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Inorganic pollution of the sediments of the River Torrens, South Australia

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Abstract The River Torrens plays a vital role in the economic, social and environmental life of South Australia. The river rises on the Adelaide Hills and flows west across the Adelaide Plains, bisecting the city of Adelaide and reaching the sea at the Gulf of St Vincent. The bed sediments of the Torrens were sampled from its headwaters to the coast and analysed for cadmium, chromium, copper, lead, phosphorus and zinc. With the exception of chromium, the concentration of every metal investigated lies above the national trigger value for sediment quality at some point along the course of the river. The sediments of the headwaters exhibit high values of copper and zinc, although these probably reflect natural background conditions rather than pollution. By contrast, in the residential areas that dominate the Adelaide Plains, almost every site is contaminated by lead and zinc, some to well beyond the point of biological damage. Several residential sites, notably those downstream of the city of Adelaide, are also polluted by cadmium. Within the industrial zone around the city, every site is contaminated by lead and zinc, with concentrations at some locations far beyond the threshold for ecological

damage. Several industrial sites are also polluted by cadmium and copper. There are no national guidelines against which to assess the phosphorus content of the sediments. However, there is strong evidence that human activities have had a significant impact on phosphorus levels in the river. Major cyanobacterial blooms along the lower Torrens have been linked to the release of nutrients from the sediments, and phosphorus concentrations in the water have reached dramatic levels. Much of this contamination appears to be a consequence of past pollution practices. In particular, the severe pollution along the reach immediately to the west of the city may be largely attributed to the former concentration of metallurgical and chemical industries in that area. These problems are likely to persist indefinitely as modifications to the flow behaviour of the river mean that bed sediments are neither being moved downstream and flushed out of the system nor diluted by mixing with relatively uncontaminated deposits.

Keywords Australia · Adelaide · River Torrens · Fluvial sediments · Trace element pollution · Nutrient pollution

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Introduction

Most studies of the pollution of river systems focus on water quality. This is usually because of concerns about drinking water supplies or because water quality data may be directly related to potentially toxic effects in organisms. However, audits of water quality are likely to be inconclusive unless measurements are made over long periods of time and under a range of conditions. Variations in river discharge and pollutant source areas, irregular pollutant emissions, and changes in temperature, pH and Eh may all result in large short-term fluctuations in water quality. The solution is long-term monitoring of river waters, but this is costly as well as time-consuming. Moreover, water quality data alone rarely reflect all the possible adverse effects of pollution on aquatic biota. One reason for this is that the interaction of organisms with the river environment is not restricted to the direct uptake of pollutants from the water. In particular, contamination of the channel bed and toxicity of suspended particulate matter may have serious consequences for the ecology of aquatic systems.

By contrast with the temporally variable and difficult to interpret record of river contamination offered by water analysis, fluvial bed sediments provide a composite picture of pollution integrated over long periods of time. Bed sediments also integrate the effects of pollution over space, with contaminants from the contributing catchment being reworked into and along the channel. Finally, although the bedload most obviously acts as a sink for coarser particulate pollutants, fluvial bed sediments also incorporate materials transported in solution and suspension, deposited by mechanisms such as adsorption, chelation and precipitation. In this way, they unify, at least in part, the dissolved contaminant load, the suspended pollutant load and the pollutant bedload.

As major sinks for contaminants, channel sediments may form significant repositories of toxic materials. Concentrations of trace metals in river sediments may be 10^4 – 10^5 times higher than those in the corresponding river waters (Horowitz 1985), making sediments the major carriers of pollutants along the length of the channel. Sediments may represent a source of bioavailable contaminants to benthic biota, and hence potentially to the aquatic food chain, and may provide an important secondary source of dissolved and suspended contamination of the river water. By this means, sediment quality may exert a major influence on water quality and indirectly on all aquatic organisms.

Because sediment quality is a major determinant of the biodiversity and ecological health of rivers, sediment analysis provides a rapid and cost-effective way of characterising channel pollution and its ecological consequences. It can also play a key role in the detection of

pollution sources and dispersion pathways, and may be useful in the selection of critical sites for routine water sampling.

