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CHAPTER 11

AVON BASIN, WA WHEATBELT: ACIDIFICATION AND FORMATION OF INLAND ASS MATERIALS IN SALT LAKES BY ACID DRAINAGE AND REGIONAL GROUNDWATER DISCHARGE

Brad Degens¹, Rob Fitzpatrick^{2,3} and Warren Hicks^{3,4}.

¹*Department of Water, WA., P.O. Box K822, Perth, WA (Corresponding author)*

²*CSIRO Land and Water, PMB 2, Glen Osmond, SA 5064*

³*Co-operative Research Centre for Landscape Environments and Mineral Exploration, PO Box 1130, Bentley, WA 6102.*

⁴*CSIRO Land and Water, GPO Box 1666 Canberra ACT 2601*

INTRODUCTION

Shallow, acidic (pH<4) saline groundwaters are widespread in lowlying landscapes of the eastern WA Wheatbelt (Shand and Degens 2008). In many parts of the WA Wheatbelt, watertables are continuing to rise (George *et al* 2008) and increase the discharge of these groundwaters, with associated salinity and acidity, to broad valley floors. Deep open drains are increasingly being used by landholders to manage the rising water-tables and recover or protect land from salinisation in these areas (Dogramaci and Degens 2003; Kingwell and Cook 2007). Such drains are frequently acidic as a result of intercepting shallow acidic saline groundwater. Furthermore, drains commonly discharge to sacrificial lakes or floodways, where flows eventually collect in lakes further down-stream (Dogramaci and Degens 2003; see also several chapters in Shand and Degens 2008).

The geochemical impacts of acidic saline groundwater in the WA Wheatbelt are poorly understood, though likely to be similar to that of inland Acid Sulfate Soils (ASS). Although the impacts of secondary salinisation are well documented (Hatton *et al* 2003), the prospect of regional discharge of acidic groundwaters to surface environments or discharge from deep open drains poses an additional threat to surface waterways and lakes.

Acidic groundwater has long been recognised to occur in the eastern Wheatbelt, particularly in deeper strata (Bettenay *et al* 1964; Mann 1983). Surface expressions of this acidity are noted in some large salt lakes on the Yilgarn River within the WA Wheatbelt (Mann 1983; Cale *et al* 2004) and the southern Goldfields (McArthur *et al* 1991; Clark 1994). Surface water monitoring in the eastern Avon basin also identified acidic baseflow in waterways across the inland Avon basin, indicating that the impacts of shallow acid groundwaters may be more widespread than originally thought (Degens and Muirden 2006). The significance of increasing discharge of acidic waters for trace metal mobilisation, and the risk that this poses to aquatic ecosystems, should increasing drainage occur, has not been investigated and is the main focus of this report.

A regional survey of surface waters in salt lakes of the eastern WA Wheatbelt was carried out with a nested survey of soil and sediment hydrogeological properties to investigate the impacts discharge from salt-land drainage on salt lake geochemistry. A range of reference sites, not impacted by drainage, were sampled as comparisons to nearby drainage impacted lakes.

Methods

Grab samples of surface water were taken at sixty six lakes and one constructed evaporation basin between October 2005 and August 2006 (Figure 1). Thirteen of these sites were identified as receiving

drainage waters by the Department of Water from a GIS evaluation of surface flow paths from drain sites sampled in October 2004 (Fitzpatrick *et al* 2008) using aerial photography and spatial data on watercourses and flow paths. Verification that drain flows discharged into lakes or that lakes were in the immediate flow-path downstream of drain discharge points was conducted as part of on-ground investigations. A similar process was used to identify reference lakes, which were control sites not receiving drainage or off-line from main water courses and containing water at the time of sampling.

All samples were filtered in the field through 0.45 µm membrane filters in the field and preserved by either addition of ultrapure nitric acid (to a final concentration of 0.1%) or retained unacidified and stored at 5 degrees C. Measurements of pH, electrical conductivity (EC), temperature and oxidation-reduction potential (using Ag/AgCl probe; converted to Eh) were taken on-site at most sampling points. The concentrations of Cu, Zn, Co, Ni, Cr, Mn, P, V, Fe, Al, Ca, Mg, Ti, Na, K, and S were determined by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The elements Ag, Ba, Cd, Mo, Pb, Sb, Sn, Y, Hf, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Th, U and Se were determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Arsenic was also determined using the hydride generation coupled to ICP. Selected anion analyses (SO₄, NO₃, NH₄, PO₄) were completed using ion chromatography. Only selected results from these analyses are discussed here.

Most sites were only sampled once. However, as a result of summer flooding in the Lockhart Catchment and the permanency of some water-bodies, it was possible to sample a number of these several times. Sampling of sediments for evaporite minerals and clastic sediments (Fitzpatrick *et al* 2008) was undertaken at fourteen sites during February 2006 to provide an indication of the dominant hydrogeochemical processes occurring within the lake environments including the fate of trace metals and acidity.

