Lead, Mercury, Cadmium and Arsenic in the Environment
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CHAPTER 13

Studies of Heavy Metal Pollution in Australia with Particular Emphasis on Aquatic Systems

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ABSTRACT

The reported work on heavy metal contamination in Australia has been reviewed. The great bulk of this work has been concerned with obtaining information on heavy metal concentrations in waters, sediments and biota, with the emphasis on the latter being often to allay public health concerns. There are fewer data on the effects of heavy metals on Australian biota and that available mostly relates to laboratory-based toxicity studies. Very few data are available which relate to the processes controlling the behaviour of contaminating heavy metals within the Australian environment, that is their speciation, transportation, transformation from one compartment to another and their ultimate fate.

This lack of any adequate process understanding of contaminating heavy metals is of particular concern in Australia because of the quite distinctive features of many Australian aquatic ecosystems (certainly the freshwater ones). This distinctiveness makes the relevance of overseas data relating to the effects of heavy metals on many Australian aquatic ecosystems questionable.

INTRODUCTION

Many heavy metals, including copper, zinc, cobalt and nickel, are essential trace elements. Australia has been actively involved in research on trace elements, especially their agricultural implications (Underwood, 1971). In this chapter, however, we will be concerned with environmental contamination by heavy metals.

Australia is not without examples of serious heavy metal pollution. The most notable have been associated with the mining and metal processing industry. On a smaller scale there have also been examples of localized pollution by electroplating wastes, metal-based pigments and a number of other industrial wastes. This has resulted in considerable activity over recent years, particularly by Government departments, in the study of heavy metals. Most of this activity, however, has resulted simply in the measurement of concentrations in waters, sediments and biota, leaving considerable gaps in the understanding of the processes influencing the behaviour of heavy metals in the environment and of their effects on Australian biota.

This paper reviews the current state of knowledge relating to heavy metals in the Australian environment, with particular emphasis on the aquatic environment. This emphasis arises for two reasons. First, both authors' areas of research relate to aquatic systems, and second there is a paucity of data on heavy metal contamination of Australian terrestrial ecosystems. Most attention has been given to the four metals of primary interest to this Workshop—arsenic, cadmium, lead and mercury. The chapter is structured with reviews on three aspects:

(a) the sources of heavy metals entering the Australian aquatic environment and their levels in various compartments (particularly biota, sediments and waters);

(b) the biogeochemical cycling of heavy metals (taking into consideration speciation, transportation, transformation, mobilization and eventual fate);

(c) the effects of heavy metals on Australian ecosystems (taking into account laboratory toxicity studies and *in situ* studies at population, community and ecosystem levels).

SOURCES

Natural processes, such as weathering and volcanic activity, continually add heavy metals to the environment (Forstner and Wittmann, 1981; Salomons and Forstner, 1984). In addition, there are now increasingly large quantities being added by man's activities. For many of the heavy metals, the amounts contributed globally from anthropogenic sources now exceed those from natural resources. This is particularly so in the case of lead, copper and zinc. Of course, a proportion of the metals mobilized by man will remain bound-up, for example, in buildings and rubbish dumps. Despite this, the amount eventually discharged into the atmosphere or the hydrosphere can be large.

A distinction needs to be made between *point* and *non-point* sources of heavy metal pollution. Point sources are those in which the pollution can be easily identified as coming from a particular factory or treatment works. Non-point sources are more diffuse; examples would include heavy metals in rainfall, urban runoff and agricultural runoff. Most of the Australian examples where serious trace metal pollution has occurred have been very localized and due mainly to one point source.

Little has been done in Australia to assess the importance of anthropogenic emissions of heavy metals to the atmosphere. Salomons and Forstner (1984) have collected together data relating to the natural and anthropogenic inputs of heavy metals to the atmosphere. These data suggest that for the metals of interest to the Workshop, anthropogenic sources exceed natural sources in the case of cadmium and lead.

The only estimates of atmospheric emissions within Australia are for lead. The Australian Academy of Science (AAS, 1981) estimated that 7000 to 8000 tonnes of lead are emitted annually to the Australian atmosphere, with motor cars contributing over 5000 tonnes annually. Considerable work has also been done on pollution from the world's largest lead smelter at Port Pirie, South Australia, where it has been shown that atmospheric emission was the largest source of lead to the environment (Cartwright *et al.*, 1977; Merry and Tiller, 1978; Ward and Young, 1981).

Wind-blown dust can also contribute large quantities of heavy metals to the atmosphere. This can be particularly severe with certain industrial complexes as was shown in Tasmania where fine contaminated dust from a zinc producing company was a significant source of zinc to the Derwent estuary and residential areas of Hobart around Risdon (Ayling and Bloom, 1976; Bloom and Ayling, 1977).

Mining operations, particularly those established a number of years ago, have resulted in serious heavy metal pollution in a number of areas in Australia. The most notable of these have been reviewed recently by Hart (1982a). These include the King River in Tasmania (mainly Cu, also Zn, Pb and Cd); South Esk River, Tasmania (Zn, Cd); Derwent River estuary, Tasmania (mainly Zn and Cd, also Hg); Captains Flat and Molongolo River in New South Wales (mainly Zn, also Cu, Cd, Pb and As); Rum Jungle and Finniss River in the Northern Territory (Cu, Zn). Also well studied have been two rivers in Victoria (Lerderderg River, Goulburn River) which contain elevated mercury levels as a result of old gold mining areas in their headwaters (Bycroft *et al.*, 1982; McCredie, 1982; Ealey *et al.*, 1983).

Although there are a considerable number of possible industrial sources of heavy metals in Australia, most States now require industrial waste discharges to a stream or the sewer to be licensed. This has resulted in two major improvements. First, considerably more attention is paid to the adequate treatment of wastes and to in-plant housekeeping. Second, there has been a searching reappraisal of many of the uses of heavy metals, with the result that some compounds have been totally banned (e.g. phenylmercury compounds used as slimicides in the paper industry), and others have been severely restricted in use.

