

Caustic magnesia / magnesium hydroxide has several key properties relevant to its use as a neutralant including:

- Reacts with water to form magnesium hydroxide ($Mg(OH)_2$);
- Saturation pH 10.8 (theoretical), pH 9.0-10 (effective);
- Relatively low solubility @ 20°C, 1-200 mg/L (effective);
- Alkalinity of around 500 mg/L $CaCO_3$ equivalent in near neutral water;
- Low solubility in neutral water relative to hydrated lime;
- Relative to carbonate minerals in near neutral water, appropriately calcined caustic magnesia and magnesium hydroxide demonstrate a much higher solubility and far more rapid dissolution kinetics;
- Sustained elevated levels of alkalinity release compared to limestone;
- Aggregate remains physically intact following contact with water;

- No known tendency to react in-situ to form less soluble mineral phases such as carbonate over time.

Caustic magnesia is produced from magnesite ($MgCO_3$) and therefore commonly contains variable amounts of calcite ($CaCO_3$) impurities. When calcined, the caustic magnesia can have up to 10% CaO which can provide additional alkalinity. Like quicklime, the grainsize and calcination temperature of the magnesite both influence the chemical properties of the caustic magnesia product.

The chemical and physical properties of caustic magnesia and solid magnesium hydroxide make it much safer and easier to handle and dispense than Ca-bearing reagents and is only weakly exothermic on hydration. This means that less specialised equipment and fewer precautions are required for handling and dispensing. For example, caustic magnesia is commonly applied to land (in aggregate form) in agricultural applications as a stock feed additive and to improve pastures by contributing soluble magnesium via rainfall interaction. There appear to be fewer concerns regarding highly alkaline runoff from such applications as there would be for application of lime-based reagents.

Caustic magnesia displays quite low OH&S and environmental risks associated with spillage or overdosing.

Caustic magnesia / magnesium hydroxide costs a similar amount per tonne of acid neutralised compared to hydrated lime. It is approximately five times lower cost per tonne of acid neutralised than caustic soda.

The solubility of caustic magnesia / magnesium hydroxide is generally too low for active treatment systems and is largely too high for passive treatment systems (ie. for direct contact with acid water).

3.3 Other Alkali Reagents

3.3.1 Caustic soda

Caustic soda (NaOH) is available as concentrated liquid (up to ~46 wt.%) or as water-soluble pellets. The key chemical properties of caustic soda relevant to its use for neutralisation include:

- Saturation pH 14;
- Solubility @ 20°C, 450,000 mg/L;
- Alkalinity of ~560,000 mg/L $CaCO_3$ equivalent in near neutral water at a concentration of ~46 wt.%.

Caustic soda is highly soluble in water and disperses rapidly. These properties result in a rapid pH response of the treated water. The use of caustic soda for treatment requires careful monitoring to prevent overdosing, especially in settings of variable acidity load and variable flow. Caustic soda is generally only used in fully engineered active treatment systems. Caustic soda display significant OH&S and environmental risks associated with spillage or overdosing.

Caustic soda is a high-cost reagent and has specialist handling requirements due to its highly caustic nature. In temperatures below ~6°C a 46 wt.% NaOH solution can freeze in pipelines causing issues during dosing.

3.3.2 Soda Ash

Soda ash (Na_2CO_3) is manufactured often as solid briquettes. It is commonly gravity fed to water from bins. The key chemical properties of soda ash relevant to its use for neutralisation are:

- Saturation pH 10.9-11.6;
- Solubility @ 20°C, 340,000 mg/L;

- Alkalinity of ~425,000 mg/L $CaCO_3$ equivalent in near neutral water depending on concentration of solution.

The high saturation pH means that treatment using soda ash needs to be carefully monitored to prevent overdosing. As a result, soda ash is generally only used in active treatment systems.

3.3.3 Other reagents

There are several other reagents that have been used for pH control during treatment. These include:

- Ammonia (NH_4OH);
- Potassium hydroxide (KOH);
- Barium hydroxide ($Ba(OH)_2$);
- Hydroxyapatite ($Ca_5(PO_4)_3(OH)$);
- Barium carbonate ($BaCO_3$);
- Red mud (bauxite processing residue containing Al hydroxides and Ca carbonates).

Key issues with all these reagents include their variable alkalinity, high cost, and limited availability.

4. NEW APPROACH TO ACID WATER TREATMENT

Based on a detailed knowledge of neutralisation reagents and acid water treatment systems, Earth Systems noted that caustic magnesia demonstrates a higher solubility and more rapid dissolution kinetics than all carbonate minerals. It was also noted that the lower solubility of caustic magnesia relative to lime-based reagents was accompanied by an enhanced physical integrity during dissolution – caustic magnesia remains in aggregate form as it slowly dissolves, rather than decomposing into a slurry or a solution. These features permitted the formulation of a new approach to treatment that involves passing clean water through a reactor vessel containing aggregate caustic magnesia. Using unpolluted water to produce elevated soluble alkalinity prevents coating of the reagent with reaction precipitates. With suitable residence time in the reactor, the clean water can become enriched (possibly saturated) with respect to the caustic magnesia, and the resulting alkaline fluid can then be piped directly (and passively) into an acid water stream.

These new systems are neither active or passive systems, and are regarded as semi-passive as they display the following characteristics:

- Fully engineered systems that are largely portable;
- Much lower capital and operating cost relative to active systems;
- Lower capital cost relative to most passive systems;
- Higher operating cost than most passive systems;
- Able to treat significantly higher acidity loads than passive treatment systems;
- Ideally having no external power requirements;
- Require regular but infrequent reagent addition (many months);
- Can operate unattended for extended periods (ie. months);
- Have lower environmental and OH&S risks due to relatively benign reagent.

While not commercially proven, this novel approach can provide some of the key benefits of both active and passive treatment technologies such as:

- System could be transportable, so could be installed and removed with minimal impact on the environment.
- Could be located at the head of the swamp to optimise ecosystem protection within the swamp.
- Treatment precipitates would largely be trapped in the swamp, thereby mitigating / minimising impacts in Boundary Creek / Barwon River and the ocean.
- This approach requires no power if pre-reactor clean water and post reactor alkalinity loaded water can flow to and from the reactor under gravity.
- Alkalinity loads from a caustic magnesia reactor are expected to be sensitive to flow rate (ie. increased flow should be proportional to increased alkalinity release), thereby providing a simple and potentially passive mechanism to adjust dose rates as acidity loads change (laboratory and field work will help to confirm).
- Using caustic magnesia to produce alkalinity will minimise precipitate formation (ie. no gypsum).
- The residence time required for interaction between caustic magnesia and water means that large volumes of caustic magnesia are necessary for each reactor vessel, and this in turn means that reagents do not require regular replenishment (eg. possibly every 6-12 months).
- Low effective saturation pH values for caustic magnesia minimises its potential for environmental impacts associated with accidental spills.
- The effective saturation pH can also minimise the need for complex control systems to prevent overdosing.
- The chemical and physical properties of caustic magnesia also make it a much safer compound to transport and handle in terms of OH&S issues.

- The capital expenditure costs for a caustic magnesia reactor will be quite low relative to a full automated active treatment system.
- Caustic magnesia costs approximately five (5) times less per tonne of acid neutralised than caustic soda (delivered to site).
- Operating costs should be minimal if the system is gravity fed, as no regular maintenance should be necessary.
- Unlike fully passive treatment systems, there will be no spent reaction substrates post treatment.

Key limitations of this new approach include:

- Caustic magnesia is more limited in its application to acid water treatment issues because it is significantly less soluble in clean water than most other Ca or Na based reagents. It is possible that a reactor containing 50 tonne of caustic magnesia may only be able to dispense a maximum of between 500 and 1,000 kg of $CaCO_3$ alkalinity per day. Laboratory testwork and field trials will assist in clarifying these maximum dose rates.
- Favourable topography and a proximal source of unpolluted water (with appropriate flows) is necessary for caustic magnesia systems to remain passive and successfully treat water.
- A mechanism is required to passively vary the alkalinity rate as a function of the flow rate in the polluted system.
- Unlike conventional passive systems that may not need to be replenished with reagent substrates for 10-30 years, the caustic magnesia reactor would need routine reagent replacement (eg. 6-12 months, depending on acidity loads).

A treatment approach that requires no electrical power, no daily human oversight and no sludge management would normally be classified as passive. However, the need for regular reagent addition suggests that the definition of semi-passive is more appropriate for this new treatment approach.

4.1 Appropriate Water Treatment at Big Swamp

The key physicochemical features of the acid and metalliferous drainage from Big Swamp, described in Section 2.1 impose clear constraints of suitable treatment technologies, which are referred to in Sections 2.2 (active) and Section 2.3 (passive). Most active treatment systems could readily handle the water chemistry (high aluminium and low redox state), and the extreme variability in acidity and flow rate. A potential active treatment option using caustic soda is described below (Section 4.1.2). This option is predicted to be slightly lower risk and cost than that proposed by Jacobs in Barwon Water (2021).

Conventional passive treatment systems appear to be uniformly inappropriate for dealing with drainage from Big Swamp on the basis of excessive and highly variable acidity loads, elevated soluble aluminium concentrations, and excessive seasonal flow rates. Not only would anaerobic wetland systems not be able to cope with the elevated soluble aluminium concentrations, but they would require the construction of a wetland of similar dimensions to the entire existing swamp (eg. min. 12 Ha). Even large wetlands could not easily cope with the high flows that are seasonally encountered in Big Swamp.

The semi-passive caustic magnesia treatment approach proposed here avoids water chemistry constraints (metal concentrations or redox issues), surface area requirements and limitations posed by highly variable acidity loads due to seasonal fluctuations in acidity and flow. The semi-passive approach remains a good option for Big Swamp treatment (refer to Section 4.1.1).

4.1.1 Semi Passive treatment with Caustic Magnesia

A good treatment option that should fulfil the water chemistry, flow rate and acidity load requirements of Big Swamp is the novel semi-passive system descried above. Theoretically, the caustic magnesia treatment system should be fully capable of managing the acidity loads within and downstream of Big Swamp. As described in Section 3, there are several potential cost, risk minimisation and operational advantages of using caustic magnesia over caustic soda.

The main risk associated with this treatment process is that it is currently not commercially proven. The only way of quantifying the benefits and clarifying the capital and operating costs of the semi-passive system is to conduct laboratory testwork to measure the solubility and dissolution rates of various samples of caustic magnesia as a function of residence time and grainsize. Such data would identify alkalinity release rates as a function of flow rate (residence time) through a caustic magnesia reactor. This data would then need to be used to design a small-scale caustic magnesia reactor to test in the field. Similar tests to those performed in the laboratory would need to be conducted in the field on Boundary Creek water upstream of Big Swamp.

Barwon Water has committed to assessing the likely performance of the semi-passive caustic magnesia treatment system at Big Swamp through laboratory testwork.

4.1.2 Active treatment with Caustic Soda

If Barwon Water finds that semi-passive caustic magnesia treatment is not suitable for Big Swamp, an active treatment system can be utilised. Barwon water (2021) proposed treatment contingency options for Big Swamp involving a chemical dosing system using caustic soda (NaOH). The proposed system would have a liquid chemical storage tank with dosing controlled by a pH monitoring system. Power would be supplied to the system via diesel generator, with some solar powered elements. The system along with dosing points for the alkaline reagent was proposed to be downstream of Big Swamp.

Earth Systems regards this type of active treatment system to be fully capable of handling the treatment requirements of Big Swamp under virtually all circumstances. Such a system would be capable of handling significant variations in flow and acidity, as well as any component of the water chemistry. The key drawbacks of such a system include:

- Relatively high capital cost;
- High operating cost, with regular refuelling (every few days) and routine reagent addition (eg. every 4-6 days), as well as some ongoing maintenance costs;
- Very high cost per tonne of acid neutralised by using caustic soda;
- Significant OH&S issues related to the transport and handling of caustic soda;
- Greater potential environmental issues related to the accidental spillage or overdoing of caustic soda due to its high saturation pH, as well as the accidental spillage of diesel.

