8 Tracing the Outputs from Drained Acid Sulphate Flood Plains to Minimize Threats to Coastal Lakes

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Abstract

Drainage of acid sulphate flood plains for agriculture and urban development has led to the acidification of coastal waterbodies, major fish kills and other environmental effects in the subtropical areas of eastern Australia. These have produced problems for local governments and conflicts in communities. Here, we trace the effects of drainage from an acidified, subtropical flood plain on water quality and sediments in an estuarine lake, Cudgen Lake, in northern New South Wales. This shallow, brackish lake was once a renowned fish and prawn nursery. The local government has monitored water quality in drains and the lake since 1990. This has revealed episodic discharge events with pH as low as 2 and concentrations of dissolved iron and aluminium that are toxic to gilled organisms. Highly acidic waters were found to accumulate in drainage channels after rains following long dry periods. These were then discharged into the lake, causing major fish kills, low benthic organism biodiversity and infestations of acid-tolerant reeds and disease-bearing mosquitoes. High concentrations of arsenic, mercury and lead were found to have accumulated in iron monosulphides in the lake sediments, together with massive amounts of aluminium and iron. Ion ratios show that these metals were mobilized by drainage from the acidified soils within the flood plain. Although the lake sediments at present represent a sink for these metals, disturbance and oxidation of the monosulphides in the sediments could release major contaminants into the lake. The heavy metals sequestered in the lake sediments could partly explain the low benthic biodiversity. These results provide pointers for enhancing the conservation and fishery values of the lake.

Introduction

Pressure is increasing to develop and drain coastal lowlands to reduce flooding and waterlogging, particularly in the Asia–Pacific region. Many of these coastal flood plains contain iron pyrite (FeS_2), with concentrations sometimes averaging over 3.5% (w/w),

 Environment and Livelihoods in Tropical Coastal Zones (eds C.T. Hoanh, T.P. Tuong, J.W. Gowing and B. Hardy)

deposited under brackish, reduced conditions during and following the last sea-level rise. Drainage promotes oxidation of sulphides to sulphuric acid, acidifying groundwater and accelerating mineral weathering (Dent, 1986). Discharge from drained coastal flood plains following flooding can export hundreds of tonnes of acidic products into coastal streams, with devastating effects on fisheries and coastal communities (Sammut *et al.*, 1996).

The well-studied primary environmental impacts of acid drainage are partly due to the presence of dissolved metals, particularly aluminium and iron, but also other heavy metals (Willett *et al.*, 1993; Tin and Wilander, 1994; Åström and Björklund, 1995; Sammut *et al.*, 1996). However, the fate of these exported metals has been less well studied. There is potential for them to be sequestered in iron monosulphide (FeS)-rich sediments in receiving waterbodies (Billon *et al.*, 2001), with the risk that, under certain conditions, metals can be remobilized, causing secondary environmental effects.

Many sulphidic coastal flood plains in eastern Australia have been drained for agriculture. Massive fish kills have followed (Easton, 1989), generating conflicts, particularly between fishers and farmers. Often, local governments have jurisdiction over these drained flood plains and it falls to them to minimize conflicts and environmental, economic and social impacts. In this chapter, we describe collaborative work between researchers and local government aimed at providing information to governments and their communities on the processes occurring in drained acid sulphate flood plains discharging into coastal lakes, on the potential risks of secondary impacts and on possible remediation measures.

Cudgen Lake Study Area

This study was conducted in the subtropical Cudgen Lake catchment on the east coast of Australia (28°20′S, 153°29′E) in northern New South Wales. Average annual precipitation is 1620 mm, with 70% of rainfall occurring from December to May, and average annual evaporation is 1100 mm. The Cudgen Lake flood plain was formed following sea-level rise 12,000 years ago (Roy, 1973; Chappell, 1991) and has soils rich in reduced sulphides, such as pyrite. The area of acid sulphate flood plain is 20 km^2 and the total Cudgen Lake catchment area is 100 km^2. Figure 8.1 shows the extent of acid sulphate soils within the catchment. Cudgen Lake is a shallow (1–2 m), weakly tidal (tidal range 30–50 mm), brackish lake that covers 160 ha (Fig. 8.1). It has restricted drainage to the sea through Cudgen Creek, which discharges through an interbarrier depression.