Sewage effluents and sludges also represent a potentially large source of heavy metals to the environment. We are not aware of any reports in which the concentrations of heavy metals in Australian wastewaters or sludges have been systematically collated. Nor indeed has there been any National assessment of the amounts of heavy metals emitted to the Australian environment from these sources. The major proportion of the sewage and sludge disposal in Australia is to estuarine and coastal marine waters.

A recent study of urban stormwater quality in Melbourne (a city of about 3.5 million people) has shown that this can be an important diffuse source of heavy metals (AWRC, 1981). Table 13.1 summarizes the concentrations of heavy metals found in stormwater from four of the catchments studied.

Table 13.1 Concentrations of heavy metals in μg/litre [mean(range)] in unfiltered urban stormwater samples taken from four stormwater drains in Melbourne*

	Catchment			
Metal	A	B	C	D
Cd	11(10–20)	10(2–10)	9(9–10)	10(9–10)
Cu	480(10–6800)	91(9–310)	38(9–320)	26(9–100)
Cr	580(20–4200)	24(7–30)	20(20–30)	23(20–50)
Pb	490(50–1950)	530(70–2800)	260(30–1370)	160(30–1020)
Ni	20(10–50)	22(9–360)	26(10–40)	22(10–50)
Hg	0.1(<0.1–0.1)	0.1(<0.1–0.1)	—	0.1(0.1–0.2)
Zn	5800(420–19 400)	1230(190–4400)	550(10–2750)	210(9–1050)

Source: AWRC, 1981.
A: Mainly light industrial; B: residential, with two large commercial shopping complexes; C: residential, less than 10 years old; D: mainly undeveloped, orchards and grazing.
* Numbers of samples for Cd, Cu, Cr, Pb, Ni, Zn: A-17, B-55, C-59, D-51; for Hg: A-3, B-15, C-0, D-7.

In summary, the main sources of heavy metals entering the Australian aquatic environment have been identified. In very few cases, however, have we been able to quantify with any degree of confidence the total quantities coming from any of these sources. Such information is, of course, essential if one is to place any priorities upon reducing the amounts.

LEVELS

As noted in the introduction, there has been considerable activity in recent years, particularly by Government departments, in the study of heavy metal contamination in Australia. However, most of this activity has resulted simply in the measurement of concentrations of heavy metals in biota, waters and sediments. Table 13.2 summarizes the number of published papers devoted to the measurement of heavy metal concentrations in various polluted and unpolluted aquatic systems in Australia. Table 13.3 shows more specifically the studies relating to the four metals of most interest to this Workshop.

Table 13.2 Studies on aspects of the biogeochemical cycling of heavy metals through Australian aquatic ecosystems (×= a published study)

System	Polluted/ unpolluted	Sources, levels	Information on process understanding	Effects
Molongolo river (NSW/ACT)	Polluted	××	×	××××××××
King river (Tas.)	Polluted	××	××	×
South Esk river (Tas.)	Polluted	××	×	×××××
Finniss river (NT)	Polluted	××	×	××
Lerderderg river (Vic.)	Polluted	××	×	
Goulburn river (Vic.)	Polluted	××××	×	×
Derwent estuary (Tas.)	Polluted	×××××××××	×	×
Port Pirie/ Spencer's Gulf (SA)	Polluted	××××××××××	××	××××
Port Phillip Bay/ Yarra river (Vic.)	Part-polluted	×××××××××××	××××	×××
Magela creek (NT)	Unpolluted	××××	×××××	××××
Westernport bay (Vic.)	Unpolluted	×××	×××	×××××××××
Great Barrier Reef (Qld.)	Unpolluted	×××××		××
Cockburn Sound (WA)	Unpolluted	××××××		×

Table 13.3 Information on As, Cd, Pb and Hg in the Australian aquatic environment

	Levels, source	Process understanding		Effects	
Arsenic					
Use in Australia	BMR, 1979	As forms in:	Edmonds and Francesconi, 1977		
waters	DOE, 1973	rock lobster	Edmonds *et al.*, 1977		
	Harrison and Dix, 1973		Cannon *et al.*, 1979		
	Bloom and Ayling, 1977	school whiting	Edmonds and Francesconi, 1981		
	Smith, 1984	giant clams	Benson and Summons, 1981		
Sediments	DOE, 1973				
	Harrison and Dix, 1973				
	Davies, 1974				
	Bos, 1984				
Biota (seafoods)	WGMF, 1980				
	Mackay *et al.*, 1975				
	Bebbington *et al.*, 1977				
Cadmium					
Sewage effluent	Hart and Davies, 1979	Speciation	Florence, 1977, 1982a	Toxocity:	
Urban stormwater	AWRC, 1981		Hart and Davies, 1981a,b	invertebrates	Lake *et al.*, 1979
Polluted waters	Doolan and Smythe, 1973		Blutstein and Smith, 1978		Thorp and Lake, 1974
	Norris *et al.*, 1981		Batley and Gardner, 1978		Skidmore and Firth, 1983
	HEC, 1979		Fisher and Frood, 1980		Ahsanullah, 1976
	Ferguson, 1983		Mackey, 1984		Ahsanullah and Arnott, 1978
Unpolluted waters	Hart *et al.*, 1982a				Arnott and Ahsanullah, 1979
	Mackey, 1984	Uptake mechanisms:			Ahsanullah *et al.*, 1981a,b
	Burdon-Jones and Denton, 1984	oysters	Ward, 1982a,b		Sullivan, 1977
Sediments	Bloom, 1975	algae	Gipps and Coller, 1980, 1982	fish	Negilski, 1976
	Norris *et al.*, 1981	sea grass	Fabris *et al.*, 1982		Cassidy and Lake, 1975
	Smith *at al.*, 1981	mussels(FW)	Jones and Walker, 1979		Ehl, 1975
	Ellaway *et al.*, 1982	mussels (MW)	Marshall and Talbot, 1979	field study	Norris *et al.*, 1982
	Ferguson, 1983	invertebrates	Lake *et al.*, 1979	seagrass fauna	Ward, 1984
Biota	Hart, 1982a (summary)				
	Talbot and Chegwidden, 1982	Transport	Hart *et al.*, 1982a		
	Norris and Lake, 1984				
	Talbot, 1985				
	Burdon-Jones and Denton, 1984				
Food intake	Miller *et al.*, 1976				
Soil	Beavington, 1973				