One method to lower the capital and operating costs, as well as the OH&S and environmental risk of employing a caustic soda dosing system, would be to deploy a 10,000 to 20,000 L isotainer of caustic soda close to the upstream end of the swamp in a topographically elevated location. Gravity discharge of a caustic soda solution from the isotainer would dramatically simplify treatment using this chemical. This approach could avoid the need to use a diesel-powered system. Caustic soda could be gravity fed into the acidic pools in the upper portion of the swamp from the isotainer. Dose rates could be controlled by pH feedback from either within the swamp or at the end of the swamp, and the dose control valve could be battery controlled with a solar powered recharge system. A 20,000 L container would not require refilling every few days and may only need to be replaced every 1-2 months, significantly lowering the risk of accidental spills and OH&S issues during reagent delivery.

4.1.3 Summary

A semi-passive caustic magnesia system is a good option for Barwon Water but will be slower to implement as a trial is required to confirm its performance. Key potential benefits of persisting with assessment of a caustic magnesia reactor are substantially lower capital and operating costs, and much lower OH&S and environmental risks compared to an active caustic soda dosing system. A semi-passive caustic magnesia treatment approach is Earth Systems' preferred treatment option at present.

If the semi-passive caustic magnesia system Is found to be unsuitable, an active treatment option involving gravity fed dosing of caustic soda from an isotainer located near the head of Big Swamp is a technically viable option for Barwon Water. The control system would be based on a battery-controlled valve (ie solar powered recharger) that received telemetered feedback from the pH probe immediately downstream of the swamp.

5. TRIAL TREATMENT PLAN FOR BIG SWAMP

As previously noted, Barwon Water has committed to assessing the likely performance of the semi-passive caustic magnesia treatment system at Big Swamp through laboratory testwork with a distilled water dissolution assessment. If this work proves successful, then attention needs to be turned to field trials. The primary rationale for the small-scale field trials is to assess chemical interaction between Boundary Creek water upstream of the swamp and the caustic magnesia under a range of scenarios.

With the proposed treatment trials (described below), it is not possible to fully treat the swamp for a small period of time. At best the trials will only permit the treatment of a very small proportion of the total acidity in the swamp during each of the trial campaigns listed below.

Key equipment components and operational parameters of the proposed treatment trials at for Big Swamp are documented below and shown in Figure 5-1. Implementation of the trial treatment program will be contingent on favourable outcomes from the laboratory testwork program.

5.1 Water Extraction, Transfer and Storage

"Clean" Boundary Creek water taken from upstream of Big Swamp at the road crossing will be directed by pump and pipeline to the east along the existing access track to a temporary poly water storage tank (eg. 10,000 L) located at the end of Jones track (see Figure 5-1). The tank will need to be placed on a flattened area, possibly on hardstand. 500 m of 2" pressure HDPE pipeline will need to be installed along the margin of this track. Water will be pumped from upstream of the swamp to the storage tank on an "as needed" basis. Field trials will involve controlled discharge (ie. measured flow rates) from the storage tank into a caustic magnesia reactor to ensure controlled residence times for water within the reactor.

The storage tank may be filled 10-20 times over the course of the trial work (eg. ~4-6 weeks).

Refer to Figure 5-1.

5.2 Caustic Magnesia Reactor

The caustic magnesia reactor will comprise a 1-2 m^3 vessel constructed from 304 stainless steel that is pre-plumbed to allow Boundary Creek water (from the storage tank) to rise vertically through the caustic magnesia reactor bed and discharge via gravity through a 2" HDPE pipe to the Alkalinity Mixing Zone. The reactor will be designed and operated to minimise the capture of any treatment precipitates, to avoid undue pressure increases within the reactor, and to enable free magnesium carbonate precipitation on the surface of the discharge water zone.

The reactor vessel will be located within approximately 10-20 m of the storage tank, but at least 2-4 m topographically lower than the base of the storage tank.

Refer to Figure 5-1.

5.3 Alkalinity Mixing Zone

Alkalinity enriched water discharging from the top of the caustic magnesia reactor will be passively directed by pipeline (2" HDPE low pressure) down to an open pond within Big Swamp close to BH15. The swamp water is already relatively acid at this point (pH~3.5). The magnesia amended alkaline water will enter the acid swamp water at the top end of the pond so that it is able to mix and blend and at least partially neutralise it. Alkalinity addition will be conducted in a manner that ensures that the pH of the fully mixed water (near the lower end of the acid water pond) never exceeds a value of 9 to prevent any potential ecological impacts. This limitation will be managed by manipulating alkalinity discharge rates from the reactor.

Refer to Figure 5-1.

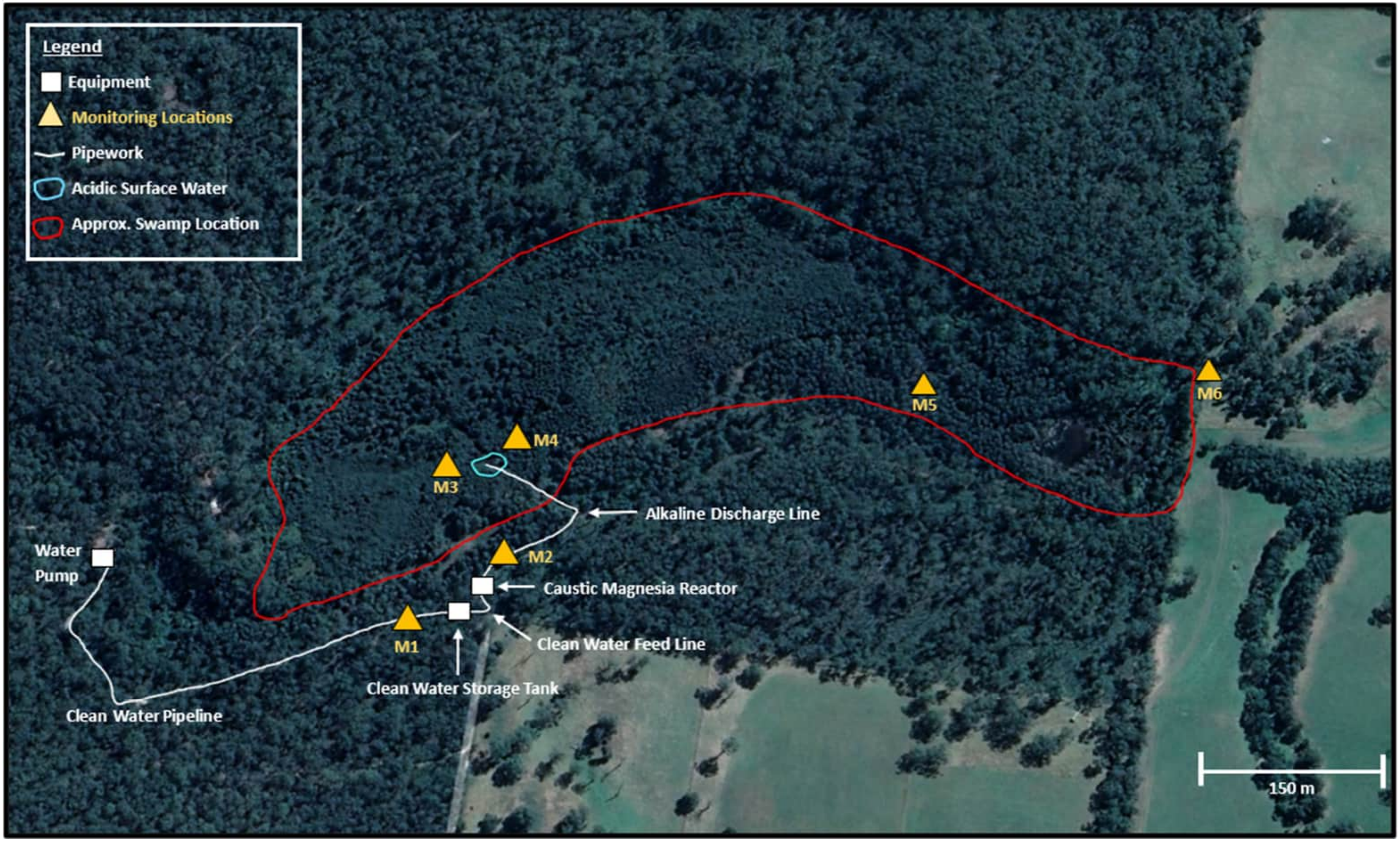

Figure 5-1. Location plan showing proposed trial treatment equipment and monitoring sites at Big Swamp.

5.4 Monitoring Strategy

In order to quantify the behaviour of the caustic magnesia within the reactor and its influence on the swamp water quality over a range of reactor flow rate and caustic magnesia grainsize conditions, Table 5-1 outlines the monitoring strategy that will be conducted during each trial run (refer to Table 5-2).

Table 5-1. Monitoring strategy for the magnesia reactor treatment trials at Big Swamp.

<table>
<tr><th rowspan="2">Map ID</th><th rowspan="2">Location</th><th colspan="2">Field</th><th colspan="2">Laboratory</th></tr>
<tr><th>Parameters</th><th>Frequency</th><th>Parameters</th><th>Frequency</th></tr>
<tr><td>M1</td><td>Upstream Big Swamp</td><td rowspan="6">• pH
• EC
• Temperature (°C)
• Oxidation Reduction Potential (ORP)
• Total Suspended Solids (TSS)
• Alkalinity if pH >6 or Acidity if pH < 6
• Major Cations (Ca, Mg)</td><td>1 per Clean Water Storage Tank Refill</td><td rowspan="6">• pH
• EC
• TSS
• Alkalinity if pH > 6 or Acidity if pH < 6
• Total Major Ions (Ca, Mg, Na, K, SO₄, Cl,)
• Nutrients (total N and total P)Total and Dissolved Trace Elements (Al, As, Cd, Co, Cu, Fe, Mn, Ni, Zn)</td><td>1 per day per Run</td></tr>
<tr><td>M2</td><td>Downstream Magnesia Reactor</td><td>8 per Day</td><td>1 per day per Run</td></tr>
<tr><td>M3</td><td>Upstream Acidic Pond</td><td>8 per Day</td><td>1 per day per Run</td></tr>
<tr><td>M4</td><td>Downstream Acidic Pond 1</td><td>8 per Day</td><td>1 per day per Run</td></tr>
<tr><td>M5</td><td>Downstream Acidic Pond 2</td><td>8 per Day</td><td>1 per day per Run</td></tr>
<tr><td>M6</td><td>Downstream Big Swamp</td><td>2-3 per Day</td><td>1 per day per Run</td></tr>
</table>

5.5 Trial Runs

Based on information on commercially available caustic magnesia (from Australia and China), Table 5-2 outlines the magnesia reactor trials that are proposed using Boundary Creek water upstream of Big Swamp.

Table 5-2. Experiment parameters for the magnesia reactor treatment trails at Big Swamp.

Reagent Grainsize	Trial Number	Trial Duration (days)	Water Feed Rate to Reactor (mls/second)	Water Residence Time in Reactor* (Mins)	Potential Daily Alkalinity Loads^ ($CaCO_3$/day)
30 mm aggregate	1	5-7	10	833 (13.9 hours)	0.3
	2	5-7	100	83	2.6
	3	5-7	1000	8	25.9
5 mm aggregate	4	5-7	10	833 (13.9 hours)	0.3
	5	5-7	100	83	2.6
	6	5-7	1000	8	25.9

*Assumes 1.0 m^3 of 50 % porosity MgO aggregate in the reactor.

^ Assumes available alkalinity discharging from the reactor in 300 mg $CaCO_3$/ L.