The study area

The importance of the River Torrens to the economy and environment of South Australia, the driest state in the driest inhabited continent, is out of all proportion to its size. Although the river drains only 503 km² (Torrens Catchment Water Management Board 2002), within its catchment lies the city of Adelaide, which houses 81% of the state's population. The primacy of the city has ensured that the river plays a vital industrial, ecological and recreational role in the life of the state. The catchment has a Mediterranean hot summer climate [of Csa type according to Köppen's (1936) classification]. It experiences a highly seasonal rainfall regime and river flow is negligible or non-existent during the summer.

The River Torrens rises on the Adelaide Hills and flows west across the fault scarp of the Eden Fault onto the Adelaide Plains (Fig. 1). Here, the trunk stream is joined by a series of left-bank tributaries, whose headwaters also flow off the Hills and across the escarpment. The modern river continues westward across the Plains, reaching the Gulf of St Vincent at Henley Beach–West Beach. Prior to 1937, however, the Torrens did not discharge directly into the sea, but flowed into lagoonal swamps dammed by the coastal dune ridge. To minimise seasonal flooding in this part of the catchment, a channel was cut through the dune barrier to the sea. For the final 3 km of its course, therefore, the river now follows a wide, straight, artificial channel. The middle reaches of the river have also been modified: the courses of the tributaries across the Plains have been artificially constrained, many kilometres of channel have been lined and much of their flow has been diverted through underground conduits. Similarly, water levels in the channels have been maintained by the construction of dozens of weirs and sluice gates, particularly along the trunk conduit of the Torrens itself.

The Adelaide Hills support a mosaic of small-scale farms, villages and woodlands. The major land uses are pastoral farming, with some horticulture and viticulture, forestry plantations, native woodlands and national parks. The Adelaide Plains, by contrast, are largely covered by low-density suburbs, among which is a variety of light and heavy industries. The city of Adelaide lies in the middle of the Plains, straddling the river. A range of industrial and manufacturing operations is located on the city fringes, particularly to the north and west, although many of the older factories have either closed or moved to more distant locations in the last few decades.