Lead					
Sources	Noller and Smythe, 1974	Speciation	Batley and Florence, 1976	Field study:	
	AAS, 1981		Batley and Gardner, 1978	seagrass fauna	Ward and Young, 1982
	Ferguson, 1983		Blutstein and Smith, 1978		Ward, 1984
Stormwater	AWRC, 1981		Florence, 1977	epifauna	Ward and Young, 1983, 1984
Polluted waters	Anon., 1974; HEC, 1979		Hart and Davies, 1981a,b		Ward *et al.*, 1984
Unpolluted waters	Burdon-Jones and Denton, 1984				
Biota	Hart, 1982a, (summary)				
	Talbot, 1985	Uptake:			
Sediments	Smith *et al.*, 1981	marine mussels	Marshall and Talbot, 1979		
	Ellaway *et al.*, 1982				
	Ward and Young, 1981				
	Ferguson, 1983				
	Ward *et al.*, 1984				
Soils	Cartwright *et al.*, 1977				
	Dossis and Warren, 1980				
Mercury					
Sources	WGMF, 1980	Speciation in biota	WGMF, 1980	Toxicity:	
	Bycroft *et al.*, 1982		Walker, 1982	invertebrate	Ahsanullah, 1982
	Coller, 1983		Walker *et al.*, 1982		Wisely and Blick, 1967
Stormwater	AWRC, 1981			algae	DeFilippis and Pallaghy, 1976a–c
Biota	WGMF, 1980 (summary)	Biota uptake	Denton and Burdon-Jones, 1981	invertebrate	Wisely and Blick, 1967
	Hart, 1982a (summary)			Field study	Beumer and Bacher, 1982
	Bycroft *et al.*, 1982				
	McCredie, 1982				
	Denton and Breck, 1981				
	Walker, 1976, 1981, 1982				
	Walker *et al.*, 1982				
	Lyle, 1984				
	Burdon-Jones and Denton, 1984				
Sediments	Bloom, 1975				
	Bycroft *et al.*, 1982				
	McCredie, 1982				
	Thomas *et al.*, 1981				

This review of the Australian data relating to the concentrations of heavy metals in biota, waters and sediments leads to the following conclusions:

(a) The largest amount of data relates to heavy metal concentrations in marine biota used for human consumption, particularly oysters, lobster and fish. Heavy metal contamination in freshwater biota has been largely neglected.

(b) There are considerable data on concentrations of heavy metals in sediments and waters, with particular emphasis on a small number of well studied systems (e.g. Derwent estuary, Spencer's Gulf, Port Phillip Bay—Table 13.2 and 13.3).

(c) Considering those Australian ecosystems that have been the subject of any degree of examination for heavy metals, it is a sad fact that for no heavy metal do we possess a clear understanding of the pathways of metal movement. One of the major gaps in our knowledge in this area concerns the pathways connecting the abiotic environmental repositories of the heavy metals with the biotic components in any ecosystem. Thus, for no animal investigated in terms of bioaccumulation and biomagnification, do we have a full appreciation of the various pathways and mechanisms of metal uptake.

(d) In the terrestrial environment, the analysis of biota for heavy metal contamination has been limited in scope. The relatively small number of studies of concentrations of heavy metals in human beings in Australia have concentrated heavily on lead; these data are well summarized in the document 'Health and Environmental Lead in Australia' by the Australian Academy of Science (AAS 1981). Concentrations of other heavy metals in humans (e.g. cadmium; Spickett and Lazner, 1979), have received little attention. In terms of medical research effort, very little is carried out in Australia on the levels in humans and toxicity to humans of heavy metals.

BIOGEOCHEMICAL CYCLING OF HEAVY METALS

To assess properly the possible short-and long-term problems associated with the release of heavy metals to the aquatic environment, it is necessary to understand the biogeochemical cycling in such systems. The cycling of heavy metals can best be understood by using a conceptual model for an aquatic system which consists of a number of *compartments* or reservoirs coupled by *transfer pathways*. Figure 13.1 (Hart, 1982a) illustrates a possible model for heavy metal cycling in a lake, where the system is considered to consist of four main compartments:

