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A 12-month Field Trial to Remediate an Exposed "Tailings Beach" in Tasmania

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Abstract The King River is one of the most polluted rivers in Australia; it has been predicted that acid mine drainage will be produced in the river for several hundred years, with 2.0 tonnes of copper and 155 kg of sulfuric acid entering the river system each day. Reversing the damaging effects of dumped tailings on this scale is financially and operationally impossible; the only hope for recovery is natural weathering and, where possible, interventions that raise pH and reduce contaminants entering the system, thereby allowing revegetation of the exposed "tailings beach". Drawing from descriptive, empirical and photographic evidence, this study documents the findings of a 12-month field trial conducted in the King River delta. Treatment of tailings included applications to areas of contaminated tailings: Area #1, control; Area #2, lime and fertilizer; Area #3, soil; Area #4, sand; and Area #5, Terra B; each area was seeded using local tree species, with vegetative cover density and type the main criteria of successful remediation. Evidence suggests lime and fertilizer, and soil and sand amendments had no effect on tree growth after 12 months; the control and these amended areas did not support revegetation. However Area #5 had a pH of 3.9 before and 7.9 after treatment, and leachable metals had been reduced by an average 88%, with total actual and potential acidity reduced to zero. Every type of plant tree species thrived in the more favourable pH conditions, and grass self-seeded and proliferated after 12 months. These findings suggest a potentially fertile area for future research, and possible solution to the ongoing acidification of tailings and risks associated with airborne dust from the King River delta.

Keywords King River, Tasmania, Tailings, Remediation, Revegetation

1. Introduction

The King River in western Tasmania is one of the most polluted rivers in Australia, and has been described as a "pollution masterpiece" [1]. The 3.5 square kilometres of exposed contaminated mine tailings along and at the mouth of the river have been recognized as a "world-scale environmental problem" [2].

The King River flows from the southeast and discharges into Macquarie Harbour, which is home to Tasmania's salmon fisheries industry. A delta at the mouth of the river was formed by a 100 years of dumping of tailings into the Queen and King Rivers from the Mount Lyell Mining and Railway Company located 25 km inland from the delta, which mined for copper, silver and gold near Queenstown, causing the accumulation of contaminated deltaic sediments more than 100 metres deep in some places. The discharge of acid mine drainage (AMD) from the river system is expected to continue for the next 600 years, with about 2.0 tonnes of copper and 155 kg of sulfuric acid entering the local ecosystem every day [3, 4]. A photograph of AMD in the river is shown in Figure 1. It is estimated that until 1994 when dumping was stopped by a subsidiary of Renison Goldfields, 97 million tonnes of mine tailings and 1.5 million tonnes of slag had been dumped into the Queen and King rivers by the mine, forming large deposits on river beds and banks (two types of sediment banks have been identified: high mounded upstream banks, and low, flat-topped downstream banks) creating the exposed "tailings beach" at the mouth of the King River [4, 5].

With so much hazardous waste deposited into the river during the 20th century, the King River is polluted with heavy metal and metalloids, including arsenic, copper, lead, mercury and selenium, and a range of other elements that are potentially harmful to the environment and human health. For example, Williams stated that in a "small copper-polluted stream near Queenstown" which feeds into the King River he was unable to "recover a single living macroscopic animal in February 1963" [6], and reported that "all aquatic life in the Queen River and lower King River has been killed" and "waterways contaminated with toxic metals, particularly copper, represent a hazard to the fishing industry and other harbour uses" [7].

To put the King River delta into the broader environmental context, its formation and characteristics bear

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a striking similarity to the 300 metre wide exposed tailings beach formed in the Bahia de Portmán, near Murcia in southern Spain, which formed when cadmium-, cyanide-, lead- and zinc-contaminated mine tailings were discharged into the Mediterranean by miner Penarroya at a rate of 7,000 tonnes per day between 1957 and 1990 for a total of more than 60 million tonnes deposited. The tailings beach at Portmán, not unlike the King River delta, is up to 150 metres deep [8, 9]. As a consequence, the Bay of Portmán has been described as the most degraded zone in the Mediterranean caused by mining, with elevated concentrations of arsenic, cadmium and lead routinely found in wild mussels (*Mytilus galloprovincialis*) and red mullet (*Mullus barbatus*) 15 years after operations ceased [10].