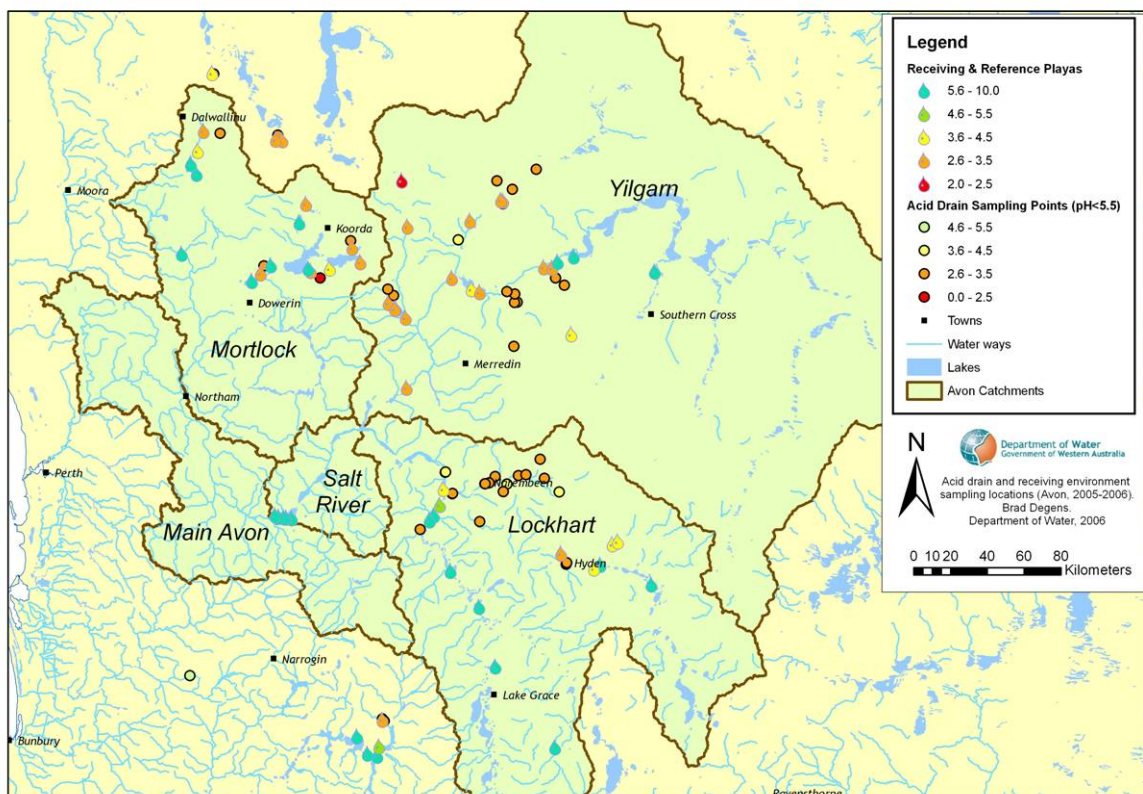


Figure 1. Outline map of reference and receiving lake sampling sites, drains discharging to the receiving lakes and the pH of these in the Avon catchment (WA).

Along with water samples, observations of water depth, recent maximum filling depth, sediment characteristics, hydrological connectivity (open or closed to low flows upstream or from the localised catchment) and evidence of aquatic/faunal life were made, where possible.

Sediment samples were collected and analysed, as described in (Fitzpatrick *et al* 2008), from 14 lakes (7 receiving lakes/sites and 7 reference lakes) in summer-autumn, corresponding with maximum formation of evaporate minerals. Briefly, sediment samples were collected at a number of zones within each lake, selected to provide information on geochemical processes above the high-water mark (beach), in the evaporation zone and within the bed sediments. Localised variations in morphology, determined by colour, texture, mineral precipitates and depth below surface, guided sampling within each zone.

Sediments were analysed for basic soil properties ($\text{pH}_{1.5}$, $\text{EC}_{1.5}$, organic C and carbonate C), major and minor elements by XRF and ASS properties. The latter analyses included potential acidity determined by analysis of sulphide-S using the chromium reducible S method (Ahern *et al* 2004) and existing acidity (total actual acidity) determined by titration to pH 6.5 with NaOH in a 1M KCl suspension (standard acid sulfate soil analysis method 23F; Ahern *et al* 2004). These analyses allowed better understanding of the extent to which sediments had acidified that was not apparent from pH alone.

RESULTS AND DISCUSSION

Surface Water Acidity and Salinity

Surface waters within reference lakes ranged from acidic ($\text{pH}<5.5$) to alkaline ($\text{pH}>7$). Over 45% of reference lakes were alkaline ($\text{pH}>6.5$; Figure 1 and 2), particularly in upper Lockhart River and mid-North Mortlock catchments. However, there were numerous lakes with acidic water (the majority less than pH 4) in the upper North Mortlock and central Yilgarn catchments (Figure 1), despite there being no known deep drainage discharge in the catchments of these lakes. Few lakes were found to contain alkaline water because many of these may only fill to any extent after significant rainfall events (eg $>50\text{mm}$). In contrast, many acidic lakes were likely dominated by groundwater discharge and/or down-stream of floodways with near surface groundwater which provided runoff conditions for these lakes to be filled to a depth of least 100mm after small rainfall events (eg $<20\text{mm}$).