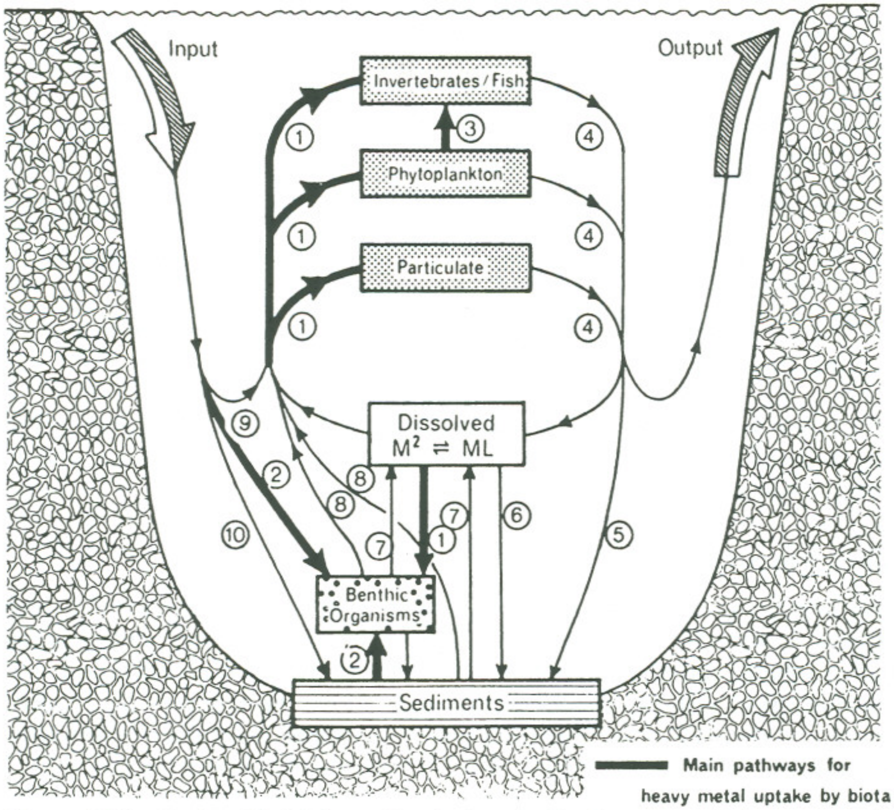

Figure 13.1 A simplified biogeochemical cycle for heavy metals in an aquatic system

(a) the 'dissolved' compartment—containing free metal ions and complexed and colloidally bound metal species;

(b) the (abiotic) particulate compartment—consisting of both inorganic and organic particulates;

(c) the (biotic) particulate compartment—consisting mainly of phytoplankton (and bacteria) in lakes and the deep ocean, littoral areas in estuaries and attached plants in streams;

(d) bottom sediments—the largest compartment of heavy metals in most aquatic systems.

The various transfer processes involved in the transformations and transporting of heavy metals from one compartment to another have been discussed in some detail by Hart (1982a) and Salomons and Forstner (1984).

In particular a detailed assessment of the potential problems associated with heavy metals released to the environment will include a knowledge of the following:

(a) the physico-chemical forms in which the heavy metals can exist in the various compartments (i.e. speciation);

(b) the processes responsible for transporting the metals through the system;

(c) the processes by which the metals in the various compartments are transformed from one to the other;

(d) the most important pathways by which the trace metals interact with the biota.

A quick scan of the data contained in Tables 13.2 and 13.3 shows that the study of biogeochemical cycling of heavy metals in Australian aquatic systems is noticeably lacking.

Speciation Studies

The behaviour of heavy metals in aquatic and terrestrial systems is very largely governed by the speciation. Speciation will influence heavy metal bioavailability and toxicity to biota, its transportation and mobilization, and its interaction with the sediments and soils. Since there is very little information on this aspect for terrestrial systems in either Australia or elsewhere, most of the following discussion will concentrate on aquatic ecosystems.

Heavy metals are present in trace amounts in most natural waters, concentrations generally being less than 1 μg/1itre. Florence and Batley (1980) have noted that while the concentrations of heavy metals in unpolluted waters around the globe are relatively similar, the same conclusion does not necessarily hold for the physico-chemical forms in which the metals exist. The actual metal speciation is influenced by factors such as pH and the types and concentrations of inorganic ligands, organic ligands and colloidal species present.

There is increasing evidence to suggest that the formation of metal-organic complexes is very important in determining the speciation of many heavy metals. These complexes may form by the direct complexation of heavy metal ions by natural organic compounds, such as fulvic acid, or by association of metal ions with colloidal matter, either organic colloids or inorganic colloids with their surfaces coated with natural organics. There is now very good evidence that all colloidal and particulate matter in natural waters is so coated (Hart 1982b; Salomons and Forstner, 1984).

Chemical analysis at these low concentrations requires great care and skill (Florence and Batley, 1980; Florence, 1982a). Obviously these difficulties are magnified if, rather than just determining the total concentration, it is required to separate the total into a number of individual fractions. The experimental techniques presently available to speciate natural water samples are generally limited because they are either insufficiently sensitive or selective. Despite the many analytical limitations, considerable insight into the heavy metal speciation in natural fresh, estuarine and marine waters has been obtained by use of analytical techniques such as anodic stripping voltammetry, ultrafiltration, ion-exchange or chelating resins, dialysis and UV irradiation, either singly or in combination (for recent reviews on metal speciation studies see Florence and Batley, 1980; Florence, 1982a and Hart, 1982c).

Australian workers have been particularly prominent in the development of analytical methods for heavy metal speciation. Table 13.4 summarizes some of the speciation studies conducted on Australian waters. These generally represent analysis of a single sample only from the aquatic system. Additionally, the data available are almost specifically for the four metals cadmium, copper, lead and zinc that are best studied by anodic stripping voltammetry.

Transfer Processes

There have been very few systematic investigations of either the *biologically available forms* or the *mechanisms* or *processes* responsible for the transfer of heavy metals from the abiotic to biotic compartments in Australian ecosystems (Tables 13.2 and 13.3).

One of the best studied systems has been Magela Creek in northern Australia. The impetus for these studies was the establishment of a uranium mining and processing plant in the catchment (Fox *et al.*, 1977). Studies by Hart *et al.* (1982a, 1986) have shown that only relatively small amounts of heavy metals are presently transported by Magela Creek with a considerable proportion of this being associated with particulate matter (Fe 80%; Mn 55%; Cu 55%). There is also published work relating to the complexing capacity of these waters (Hart and Davies, 1981c; Hart and Jones, 1984); the transfer of copper from the water column to macrophytes (Hart *et al.*, 1983); and the processes important in cycling of heavy metals added to billabongs in the system (plastic enclosure experiments—Hart *et al.*, 1982b, 1985).