Drainage of the flood plain

The Cudgen flood plain was once an extensive wetland. European settlers began to clear the flood plain for agricultural production in 1869. Drainage of the flood plain began in 1907, primarily for dairying. Mechanization greatly accelerated the rate of drainage from the 1940s to the 1980s. There are multiple land uses within the Cudgen catchment, including grazing, sugarcane production, tea tree, tropical fruits, tea, wetland conservation areas, and urban, recreation and transport infrastructure. In 1995, Cudgen Lake and its surrounding area was declared a state nature reserve because of its fisheries and conservation values.

The Cudgen Lake flood plain is the most extensively drained coastal flood plain in NSW, with a drainage density of 70 m/ha. Drainage and resort developments have caused widespread oxidation of sulphides within the flood plain and have led to conflicts within the catchment community, which have generated problems for the local government, the Tweed Shire Council.

Environmental impacts of flood plain drainage

Cudgen Lake was once a renowned nursery for fish and prawns. However, following massive drainage developments in the late 1980s, major fish kills occurred in the lake in May/June and December 1991. An addi-

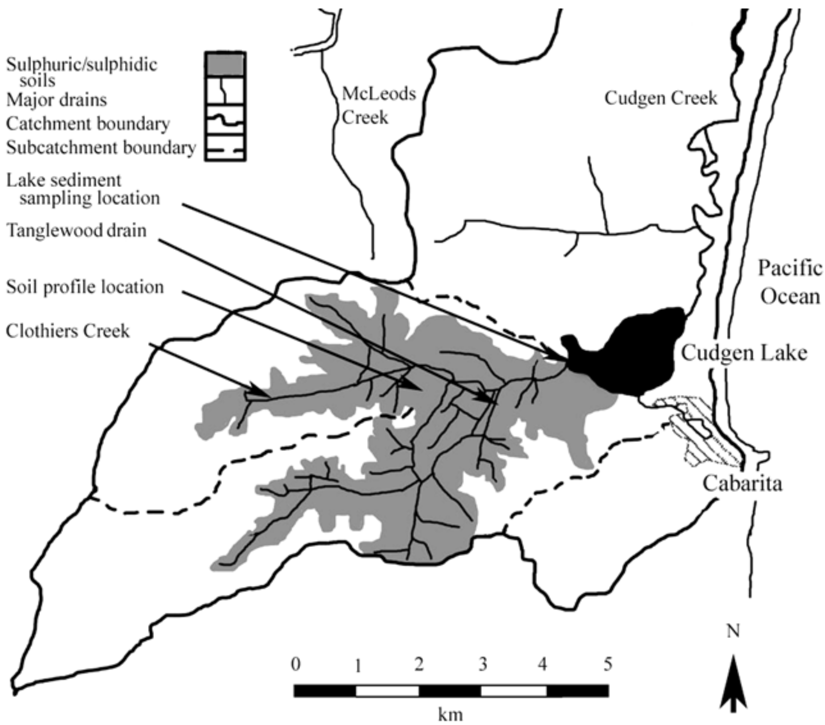

Fig. 8.1. Cudgen Lake study site showing the lake, its catchment boundary, main drains and streams, and the distribution of acid sulphate soils in the flood plain (from Macdonald *et al.*, 2004).

tional major fish kill occurred in August 1998, when intense rains followed a prolonged dry period. These fish kills generated widespread community concern, particularly among recreational and commercial fishers.

Monitoring by the Tweed Shire Council following the 1987 fish kills showed highly acidic water (pH 2.5), with large concentrations of dissolved aluminium (approx. 60 mg/l) being discharged into the lake (White *et al.*, 1997). The continued discharge of oxidation products from the flood plain has severely affected water quality, compromised the conservation value of the reserve and changed the lake's ecology. In addition, significant scalded areas, devoid of vegetation, have developed in the catchment, thus reducing grazing and cropping productivity.