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Attachment A
Selected Passive Treatment System Options

7. PASSIVE TREATMENT SYSTEMS

7.1 Aerobic wetlands

Aerobic wetlands are essentially water retention ponds that store alkalinity (Figure 7-1). They contain vegetation planted in relatively impermeable sediments (eg. clay). Aerobic wetlands differ to all other passive treatment techniques in that they do not neutralise the acid water. They receive net-alkaline water, often diverted from a pre-treatment passive system, and solely provide residence time and aeration to allow certain metals whose solubility is dependent on the redox state of the water (eg. Fe, Mn, Cr, As), to precipitate. Precipitates are retained on plant surfaces in the wetland, or downstream.

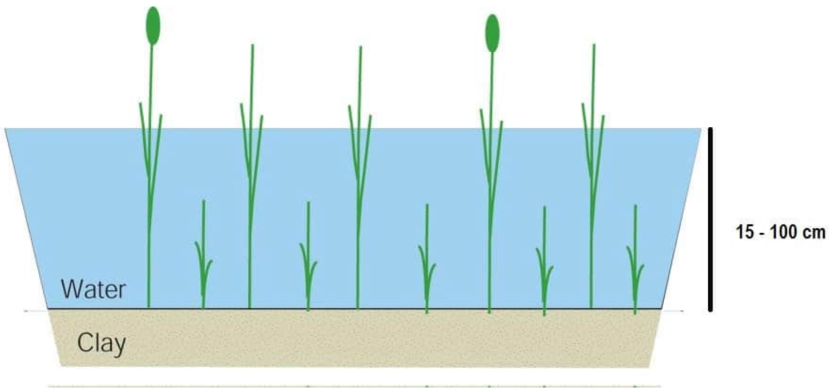

Figure 7-1: Aerobic Wetland.

Successful performance of aerobic wetlands requires the influent water to have the characteristics shown in Table 7-1. Moreover, dissolved oxygen concentrations need to have reached saturation with respect to the atmosphere early within the residence time of the water in the wetland.

Table 7-1: Characteristics of influent waters required for successful passive treatment using Aerobic Wetlands (Taylor et al 2005).

Av. Acidity Range (mg $CaCO_3$/L)	Av. Acidity Load (kg $CaCO_3$/300m^2 of wetland)	Flow Rate	Oxygen Concentration	Typical pH range	Max pH attainable
< 500	< 1 (Kilborn, 1999)	Permit maximum residence time eg. 1-5 days	Ambient	> 6	n/a

Where acidity loads exceed the recommended limit of 1 kg $CaCO_3$/300m^2 (Table 7-1), a neutralising reagent (eg. NaOH) may be added directly to the wetland, however this creates additional problems regarding sludge disposal. The size of the wetland is an important factor in the success of treatment. Design must take into account total acidity loads and water flow rates. Often wetlands are undersized leading to inadequate retention times and poor effluent water quality.

Although aerobic wetlands have proven effective in many situations for the removal of Fe (60 – 95%) from solution, they generally fail to adequately remove Mn. Commonly, less than 10% of Mn is precipitated out of solution in aerobic wetlands due to insufficient alkalinity levels, and an inability of the system to reach pH levels greater than

8. Also, issues arise regarding the removal and disposal of the metal precipitates deposited within or downstream of the wetland.

Key considerations for the potential use of aerobic wetland's for treatment of the acidity at Big Swamp include:

- The acidity load is too high,
- Will not neutralise the acid water,
- The flow rate is too high,
- Likely to be insufficient space to achieve required residence time,
- Dissolved metal concentrations of Fe (Al?) are likely to be too high.

7.2 Anaerobic wetlands

Anaerobic wetlands are water retention ponds that encourage acid water passage through organic-rich substrates that strip oxygen from the water resulting in anaerobic conditions. The wetlands may contain a layer of limestone beneath the organic substrate, or the limestone may be mixed among the organic matter (Figure 7-2).

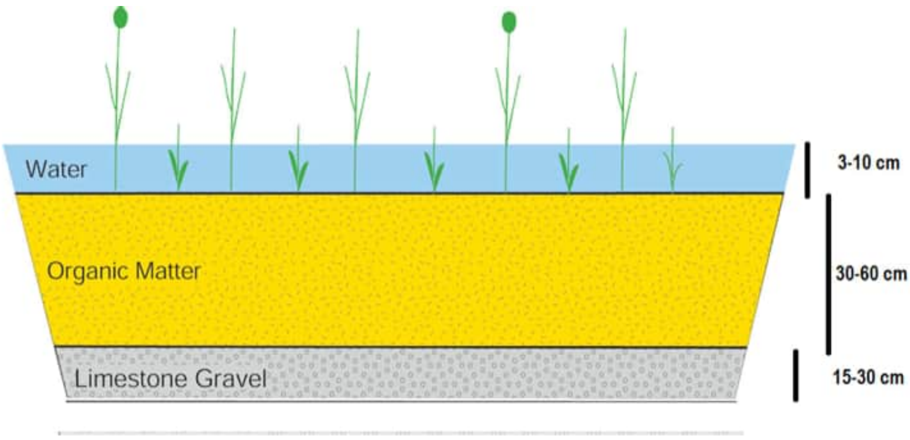

Figure 7-2: Anaerobic Wetland.

Alkalinity in the wetlands is generated by sulfate reducing bacteria (SRB), which use the organic matter as a carbon source and sulphate as an electron acceptor for growth. In the bacterial conversion of sulphate to hydrogen sulphide, bicarbonate alkalinity is produced (Reaction 3).

$$2\,H_2O + SO_4^{2-} + C_{(\text{organic matter})} \Leftrightarrow H_2S + 2\,HCO_3^{-}{}_{(\text{bicarbonate alkalinity})} \qquad \text{(Reaction 3)}$$

Alkalinity can also be generated from the dissolution of limestone upon contact with acid water. Metal concentrations are decreased via metal sulphide precipitation in the reduced (anaerobic) organic layer and hydroxide precipitation in the oxidised (aerobic) surface layer.

Anaerobic wetlands are best suited to treat waters with the characteristics shown in Table 7-2. While ambient oxygen concentrations can be tolerated, more reducing conditions favour extended life expectancies of anaerobic wetlands.

Insufficient wetland area and metal overloading has been responsible for the reduced lifetime of many anaerobic wetland systems. High influent metal concentrations can result in the precipitation of metal oxides/sulphides on limestone particles, reducing their available neutralising capacity. Excess metal precipitation can also lead to the exhaustion of sorption sites on organic material. Artificial inputs of organic matter have been used as a successful strategy to temporarily renew this adsorption capacity in the field (Eger and Melchert, 1992). Ongoing maintenance may also involve routine nutrient addition for bacterial growth.

Table 7-2: Characteristics of influent waters required for successful passive treatment using Anaerobic Wetlands (Taylor et al 2005).

Av. Acidity Range (mg $CaCO_3$/L)	Av. Acidity Load (kg $CaCO_3$/200-500m^2/day)	Flow Rate	Oxygen Concentration	Typical pH range	Max pH attainable
< 500	1 (Kilborn, 1999)	Permit maximum residence time eg. 1-5 days	Ambient near surface < 1 mg/L subsurface	> 2.5	6-7

Key considerations for the potential use of anaerobic wetland's for treatment of the acidity at Big Swamp include:

- The acidity load is too high,
- The flow rate is too high,
- Likely to be insufficient space to achieve required residence time,
- Dissolved metal concentrations of Fe (Al?) are likely to be too high.
- Cost to implement a system even to deal with part of the acidity load would be prohibitive.

7.3 Biochemical reactors (BCR)

Biochemical reactors (BCR) use a combination of organic matter and crushed limestone below a surface pond which limits oxygen ingress. Flow or level control devices are required to maintain the water cover and to prevent oxidation within the system.

Biochemical reactors work by producing alkalinity by the same methods used by anaerobic wetlands. Sulfate reducing bacteria (SRB) use the organic matter to generate bicarbonate alkalinity (Reaction 3), while limestone and/or dolomite neutralise acidity. Carbonate material also suppresses fermentation bacteria, which while required, are not desirable in quantity, as the fermentation process can lower pH (INAP, 2019).

The original BCR's were effectively anaerobic wetlands with flow across the surface of the wetland. More recently BCR's use a vertical flow configuration with water flowing down from the top and out through the base.

BCR are commonly followed by aerobic cells to assist with oxidation and the precipitation of some metals.

Acidity and acidity load restrictions are expected to be similar to anaerobic wetlands, however there is limited information on other parameters limiting the use of these systems.

Key considerations for the potential use of biochemical reactors for treatment of the acidity at Big Swamp are similar to that of anaerobic wetlands due to their similarity of operation. The size and cost to implement BCR's is currently unknown.

7.3.1 Reducing and alkalinity producing systems / wetlands (RAPS)

A range of approaches, collectively termed Reducing and Alkalinity Producing Systems (RAPS), have been devised to treat low acidity, low flow, low acidity Load, relatively reduced water flows. These include Alkalinity Producing Systems (APS), Successive Alkalinity Producing Systems (SAPS), Vertical Flow Wetlands (VFW) and Reverse Alkalinity Producing Systems (see Figure 7-3). While the precise names and construction details of these systems vary from place to place, all of these approaches have a number of factors in common (Milavec, 2002; Demchal et al., 1996).

Reducing and Alkalinity Producing Systems:

1. Utilise mixtures of limestone and organic matter and thereby represent combined inorganic and organic approaches to treat acidity.
2. Rely on alkalinity generation via limestone dissolution and sulphate reducing bacterial (SRB) activity.
3. Enhance reducing conditions (to enable sulphide precipitation and to minimise untimely iron/manganese oxidation and precipitation/armouring).
4. Provide sites for metal adsorption (ie. on the organic matter).
5. Raise the pH of the water to near neutral conditions.

The successful performance of these systems requires the influent waters to have the characteristics shown in Table 7-3.

Table 7-3: Characteristics of influent waters required for successful passive treatment using Reducing and Alkalinity Producing Systems (RAPs) (Taylor et al 2005).

Av. Acidity Range (mg $CaCO_3$/L)	Av. Acidity Load (kg $CaCO_3$/day)	Av. Flow Rate (L/s)	Dissolved Oxygen (mg/L)	Typical pH range	Max pH attainable
< 300	< 100	< 15	< 1-3	> 2.5	6-7

Figure 7-3 shows a schematic cross section of a RAPS. Although discussed separately (above), anaerobic wetlands are also a type of RAPS.

RAPS are not walk-away solutions. These systems have a high capital cost and are subject to limitations associated with pore clogging by gypsum and metal precipitates. Permeability can be lowered by progressive compaction of the substrate, and high maintenance (eg. flushing) is required if aluminium precipitation cannot be prevented.

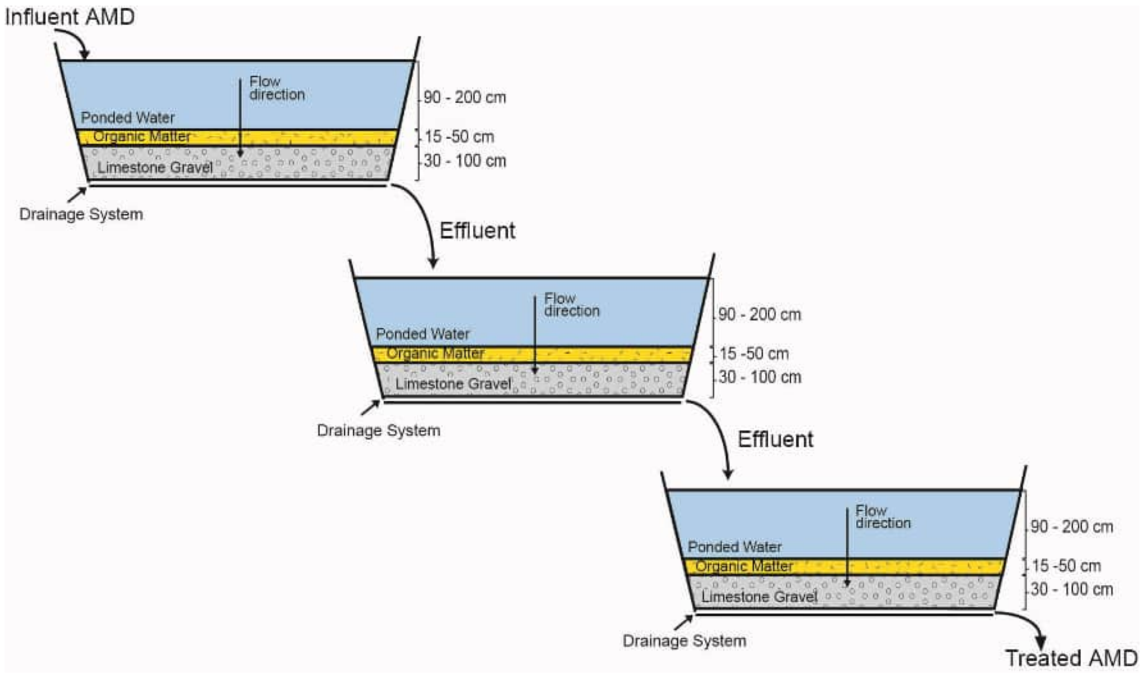

Figure 7-3: Typical layout of a Reducing and Alkalinity Producing System (RAPS), which utilises organic matter and limestone for the passive treatment of AMD. The system shown in this diagram is also commonly referred to as a "Successive Alkalinity Producing System" (Taylor et al, 2005).