This survey indicates that acidic lakes may occur across a much larger area of the eastern WA Wheatbelt than previously recognised. Waters in lakes in the eastern Wheatbelt around Narembeen and Bruce Rock are considered to be naturally acidic (Halse *et al* 1993) and there are reports of acidic ground-waters discharging to lakes (Mann 1983; McArthur *et al* 1991), though some of these contained alkaline surface waters (Mann 1983). Prior to clearing it was likely that there were localised discharges of acidic ground-waters on the margins of some lakes and from sand seeps (Bettenay *et al* 1964; McArthur *et al* 1991), however it is unlikely that significant acidity in surface waters was present to the large spatial extent found in this survey.

Discharge of regional acidic groundwaters may have contributed to the acidification of lakes that were acidic in the absence of drainage discharge and this may be increasing with on-going ground-water discharge. Many acidic reference lakes were not open to annual surface-water inflows (ruling out any possible unidentified drainage impacts) and were effectively closed basins primarily under the influence of rising regional ground-waters (Figure 3). Acidic groundwater is widely distributed in the WA Wheatbelt (Shand and Degens 2008) and it is possible that discharge of this to lakes, floodways and creeklines with poor neutralising capacity would result in acidification of some of these water-features. The similar chemistry of acidic reference lakes and acidic drain receiving lakes (Figures 2 and 4) also indicates a similar acid origin. The titratable acidity of surface waters in many acidic drainage receiving lakes was similar to that of acidic reference lakes (Figure 4) and is dominated by dissolved aluminium (Figure 4).

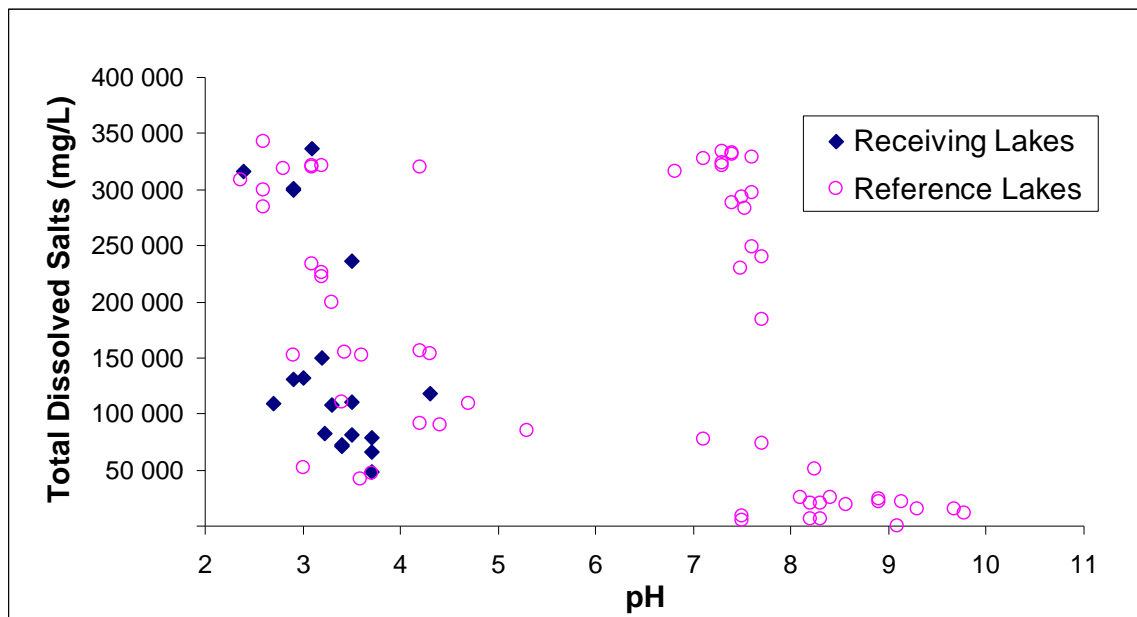


Figure 2. Lake water pH and salinity (total dissolved salts; TDS) in reference and receiving lakes in the Avon catchment, WA (at various stages of drying).

Lakes into which acidic drainage water directly discharge (receiving lakes) or those immediately downstream of floodways receiving acidic drainage water all contained acidic waters (with $\text{pH} < 3.8$; Figure 1). Over 75% of these lakes also contained waters with $> 50\,000\text{ mg l}^{-1}$ TDS at the time of sampling (Figures 1 and 2). Lakes may have acidified as a result of discharge or were acidic prior to discharge (this was not readily distinguishable in all cases). If lakes were alkaline prior to discharge, it was clear that there is limited capacity of any lakes to neutralise acidic drainage waters – at least in the short-term (< 5 years).



Figure 3. An example of an acidic reference lake acidified by regional groundwater discharge (Askews Lake, Beacon)

A wide range of salinity levels were found across all the sites, with many sites containing waters exceeding 150 000 mg l⁻¹ TDS (Figure 2), which in many cases indicated that many lakes were in advanced stages of drying, reflecting limited rainfall in the months prior to sampling. Where lakes contained waters with less than 50 000 mg l⁻¹ TDS, this was commonly due to recent filling by surface water inflows, either by high winter rainfall during 2005 or remnant-cyclone rainfall occurring during the summer of 2006.