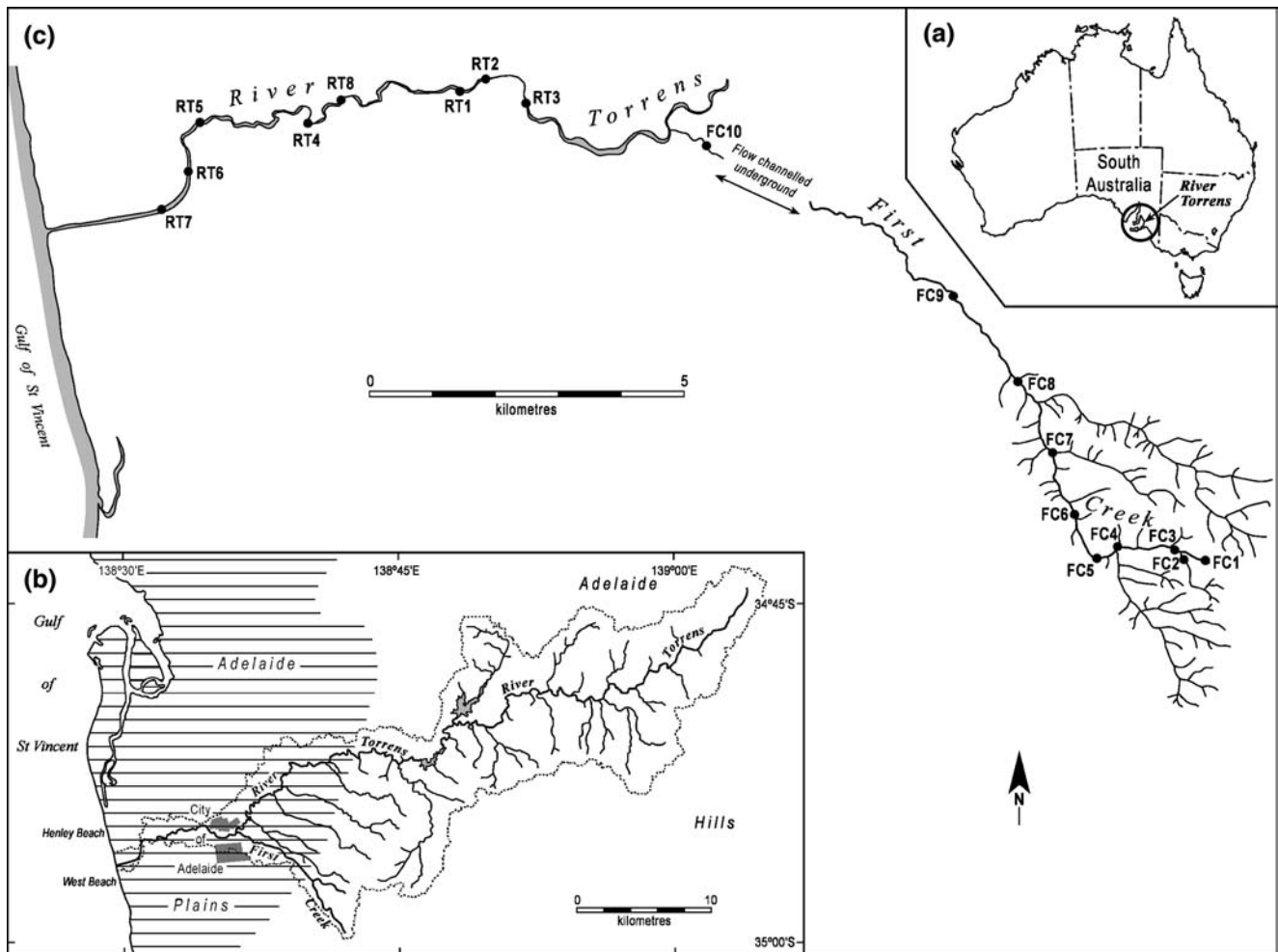


Fig. 1 a The location of the River Torrens in South Australia, b the catchment of the River Torrens and c sediment sampling sites along First Creek and the River Torrens

Aims

There is currently no information on the incidence of metals in the sediments of the River Torrens (Torrens Catchment Water Management Board 2002), nor has any record been found of work on sediment nutrient loads along the system. It has recently been claimed, however, that Adelaide lies on the dirtiest river of any capital city in Australia (Hodge 2003). On the basis of a single water sample it was asserted that the Torrens has the highest levels of copper, lead and faecal coliforms, and the second highest levels of nitrogen and phosphorus of any river in any state capital. It was concluded that, although the quality of the water has greatly improved, ‘... generous traces of heavy metals remain in the sediments of all our city waterways.’

In an attempt to test such claims, this work aims to establish the regional pattern of inorganic pollution in

the sediments of the Torrens and its tributaries. Baseline data of this sort will allow the assessment of the impact of past and current land uses on the river and may assist in developing future environmental strategies for the catchment.

Australian sediment quality standards

National guidelines have recently been established for sediment quality in Australian aquatic ecosystems (ANZECC and ARMCANZ 2000). These are based on disturbance to biological indicators rather than on consequences for human health. Those guidelines relevant to the contaminants considered in this study are listed in Table 1. The ‘high’ values are those at which ecological damage is deemed to have already occurred. However, as it is important to intervene before damage takes place, ‘trigger’ values have also been established as

Table 1 Interim guidelines for sediment quality in aquatic ecosystems in Australia and New Zealand (ANZECC and ARM-CANZ 2000). Only those guidelines applicable to the metals investigated in this study are listed

Contaminant	Interim sediment quality guideline	
	Low (trigger value) ($\mu\text{g g}^{-1}$)	High ($\mu\text{g g}^{-1}$)
Cadmium	1.5	10
Chromium	80	370
Copper	65	270
Lead	50	220
Zinc	200	410

prompts for further action. No specific guidelines have been established for nutrients such as phosphorus. Nevertheless, these may have significant impacts on stream systems. In particular, they may stimulate blooms of cyanobacteria, algae and macrophytes. These may result in the displacement of endemic species, the clogging of waterways and the smothering of the streambed, altering aquatic habitats and threatening benthic communities. Some cyanobacteria and algae release toxins into the water, while blooms may alter stream pH and deplete dissolved oxygen, killing aquatic organisms.