Following acidification of the lake, the acid-tolerant spike-rush (*Eleocharis* spp.) and sedge (*Schoenoplectus litoralis*) have become the dominant vegetation. These have restricted fishing and recreation activities, such as sailing and boating. In the acidified areas of the lake, benthic diversity is also low and reed-infested areas are devoid of benthic life. The acidification of the lake also threatens the health of the local community. The mosquito larva *Aedes vigilax*, responsible for carrying Ross River Fever, an infection caused by a member of the *Togaviridae* family of viruses, occurs in acidified areas of the lake.

The conservation and fisheries values of Cudgen Lake, the extensive disturbance of acid sulphate soils and the presence of major scalds within its flood plain have led to the identification of the Cudgen Lake flood plain as one of 13 acid sulphate soil 'hot-spot' priority areas by the NSW Acid Sulphate Soil Management Advisory Committee.

Measurements

Soil profile and water quality samples were collected from the flood plain, from drains and from Cudgen Lake. Measurements of pH and electrical conductivity (EC) were made in the field. Soil water content, soluble and exchangeable cations (1:5 extracts), organic carbon, acidity and pyrite content, and aluminium, iron, chloride and sulphate content were determined in the laboratory (Macdonald *et al.*, 2004). Cudgen Lake sediment samples were collected from near the inlet of Clothiers Creek, which drains the 20 km^2 acid sulphate flood plain (Fig. 8.1). Two 0.4 m sediment cores were extracted and frozen with liquid nitrogen for transport back to the laboratory. A 1 m core was extracted using a sediment gouge, and sediment descriptions, field pH and redox were measured immediately. Bulk density of the upper sediments, reactive iron, total S and C, organic S and C, FeS and FeS_2 were determined at 0.02-m intervals. A separate 0.4-m sediment core was dried and crushed for total elemental analysis using concentrated HNO_3 that extracts metals from all but the most weathering-resistant minerals. Sediment porewaters were sampled using diffusion-controlled dialysis membrane samplers, 'peepers' (Hesslein, 1976). Peepers were removed after 10 days' equilibration and the porewaters analysed for metals, cations and nutrients (Macdonald *et al.*, 2004).

Results and Discussion

Flood plain soil properties

The upper 0.25 m of the flood plain soil profile had greater than 60% organic C and the top 0.5 m contained sulphide oxidation products, with aluminium and iron, followed by sodium, as the dominant soluble and exchangeable cations, and pH as low as 2.7. This acidic layer had bulk densities as high as 1.2 t/m^3 and volumetric water contents around 0.35 m^3/m^3. The exchangeable Al and Fe species represent a store of about 5×10^5 moles H^+/ha of acid products in the flood plain topsoil. Below 0.5 m was unoxidized blue–grey sulphidic clay gel with pH from 5.5 to 7, organic C less than 2%, bulk density around 0.4 t/m^3 and volumetric water contents around 0.9 m^3/m^3. The predominant soluble and exchangeable cations in this sulphidic layer are the base cations magnesium, calcium and sodium. Their concentrations are greater in the unoxidized layer than in the topsoil. The soil profile illustrates the oxidation processes that occur within these coastal flood plain soils. The oxidation of pyrite ultimately can be written as (Dent, 1986)

$$\begin{aligned} &FeS_2 + 15/4H_2O \rightarrow Fe(OH)_3 \\ &+ 2SO_4^{2-} + 4H^+ \end{aligned} \tag{8.1}$$

The acidified porewaters react with common estuarine clay minerals such as illite to release metal ions, principally Al^{3+}, K^+, Fe^{2+}, Na^+, Mg^{2+} and Ca^{2+} (White *et al.*, 1997):

$$\begin{aligned} &(K_{0.5}Na_{0.36}Ca_{0.05})(Al_{0.45}Si_{3.46})\,O_{10}(OH)_2 \\ &+ 7.41H^+ + 2.59H_2O \rightarrow 0.5K^+ + 0.36Na^+ \\ &+ 0.05Ca^+ + 0.3Mg^{2+} + 0.25Fe\,(OH)_3 \\ &+ 1.95Al^{3+} + 3.46H_4SiO_4 \end{aligned} \tag{8.2}$$

These acid-weathering products increase the EC of porewaters. Higher-valence cations exchange with lower-valence cations on clay exchange sites in the acidified topsoil, building up a store of acid products. The acid porewaters also release heavy metals associated with clays or other minerals into the soil porewaters, which may be transported into the topsoil or exported into adjacent waterways. Drainage of the Cudgen flood plain has transformed the soil from a sink for reduced sulphur, metals and carbon to a transient store, from which they are mobilized by rainfall into the flood plain drains.