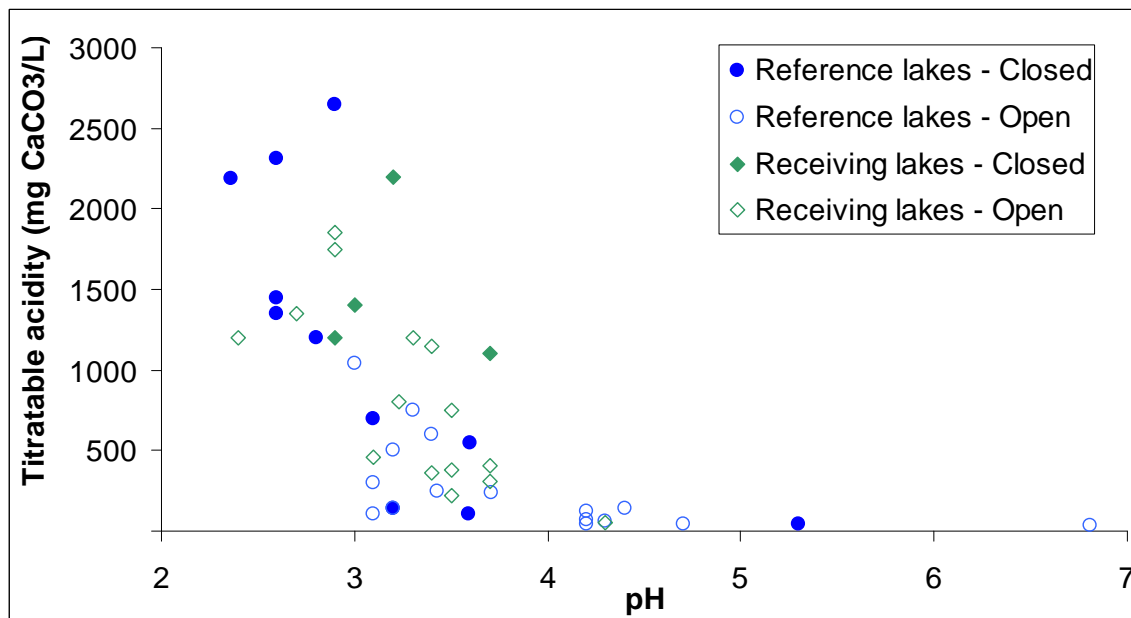


Figure 4. pH of lake waters in relation to titratable acidity for reference and receiving lakes (where pH<7) in the Avon catchment, WA (distinguished by whether the lakes were deemed open or closed to regional surface water flows).

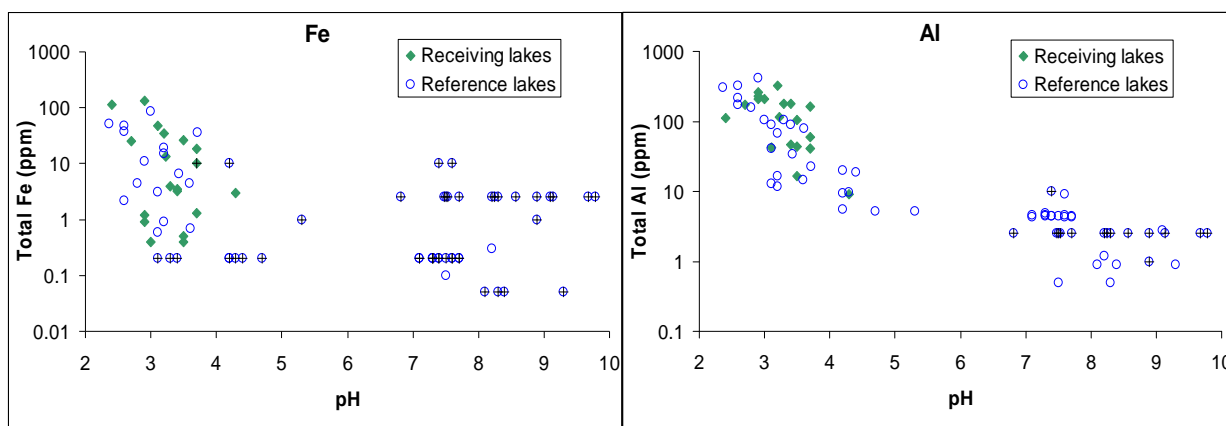


Figure 5. Distribution of soluble iron and aluminium concentrations in relation to pH for reference and receiving lakes. NB: Values below detection are plotted at the detection limit (marked with +) and concentrations are shown on a logarithmic scale.

Trace elements in surface waters

The acidic lake waters contained high solute concentrations of some trace elements (including Al, Fe, Co, Ni, Pb, and the rare earth elements) at generally more than 10 times the concentrations occurring in non-receiving lakes with alkaline waters (Figure 5 and 6). Other trace elements such as As, Cu, Su, U and Zn were not dissimilar between acidic and alkaline reference lakes (Figure 5).