Key considerations for the potential use of RAPS's for treatment of the acidity at Big Swamp include:

- The acidity load is too high,
- The flow is too high,
- Dissolved metal concentrations of Fe (Al?) are likely to be too high.
- Once installed RAPS's are permanent structures (unless further earthworks are undertaken to remove them).
- Installation of a RAP is likely to permanently damage the current swamp environment / ecosystem.

7.4 Open limestone drains (OLD)

Oxic or Open Limestone Drains (OLD) are open channels containing coarse limestone aggregate (Figure 7-4; Ziemkiewicz and Brant, 1996). These systems make no attempt to exclude oxygen or minimise precipitate formation, and hence may have a short operational life if installed in inappropriate situations. A larger amount of limestone is used in these systems compared to Anoxic Limestone Drains (ALD; see below) to cater for the greater formation of iron and aluminium hydroxides that coat limestone particles and reduce their neutralisation effectiveness. OLDs can be constructed (artificial) drains or they can be implemented along existing drainage systems; to meet flow and acidity load requirements, large areas may be required for effective OLD operation.

The channel dimensions (particularly length) and slope directly affect the success of Oxic Limestone Drains. For example, the drain must be long enough to ensure that the water has sufficient contact time with limestone (eg. at least 15 hours) for neutralisation to occur. Where the slope exceeds 10°, water moves across the limestone quickly, preventing sufficient alkalinity generation in most cases. Where the slope is less than 10°, lower water velocities allow metal precipitates (commonly $Fe(OH)_3$, $Al(OH)_2$ and $CaSO_4$) to accumulate around limestone particles and within void spaces. This reduces the neutralising capacity of the limestone and results in the reduced lifetime of the OLD.

OLDs are designed to raise the pH of water to 6-7, introduce alkalinity, neutralise acid and lower soluble metal concentrations. OLDs are best suited to treatment of waters with the characteristics shown in Table 7-4.

Table 7-4: Characteristics of influent waters required for successful passive treatment using Open/Oxic Limestone Drains (OLDs) (Taylor et al 2005).

Av. Acidity Range (mg $CaCO_3$/L)	Av. Acidity Load (kg $CaCO_3$/day)	Av. Flow Rate (L/s)	Oxygen Concentration	Typical pH range	Max pH attainable
< 500	< 150	< 20	Ambient	> 2	6-7

Figure 7-4: Open limestone drain showing abundant brown Fe-hydroxide precipitates.

Key considerations for the potential use of OLD's for treatment of the acidity at Big Swamp include:

- The acidity load is too high,
- Dissolved metal concentrations of Fe (Al?) are likely to be too high.
- Elevated Fe(II) in the waters is likely to precipitate as Fe-hydroxides / Fe-Oxyhydroxides thereby armouring the limestone and reducing the drains effectiveness.
- The channel dimensions required to obtain the required retention time to offset even half the acidity will be too large and require substantial earth works.
- Once installed OLD's are permanent structures (unless further earthworks are undertaken to remove them).
- Installation of an OLD is likely to permanently damage the swamp environment / ecosystem.

7.5 Anoxic limestone drains (ALD)

Anoxic Limestone Drains (ALD) are buried trenches of coarse limestone aggregate layered in carefully constructed drainage lines along gently graded slopes (Kilborn, 1999). The limestone drain is encased within a low permeability liner and capped with clay. Care is taken to avoid the possibility of covering the limestone with clays or organic matter during operation, and to ensure that negligible air can be entrained into the drain. Synthetic liners are often used to cover the aggregate filled channels to facilitate oxygen exclusion. Raw and highly acidic water is delivered directly into the covered drains as close to the source as possible, to avoid its significant oxidation. Low oxygen conditions are maintained within the drain in order to keep dissolved iron in its reduced state (ie. ferrous iron; Fe^{2+}). A higher concentration of dissolved oxygen within the influent waters promotes the oxidation of ferrous iron to ferric iron (Fe^{3+}), which precipitates as iron-oxide/hydroxide (eg. $Fe(OH)_3$). Formation of these precipitates may result in the premature system failure due to limestone armouring, which significantly reduces the rate of limestone dissolution. Almost all ALD's constructed in the field experience some retention of iron due to armouring. Long residence times, eg. at least 15 hours, are encouraged to prolong the interaction between the acid water and limestone.

The prime function of Anoxic Limestone Drains is to raise the pH of influent water to 6-7 and introduce bicarbonate alkalinity up to a maximum of approximately 300 mg $CaCO_3$/L. Aerobic ponds at the outflow end of ALD's facilitate oxidation and precipitation of iron and other metal precipitates. However, not all metals will precipitate post treatment as effluent from ALD's reaches a maximum pH of only 6-7.5. Further acid (H^+) will be generated upon precipitation of these metals; however, it is the intention of ALD's that sufficient excess alkalinity is produced to neutralise the additional acid that is generated when precipitation occurs.

ALD's are most effective for influent water with the characteristics shown in Table 7-5.

Table 7-5: Characteristics of influent waters required for successful passive treatment using Anoxic Limestone Drains (ALDs) (Taylor et al 2005).

Av. Acidity Range (mg $CaCO_3$/L)	Av. Acidity Load (kg $CaCO_3$/day)	Av. Flow Rate (L/s)	Dissolved Oxygen (mg/L)	Typical pH range	Max pH attainable
< 500	< 150	< 20	< 1	> 2	6-7

Key considerations for the potential use of ALD's for treatment of the acidity at Big Swamp include:

- The acidity load is too high,
- Dissolved metal concentrations of Fe (Al?) are likely to be too high.
- The channel dimensions required to offset even half the acidity will be too large and require substantial earth works.
- Once installed ALD's are permanent structures (unless further earthworks are undertaken to remove them).
- Installation of an ALD is likely to permanently damage the swamp environment / ecosystem.

7.6 Limestone Diversion Wells (LDW)

Limestone Diversion Wells (LDW) are an option for sites that offer a suitable topographic fall. LDW's consist of a well (eg. an in-ground metal or concrete tank) that contains crushed limestone aggregate (Figure 7-5). Part of a fast-flowing AMD stream is diverted, often via a pipeline, into the well (Milavec, 1999; Ziemkiewicz and Brant, 1996). The hydraulic force causes grinding and abrasion of the limestone gravel, ensuring that armouring of the aggregate is prevented and a fine-grained limestone slurry overflows from the top of the well back into the main body of the stream. In this way, excess alkalinity is introduced into the waterway.

LDW's are suitable for treating waters with the characteristics shown in Table 7-6.

Table 7-6: Characteristics of influent waters required for successful passive treatment using Limestone Diversion Wells (LDWs) (Taylor et al 2005).

Av. Acidity Range (mg $CaCO_3$/L)	Av. Acidity Load (kg $CaCO_3$/day)	Av. Flow Rate (L/s)	Oxygen Concentration	Typical pH range	Max pH attainable
< 500	100 – 1,000	< 1000	Ambient	> 2	6-7

The successful use of a LDW requires a minimum 10 metre elevation change between the locations of the diversion and the well. If the elevation change is less than 10 metres, there will generally be insufficient water velocity to turbulently mix and abrade the limestone particles. Furthermore, insufficient alkalinity will be produced, and metal precipitates will clog the well, subsequently reducing the lifetime of the system. During periods of higher-than-normal flow, the influent waters may not experience adequate retention time within the well to be suitably neutralised. There have been both successes and failures regarding the use of LDW's in the field.

Significant maintenance is required for the operation of a LDW that discourages the remote operation of these systems. Limestone can only be added to the well in small amounts so that frequent refilling with clean limestone is required to assure continued treatment. Nevertheless, limestone is inexpensive and readily available. Hopper feed systems can be installed to allow limestone to be automatically fed into the LDW as the reagent is consumed. Hopper feed systems do not eliminate the requirement for regular refilling of the LDW, but they reduce the frequency of refilling by increasing the reagent storage capacity of the system. Maintenance of LDW's also involves the regular removal of leaves and other debris from the well to avoid blocking.

As the metal precipitates are not captured within the LDW, sludge tends to accumulate within the waterway and may require removal (eg. by construction of a settling pond).

Key benefits of LDW's include the minimisation of limestone armouring due to the vigorous mixing of the inflow and limestone aggregate, and greater efficiency of limestone use compared to OLD's and ALD's. However, reagent use is typically only 50% efficient, and LDW's are not walk-away solutions.

Key considerations for the potential use of LDW's for treatment of the acidity at Big Swamp include:

- Insufficient elevation change,
- Significant maintenance (cleaning) and frequent filling with limestone,
- Dissolved metal concentrations of Fe (Al?) are likely to be too high.
- Once installed LDW's are permanent structures (unless further earthworks are undertaken to remove them).
- Installation of an LDW is likely to permanently damage the swamp environment / ecosystem.

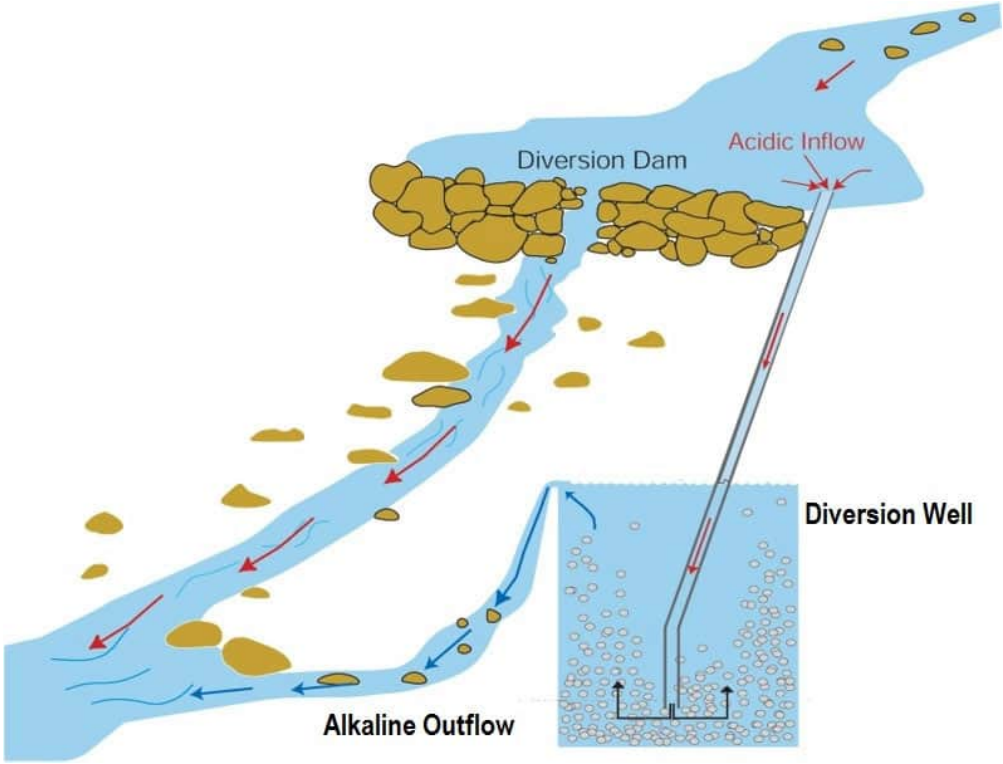

Figure 7-5: Limestone diversion well showing active suspension of particulate limestone which has been generated by aggregate abrasion in the well.