Flood plain drain-water quality

After rainfall, water quality in the flood plain drains deteriorates and pH decreases, whereas EC, concentrations of Fe and Al, and the ratio of SO_4^{2-}:Cl, increase (Fig. 8.2). Provided Cl^- is a conservative ion, increasing SO_4^{2-}:Cl^- indicates transport of SO_4^{2-} from the soil profile to drains (Sammut *et al.*, 1996). The relation between Al concentration and pH in Fig. 8.2 is

$$\log_{10}[\mathrm{Al}] = 3.53 - 0.68\ \mathrm{pH} \quad (8.3)$$

The mean dissolved Al concentration in the Tanglewood drain in Fig. 8.2 is 28 mg/l and that for iron is 12 mg/l. This Al concentration is greater than the average concentration for 147 acid mine drainage sites (20 mg/l) (Singh *et al.*, 1997). The mean annual discharge into Cudgen Lake is 6×10^4 Ml (Heath *et al.*, 2001). The Tanglewood drain appears to be representative of other drains within the catchment, so that the approximate mean annual discharge to the lake is 1680 t of dissolved Al and 720 t of dissolved Fe. The peak discharge of oxidation products occurs during the recession phase of a flood event, when groundwater inputs are at a maximum (Sammut *et al.*, 1996; White *et al.*, 1997).

Lake sediment characteristics

The Cudgen Lake sediment core had three distinct layers: a black monosulphidic layer, a pyritic grey sandy clay layer and a pyritic grey clay gel layer (Fig. 8.3). The pH of the sediments was neutral but increasing at depth, whereas SO_4 and dissolved Fe were present in the top two layers but decreased when going into the gel layer (Fig. 8.3).

The sedimentation rate at the sampling site since European settlement was estimated to be 3 mm/year and is composed of an iron monosulphidic-rich facies. This surface layer of the lake sediments has high organic C, S and monosulphides (FeS) to a depth of 0.19 m. Drainage of the flood plain acid sulphate soils has increased the supply of SO_4^{2-} and Fe to the lake sediments. Their concentrations decrease with depth because of reduction and mineralization (Fig. 8.3). Reduced S in the underlying sandy clay layer (to a depth of 0.55 m) is principally pyrite (FeS_2), and, in the clay gel layer below 0.55 m, pyrite concentration is approximately 1.5%. This layer is comparable to the pyritic clay gel layer underlying the flood plain.

The monosulphide layer has elevated concentrations of Al, As, Hg (Fig. 8.4) and Pb that exceed ANZECC (Australia and New Zealand Environmental Conservation Council) guideline trigger values. These metals can accumulate in sediments by co-precipitation with FeS, adsorption to FeS or direct formation of metal sulphides. Sulphate reduction and the formation of a monosulphide layer provide a lake sediment sink for metals sourced from the flood plain acid sulphate soils.

Table 8.1 shows the approximate total mass of metals within the monosulphide layer of Cudgen Lake. This is based on assumptions of an average layer depth of 0.2 m, bulk densities of 0.124 t/m^3 and half of the 160 ha lake being covered by these sediments. There is a large store of metals within the lake system and these sediments will probably continue to accumulate because of inputs from the flood plain soils. If these lake sediments were allowed to oxidize, through dredging, by resuspension or by variations of lake pH due to acid drainage, stored metals could be released into the water column. The continued very low level of benthic organism diversity in the areas of Cudgen Lake prone to acidification may be partly due to the accumulation of heavy metals within the lake sediments.