Work on transfer mechanisms between soils and plants and plants and animals has been reported by Davy (1975) for the Finniss River system in Northern Territory. Also there have been a number of reported studies of the transfer of heavy metals between sediments and water and seagrasses in Western Port Bay in Victoria (Shapiro, 1975; Harris *et al.*, 1979; Fabris *et al.*, 1982).

Table 13.4 Australian trace metal speciation studies

System	Metals studied	Reference
Streams		
Yarra river (Vic.)	Cd, Cu, Pb, Zn	Hart and Davies, 1981a
Magela creek (NT)	Cd, Cu, Zn	Hart *et al.*, 1982b
South creek (NSW)	Cd, Cu, Pb, Zn	Florence, 1982b
Lakes		
East Basin Lake (Vic.)	Cd, Cu, Pb, Zn	Hart and Davies, 1981b
Lake Tarli Karng (Vic.)	Cd, Cu, Pb, Zn	Hart and Davies, 1981b
Tarago reservoir (Vic.)	Cd, Cu, Pb, Zn	Hart and Davies, 1981b
Albert Park Lake (Vic.)	Cd	Blustein and Shaw, 1981
Woronora reservoir (NSW)	Cd, Cu, Pb, Zn	Florence, 1977
Magela Creek billabongs (NT)	Cu	Hart and Davies, 1981c
Estuaries		
Derwent estuary (Tas.)	Zn	Fisher, 1981
Yarra estuary (Vic.)	Cd, Cu, Pb, Zn	Hart and Davies, 1981a
	Cd, Cu, Pb, Zn	Blustein and Smith, 1978
Georges R. estuary (NSW)	Cd, Cu, Pb	Batley and Gardner, 1978
	Cr	Batley and Matousek, 1980
Corio bay (Vic.)	Cd, Cu, Zn	Fisher and Frood, 1980
Coastal waters		
Bass Strait (Vic.)	Cu, Zn	Fisher, 1981
	Cd, Cu, Zn	Fisher and Frood, 1980
South Eastern Australia	Cd, Cu, Pb, Zn	Batley and Florence, 1976
	Cu	Florence and Batley, 1977
	Cd, Cu, Pb	Batley and Gardner, 1978
	Cd, Cu, Pb, Zn	Florence, 1982b
Northwest shelf	Cd, Cu, Zn, Ni	
	Cr	Mackey, 1983
	Cd, Cu, Zn, Ni	Mackey, 1984

EFFECTS OF HEAVY METALS ON BIOTA

Two types of studies can produce information relating to the effects of heavy metals on biota: laboratory based toxicity studies (acute and chronic); and *in situ* studies of polluted systems where biota are studied at the level of population, communities or ecosystems. Australian studies in both these areas are summarized in Table 13.3.

Toxicity Studies

The greatest effort in this area has been on marine biota as a result of the Victorian government studies in Port Phillip and Westernport Bays. These studies are listed in Table 13.3; the results have been summarized by Lake and Hart (1986). Most of the tests were static and not continuous flow. Even though nine series of acute toxicity tests have been performed on a variety of marine animals, the taxonomic coverage has been very incomplete. Crustaceans have received considerable attention, but it is perturbing to note that only one toxicity study on marine fish has been published. All of the above tests have been performed on temperate marine animals, with the emphasis very strongly on the metals zinc, cadmium and copper (Table 13.3). A small number of acute toxicity and uptake studies using tropical marine species have been reported (Burdon-Jones *et al.*, 1975; Denton and Burdon-Jones, 1981).

There are no chronic toxicity studies of heavy metals with Australian marine animals.

Acute toxicity data on Australian freshwater invertebrates and fish have been summarized by Firth (1981), Hart (1982a) and Skidmore and Firth (1983). For fish (due largely to the work of Firth (1981) and Skidmore and Firth (1983)), copper is the metal that has been most tested, followed by zinc. Much of the toxicity testing with fish has been stimulated by the introduction of uranium mining and processing in the Northern Territory. Apart from the tests of Cassidy and Lake (1975) and Firth (1981), all the fish tests have been static.

For freshwater invertebrates, cadmium is the metal that has received most attention followed by copper, then zinc (Table 13.3). Most tests have been static.

The range of acute sensitivity to Australian freshwater animals is 0.04–21 mg/litre (525-fold) for copper, 0.14–38 mg/litre (271-fold) for zinc, 0.0148–2000 mg/litre (135 000-fold) for cadmium and 0.05–32 mg/litre (640-fold) for lead. Firth (1981) and Skidmore and Firth (1983) concluded that all these ranges, except for cadmium, are within the lower part of the corresponding ranges for northern hemisphere animals.

Ecosystem Studies

There have been very few attempts in Australia to study the ecological effects of heavy metal pollution. A limited number of freshwater and marine studies have attempted to relate physico-chemical data on metal levels and transport to the ecological impact on the system under investigation. Clearly such system studies need to be encouraged if we are going to be able to predict the impact of heavy metals on terrestrial or aquatic ecosystems. Ideally, such studies should have as their goal a full understanding of the pathways of heavy metal movement, the relative importance of such pathways and a comprehension of the relationships between metal movements and pattern of biota distribution and abundance.