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Appendix B – Big Swamp Upstream Treatment Trial: Ecological Risk Assessment (CDM Smith, 2021)

1/30 Wangaratta Street
Richmond VIC 3121

21 December 2021
Project Number: 1001218

Will McCance
Barwon Water
Environmental Remediation Project Manager
55-67 Ryrie Street (PO Box 659)
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Dear Will

RE: Barwon Water Big Swamp Ecological Risk Assessment

Introduction

Barwon Water are currently investigating a potential semi-passive upstream treatment methodology that utilises caustic calcined magnesia (MgO) to reduce the acidity loads within Big Swamp and the downstream waterways (i.e. Boundary Creek and Barwon River). As part of this, Barwon Water are planning to conduct a small-scale field trial of the proposed treatment methodology to ground truth the suitability of this method and inform the detailed design of any potential full-scale system. Prior to the commencement of the trial, Barwon Water require a risk assessment be undertaken in order to identify potential risks to the ecological values (flora and fauna) of the swamp and downstream waterways from implementation of the trial (i.e. dosing and changes in water chemistry). CDM Smith Australia Pty Ltd (CDM Smith) has been engaged to undertake this assessment. Our approach and risk assessment are outlined below.

Objective and Intent

The objective of this risk assessment is to assess the potential impacts of the treatment trial on the ecological values of the swamp and its downstream waterways (Boundary Creek and Barwon River) and characterise the level of risk associated with the trial.

It is noted that typically a risk assessment would also include stakeholder consultation and consideration of large monitoring programs. However, due to the nature and scale of the treatment methodology, this risk assessment will be conducted as a preliminary (or rapid) risk assessment using the currently limited ecological information of the swamp to inform stakeholder engagement and highlight needs for further risk assessment. Barwon Water have informed the risk assessment will be revisited and undertaken in further detail during the detailed design phase of the trial and subsequent full scale design phase.

Risk Assessment Framework

Risk assessment is an objective, scientific assessment technique which is conducted in a standardised manner in accordance with risk assessment guidance (such as ANZECC 2000 and EPA Publication 1287). Typically, a risk assessment begins with a *problem formulation* which determines the focus and scope of the risk assessment and the management information it needs to provide. In this case, the problem under consideration is whether the proposed water treatment trial within Big Swamp poses additional risk to an already existing problem (i.e. acidification of waterways driven by recovering groundwater levels and pyritic geologies). As such, this risk assessment will consider risks for an unmitigated "base case" and a "mitigation case". For risk to exist, the conceptual risk model (CRM) elements, depicted in Figure 1 must all be present. These include:

- A source or sources (of stress inducing elements which can be chemical or physical).
- A pathway or pathways which transport stressors to receptors.
- Receptors (e.g. flora and fauna).

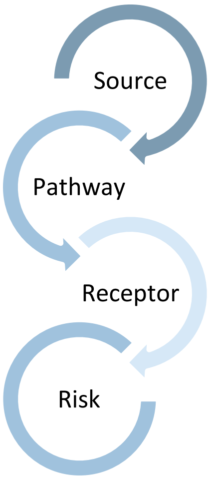

Figure 1 CRM: Source, pathway and receptor relationship

The CRM brings information together specifically relating to the site and surrounds with consideration of the chemicals or stressors of interest. The CRM elements (source, pathway and receptor analysis) then feed into an assessment of risk which is dependent on toxicity of the stressor (this is typically called a *toxicity assessment*) and exposure (called an *exposure assessment*). The toxicity and exposure are then considered together (*risk characterisation*) to estimate the level of risk.

Problem Formulation - Source, Pathways and Stressors

Four (4) sources have been identified as posing a threat to the swamp condition. These include acid sulfate soils (ASS) (S1), water management (S2), alkaline dosing and subsequent discharge (S3) and the alkaline dosing plant (itself) (S4). Sources can be thought of as the attributes which may (if exposed) contribute to system change.

Through active pathways (i.e. threats), these sources can place stress on the swamp condition, herein defined as stressors. E.g. the presence of ASS (a source) can be a treat to the swamp if a pathway (i.e. ongoing oxidation of ASS) exists, placing stress on the swamp by increasing acidity and metal concentrations within the swamp water (stressors). A total of nine (9) active pathways have been identified as occurring under current (base case) and mitigation scenarios.

The sources and their pertaining pathways and stressors are listed in Table 1.

Table 1 Identified Sources, Pathways and Stressors

Scenario	Threat		Stressors (measurable variable)
	Source	Pathway	
Base case	Acid Sulfate Soils (S1)	Ongoing oxidisation (P1)	Acidity and metals (Al, Fe, Mn, Ni, Zn) loading/precipitation to swamp and downstream waterways
		Mobilisation and distribution (P2)	
	Water management (S2)	Reduced water levels (P3)	Loss of habitat
		Fire (P4)	Loss of habitat
		Encroachment of undesired plant species (P5)	Loss of habitat
		Depth of inundation (P6)	Loss of habitat
Mitigation	Acid Sulfate Soils (S1)	Ongoing oxidisation (P1)	Acidity and metals (Al, Fe, Mn, Ni, Zn) loading to swamp and downstream waterways
		Mobilisation and distribution (P2)	
	Water management (S2)	Reduced water levels (P3)	Loss of habitat
		Fire (P4)	Loss of habitat
		Encroachment of undesired plant species (P5)	Loss of habitat
		Depth of inundation (P6)	Loss of habitat
	Alkaline dosing discharge (S3)	Treatment related loading and precipitation (P7)	MgO
			Accumulation of metals
			Mobilisation of metals
			Mobilisation of nutrients
			Increased alkalinity
			Persistent acidity
			Other
	Alkaline dosing plant (S4)	Spill of dosing materials (P8)	MgO
			Accumulation of metals
			Mobilisation of metals
			Mobilisation of nutrients
			Increased alkalinity
			Persistent acidity
			Other
		Spill of fuel/hydrocarbons (P9)	Contamination of water and sediment

Problem Formulation - Receptors

The receptor (R) represents the component or receiving environment of an ecological value (EV) (Table 2). The receptors have been identified based on historical vegetation assemblages within the swamp prior to swamp degradation outlined by CDM Smith (2021). Further input from local aquatic ecologists has been sought to derive the aquatic fauna expected within the areas identified within Big Swamp and its lower tributaries.

Table 2 Identified Receptors

Area	Receptors (R)									
	Unit 1 Peat wetland; State 3 (simplified wetland) unsampled (R1)	Unit 2 Peat wetland; State 3 (simplified wetland) Q4/Q3 (R2)	Unit 3 Peat wetland; State 3 (simplified wetland) unsampled (R3)	Unit 3 Peat wetland; State 4 (recovering wetland) Q1 (R4)	Unit 4 Drainage line tall shrubland; State 3 (simplified wetland); unsampled (R5)	Unit 6 Damp margins woodland/forest; (non wetland); Q5 (R6)	Unit 5 Drainage line Woodland; State 4 (Recovering wetland); Q2 (R7)	Macroinvertebrate community (R8)	Fauna (fish / platypus) (R9)	Stock and domestic water use (R10)
West swamp	✓	✓	✓		✓	✓		✓		
East swamp				✓			✓	✓		
Boundary Creek								✓	✓	✓
Barwon River								✓	✓	✓

Notes: Refer to prior CDM Smith report for definitions of Units 1 to 6 (R1 – R7) Plus current state; Q# - refers to the 8x8 m quadrats reported in Ecological Australia 2020 (Big Swamp Vegetation Monitoring Report)
✓ not surveyed

Toxicity Assessment

This toxicity assessment is intended to provide project managers and stakeholders with relevant information about each stressor as it pertains to the receptors. The default guideline values (DGVs) provide a holistic point of comparison for stressors, however, in this case it is important to consider toxicity to specific stressors to inform management and monitoring plans for mitigation works. Table 3 provides brief summaries on the toxicity of each stressor to the key receptor groups (where this information exists). These summaries were developed based on the DGVs developed by ANZG (2018) for fresh and marine water quality, sediment quality, livestock and NHMRC (2011) Australian drinking water guidelines as well as journal publications. Note, for R10 (domestic and stock water use) recreational guidelines (i.e. short and long term triggers for irrigation or general water use) have been ignored as these do not relate to water consumption of this receptor.

Table 3 Toxicity Assessment

Receptors	Stressors								
	Acidity / Alkalinity	Al	Fe	Mn	Zn	Ni	Mg	Nutrients	Fuel (hydrocarbons)
Terrestrial vegetation (R1 – R7) [1]	• Nutrient toxicity increases at pH of 4.8 or lower • Nutrient availability decreases with increasing alkalinity	• Aluminium toxicity may persist in subsurface soil at pH <4.5. • Availability to plants reduced with increasing pH, significant decline from >5.5 pH	• Availability to plants reduced with increasing pH, significant decline from >5.5 pH	• Availability to plants reduced with increasing pH, significant decline from >5.5 pH	• DGV: 200 mg/kg dry weight [2] • GV-high: 410 mg/kg dry weight [2] • Availability to plants reduced with increasing pH, significant decline from >5.5 pH	• DGV: 21 mg/kg dry weight [2] • GV-high: 52 mg/kg dry weight [2]	• Availability to plants increases with increasing pH	• Availability to plants increases from around 4.5 pH, peaks at around 6 pH and declines steadily from around 6.5 pH	No values identified
Macroinvertebrate community (R8) [3]	• Aluminium toxicity to fish and invertebrates increased at low pH (<5.5) and >9 pH.	• Aluminium toxicity to fish and invertebrates increased at low pH (<5.5) and >9 pH. • Toxicity reduced in presence of silicon • Toxicity reduced at high water hardness (high calcium concentrations) – no data to support • Increased temperature may increase toxicity • Amphibian: Acute Bufo americanus, 4-day LC50 860 to 1660 µg/L; chronic, 8-day LC50 of 2280 µg/L. • Crustaceans: one species 48-h LC50 2300 to 36,900 µg/L; chronic three species, 7 to 28-day NOEC, 136 to 1720 µg/L. • Algae: 96-h EC50 population growth, 460 to 570 µg/L; chronic two species, NOEC, 800 to 2000 µg/L.	• Acute toxicity to aquatic insects reported at 320 – 16,000 ug/L. • The 3-week LC50 for Daphnia magna was 5900 µg/L.	• Moderate reliability trigger value of 1900 µg/L. • Crustaceans: five species, 48 to 96-hour LC50/EC50, 4.7 mg/L (Daphnia magna) to 771 mg/L (Asellus aquaticus). An additional species, a harpacticoid copepod, had a 48-hour LC50 of 54 µg/L (0.054 mg/L), but this did not satisfy screening requirements. • Annelid: one species, Tubifex tubifex, 48 to 96-hour LC50, 171 to 208 mg/L. • Macrophyte: one species, Lemna minor, 96-hour EC50, growth, 32 mg/L.	• Toxicity decreases with increasing hardness and alkalinity. • Update and toxicity generally decrease as salinity increases. • Zinc toxicity generally decreases with decreasing pH, at least below pH 8. Trends are complex above pH 8. • Acute toxicities for Australian freshwater species ranged from 140 µg/L to 6900 µg/L. **NOEC values:** • Amphibians: one species, Ambystoma opacum, 180 µg/L (from LOEC). • Crustaceans: three species, 5.5 µg/L (C. dubia; from LC50) to 25.3 µg/L (C. dubia), plus a figure of 18,480 for the crayfish Orconectes virillis). • Molluscs: three species, 54 µg/L (Dreissena polymorpha) to 11,200 µg/L (Velesunio ambigua), a NOEC of 487 µg/L was measured for Physa gyrina. • Annelid: one species, Limnodrilus hoffmeisteri, 560 µg/L (from LC50).	• Nickel toxicity decreases with increased hardness and a hardness algorithm is available. • Toxicity of nickel increases as pH decreases. • Nickel is weakly complexed by dissolved organic matter and is less bioavailable when adsorbed to suspended material. • Bioconcentration of nickel is not a significant problem in aquatic environments. • A freshwater high reliability trigger value of 11 µg/L was calculated for nickel using the statistical distribution method at 95% protection. This applies to low hardness waters, 30 mg/L as CaCO3. **TVs** • Amphibian: one species, Ambystoma opacum, 31 µg/L, from 8-day LC50. • Crustacean: one species, D. magna, 13.5 µg/L, from 5 to 30-day EC50. Lowest experimental chronic figure (after hardness correction) was 67 µg/L.. • Mollusc: one species, Juga plicifera, 39.5 µg/L. An experimental NOEC of 69 µg/L was reported.	Rehabilitation standard for aquatic ecosystems • Dissolved Mg:Ca mass ratio no greater than 9:1 [4]	**Ammonia:** • Freshwater trigger value reliant on pH with range given for 2.57 mg/L at 6 pH to 0.18 mg/L at 9 pH • Freshwater fingernail clam Sphaerium novaezelandiae was very sensitive to ammonia in 60-day exposures at pH 7.5 and 20°C. LC50 and IC50 (juvenile production) figures respectively were 37 and 13 µg/L, based on un-ionised ammonia (NH3-N), and 3800 and 800 µg/L based on total ammonia (N) • two mayfly species showed significant decreases in abundance at the concentrations tested: the 29-day EC50 values for total and un-ionised ammonia for Deleatidium sp. were 2.15 mg N/L and 0.145 mg N/L respectively; the NOECs were 950 and 66 g/L respectively. NOECs for Coloburiscus humeralis were 2330 and 160 g/L respectively.	Trigger values [TVs] in µg/L) recommended for slightly to moderately disturbed systems • Amphibians 190-370 ug/L • Crustacean 10-682 • Other invertebrate 10-1370