Conclusions

We have shown here how the drainage of sulphidic flood plains can redistribute sulphur and metals through the drainage system into the sediments of receiving waterbodies. Flood plain acid sulphate soils, once a sink of sulphur and metals, have become a source, and the drainage network is the conduit through which dissolved species are exported into

Table 8.1. The mean total weight (t) of acid-extractable metals in the top 0.2 m monosulphide sediment layer in Cudgen Lake (from Macdonald *et al.*, 2004).

Metal	Total weight (t)
Al	101,700
Ce	60
As	200
Co	30
Cr	37
Cu	41
Fe	401,600
V	270
Pb	100

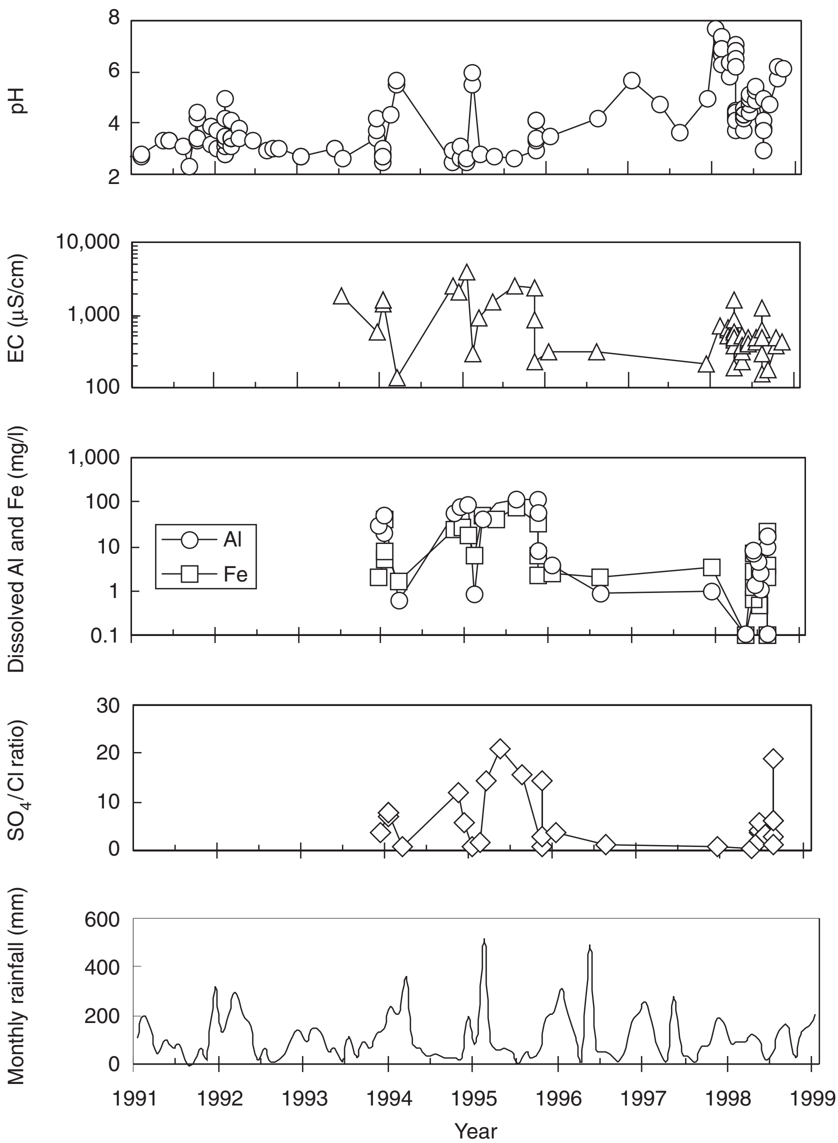

Fig. 8.2. Water quality (pH, EC, dissolved Al and Fe, SO_4/Cl) response to rainfall in a main drain, Tanglewood drain, discharging into Cudgen Lake.

downstream lakes and estuaries. Increased sulphate and organic matter inputs into these waterbodies have enhanced monosulphide formation and metal sequestering in the upper lake sediments. These accumulations of labile sulphides pose a potential threat to estuarine environments if sediments are disturbed or lakes drained. They may also explain the low benthic organism diversity in areas of the lake prone to acidification.