The best marine case studied in terms of these criteria involves the inshore marine area in Spencer's Gulf close to the lead–zinc smelter at Port Pirie, South Australia. The sediments around Port Pirie are contaminated with cadmium, copper, manganese, lead and zinc (Ward and Young, 1981; Ward *et al.*, 1984). The epibenthic fauna of the seagrass beds and the intertidal mud flats around the smelter were studied by Ward and Young (1982, 1983). They found that both contaminant metals and sediment particle size had significant effects on the community structure. The contaminant metals had more effect on fish than crustaceans, while sediment particle size affected the distribution of 15 mostly less common crustaceans. Ward and Young (1983, 1984) also studied the effects of both sediment metal concentrations and particle size on the epifauna associated with the common bivalve mollusc *Pinna bicolor*. They found the different epifaunal taxa had quite different sensitivities to metal concentrations and particle size, and recommended four species that were sensitive to metal pollution but not sediment particle size as species suitable for monitoring the effects of metal contamination on the epifauna.

In a more recent study, Ward (1984) found that acute toxicity tests using dissolved metals were unable to predict ecological effects relating to the seagrass faunal communities in the contaminated area.

Freshwater systems investigated, albeit incompletely in terms of the above criteria, include the Molonglo River in New South Wales, Lake Burley Griffin in the A.C.T., the South Esk River and King River in Tasmania, and the Finniss River in the Northern Territory (Table 13.3).

Zinc pollution of the Molonglo River has greatly reduced the abundance and diversity of the invertebrate fauna (Weatherley and Dawson, 1973; Weatherley *et al.*, 1967, 1975, 1980; Sharley, 1982; Norris, 1983). This zinc pollution has also adversely affected primary production, zooplankton community structure and benthic community structure in Lake Burley Griffin (Hillman, 1974; Weatherley *et al.*, 1980). Fish are not found in most of the Molonglo River (Weatherley *et al.*, 1967). Recent surveys of the invertebrate fauna of the Molonglo River by Nicholas and Thomas (1978), Sharley (1982) and Norris (1983) have shown that there has been no substantial alleviation in the effects of pollution in this river since the first survey in 1963, even though extensive engineering works at the major sources (Captains Flat) have been carried out in an effort to reduce the pollution.

The South Esk River in north-east Tasmania is polluted by zinc and cadmium from tin and wolfram mining operations (Thorp and Lake, 1973; Tyler and Buckney, 1973; Norris *et al.* 1980, 1981, 1982). Thorp and Lake (1973) found that both the species richness and total abundance of macroinvertebrates were low near where the pollution entered. The fauna recovered somewhat with progressive distance downstream; however, even 50 km downstream there was still a marked lack of groups such as Crustacea and

Mollusca. These, together with the Annelida, were least tolerant of the pollution. Thorp and Lake (1973) found relatively tolerant groups to include Hemiptera, Arachnida and trichopteran larvae (Leptoceridae). In a more recent study, Norris *et al.* (1982), found that as far as 80 km downstream from the pollution source the numbers of both individuals and taxa were reduced relative to upstream control sites. They were able to classify the macroinvertebrate species as:

- those relatively abundant at both uncontaminated and contaminated sites (one species of leptocerid caddisfly and one species of baetid mayfly);
- those most abundant at sites above the pollution input (two molluscs, four species of leptophlebiid mayflies and five species of caddisflies);
- those whose numbers were highest at sites below the source of contamination (two species of dipteran larvae, four species of caddisflies, one mollusc species, one amphipod species and one species of water mite).

Norris *et al.* (1982) concluded from their study that there was little correlation between the concentrations found to be lethal in laboratory studies and those found to produce harmful effects in the South Esk River.

The King River in western Tasmania is severely polluted with copper and zinc, and also with lesser amounts of lead and cadmium, from acidic drainage, from disused mine shafts and from waste rock dumps that have resulted from the mining operations of the Mt. Lyell Mining and Railway Company (Lake *et al.*, 1977; HEC, 1979). Two biological surveys have shown that Linda and Comstock Creeks, and the King River for a considerable distance downstream of the junctions with these creeks, are totally devoid of trout and yabbies (*Astacopis* spp.), and macroinvertebrate fauna are significantly reduced in numbers (Lake *et al.*, 1977; Swain *et al.*, 1981). Even as far as 15 km downstream of the pollution inputs there was little recovery in the number of benthic macroinvertebrate taxa or numbers of individuals per square metre.

The Finniss River in the Northern Territory has also been studied ecologically (Davy, 1975; Jeffree and Williams, 1980). The pollution source is an abandoned uranium-copper mine at Rum Jungle. Although mining and processing of copper and uranium ceased in 1971, there is still considerable pollution from overburden heaps, open-cut mine pits and heaps of unprocessed ore as a result of bacterial action on pyritic minerals (Davy, 1975). The main pollution load, low pH water containing high concentrations of copper, zinc, manganese and sulphate, is discharged to the Finniss River during the wet season and at the beginning of the dry season. Jeffree and Williams (1975, 1980) found the biota were significantly affected by this polluted water. There were very few aquatic macrofaunal species that survived in the East Branch downstream of the mining area. Fish and decapod crustacea were also reduced in numbers of species and individuals in the Finniss River downstream of the confluence with the East Branch, although by 30 km downstream of the confluence the effects of the heavy metal pollution were not observable. Fish kills were observed in the Finniss River when moderate inflows from the east Branch coincided with low flow rates in the river itself, producing high pollutant concentrations in the main stream.

DISTINCTIVE FEATURES OF AUSTRALIAN AQUATIC SYSTEMS

The lack of any adequate understanding of the processes controlling the behaviour of heavy metals is of particular concern in Australia because, as is becoming increasingly apparent, many Australian aquatic ecosystems (certainly the freshwater ones) have a number of distinctive features, the most obvious of which are summarized below (Hart, 1982a; DeDeckker and Williams, 1986). These distinctive features preclude the simple use of overseas information relating to cycling and biological effects of heavy metals and make it imperative that we develop new methods for managing river ecosystems in Australia that take account of their individualistic and stochastic nature (Lake, 1985).