The greatest concentrations of trace elements such as Cu, Co, Ni, Pb, U and Zn occurred in waters in lakes receiving acidic drainage and were generally at least 1.2 times greater than the maximum concentrations in acidic reference lakes (Figure 5). However, the ranges of most trace element concentrations in lakes receiving acidic drainage were similar to those in acidic reference lakes. For example, waters of a receiving lake north of Bodallin contained $2500 \mu\text{g Pb l}^{-1}$, but a non-receiving lake at Beacon (100 km north-west) contained $2300 \mu\text{g Pb l}^{-1}$. Similarities between the waters in receiving and non-receiving lakes may reflect the similar geochemical processes at the sites determining metal solubility (e.g. precipitation and adsorption driven by evapo-concentration and mineral precipitation processes). These may have diminished any original differences that might be due to different rates of metal loading (from drains or direct regional ground-water discharge).

The risk posed by metals in lakes receiving acidic drainage and acidic reference lakes is unclear. Algae and aquatic crustaceans (eg *Paratemia* spp) were observed at a number of acidic reference lakes (e.g. King Rocks Rd, East Hyden; McKay Rd, Pithara and Doodlakine-Kununoppin Rd lake, Trayning). The presence of these organisms presents the possibility that there may well be pathways by which bioaccumulation of some metals (e.g. Pb, U, Cd) could occur, thereby posing some risk to bird-life evident at many lakes and reported to occur elsewhere (Goodsell 1990). There has been very little investigation of ecotoxicological effects of metals in hyper-saline waters (Wang 1987) and even less is known about the ecological impacts in temporary or ephemeral lake systems (Smith *et al* 2004). The high concentrations of Cl in seawater may reduce uptake of some metals by aquatic organisms (i.e. reduce bioavailability), although, in contrast there are some metals (e.g. Cd) where high Cl concentrations can increase uptake by aquatic organisms (Wang 1987 and Campbell 1995). Greatest risks may also occur in the period after filling by floodwaters, when the pH of lake waters can increase, salinity decreases and aquatic food-chains can be most active (Davis *et al* 2003).

Inland acid sulfate soil materials in lake and shoreline sediments

Discharge of acidic drain waters and regional groundwater seepage has promoted the formation of inland actual ASS materials in the sediments of lakes. Lakes (and the one new evaporation basin) receiving acidic saline waters (<pH 5.5; as sampled in spring, 2005) also contained acidic bed sediments (pH<5.5 in 1:5 deionised water). Likewise, reference sites with acidic waters also contained acidic bed sediments. Conversely, lakes with alkaline waters contained alkaline sediments.

Acidic drainage waters have the capacity to acidify some lake bed sediments. Seepage of acidic drainage waters into alkaline sediments (pH>7 in 1:5 deionised water) was still evident at one receiving site (Gambles Rd, Cowcowing) where a thin layer of acidic surface sediments (pH<4, 0-1cm) overlay more alkaline bed sediments (pH>6.3, 1-30 cm). There were no free carbonates in the deeper sediments of this lake, though these may have been present at some time in the past, since the bed sediments of an adjoining reference lake (Ski Lake, Cowcowing) contained up to 9% by mass CaCO_3 within the surface 15 cm.

The majority of acidity in acidic receiving and reference lakes is contained in the shallow sediments (<40cm) rather than overlying waters (Table 1). Some sites contained up to several thousand times more existing acidity in sediments than in waters at the time of sampling in spring 2005 (Table 1). These results indicate that neutralisation of acidic waters in acidic drain receiving lakes must take into account the acidity store within the sediments since these will tend to buffer the pH of the system. Significant amounts of reactive soluble and exchangeable acidity can be present in shallow lake sediments requiring up to 9.7 tonnes per hectare of pure limestone (as CaCO_3) to neutralise, even in acidic reference lakes. Notably, these estimates only indicate the more readily neutralisable acidity, generally present as exchangeable cations and soluble Al and Fe minerals, and do not include less reactive forms of acidity (McElnea *et al* 2002) that were present as iron (e.g. jarosite and natrojarosite) and aluminium hydroxysulfate (e.g. alunite) minerals at some sites.