Figure 1. Example of acid mine drainage in the King River

Similarly, contamination of the King River has affected biodiversity throughout the Macquarie Harbour catchment, with abnormal (or "weird" to quote Davies [11]) age and size distributions of fish and eel populations, such as the spotted galaxias (*Galaxias truttaceus*), climbing galaxias (*G. brevippinis*) and short-finned eel (*Anguilla australis*), in the King River catchment, as well as abnormalities in fish populations in tributaries which restrict migration to Macquarie Harbour to spawn [11, 12]. Prior to the cessation of dumping, mercury had also been found in farmed fish in Macquarie Harbour at or above the level recommended by the National Health and Medical Research Council [13].

Reversing the damaging effects of dumped tailings in the King River delta is financially and operationally impossible; the likelihood of either the Tasmanian state or Australian federal governments allocating the necessary resources to fully rehabilitate the King River delta seem remote, although earlier reports of the Mt Lyell Remediation Research and Demonstration Program suggested their remediation program in 1994 was "one of Australia's most comprehensive response (s) to large-scale environmental damage" ever conducted [7].

The only hope for recovery of the delta is natural weathering over centuries and, where possible, the intervention of strategies designed to reduce short- and long-term acidification reactions and contaminant loadings entering the environment and to revegetate the exposed tailings beach, if at all practicable.

The exposed tailings beach, which is shown in Figure 2, is composed of layers of oxidised and un-oxidized deposits. When the oxidized upper layers of the tailings are translocated by wind and water, the un-oxidized lower tailings are exposed and leach acid and heavy metals into Macquarie Harbour. The un-oxidized fine dry tailings can also be blown into the neighbouring town of Strahan and cyclically form dunes or sediment banks which cause die-back of contiguous plant and animal life. In 1996, Taylor [4] explained that "the upper layers of the tailings sediment are not saturated with water, and this permits infiltration by air. Acid production in the tailings is initiated by the reaction of sulfide minerals with atmospheric oxygen.

For example, the upper 1.5 m of the delta containing about 4.4 Mt of tailings is under-saturated with water and is the most significant source of acid and metals, at least from the delta sediments". He went on to explain that "preliminary estimates indicate that almost complete oxidation of pyrite in permanently unsaturated tailings takes place in one to four years. Interaction between the products of sulfide oxidation and water produces sulfuric acid, and a range of soluble heavy metals. The oxidation of aqueous iron compounds at and above the water table results in further acidity and widespread formation of iron-oxide precipitates which coat most of the sediment grains".

Figure 2. Photograph of the exposed tailing beach at the King River delta where the field trial was conducted

This description of AMD formation in the King River delta indicates that sulfuric acid is generated due to the interaction of oxidizing sulphides in the tailings and water, but the oxidation of sulfides can follow a variety of different pathways depending on factors such as pH and availability of ferric iron and other potential oxidants. As observed in the King River tailings [4], additional pathways of decomposition may also arise where reactions are mediated by the presence of bacteria, such as *Thiobacillus thiooxidans* or *T. ferrooxidans*, which can increase the rate of oxidation and thus acid generation and metal solubilization.

In addition to the release of acid as sulfide minerals oxidize, acid can be generated when metal ions react with water. For example, iron and aluminium, two of the most common metal ions associated with AMD, can produce acid when they react with water to form metal hydroxide precipitates. Because each atom of metal that precipitates can generate three hydrogen ions, it is important to know the concentrations of dissolved iron and aluminium in addition to pH when determining how much alkalinity is required to neutralize both actual and potential acidity and thereby effectively counter the polluting properties of AMD [14].