Rivers and Streams

A large proportion of Australia is without rivers or permanent lentic (standing) waters because of low and uncertain rainfall, flat topography, high evaporative losses, and a lack of permanent snow fields from which melting snow can replenish rivers and streams during summer. Most of the permanent streams are confined to a narrow strip along the northern and eastern coasts, along small stretches of the southern coast and in Tasmania (AWRC, 1976).

Flow Variability

A direct consequence of the highly variable rainfall is the variability in annual stream flow of many Australian rivers. Stream flows can vary from no flow up to hundreds of times the long-term mean annual discharge; ratios of highest to lowest discharge of up to 300 are common in Australian rivers. In terms of annual flow variability, Australian rivers form a distinctive and extreme group in comparison to world average streams (McMahon, 1982). Because of the great variability in stream flow, many of Australia's major rivers have been impounded, causing drastic changes to their ecology.

Many of Australia's rivers of major economic importance have their source in the Eastern Highlands, or Great Dividing Range, and from here flow either east or west (in some parts of Victoria also north and south). The easterly flowing streams have relatively short courses, descend rapidly from the mountains and frequently change their grade as they make the transition from steep mountain streams to slower coastal rivers. The streams flowing west or south west are very different. Typically they are wide, slow moving and muddy. Rivers such as the Darling and Lachlan may, after several dry seasons, dry up to a chain of waterholes extending over several hundred kilometres. After heavy rains these rivers tend to flood over extensive areas of land because their catchments are flat. This flooding pattern is extremely important to the distribution and reproduction of native fish (Weatherley, 1967).

Tropical rivers, such as those northerly flowing rivers in the Northern Territory and the northern part of Queensland, have received some attention in recent years. They are influenced by a monsoonal climate so that most flow only in the wet season between December and April, and dry up to a series of waterholes during the dry season.

Water Quality

With such a wide range of river systems, it is rather difficult to generalize about water quality (Hart and McKelvie, 1986). When flowing, most rivers have total dissolved solids (TDS) concentrations of less than 500 mg/litre; this equates with a conductivity of around 800 μS/cm. The highest TDS concentrations are found in the slower moving inland streams and the lowest in the fast moving coastal streams (Garman, 1983). There is considerable concern over the increasing salinity in many Australian streams, particularly the River Murray, and rivers in Western Australia and inland Victoria (Garman, 1983; Loh *et al.*, 1984).

Gibbs (1970) postulated that three main mechanisms—rock dominance, atmospheric precipitation and evaporation—control the surface water chemistry in river systems. Precipitation chemistry appears to dominate the water chemistry of the fast flowing, permanent coastal streams in eastern Australia, including Tasmania (Reinson, 1976; Bek and Bruton, 1979; Buckney, 1980). In these cases, sodium is always the dominant cation, with chloride or bicarbonate the dominant anion; the coastal flowing streams of eastern Victoria have the following ionic dominance $Na > Ca = Mg > K$, $Cl = HCO_3 > SO_4$. Reinson (1976) and Buckney (1977, 1980) have shown that, while rainfall is the dominant source of soluble ions (mainly sodium and chloride) in these streams, rock weathering can contribute increased amounts of calcium, magnesium and bicarbonate ions.

Inland flowing streams can, however, have a quite different ionic composition, particularly in their lower reaches. Many of these streams have their headwaters in the Great Dividing Range, and here show an ionic dominance similar to the easterly flowing streams. For example, the upper reaches of the River Murray have an ionic dominance Na > Ca = Mg and HCO_3 = Cl > SO_4 (Walker and Hillman, 1977; RMC, 1980), and the Cudgegong River Na > Mg > Ca and Cl > HCO_3 (Muir and Johnson, 1979). After the Cudgegong River has flowed some 240 km northeast, magnesium becomes the dominant cation and bicarbonate the dominant anion, mainly due to the weathering of magnesium minerals in the catchment.

Buckney (1980) has suggested that diluted seawater is a more appropriate reference water for Australia than the world standard freshwater given by Livingstone (1963). This may well be true for coastal streams but is clearly not appropriate for inland flowing streams.

Australian streams vary enormously in their turbidity or suspended solids concentrations. As a generality, inland streams have relatively high turbidity and coastal streams mostly low turbidity; the turbidity levels are very much influenced by flow and land-uses within the catchment.

Lakes

Except for the Antarctic, Australia is the continent most deficient in permanent lakes, lagoons and ponds. In fact, the only extensive area of permanent lakes is the Tasmanian Central Plateau. There are a very large number of farm dams in Australia and it seems that as time passes, the overwhelming bulk of standing water in Australia will be in artificial storages rather than in natural lakes.

Many of the lakes in Australia are saline, with TDS values greater than 3000 mg/litre (Bayly and Williams, 1973; DeDekker, 1983; Hart and McKelvie, 1986); in fact, the ratio of saline to freshwater standing water bodies is higher in Australia than for most other countries in the world. The high TDS concentrations reflect the general aridity of the continent. In Victoria, the best watered State on the mainland, more than half the natural lakes of significant size contain water with a TDS greater than 100 mg/litre, and fewer than 3% contain water with a TDS of less than 200 mg/litre. The range of TDS concentrations recorded for natural lentic waters in Australia is from 2.4 mg/litre in Lake Cootapatamba situated in the Kosciusko Plateau to 352 000 mg/litre in Lake McDonnell in South Australia (Williams, 1967; Williams *et al.*, 1970).

In the great majority of Australian lentic waters, sodium is the dominant cation and chloride the dominant anion. Sometimes bicarbonate becomes the dominant anion and, less often, calcium the dominant cation (Buckney, 1980). In arid areas, where evaporation is significant, the precipitation of calcium and magnesium carbonates probably accounts for the reduced proportions of calcium, magnesium and bicarbonate compared with sodium and chloride.