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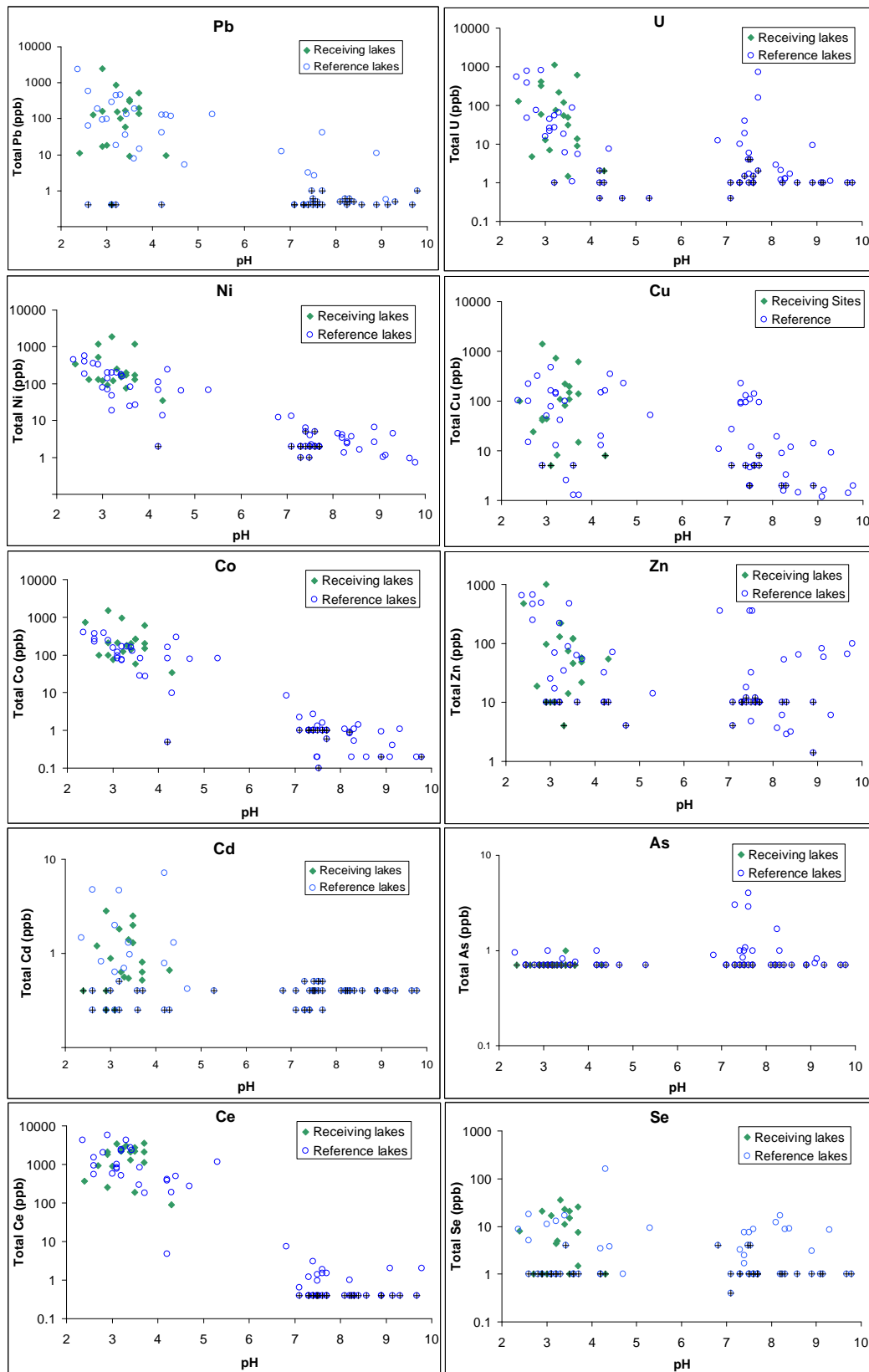


Figure 6. Concentrations of selected trace elements in reference and receiving lake waters of varying pH. NB: Values below detection are plotted at the detection limit (marked with +) and concentrations are shown on a logarithmic scale.

The soils fringing many acidic lakes (in the beach zone) contained greater amounts of existing acidity than those in the mid-part of lakes (Table 1). The accumulation of acidity and formation of inland actual ASS soils in these zones at most acidic reference lakes was probably due to concentration of acidity by

evaporation of local ground-water discharge on the margins of the lakes. This process has also been reported in larger, less hydrologically disturbed salt lake systems in the goldfields (McArthur *et al* 1991) and is likely to be increasing with rising water tables in many lakes in the eastern WA Wheatbelt. Lateral leakage of acidic waters from the main lake (with evapo-concentration in surface soils) may also have contributed to the accumulation of acidity in the beach zone at some sites receiving acidic drainage discharge, though the effect is constrained to within 10's of metres of the lake edges. The beach zone at many sites included an area inundated by water during winter 2005 (a year when generally average rainfall fell across the Wheatbelt) and at all sites would certainly be inundated during flooding events (except for the Bodallin evaporation basin which is protected from the hydrological impacts of flooding). Acidity accumulated in Al- and Fe-bearing surface salt efflorescences (e.g. rozenite) would be rapidly washed into the main water body during most winters and after flood filling.

Potential acidity was also present as sulfides in the bed sediments and occasionally beaches of eight receiving and reference environments (Table 1), as well as at three alkaline lake sites (not listed in the table). It was notable that the majority of acidic reference and receiving lakes did not contain sulfides. In the acidic lakes, the potential acidity in the sediment was generally more than an order of magnitude greater than that present as titratable acidity in the profiles (Table 1). The acidity stored in the sulfidic materials does not pose a threat to the environment providing that the lake beds remain anoxic (waterlogged) and/or saturated and are not disturbed by excavation.