As a consequence, any estimate of AMD neutralizing requirements needs to be based on the titratable acidity of AMD not just on pH, because titratable acidity takes into account all potential acid-generating precipitation reactions which may occur as the AMD is neutralized (i.e., the "potential" acidity), not simply be based on the "actual" acidity that exists in a solid at any given point in time. The same underlying principle applies to estimating neutralization requirements for tailings, because metal hydroxides, particularly iron and aluminium oxyhydroxides which are often abundant in tailings, have a high charge-to-mass ratio, making them extremely "surface reactive". Hence, the fine particles in tailings such as those in the King River delta have an excellent ability to adsorb or co-precipitate trace metals, including potentially acid generating ions (such as Fe_3+ or Al_3+), and can adsorb hydrogen ions making them especially prone to AMD generation and downstream polluting consequences.

The most common form of chemical intervention for neutralizing acidity in mine tailings is the addition of lime, usually as calcium carbonate ($CaCO_3$); indeed the acid neutralizing capacity (ANC) of calcium carbonate (the so-called "$CaCO_3$-equivalent") is the benchmark against which neutralizing properties of chemical agents are measured, and researchers use this benchmark when estimating the ANC of neutralizing strategies at mine sites [15]. Blending sulfidic tailings with lime is relatively cheap, has been proven at mine sites around the world, and has been applied to acidic mine wastes for more than 2,000 years with efforts to understand the exact role of lime in acid neutralizing reactions increasing markedly since the 1960s [16, 17]. However, since lime is slightly soluble in rainwater and seawater, if a series of wet seasons precede a dry period or treated tailings, in this example, are inundated with seawater, some or all of the blended lime may leach or wash from the tailings before stored acid has been produced, subsequently leading to poor long-term neutralization outcomes. This effect is only heightened when the more reactive calcium oxide (CaO) or calcium hydroxide (CaOH) forms of lime are applied.

Furthermore, the presence of lime increases the availability of bicarbonate ions that can catalyze the decomposition of sulfides and thereby accelerate acidification and metal releases to the environment; the development of coatings on particles of lime mixed with sulfidic tailings and the precipitation of gypsum may also reduce the effectiveness of lime due to the reduction of these reactive surfaces. As a consequence, lime addition appears to initially change pH and adsorb metals, but over time may re-release these same metals to the environment as stored acidity within the tailings is oxidized over time. For these reasons, it has been concluded that the addition of lime to acidic tailings may initially neutralize acid and bind metals, but in the long-term may not prove sustainable.

On the other hand, Terra B reagent, a chemical formulation derived from modified alumina refinery residue mixed with other benign chemicals, has been used to neutralize acid and sequester heavy metals in tailings [18, 19]. The ANC of minerals in Terra B is largely provided by carbonate, hydroxide and hydroxycarbonate minerals, which have low solubility and hence react slowly with acid-generating minerals. For example, Terra B contains a complex cocktail of metals and minerals, including hematite (Fe_2O_3), beohmite (õ-AlOOH), gibbsite ($Al[OH]_3$) and sodalite ($Na_4Al_3Si_3O_{12}Cl$), anatase (TiO_2), aragonite ($CaCo_3$), brucite ($Mg[OH]_2$), diaspore (ß-$Al_2O_3.H_2O$), ferrihydrite ($Fe_5O_7[OH].4H_2O$), gypsum ($CaSO_4.2H_2O$), hydrocalumite ($Ca_2Al[OH]_7.3H_2O$), hydrotalcite ($Mg_6Al_2CO_3[OH]_{16}.4H_2O$), and p-aluminohydrocalcite ($CaAl_2[CO_3]_2[OH]_4.3H_2O$). Of significance in these formulae is the presence of hydroxides and oxyhydroxide compounds which contribute to the acid neutralizing capacity of Terra B, as well as the positively charge iron-, aluminium-, magnesium- and titanium-based molecules which not only initially adsorb metals but lead to precipitation and isomorphic substitution reactions; these reactions are largely responsible for the long-term "sequestration" phenomena of inorganic species described above.