It is clear that the continuing discharge of acidified products into Cudgen Lake will continue to affect the conservation and fisheries value of the lake unless this problem is examined. Work is under way to cap scalded areas in the flood plain with clean fill. In

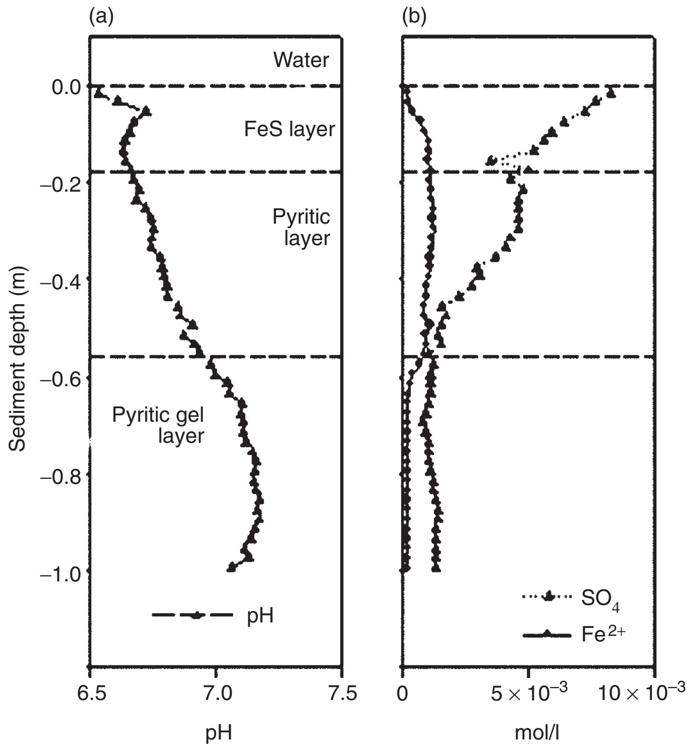

Fig. 8.3. Profiles of pH (a) and dissolved iron and sulphate (b) in Cudgen Lake sediments (from Macdonald *et al.*, 2004).

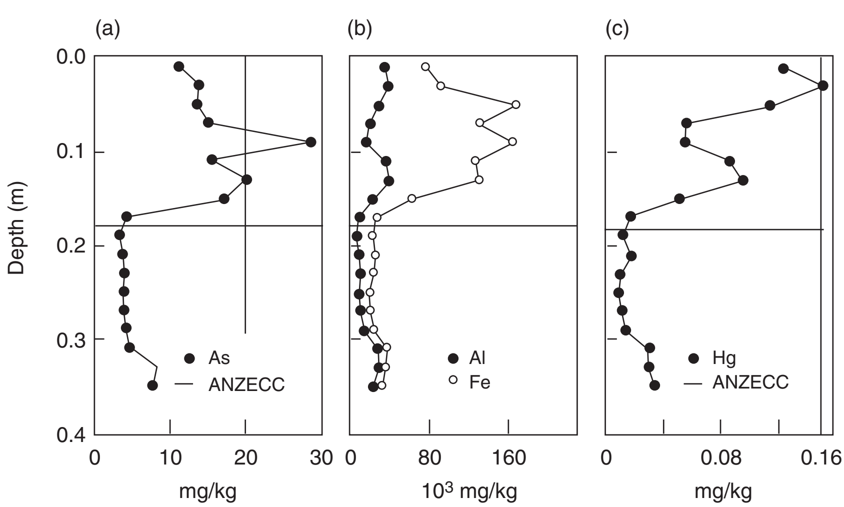

Fig. 8.4. Concentrations of arsenic (a), aluminium and iron (b) and mercury (c) metals in Cudgen Lake sediments and the ANZECC trigger value for contaminated sediments (from Macdonald *et al.*, 2004).

addition, ways to decrease drainage density are being examined and lime dosing of drainage discharge has been tested. A useful corollary of this work is the suggestion that artificially constructed wetlands may be useful for treating discharge from drained acid sulphate soils by trapping acid products and dissolved metals in monosulphide layers.

Acknowledgements

This work was supported by the Australian Research Council under grants LP0219475 and DP0345145 and by the NSW ASSPRO initiative.

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