Receptors	Stressors								
	Acidity / Alkalinity	Al	Fe	Mn	Zn	Ni	Mg	Nutrients	Fuel (hydrocarbons)
Fauna (fish / platypus) (R9) [3]	• Aluminium toxicity to fish and invertebrates increased at low pH (<5.5) and >9 pH.	• Aluminium toxicity to fish and invertebrates increased at low pH (<5.5) and >9 pH. • Toxicity reduced in presence of silicon • Toxicity reduced at high water hardness (high calcium concentrations) – no data to support • Increased temperature may increase toxicity • Fish: Acute 48 to 96-hour LC50 five species: 600 (Salmo salar) — 106,000 mg/L; chronic seven species, 8 to 28-day converted NOEC, 34 to 7100 µg/L. The lowest measured chronic figure was an 8-day LC50 of 170 µg/L for Micropterus sp.	• A reduction of 50% in the hatchability of fathead minnow eggs occurred at iron concentrations of 1500 µg/L.	• Moderate reliability trigger value of 1900 µg/L. • Fish: three species, 48 to 96-hour LC50, 33.8 to 4540.0 mg/L (i.e. x 1000 µg/L); Chronic 28-day no observed effect concentration (NOEC) for additional species, Pimephales promelas, 1270 to 9990 µg/L (growth and mortality).	• Toxicity decreases with increasing hardness and alkalinity. • Update and toxicity generally decrease as salinity increases. • Zinc toxicity generally decreases with decreasing pH, at least below pH 8. Trends are complex above pH 8. • Acute toxicities for Australian freshwater species ranged from 140 µg/L to 6900 µg/L. **NOEC values:** • Fish: 11 species, 24 µg/L (Oncorhynchus tshawytscha; from LC50) to 1316 µg/L (Ptylocheilus oregonensis; from LC50); seven species had geometric means < 250 µg/L and a measured NOEC of 38 µg/L was reported for Pimephales promelas.	• Nickel toxicity decreases with increased hardness and a hardness algorithm is available. • Toxicity of nickel increases as pH decreases. • Nickel is weakly complexed by dissolved organic matter and is less bioavailable when adsorbed to suspended material. • Bioconcentration of nickel is not a significant problem in aquatic environments. **TVs** • A freshwater high reliability trigger value of 11 µg/L was calculated for nickel using the statistical distribution method at 95% protection. This applies to low hardness waters, 30 mg/L as CaCO3. • Acute LC50 values ranging from 510 µg/L for a cladoceran to 43,000 µg/L for fish at low hardness • Fish: one species, Fundulus heteroclitus, 30 000 µg/L from 7-day LC50.		**Ammonia:** • 96-h LC50 for juvenile inanga (Galaxias maculatus) at 15°C pH 8.2 was 1600 µg NH3/L un-ionised ammonia. • Acute toxicity of ammonia to seven New Zealand indigenous fish (banded kokopu Galaxias fasciatus, common bully Gobiomorphus cotidianus, common smelt Retropinna retropinna, redfin bully G. huttoni, inanga Galaxias maculatus, and longfin and shortfin eels Anguilla dieffenbachii and A. australis; and one indigenous crustacean species. Shrimp (Paratya curvirostris) was the most sensitive. The 9-hour LC50 at 15°C pH 7.5 or 8.2 ranged from 0.75 to 2.35 mg/L NH3/L for these species.	•
Stock and domestic water use (R10) [5] [6]	Domestic use TVs: • 6.5-8.5 pH Stock water: • 5 – 9 pH	Domestic use TVs: • 0.2 mg/L (no health-based guideline can be established currently) Stock water: • 5 mg/L	Domestic use TVs: • Taste threshold 0.3 mg/L. Stock water: • N/A	Domestic use TVs: • >0.1 mg/L causes taste, staining. • <0.05 mg/L desirable. Stock water: • N/A	Domestic use TVs: • Taste problems >3 mg/L. Stock water: • 20 mg/L	Domestic use TVs: • 0.02 mg/L health guideline value Stock water: • 1 mg/L		Domestic use TVs: • 50 mg/L nitrate • 3 mg/L nitrite Stock water: • 400 mg/L nitrate • 30 mg/L nitrite	Domestic use TVs: • 0.001 mg/L benzene

Notes:
1. DPIRD (2018) Agriculture and Food, Government of Western Australia
2. ANZG (2018) guidelines for sediment quality.
3. ANZG (2018) guidelines for fresh and marine water quality.
4. van Dam RA, Hogan AC, McCullough CD, Houston MA, Humphrey CL, Harford AJ. Aquatic toxicity of magnesium sulfate, and the influence of calcium, in very low ionic concentration water. Environ Toxicol Chem. 2010 Feb;29(2):410-421. scientist/publications/rehabilitation-standards.
5. ANZG (2018) livestock water guidelines.
6. NHMRC (2011) Australian drinking water guidelines

Exposure Assessment

Table 4 outlines the modelled water chemistry following treatment of water to pH 9 using MgO at the treatment point. These concentrations form part of an "exposure assessment" which highlights the likely concentrations within each of the areas the EVs reside. Note, only the stressors which have been assessed as part of the hydro chemical modelling have been included in this exposure assessment.

Table 4 Exposure Assessment – modelled water chemistry following treatment

Area	Key Stressors									
	Acidity	Alkalinity	Al	Fe	Mn	Zn	Ni	Mg	Nutrients	Fuel (hydrocarbons)
West Swamp	• 5.7 pH	• 22.3 mg/L $CaCO_3$	• 2.7 mg/L	• 29 mg/L	• 0.023 mg/L	• 0.07 mg/L	• 0.024 mg/L	• 6.4 mg/L	• Nitrate: 0.045 mg/L • Nitrite: 0.01 mg/L • Ammonia: 0.25 mg/L	Unlikely
Change from baseline (+/-)	• 0%	• 0%	• 0%	• 0%	• 0%	• 0%	• 0%	• 0%	• 0%	-
Toxicant value exceedance	×		×××	××	Nil	Nil	×	Nil	Nil	-
East Swamp	• 9 - 5.1 pH	• 9 – 5.1 pH • 415.17 – 5.15 mg/L CaCO3	• 2.7 – 7.18 mg/L	• 0.03 – 14.97 mg/L	• 0 – 0 mg/L	• 0.047 – 0.175 mg/L	• 0.194 – 0.059 mg/L	• 117.58 – 39.49 mg/L	• Nitrate: 1.33 – 4.16 mg/L • Ammonia: 0 - 0 mg/L	Unlikely
Change from baseline (+/-)	• +3.3 units	• 1,762%	• 0%	• -100%	• -100%	• -33%	• -19%	• 1,737%	• Nitrate: 2,856% • Ammonia: -100%	-
Toxicant value exceedance	×××		×××	××	Nil	××	×	××	Nil	-
Boundary Creek (upper)	• 5.1 pH	• 5.15 mg/L	• 7.18 mg/L	• 14.97 mg/L	• 0 mg/L	• 0.175 mg/L	• 0.059 mg/L	• 39.49 mg/L	• Nitrate: 4.16 mg/L • Ammonia: 0 mg/L	Unlikely
Change from baseline (+/-)	• 1 unit	• 158%	• 21%	• -84%	• -100%	• -24%	• -22%	• 558%	• Nitrate: 41,500% • Ammonia: -100%	-
Toxicant value exceedance	×××		×××	××	Nil	××	×	××	Nil	
Barwon River	• 7.1 pH	• 7.43 mg/L $CaCO_3$	• 0.58 mg/L	• 0.34 mg/L	• 0 mg/L	• 0.025 mg/L	• 0.009 mg/L	• 13.35 mg/L	• Nitrate: 0.58 mg/L • Ammonia: 0 mg/L	Unlikely
Change from baseline (+/-)	• +2.3 units	• +102%	• +17%	• -3,983%	• -100%	• -40%	• -29%	• 35%	• Nitrate: +17% • Ammonia: 0%	-
Toxicant value exceedance	Nil		×	×	Nil	Nil	Nil	Nil	Nil	-

Notes: "-" denotes not applicable
× denotes value exceeds toxicant value for terrestrial vegetation
× denotes value exceeds toxicant value for macroinvertebrates
× denotes value exceeds toxicant value for fish
× denotes value exceeds toxicant value for domestic and/or stock water use

Table 5 provides the estimated flow rates through the swamp over the trial period. The flow data is conservative as it assumes a maximum of 0.3 ML/d flow despite significantly higher flows being recorded historically. Ramping of offtake (water consumed by the treatment cell) occurs during the trial as the proportion of treated water added to the swamp increases as the trial progresses, eventually reaching a maximum diversion of 0.17 ML/d (~2 L/s) after day 5. The rate in which the chemistry of the swamp water is expected to change (from baseline to the modelled concentrations shown in Table 4) is around 2 days.

Table 5 Estimated River flow and offtake during trial

Flow in BC (ML/Day)	Offtake for trial (ML/Day)	Proportion of offtake (%)
0.3	0.00864	2.9%
0.3	0.0216	7.2%
0.3	0.0432	14.4%
0.3	0.0864	28.8%
0.3	0.1728	57.6%

Risk Characterisation

To characterise the risk posed to the swamp by the trial of the proposed treatment method, a qualitative risk assessment methodology has been used for this assessment. Table 6, 7 and Table 8 outline the qualitative measures for deriving the level of risk, noted to be a function of likelihood and consequence.