Examples of how metal sequestration and oxidation work synergistically in environmental remediation, including the revegetation of tailings, and mining have been discussed elsewhere [20, 21], and applications utilizing these and related reagents in the treatment of coal waste and in industrial site remediation have been examined [14, 22, 23, 24, 25]. Terra B had been used in metal sequestration and revegetation at another Tasmanian government-run mine site [26], making it a logical choice for application in the present field trial; other core technical issues associated with the technology associated with the preparation of Terra B have been the subject of specialist scientific papers [27].

From this review of the King River delta, it is clear that actual and potential acidity in the tailings must be neutralized and once stabilized efforts should focus on rehabilitation of the tailings beach. Therefore, the present study asks the following research questions: What impact does the blending of a range of neutralizing and stabilizing additives, including lime and Terra B, have on the treatment and revegetation of King River tailings, and how do these impacts compare to an unamended control over a 12-month period?

2. Methodology

The field trial documented in this study was implemented by staff of the West Coast Council based in Zeehan and volunteers of the King River Action Group based in Strahan; the project was funded through Environment Australia by the Australian federal government. The main objective of the field trial was to determine which additives would sufficiently neutralize acid, sequester heavy metals, and provide the King River tailings with enough nutrients to support long-term grass and tree growth.

However, establishing a vegetative cover over the tailings was considered the primary goal of the project because this would minimise and control the dispersal of dust into the nearby community of Strahan (about 5 km to the north) during the summer months. The prevailing wind in the delta is from the south, and the effect of dust on the town was a particular concern to local residents and government health officials.

Because of the previous work of Taylor, 20kg samples were collected of both the upper (100 mm) and lower (300 mm) layers of tailings prior to the field trial by staff of the West Coast Council and analyzed to establish a chemical reference point and determine ANC requirements for lime and Terra B. Both upper and lower layers had a pH of 3.9, a total actual acidity of 29 moles H+/tonne, a total potential acidity of 84 (upper layer) and 78 (lower layers) moles H+/tonne, and a total titratable reduced inorganic sulfur content of 6.3 %Scr (upper layer) and 5.9 %Scr (lower layer), meaning the pH of tailings was predicted to drop to 2.9 in the future. These data were confirmed by samples collected and analyzed at the start of the field trial for all areas, as presented in Table 1.

Table 1. Analysis of tailings before, and Area #5 after, 12 months

Parameters	Control Tailings Before Trial	Tailings in Area #5 After 12 Months	Percent Reduction (%)
pH	3.9	7.9	—
Total actual acidity (moles H^+/tonne)	29	0	100
Potential pH without neutralization	2.9	7.5	—
Total potential acidity (moles H^+/tonne) without neutralization	84	0	100
Leachable As	1.0	0.001	99
Leachable Cd	0.01	<0.001†	100
Leachable Cr	0.25	0.02	20
Leachable Cu	1.6	0.62	62
Leachable Fe	10.0	2.5	75
Leachable Hg	0.01	0.001	90
Leachable Mn	0.03	0.01	66
Leachable Ni	0.76	0.03	96
Leachable Pb	0.1	0.006	94
Leachable Se	1.0	<0.001†	100
Leachable Zn	0.11	0.07	37
Average percent reduction of leachable metals	—	—	88

† Below the limit of detection

No significant difference in total metals were observed between the upper and lower layers, with copper, lead, manganese and zinc being the predominant metals; these data were: arsenic = 17mg/kg; cadmium = 0.1 mg/kg; chromium = 9.6 mg/kg; copper = 440 mg/kg; iron = 5.2 mg/kg; mercury = 0.1 mg/kg; lead = 41 mg/kg; manganese = 167 mg/kg; nickel = 8.8 mg/kg; selenium = 4.1 mg/kg; and zinc = 137 mg/kg. This analysis also showed that both layers were uniformly high for sodium (468 mg/kg), potassium (945 mg/kg), calcium (804 mg/kg), magnesium (5,316 mg/kg), and sulfate (14,969 mg/kg), and uniformly low for carbon (0.1 mg/kg), nitrogen (0.03 mg/kg), and phosphorus (1,251 mg/kg).