Sulfide minerals were generally concentrated in the shallowest 10 cm of bed sediments (up to 0.6% S) and often occurred with significant accumulations of organic matter (up to 2.4% organic C in some horizons). It is likely that sulfides accumulating in bed sediments of the smaller lakes (in particular) have formed due to microbial sulfate reduction fuelled by organic inputs to the lakes and maintenance of water-logged conditions in the early stages of secondary salinisation. Organic C inputs may have occurred as a result of algal and macrophyte blooms during past lake filling events (evident at some sites as dried macrophytic material deposited on shorelines during most recent lake filling events) and/or as deposition of sediments and organic residues washed from the topsoil of adjacent agricultural areas during flood events. Waterlogged conditions in bed sediments between these events were probably maintained by rising ground-water levels due to land-clearing. Sulfide minerals present in lakes with acidic waters and sediments (receiving and reference) were most likely formed prior to acidification, since sulfate reduction and sulfide formation is generally favoured in alkaline environments (Langmuir 1997, Ward *et al* 2004). Occurrence of sulfides in acidic reference lakes may be evidence that the lakes were alkaline in the past and have undergone acidification in recent times, most likely because of increased discharge of acidic ground-waters occurring after land-clearing.

Data from this broad survey indicated that the concentrations of most trace metals in the bed sediments of most lakes receiving acidic drainage were not obviously elevated compared with the acidic reference lakes and two alkaline reference sites. Limited sampling within each receiving or reference environment (<4 sites) might have failed to detect differences in metal accumulations due to large spatial variation in metal accumulation. Spatial variation in deposition of precipitates (and associated trace metals) in the lakes receiving acidic drainage may be uneven, particularly where prevailing winds result in re-suspension and deposition of precipitates on the leeward side of lakes. It is also possible that some receiving lakes were acidic prior to drain discharge and the magnitude of discharge impacts (i.e. accumulation of trace metals) was indistinguishable compared with trace metal accumulation from previous regional acidic ground-water discharge.

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Table 1. Estimated acidity (as equivalent kg CaCO₃ per ha) in different zones within lakes (ponded waters, sediments and beach zones) for acidic reference lakes and lakes receiving acidic drainage (see footnotes for explanation of acidity pools).

Site ¹	Acidity in ponded waters (as equivalent kg CaCO ₃ /ha) ^{2,3}	Existing acidity ³ in lake bed sediments (as equivalent kg CaCO ₃ /ha)	Existing acidity ³ in beach soils (as equivalent kg CaCO ₃ /ha)	Potential acidity ⁴ as sulfides in lake-bed sediments (as equivalent kg CaCO ₃ /ha)
McKay Rd lake, Pithara (Ref)	0.4	9	267	439
Carter Rd lake, Jibberding (RE)	0.9	833	1 454	11 776
Gambles Rd lake, Cowcowing (RE)	1.8	288	209	16 519
Doodlakine-Kununoppin Rd, Trayning (RE)	3.0	4 018	Not sampled	393
Doodlakine-Kununoppin Rd, Trayning (Ref)	1.2	5 165	3 039	0
Yilgarn lake, Boodarockin (RE)	0.9	7 879	26	0
Yilgarn lake, Boodarockin (Ref)	0.4	416	2 304	0
Bodallin Evaporation Basin (RE)	11.0	2 596	2 919	0
Lake Ardath (RE)	4.1	2 564	664	0
King Rocks Rd, East Hyden (Ref)	0.6	9 745	Not sampled	0
Lake Gounter, Hyden (RE) ⁵	1.4	773	3 843	8 691

¹ Ref = reference site, RE = receiving site. Site location details in Shand and Degens, 2008.

² Estimated from depth of water in lake at time of sampling in early October 2005 and titratable acidity.

³ Existing acidity expressed as equivalent kg of H₂SO₄ estimated by summation of total actual acidity for all horizons in a profile (<40cm depth) calculated on a per hectare basis assuming a uniform bulk density of 1.5g/cm³ for all materials (Note: this is a conservative estimate since bulk density of hydrated materials may be less, which would increase acidity storage/ha). Total actual acidity is determined by titration to pH 6.5 of a 1M KCl-soil suspension (Ahern *et al* 2004). Acidity is expressed as equivalent weight of H₂SO₄ (in kg) per hectare that would need to be neutralised to raise the pH of the soils to 6.5.

⁴ Potential acidity = acidity within sulfides determined by chromium reducible S analysis (assuming no contribution of acidity from monosulfides). These were calculated as equivalent kg of H₂SO₄ and summed for all horizons in a profile and calculated on a per hectare basis assuming a uniform bulk density of 1.5g/cm³ for all materials.

⁵ Calculations for Lake Gounter focus on smaller permanently inundated NW corner of lake and not the larger eastern and SE flood fill zone (which was only occasionally inundated).

Drain discharge may increase surface concentrations of some trace elements in lakes, though this was not consistent for all receiving lakes. Elevated concentrations of some elements (e.g. Pb and U) were evident

in surface horizons at several sites receiving acidic drainage (Doodlakine-Kununoppin Rd receiving lake, Trayning and Gambles Rd receiving lake, Cowcowing). Such an assessment was based on evidence of increasing concentrations of the metals in surface horizons relative to deeper horizons and comparison of concentrations of the trace metals with respect to horizons of a nearby reference lake. However, sediment concentrations of some elements may be similar in all environments. For example, Pb and U concentrations were generally similar (5-52 mg l⁻¹) in lake bed and beach sediments in an acidic reference lake, a lake receiving acidic drainage and an alkaline reference lake near Boodarockin. Notably, this survey identified concentrations of Pb that were frequently an order of magnitude greater than acid digestible metal concentrations in an earlier survey of sediments in WA lakes (Lyons *et al* 1990), although Cu, Zn and Cd concentrations were generally within similar ranges.