Many Australian lakes receive water inputs very sporadically, often after a considerable dry period which may be in excess of one year. Under such conditions the quality of the 'first flush' of water will be very much different from the rest of the input (Hart and McKelvie, 1986). Buckney (1980) has suggested these first flushes will be typically highly coloured and turbid, and have low pH, a predominance of sodium and chloride ions, and often high concentrations of bicarbonate and nutrients.

Commonly, lakes situated in the more temperate regions of Australia stratify only *once* per year with complete mixing taking place in the winter; such lakes are called monomictic. This is quite different from the seasonal pattern observed in northern hemisphere temperate lakes where two mixing periods occur, one after marked stratification during the summer and the other after ice cover in the winter; these lakes are called dimictic lakes. There are very few dimictic Australian lakes; one or two exist in Tasmania. Many of the water bodies in Northern Australia appear to be polymictic, in that they have no persistent periods of stratification (Hart and McGregor, 1980).

Biota

A large part of the aquatic fauna in Australian fresh waters has distinctive characteristics. Most of Australia's 130 native freshwater fish are endemic. Australia's long separation from other lands has ensured that none of the truly freshwater groups of fish from the northern hemisphere reached Australia by natural means. With very few exceptions, the freshwater fish fauna of Australia has a closer evolutionary relationship with marine fish than occurs in other continents. Until European settlement, Australia lacked salmonids (e.g. trout), cyprinids (e.g. carp) and true freshwater percids (Lake, 1971). There is a generally low diversity of freshwater fishes in Australia, which may be due to the scarcity of permanent water bodies. Many of the Australian native fish have evolved remarkable reproductive strategies suitable for the regimes of flood and drought. Adaptations include mouth brooding of eggs to survive low dissolved oxygen levels, and spawning on temporarily inundated land.

More than 2000 species of fish have been recorded from Australian marine waters. Less than 10% of these are exploited commercially.

Many of the Australian freshwater invertebrates are also endemic, probably with a large number still unknown to science. This endemicity is not restricted to the species level since the nature of the Australian freshwater fauna is also largely different at the generic levels. Most of the genera of Australian mayflies, stoneflies, caddisflies and odonatans are endemic, and the composition of fauna in Australian streams is very different from that in northern hemisphere streams. Thus, outside Australia, the Gripopterygidae, the most abundant stoneflies in Australian streams, are found only in New Zealand, Fiji and South America. Similarly, Australia's predaceous stone flies, the Eustheniidae, occur outside this country only in New Zealand and South America. Within the Ephemeroptera, the Leptophlebiidae dominate the Australian fauna in lotic habitats both in numbers of species and individuals. Of the 72 described species of Australian mayflies, 43 are leptophlebiids. This situation contrasts with that in North America north of Mexico, where the leptophlebiids are a relatively insignificant part of the fauna with some 64 leptophlebiids described out of a total mayfly fauna of 622 species. The above data suggest that there are considerable physiological differences between Australian fauna and the northern hemisphere fauna.

Lake (1982) has stated that the Australian stream invertebrate fauna is quite diverse and not depauperate as has been suggested by some. Additionally, he and others (e.g. Williams, 1980) have observed that the fauna are characterized by flexible life histories. Williams (1980) has related this to the unpredictable nature of the Australian climate and to the lack of a seasonal leaf fall in Australian forests. Lake (1982) has also suggested that the flexibility in life history of Australian stream invertebrates is fundamentally related to temperature and flow variations, but he casts doubt on the influence of the supposed 'aseasonal' litter input. In fact, Lake (1982) has collated data showing that Australian forests, from paperbark woodlands and wet sclerophyll forests to temperate and subtropical rain forests, do have a very distinctive seasonal leaf fall, with most (up to 70%—Attiwill *et al.*, 1978) occurring in summer. This is in contrast with the northern hemisphere where most occurs in the autumn. Perennial and temporary Australian streams are at least as rich in stream invertebrates as their northern hemisphere equivalents (Lake *et al.*, 1986).

Schemes of longitudinal stream zonation proposed from a temperate northern hemisphere background have been found wanting in their application to Australian streams (Lake *et al.*, 1986). This applies to both the longitudinal zonation scheme of Illies (1961) and to the longitudinal zonation scheme arising from the River Continuum Concept (Vannote *et al.*, 1980).

According to Williams (1980), the Australian freshwater flora is more like the freshwater flora in other continents than the fauna is like the fauna elsewhere. In the case of algae, the fact that they are cosmopolitan and easily transported and dispersed probably contributes to their similarity to algae in other continents. Macrophytes are considerably more distinctive, with Aston (1973) reporting that 40% of the 200 or more species found in Australia are endemic.

Implications for Aquatic Ecosystem Management

Lake (1985) has suggested that the currently accepted perception of the ecological nature of river communities in particular may have to be revised and that this revision could result in major changes in the management of rivers. In particular, he argues that stream communities are *individualistic*, that is the community is a collection of species that simply happen to exist together through converging accidents of space, time and similar environmental needs (Richardson, 1980).

Lake (1985) also argues that stream communities are *stochastic* rather than deterministic (see also Grossman, 1982, and Grossman *et al.*, 1982). Stochastic communities are conceived as collections of species, not in equilibrium, but changing with environmental changes in a probabilistic rather than predictive way. Deterministic communities are collections of species in equilibrium and with a predictable structure.

The generally accepted principles in water quality management involve the use of water quality criteria to protect various beneficial uses. These criteria are obviously based on a deterministic view of streams.

It seems clear that, particularly for Australian rivers, stream management principles must change to consider the stream ecosystem as individualistic and stochastic. This will also involve a change in the way streams are studied; a multivariate and probabilistic approach will be needed to predict the impact of pollution. If indeed stream communities are stochastic, considerably more long-term research will be needed to obtain the necessary understanding of them.

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