Of particular concern to local residents in Strahan was the unexpected discovery that the tailings contained selenium. Selenium (Se) is often overlooked as a contaminant of concern because selenium deficiencies are common in Australia and many scientists and regulators do not consider its significance when evaluating remediation programs. However, the high concentrations of Se in the King River tailings was considered important by local Tasmanian authorities because Se can accumulate up the food chain, and exposure can cause adverse health effects in humans causing nausea, vomiting and diarrhoea. Brief exposures to Se in air can result in respiratory tract irritations, bronchitis, breathing difficulties, and stomach pain, and longer term exposure can cause bronchial spasms and coughing. Chronic exposure to Se can cause selenosis, the major signs of which are hair loss, nail brittleness, and neurological abnormalities. Animal studies have shown that a high selenium intake can affect sperm production and the female reproductive cycle. However, in Tasmania only leachable metal concentrations are used to classify solids, and the King River tailings were classified as “contaminated soil” under Department of Primary Industries, Water and Environment standards due to the high leachability of arsenic, mercury and selenium, as shown in Table 1.

As shown in Table 2, five, 40 m x 40 m trial areas were demarcated above the high water mark on the exposed tailings beach, each about 100 m from the Macquarie Harbour shoreline. The five areas were designated and labelled: Area #1—control and seed; Area #2—lime, fertilizer and seed; Area #3—soil and seed; Area #4—sand and seed; and Area #5—Terra B and seed. Area #1 was an unamended control without treatment of any kind; the additives used in each of Areas #2 through #5 were blended to a depth 300mm by rotary hoe at an addition rate of 3% w/w.

Table 2. Details of the five field-trial Areas

Area	Size	Amendment
#1	100m^2	No amendment and seed
#2	100m^2	Lime, fertilizer and seed
#3	100m^2	Soil and seed
#4	100m^2	Sand and seed
#5	100m^2	Terra B and seed

Area #2 consisted of 3% calcium carbonate ($CaCO_3$) and nitrogen, phosphorus and potassium (NPK)-based fertilizer blended into tailings; Area #3 consisted of a standard topsoil used by landscape gardeners to condition soil blended into tailings; Area #4 consisted of washed river sand blended into tailings; and Area #5 consisted of Terra B reagent blended into tailings. All five areas were seeded with the same number and density of locally collected tree and grass species, including tea tree (*Leptospermum*), paper bark (*Melaleuca*), wattle (*Acacia*), weeping cassuarina (*Allocassuarina*), and common groundsel (*Senecio vulgaris*).

After seeding, all five areas were covered with the same amount of native tea tree "slash" and covered with plastic netting to hold down the slash during high wind events and to reduce the translocation of dust. The tailings were monitored by local council and community representatives for 12 months after implementation, but no further work was carried out at the site after initial treatment. Although the location of the field trial site was chosen to minimize the effects of seawater on the treatment areas, during the field trial all five areas were inundated several times by high tides and surging seawater.

3. Results

Figures 3 through 6 provide photographic evidence of the outcomes of the field trial, with all photographs taken at the same time 12-months after treatment and revegetation. Figures 3, 4, 5 and 6 showing Areas #1, #2, #3 and #4 are consistent in that little or no vegetation is visible on any of the revegetated areas, although some limited grass had self-seeded and was growing on Area #2.

This finding is largely consistent with controlled studies that examined the role of different additives, including lime, in acidic waste rock treatment at a mine site in New South Wales over a 14-year period [28].