The risk assessment assesses each of the identified sources against the pathways and receptors outlined in the earlier subsections of this report. Using the qualitative framework, risk levels have been characterised for both baseline and mitigation (i.e. treatment) scenarios. The risk assessment is provided in Tables 9 to 12 with each table describing the level of risk on each receptor within their pertaining areas. Note only the receptors present in each of the areas have been shown in their relevant table. Barwon Water has informed a stock pipeline has been installed to supply existing licence holders. Therefore, this receptor has been excluded from further risk assessment.

An example on how to interpret the risk assessment tables (Tables 9 to 12) is presented below with reference to the first source (S1) and pathway (P1) in Table 9:

- Acid sulfate soils (S1) is linked via pathway P1 (ongoing oxidation) to the receptors within the western swamp (R1, R2, R3, R5, R6 and R8) which poses a number of stressors (i.e. acidity and metals loading and precipitation).
- The likely hood of the pathway occurring is considered likely (Table 6), and the consequence moderate (Table 7).
- Using Table 8 as guidance, the risk is considered high (A2).

Table 6 Qualitative measures of likelihood

Level	Likelihood	Description
A	Likely	Will probably occur in most circumstances
B	Possible	Might occur or should occur at some time
C	Unlikely	Could occur at some time / exceptional circumstances

Table 7 Qualitative measures of consequence

Level	Consequence	Description
1	Minor	No measurable change from baseline (pre millennium drought) condition or improvement to swamp
2	Moderate	Measurable negative change – non-permanent i.e. system expected to recover in short term
3	Major	Measurable negative change – permanent i.e. system not expected to recover in mid-long term

Table 8 Qualitative risk analysis matrix: level of risk

Likelihood	Consequence		
	1 Minor	**2 Moderate**	**3 Major**
A (Likely)	Medium (A1)	High (A2)	High (A3)
B (Possible)	Low (B1)	Medium (B2)	High (B3)
C (Unlikely)	Low (C1)	Low (C2)	Medium (C3)

Table 9 Risk Assessment – West Swamp

Source	Pathway	Receptor	Baseline			Treatment Trial			Comments	Mitigation
			Likelihood	Consequence	Risk	Likelihood	Consequence	Risk		
Acid Sulfate Soils (S1)	Ongoing oxidisation (P1)	R1, R2, R3, R5, R6	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Moderate (2)	High (A2)	• Reduced river flow through this section of the swamp due to the offtake needed for the trial (potentially up to more than half) could see further drying out of the peat than would otherwise be the case, which in turn could drive ongoing oxidation (at least on some areas). Further information would be needed to pinpoint exactly which areas.	• Water levels in western swamp could be mitigated by diverting additional water through the swamp therefore, reducing the inherent risk.
		Macroinvertebrate (R8)	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Major (3)	High (A3)	• As suggested by current chemistry in western swamp (Table 4), ongoing oxidation and subsequent release of acid and metals unlikely to have major consequence on macroinvertebrate. Under the treatment scenario the oxidation may be exacerbated, and consequently increased due to diversion of flow from the upper swamp to the treatment cell.	
Water management (S2)	Mobilisation and distribution (P2)	R1, R2, R3, R5, R6	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Moderate (2)	High (A2)	• Reduced flow under the trail would suggest less mobilisation and distribution of acidity and metals in this section of the swamp. Treatment not expected to reach western swamp. No change from baseline	
		Macroinvertebrate (R8)	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Major (3)	High (A3)	• As per above	
	Reduced water levels (P3)	R1, R2, R3, R5, R6	Unlikely (C)	Moderate (2)	Low (C2)	Possible (B)	Moderate (2)	Medium (B2)	• Latent recovery of the mesic flora in this section of the swamp (as reflected in limited recent quadrat data) is potentially vulnerable to reduced river flows due to trial offtake. Further information would be needed to pinpoint exactly which areas.	
		Macroinvertebrate (R8)	Unlikely (C)	Major (3)	Medium (C3)	Possible (B)	Major (3)	High (B3)	• Reduction in water levels is possible under treatment scenario resulting in potentially higher level of risk when compared to the baseline.	
	Fire (P4)	R1, R2, R3, R5, R6	Unlikely (C)	Major (3)	Medium (C3)	Unlikely (C)	Major (3)	Medium (C3)	• Fire is possible again under extreme fire conditions as long as the swamp remains poorly hydrated and while the offtake trial will potentially see reduced flows in this section of the swamp, this is not likely to significantly change the chance of fire or the extent of impact. No change from baseline.	• N/A
		Macroinvertebrate (R8)	Unlikely (C)	Moderate (2)	Low (C2)	Unlikely (C)	Moderate (2)	Low (C2)	• Consequence of fire on macroinvertebrates is expected to be short term and wetland macroinvertebrates are adapted to wetting and drying events and therefore the consequence is considered moderate. No change from baseline.	• N/A
	Encroachment of undesired plant species (P5)	R1, R2, R3, R5, R6	Possible (B)	Moderate (2)	Medium (B2)	Possible (B)	Moderate (2)	Medium (B2)	• This section of the swamp is already severely impacted by undesired plant encroachment (esp. trees). This process is likely to continue in a more or less similar way in the context of the offtake trial. No change from baseline.	• N/A
		Macroinvertebrate (R8)	Possible (B)	Moderate (2)	Medium (B2)	Possible (B)	Moderate (2)	Medium (B2)	• Encroachment of undesired plant species may reduce available habitat for aquatic macroinvertebrates although they are adaptable to changed conditions.	• N/A
	Depth of inundation (>30cm) (P6)	R1, R2, R3, R5, R6	Unlikely (C)	Moderate (2)	Low (C2)	Unlikely (C)	Moderate (2)	Low (C2)	• As per bullet 1, reduced river flow due to the offtake trial will likely also impact flooding regime esp. extent and depth of inundation – potentially compromising the latent recovery of the mesic flora in this section of the swamp.	• N/A
		Macroinvertebrate (R8)	Unlikely (C)	Moderate (2)	Low (C2)	Unlikely (C)	Moderate (2)	Low (C2)	• As per above. Depth of water changes associated with treatment trail may reduce available habitat for aquatic macroinvertebrates.	• N/A
Alkaline dosing discharge (S3)	Treatment related precipitation and loading (P7)	R1, R2, R3, R5, R6	N/A	N/A	N/A	Unlikely (C)	Moderate (2)	Low (C2)	• A pH of 5.7 is currently reported and the anticipated range for natural fen-like wetlands is assumed to be pH 6 to 8. Alkaline dose (pH = 9?) will likely increase pH into this fen-like wetland range (over part of the west section of the swamp only), but there is some risk that it will go beyond this level. Exceeding this range could contribute to minor and short-lived negative impacts on the recovering wetland state in this section of the swamp (as reflected in limited recent quadrat data).	• N/A
		Macroinvertebrate (R8)	N/A	N/A	N/A	Unlikely (C)	Moderate (2)	Low (C2)	• Treatment related precipitation and loading not likely to impact western swamp and therefore macroinvertebrates due to location of discharge point at eastern most margins of the western swamp.	• N/A
Alkaline dosing plant (S4)	Spill of dosing materials (P8)	R1, R2, R3, R5, R6	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• Some chance of spill but likely only modest quantities with small and temporary impacts on this section of the swamp where the recovery of the mesic flora is limited (as reflected in limited recent quadrat data).	• Could be mitigated by storing caustic magnesia outside of swamp area.
		Macroinvertebrate (R8)	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• As above, treatment spillage unlikely to impact macroinvertebrates in long-term.	
	Spill of fuel/hydrocarbons (P9)	R1, R2, R3, R5, R6	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• Some chance of spill but likely only modest quantities with small and temporary impacts on this section of the swamp where the recovery of the mesic flora is limited (as reflected in limited recent quadrat data).	• N/A
		Macroinvertebrate (R8)	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• As above, treatment spillage unlikely to impact macroinvertebrates in long-term.	• N/A

Table 10 Risk Assessment – East Swamp

Source	Pathway	Receptor	Baseline			Treatment Trial			Comments	Mitigation
			Likelihood	Consequence	Risk	Likelihood	Consequence	Risk		
Acid Sulfate Soils (S1)	Ongoing oxidisation (P1)	R4 & R7	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Moderate (2)	High (A2)	• There should be no net change in flows in this section of the swamp under the trial and so no further drying out of the peat (which in turn could drive ongoing oxidation - at least on some areas) is anticipated. No change from the baseline.	• N/A
		Macroinvertebrate (R8)	Likely (A)	Major (3)	High (A3)	Likely (A)	Moderate (2)	High (A2)	• As per above, no additional effects associated with ongoing oxidation expected. Swamp chemistry may increase favourably for macroinvertebrate (pH 5.1 to 9), however, may pose stresses on system close to treatment water release point and at most eastern margins of the swamp.	• N/A
Water management (S2)	Mobilisation and distribution (P2)	R4 & R7	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Moderate (2)	High (A2)	• As per above, no net change in flows suggests no change in current mobilisation and distribution of acidity and metals in this section of the swamp. No change from baseline.	• N/A
		Macroinvertebrate (R8)	Likely (A)	Major (3)	High (A3)	Likely (A)	Major (3)	High (A3)	• No change from baseline.	• N/A
	Reduced water levels (P3)	R4 & R7	Unlikely (C)	Moderate (2)	Low (C2)	Unlikely (C)	Moderate (2)	Low (C2)	• The very poor recovery of the mesic flora in this section of the swamp (as reflected in limited recent quadrat data) suggest even if there were reduced river flows due to trial offtake, the impacts would be minimal. Furthermore, likelihood of swamp water levels decreasing will diminish as the lower tertiary aquifer recovers. No change from baseline.	• N/A
		Macroinvertebrate (R8)	Unlikely (C)	Major (3)	Medium (C3)	Unlikely (C)	Major (3)	Medium (C3)	• No change from baseline.	• N/A
	Fire (P4)	R4 & R7	Unlikely (C)	Major (3)	Medium (C3)	Unlikely (C)	Major (3)	Medium (C3)	• Fire is possible again under extreme fire conditions as long as the swamp remains poorly hydrated, and the offtake trial will not result in changes to flows in this section of the swamp. Thus, it is unlikely this will significantly change the likelihood of fire or the extent of impact. No change from baseline.	• N/A
		Macroinvertebrate (R8)	Unlikely (C)	Moderate (2)	Low (C2)	Unlikely (C)	Moderate (2)	Low (C2)	• No change from baseline.	• N/A
	Encroachment of undesired plant species (P5)	R4 & R7	Possible (B)	Moderate (2)	Medium (B2)	Possible (B)	Moderate (2)	Medium (B2)	• This section of the swamp is already severely impacted by undesired plant encroachment (esp. trees). This process is likely to continue in a more or less similar way in the context of the offtake trial. No change from baseline.	• N/A
		Macroinvertebrate (R8)	Possible (B)	Moderate (2)	Medium (B2)	Possible (B)	Moderate (2)	Medium (B2)	• As per above. Encroachment of undesired plant species may reduce available habitat for aquatic macroinvertebrates.	• N/A
	Depth of inundation (>30cm) (P6)	R4 & R7	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Moderate (2)	High (A2)	• There should be no net change in flows (incl. flooding regime esp. extent and depth of inundation) in this section of the swamp under the trial. No change from baseline.	• N/A
		Macroinvertebrate (R8)	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Moderate (2)	High (A2)	• As per above.	• N/A
Alkaline dosing discharge (S3)	Treatment related precipitation and loading (P7)	R4 & R7	N/A	N/A	N/A	Likely (A)	Minor (1)	Medium (A1)	• A pH of 5.7 is currently reported and the anticipated range for natural fen-like wetlands is assumed to be pH 6 to 8. Alkaline dose (pH = 9?) will likely increase pH into this fen-like wetland range, but there is some risk that it will go beyond this level. Exceeding this range could contribute to minor and short-lived negative impacts on the poorly recovering mesic flora in this section of the swamp (as reflected in limited recent quadrat data). Note that a moderate consequence is conservatively used here as it is possible there are still patches of better recovering mesic vegetation in some unsampled parts of this section of the swamp (Further sampling required).	• N/A
		Macroinvertebrate (R8)	N/A	N/A	N/A	Likely (A)	Minor (1)	Medium (A1)	• Water quality expected to improve which may positively affect macroinvertebrate.	• N/A
Alkaline dosing plant (S4)	Spill of dosing materials (P8)	R4 & R7	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• Some chance of spill but likely only modest quantities with small and temporary impacts on this section of the swamp were the recovery of the mesic flora is very poor/limited (as reflected in limited recent quadrat data).	• Could be mitigated by storing caustic magnesia outside of swamp area
		Macroinvertebrate (R8)	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• As above, treatment spillage unlikely to impact macroinvertebrates in long-term.	
	Spill of fuel/hydrocarbons (P9)	R4 & R7	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• Some chance of spill but likely only modest quantities with small and temporary impacts on this section of the swamp were the recovery of the mesic flora is very poor/limited (as reflected in limited recent quadrat data).	• N/A
		Macroinvertebrate (R8)	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• As above, treatment spillage unlikely to impact macroinvertebrates in long-term.	• N/A