The formation of inland ASS materials in sediments in lake systems, by whatever the cause, poses a significant risk to aquatic habitat and the long-term integrity of aquatic ecosystems. These impacts are in addition to those caused by changes in hydroperiod and increasing salinity (Halse 2004). Loss of habitat through acidification of sediments may impact greatest on sites where resting stages of aquatic organisms can survive between lake filling events. Furthermore, while acidity in surface waters might be periodically neutralised by floodwaters or during lake filling events, this is less likely to occur for the acidity within bed and shoreline sediments. Neutralisation of acidic sediments during lake filling events is likely to be slow and limited because of restricted seepage and slow diffusion of alkaline waters. In a worse case scenario, the acidic sediments could result in progressive consumption of alkalinity of lake waters after flood filling resulting in acidic conditions prevailing from the early part of the drying phase. This is a period during lake hydrological cycles that is commonly the most critical for aquatic ecosystems; when the lake is fullest, freshest and significant growth and reproduction of aquatic organisms occurs (Smith *et al* 2004; Davis *et al* 2003).

Mobilisation of trace metals from acidic sediments to water columns may also be increased under certain conditions, for example formation of anoxic bottom waters after lake filling resulting in reductive iron dissolution and release of trace metals. A similar situation can occur if bottom waters become acidic due to acidity emanating from bottom sediments.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Acidic drainage discharge to lakes can result in acidification of waters, soils and sediments and formation of inland ASS materials. However, in some cases lake waters and sediments may have been acidic prior to discharge in which case the impacts would depend on the magnitude of drain discharge compared with regional ground-water discharge. Concentrations of Al, Fe and trace metals including Pb, Ni, Co and U appear to be increased in the surface waters of sites receiving acidic drainage, particularly when compared with alkaline lakes. This acidification and associated increased trace metal solubility may result in impacts on aquatic ecosystems, including loss of habitat and reduced ecosystem functioning during lake filling events.

Lakes can be acidic in the absence of discharge from deep drains, most likely due to the discharge of regionally acidic ground-waters. Numerous acidic lakes occurring in the upper reaches of the Lockhart, Mortlock and Yilgarn catchments were found to be acidic with no evidence of deep drainage discharge. These lakes may have always been acidic since before land-clearing began, however, there is sedimentary evidence that some lakes may have become acidic in recent times. Notably, the acidic reference lakes exhibited geochemical conditions similar to those in lakes receiving acidic drainage.

Some existing alkaline lakes may be under on-going acidification pressure if discharge of regionally acidic ground-waters continues to occur. For current acidic lakes, this will result in increasing acidification and accumulation of trace elements (determined by rates of ground-water discharge). For current alkaline lakes this could result in acidification.

Preliminary results indicate that acidic drain discharge does not necessarily result in readily distinguishable elevated accumulations of trace metals compared with lakes not receiving acidic drainage. Some concentration of trace elements may occur in the shallowest sediments of receiving lakes. However,

the sampling density was too sparse for this to be certain. Further, more detailed investigations will be required to predict which drains are likely to result in increased accumulation of trace metals in receiving environments compared with acidic reference lakes. These investigations should involve comparisons of paired lakes (acidic reference and acidic drain receiving lakes) as well as before-after investigations of trace metal accumulation in environments receiving acidic saline drainage.

Initial overflows from acidic lakes (both receiving lakes and non-receiving lakes) following a rainfall events are likely to be laden with high concentrations of dissolved aluminium and iron and potentially high concentrations of trace metals. These may form significant concentrations of Al hydroxide species (e.g. $\text{Al}(\text{OH})^{2+}$, $\text{Al}(\text{OH})_2^+$) that can be toxic to aquatic to some aquatic biota and iron floc (smothering benthic communities) on mixing with neutral/alkaline floodwaters. The greatest risk of this is likely to occur during the first flush part of flood-flows and for small rainfall events that result in localised lake filling, and therefore concentration of discharge, in the Avon. These will require greatest management emphasis.

Management Implications

- Acidic lakes due regional ground-water discharge (ie not drainage) may require management of geochemical risks including acidity and soluble trace metals to protect alkaline down-stream environments
- Acidic ground-water discharge is best managed by containment and/or treatment in sites with minimal risk of down-stream transport which may be difficult to achieve which discharge to lakes in the central floodway
- Where drains discharge acidic waters to sites with poor containment, management of geochemical risks to down-stream environments will need to focus on acidic and metal mobilisation occurring during the first flush
- Containment of acidic saline discharge may require treatment with neutralising agents (e.g. limestone or coastal lime-sand) at regular intervals, depending on the risk to down-stream environments. This periodic treatment of accumulated acidity may be more cost effective than continuous treatment of drain discharges, which can be difficult in remote sites
- Soils with carbonates surrounding receiving environments could be mixed into the bed or used to line lakes to provide some capacity to neutralise acidic waters and sediments
- Use of alkaline flood flows to neutralise acidic sediments in acidic lakes may only be likely with significant volumes of water and flooding time.

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