Figure 3. Photograph of Area #1 after 12 months

Figure 4. Photograph of Area #2 after 12 months

Figure 5. Photograph of Area #3 after 12 months

Figure 6. Photograph of Area #4 after 12 months

Virtually all the slash in Areas #1 through #4 had washed away as a result of seawater inundation, and only exposed tailings with some slash and grass can be observed in these areas. Because it was apparent that the additions of lime and fertilizer, soil, and sand had apparently failed to adjust reaction pH or eliminate actual and potential acidity in the tailings, as evidenced by the lack of tree and grass revegetation that occurred in Areas #1 through #4 after 12 months, the West Coast Council decided not to analyze the post-treatment tailings in these areas. This decision was warranted given that Australian grasses and trees do not survive in soil with a reaction pH of <5.5. The difference in revegetation outcomes between Areas #1 through #4 and Area #5 can be seen in Figures 7-10. Figures 7 and 8 shows that the entire Area #5 had uniformly germinated; both trees and grass were visible after 12 months, and examples of tea tree, paper bark, wattle, weeping cassuarina and common groundsel are visible in Figures 9 and 10, and a wide variety of grasses had germinated.

Moreover, West Coast Council staff observed that Area #5 more readily shed inundated seawater and was apparently not adversely affected by repeated salt inundation. Naturally occurring, self-seeded grasses and tree species also prospered in the area treated with Terra B reagent.

The photographic evidence provided in Figures 7-10 is supported by the empirical data in Table 1. After 12 months, the pH in Area #5 had increased from 3.9 to 7.9 as a result of Terra B addition, and total actual acidity had decreased from 29 moles of acid per tonne to 0 moles of acid.

Figure 7. Photograph of Area #5 after 12 months

Figure 8. Photograph of Area #5 after 12 months

Figure 9. Close up of Area #5 after 12 months

Figure 10. Close up of Area #5 after 12 months

Similarly, total potential acidity had decreased from 84 moles of acid per tonne to 0 moles of acid, and the pH of tailings had the intervention not occurred was predicted to be 2.9.

Leachable metals and metalloids decreased when measured by TCLP, with an average reduction of 88%; leachable arsenic decreased from 1.0mg/L to 0.001 mg/L, leachable copper decreased from 1.6 mg/L to 0.62 mg/L, leachable mercury decreased from 0.01 mg/L to 0.001 mg/L, and leachable selenium decreased from 1.0 mg/L to <0.001 mg/L, the detection limit for metals and metalloids.

This finding indicates that not only did the total actual and potential acidity of the tailings decrease significantly as a result of Terra B addition, but that all metal and metalloid species were sequestered tightly enough not to be readily mobilized under future acidifying conditions. Given the TCLP leachability test is designed to mimic what would happen to tailings under acidifying conditions over a 20 years period, this finding indicates that Terra B stabilized the tailings sufficiently to maintain revegetation over the long term.

All areas were classified after 12 months against Department of Primary Industries, Water and Environment, Tasmania standards for contaminated soil; only Area #5 could be re-classified as “low-level contaminated soil” (the lowest possible reclassification category below “contaminated soil”) as a result of the field trial.

4. Conclusions

An obvious flaw in this study is the lack of empirical data for Areas #2, #3 and #4 after 12 months. While the decision by the West Coast Council may have been justified based on the physical evidence presented to them at the end of the field trial, knowing exactly what the characteristics of the treated tailings in these three areas would have been helpful.

However, given the complete absence of any significant revegetation in these areas, it can reasonably be concluded that the soil pH, total actual and potential acidity and leachable metals and metalloids of the King River tailings had not benefited from the addition of lime, soil or sand. Certainly the consistency with which Areas #2, #3 and #4 performed in relation to the control indicates that these amendments would have little or no long-term salutary effect on tailings rehabilitation in the King River delta.

On the other hand, as evidenced by the photographic and descriptive data provided by the West Coast Council, the revegetation outcomes for Area #5 were striking. When triangulated against the empirical data presented in Table 1, the photographic and descriptive evidence makes a compelling case for the larger scale application of Terra B reagent as a sustainable additive to the tailings in the King River delta [1, 29].

Certainly the findings which indicate that total actual and potential acidity were reduced to zero are reason for optimism. These results also indicate that the application of Terra B can convert toxic tailings from the King River delta from “contaminated soil”, as classified by the Department of Primary Industries, Water and Environment, to a “low level contaminated soil”, the lowest available designation for mine waste in Tasmania.

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