Table 11 Risk Assessment – Boundary Creek

Source	Pathway	Receptor	Baseline			Treatment Trial			Comments	Mitigation
			Likelihood	Consequence	Risk	Likelihood	Consequence	Risk		
Acid Sulfate Soils (S1)	Ongoing oxidisation (P1)	Macroinvertebrate (R8)	Likely (A)	Major (3)	High (A3)	Likely (A)	Moderate (2)	High (A2)	• Still has a likelihood as unsure if the predicted levels will have an effect on the macroinvertebrate population and how quickly the system can be expected to recover. Effect of ongoing oxidation and subsequent mobilisation of acid/metals from Big Swamp into Boundary Creek expected to be subdued by treatment trial.	• N/A
		Fish/platypus (R9)	Likely (A)	Major (3)	High (A3)	Likely (A)	Moderate (2)	High (A2)	• As above. Unsure as to how long it would take for fish and platypus to move back into the waterway and if they were historically present. Would depend on re-establishment of food sources (macroinvertebrates) and habitat (macrophytes and vegetation).	• N/A
Water management (S2)	Mobilisation and distribution (P2)	Macroinvertebrate (R8)	Likely (A)	Major (3)	High (A3)	Likely (A)	Moderate (2)	High (A2)	• As above	• N/A
		Fish/platypus (R9)	Likely (A)	Major (3)	High (A3)	Likely (A)	Moderate (2)	High (A2)	• As above	• N/A
	Reduced water levels (P3)	Macroinvertebrate (R8)	Unlikely (C)	Major (3)	Medium (C3)	Unlikely (C)	Moderate (2)	Low (C2)	• As above, likely to affect downstream water ways through additional mobilisation and distribution.	• N/A
		Fish/platypus (R9)	Unlikely (C)	Major (3)	Medium (C3)	Unlikely (C)	Moderate (2)	Low (C2)	• As above	• N/A
	Fire (P4)	Macroinvertebrate (R8)	Unlikely (C)	Moderate (2)	Low (C2)	Unlikely (C)	Moderate (2)	Low (C2)	• As above	• N/A
		Fish/platypus (R9)	Unlikely (C)	Moderate (2)	Low (C2)	Unlikely (C)	Moderate (2)	Low (C2)	• As above	• N/A
	Encroachment of undesired plant species (P5)	Macroinvertebrate (R8)	Unlikely (C)	Minor (1)	Low (C1)	Unlikely (C)	Minor (1)	Low (C1)	• Not occurring at present. Even if exotic plants establish in Boundary Creek, aquatic invertebrates and animals have adapted elsewhere in the catchment.	• N/A
		Fish/platypus (R9)	Unlikely (C)	Minor (1)	Low (C1)	Unlikely (C)	Minor (1)	Low (C1)	• As above	• N/A
	Depth of inundation (>30cm) (P6)	Macroinvertebrate (R8)	N/A	N/A	N/A	N/A	N/A	N/A	• Minimal habitat available at present with silty pools and minimal/ no aquatic vegetation present so a change in depth is unlikely to make a difference.	• N/A
		Fish/platypus (R9)	N/A	N/A	N/A	N/A	N/A	N/A	• Depth is unlikely to be the controlling factor in the presence/ absence of fish or platypus in Boundary Creek.	• N/A
Alkaline dosing discharge (S3)	Treatment related precipitation and loading (P7)	Macroinvertebrate (R8)	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• As for S1, unsure of how long it will take and whether the proposed dosing will be adequate to encourage reestablishment of populations. First coloniser macroinvertebrates, (those that have mobile adult life stages similar to those found in wetlands) can be expected to be the first to establish. Six monthly surveys such as that currently conducted will determine how the reestablishment is progressing.	• N/A
		Fish/platypus (R9)	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• As above	• N/A
Alkaline dosing plant (S4)	Spill of dosing materials (P8)	Macroinvertebrate (R8)	N/A	N/A	N/A	Unlikely (C)	Minor (1)	Low (C1)	• Anything that is currently present is adapted to poor water conditions. Unlikely to negatively affected by dosage spill in swamp.	• Could be mitigated by storing caustic magnesia outside of swamp area.
		Fish/platypus (R9)	N/A	N/A	N/A	Unlikely (C)	Minor (1)	Low (C1)	• As above.	
	Spill of fuel/hydrocarbons (P9)	Macroinvertebrate (R8)	N/A	N/A	N/A	Unlikely (C)	Minor (1)	Low (C1)	• As above	• N/A
		Fish/platypus (R9)	N/A	N/A	N/A	Unlikely (C)	Minor (1)	Low (C1)	• As above	• N/A

Table 12 Risk Assessment – Barwon River

Source	Pathway	Receptor	Baseline			Treatment Trial			Comments	Mitigation
			Likelihood	Consequence	Risk	Likelihood	Consequence	Risk		
Acid Sulfate Soils (S1)	Ongoing oxidisation (P1)	Macroinvertebrate (R8)	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Moderate (2)	Medium (B2)	• Still has a possible likelihood as unsure if the predicted levels will have an effect on the macroinvertebrate population and how quickly the system can be expected to recover.	• N/A
		Fish/platypus (R9)	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Moderate (2)	Medium (B2)	• No formal assessment has been completed so unsure of the current effect if any on fish and platypus but fish have been bycatch during macroinvertebrate sampling and there has been evidence of platypus and other aquatic mammals further downstream near Birregurra.	• N/A
Water management (S2)	Mobilisation and distribution (P2)	Macroinvertebrate (R8)	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Moderate (2)	Medium (B2)	• As above	• N/A
		Fish/platypus (R9)	Likely (A)	Moderate (2)	High (A2)	Likely (A)	Moderate (2)	Medium (B2)	• As above	• N/A
	Reduced water levels (P3)	Macroinvertebrate (R8)	Unlikely (C)	Moderate (2)	Low (C2)	Unlikely (C)	Minor (1)	Low (C2)	• As above, likely to affect downstream water ways through additional mobilisation and distribution.	• N/A
		Fish/platypus (R9)	Unlikely (C)	Moderate (2)	Low (C2)	Unlikely (C)	Minor (1)	Low (C2)	• As above	• N/A
	Fire (P4)	Macroinvertebrate (R8)	Unlikely (C)	Moderate (2)	Low (C2)	Unlikely (C)	Minor (1)	Low (C2)	• As above	• N/A
		Fish/platypus (R9)	Unlikely (C)	Moderate (2)	Low (C2)	Unlikely (C)	Minor (1)	Low (C2)	• As above	• N/A
	Encroachment of undesired plant species (P5)	Macroinvertebrate (R8)	Unlikely (C)	Minor (1)	Low (C1)	Unlikely (C)	Minor (1)	Low (C1)	• Not occurring at present and is unlikely to be affected.	• N/A
		Fish/platypus (R9)	Unlikely (C)	Minor (1)	Low (C1)	Unlikely (C)	Minor (1)	Low (C1)	• Not occurring at present and is unlikely to be affected.	• N/A
	Depth of inundation (>30cm) (P6)	Macroinvertebrate (R8)	N/A	N/A	N/A	N/A	N/A	N/A	• N/A	• N/A
		Fish/platypus (R9)	N/A	N/A	N/A	N/A	N/A	N/A	• N/A	• N/A
Alkaline dosing discharge (S3)	Treatment related precipitation and loading (P7)	Macroinvertebrate (R8)	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• There is some impact from precipitation at the confluence of Boundary Creek with the Barwon River, but this does not persist.	• N/A
		Fish/platypus (R9)	N/A	N/A	N/A	Possible (B)	Moderate (2)	Medium (B2)	• Unknown but as they are typically highly mobile any effects should be brief before they recolonise.	• N/A
Alkaline dosing plant (S4)	Spill of dosing materials (P8)	Macroinvertebrate (R8)	N/A	N/A	N/A	Unlikely (C)	Moderate (2)	Low (C1)	• Expected that any impact would be absorbed in Boundary Creek prior to reaching the Barwon. If it did happen to reach the Barwon, then consideration should be given to releasing flushing flows from the headwaters to dilute effects.	• Could be mitigated by storing caustic magnesia outside of swamp area.
		Fish/platypus (R9)	N/A	N/A	N/A	Unlikely (C)	Moderate (2)	Low (C1)	• As above	
	Spill of fuel/hydrocarbons (P9)	Macroinvertebrate (R8)	N/A	N/A	N/A	Unlikely (C)	Moderate (2)	Low (C1)	• As above	• N/A
		Fish/platypus (R9)	N/A	N/A	N/A	Unlikely (C)	Moderate (2)	Low (C1)	• As above	• N/A

Key Findings

The key findings of the ecological risk assessment are:

- The risk to receptors (terrestrial vegetation and macroinvertebrates) within the Western Swamp is likely to increase as a result of the treatment trial due to the diversion of water from upstream of the swamp and, following treatment, release to the middle of the swamp. However, the inherent risk associated with this method could be mitigated by diverting additional water through the swamp.
- The risk to macroinvertebrates within the eastern swamp marginally decreases as a result of the treatment trial due the water quality improvements, however, no change in risk is observed with regard to the terrestrial vegetation receptors as water flows/levels (considered as a main factor for vegetation state) through the swamp remain unchanged between baseline and treatment scenarios.
- The risk to receptors decreases slightly within Boundary creek and Barwon River as a result of improved water quality associated with the treatment trial.

Recommendations

Based on the outcomes of the risk assessment the following recommendations are made:

Timing	Reference	Recommendation
Effective immediately (prior to trial)	All swamp / trial	Based upon the outcomes of the previous recommendations a management plan needs to be developed in order to facilitate the management of the trial if risks are identified through monitoring, i.e. reduction in flow, temporal ceasing of the trail.
Effective following detailed design and prior to implementation of full-scale treatment	Table 9 and Table 10 Receptors: R1 – R6	Additional terrestrial and aquatic vegetation surveys should be undertaken on the swamp to gain a more detailed understand of the vegetation distributions and current swamp condition. This requires a specific focus on the presence of existing mesic species in relation to the area of proposed dosage release and the western swamp where flow volumes may be reduced.
	Table 9 and Table 10 Receptor R8	If not already completed, undertake macroinvertebrate surveys within the swamp to establish current populations of fauna (if present) and distribution such that the risk assessment can be more targeted to specific assemblages.
	Table 9 and Table 10 Receptors: R1 – R6 & R8	A sampling plan is being developed to assess the spatial change in soil and water chemistry on the swamp's receptors during the pilot trial. It is envisioned that the sampling will be undertaken at a sufficient temporal resolution to identify the pre-dicted changes in chemistry. The addition of this is information is recommended to better inform the risk to aquatic vegetation and macroinvertebrates within the swamp.

Sincerely

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