Methods

The trunk stream of the Torrens is fed by a series of tributaries, all of which rise on the Adelaide Hills. The headwaters of one of these branches, First Creek, lie within the Cleland Conservation Park and are thus likely to be the least affected of any tributary by the impacts of European land use. The branch may consequently provide a control against which to judge the effects of land use changes downstream. A series of sediment samples was therefore collected along the course of First Creek and along the River Torrens downstream of its junction with First Creek.

The fine and organic-rich component of fluvial sediments possesses the greatest capacity to sorb particulate and dissolved toxicants from river waters [see, for example, Warren (1981)]. Sampling was therefore restricted to sites at which either fine-grained ($< 63 \mu\text{m}$) and/or plant organic-rich sediments were found. Beginning at the upstream end of First Creek, samples were collected at every accessible reach downstream where deposits of this sort occurred in the channel (Fig. 1). To minimise problems arising from small-scale variations in the depositional environment at each site, a composite sample was taken from each sampling location. At each sampling site, a transect was established normal to the channel and sampling points were located at 1/6, 1/3, 1/2, 2/3 and 5/6 of the bank-to-bank distance along the transect. Where the width of the channel was less than

0.4 m, sampling points were located at 1/4, 1/2 and 3/4 of the bank-to-bank distance. At each sampling point, the upper 0.15 m of the sediment was cored using 30 mm internal diameter polyvinyl chloride piping. The upper 0.15 m is considered to be representative of recent contamination in the system and to encompass the biologically active zone of the sediments (USEPA 2001). At those sites at which the depth of fine-grained or organic sediments was < 0.15 m, the entire sediment depth was taken. The cores from each of the sampling points were integrated into a composite sample representative of each site.

The samples were air-dried, weighed and sieved through a 2.00 mm mesh to separate the gravel fraction (> 2.00 mm) of the deposits. Any plant organic matter retained on the sieve was broken down to < 2.00 mm and included in the fraction passing the mesh. After weighing the coarse and fine fractions, the < 2.00 mm component was split using a stainless steel riffle box to provide subfractions for further analysis. One subfraction was ground to a fine powder using a pestle and mortar and ~ 1.0000 g of the powder was digested in 9 cm^3 of concentrated (68.5–69.5% v/v) analytical reagent grade nitric acid at 120°C . After 4 h, 1 cm^3 of concentrated (31.5–33.0% v/v) analytical reagent grade hydrochloric acid was added to the digestion tubes and heating continued for a further 1.5 h. The cooled samples were filtered and diluted using ultrapure water prior to determining their elemental chemistry by inductively coupled plasma spectrometry.

The plant organic content of a second < 2.00 mm subfraction was estimated by loss on ignition at 430°C following the procedure of Gale and Hoare (1991), but without grinding the material. The silt and clay component of this subfraction was then determined by wet sieving through a $63 \mu\text{m}$ mesh.

After air-drying and weighing, the sand fractions ($63 \mu\text{m}$ – 2.00 mm) retained on each sieve were ground to a fine powder using a tungsten carbide disc mill. Subfractions of ~ 1.0000 g were digested in a mixture of nitric and hydrochloric acids and their elemental chemistry determined following procedures identical to those described earlier.

Results

The acid-soluble content of cadmium, chromium, copper, lead, phosphorus and zinc in the < 2.00 mm fractions of the samples are listed in Table 2. Most inorganic pollutants have an affinity for the clay, silt and plant organic components of sediments, while sands are comparatively unreactive (Adriano 2001). Conventional practice is thus to normalise pollutant concentrations by expressing them as a function of the proportion of mud and plant organic matter in the sediments (Förstner

Table 2 The acid-soluble content of cadmium, chromium, copper, lead, phosphorus and zinc in the <2.00 mm fraction, and the mud and plant organic fractions of samples of the bed sediment of the River Torrens (RT) and its tributary, First Creek (FC), South Australia

Sample	Rural								Residential	
	FC1	FC2	FC3	FC4	FC5	FC6	FC7	FC8	FC9	FC10
Cd in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	0.3	0.3	0.3	0.5	0.1	<u>2.1</u>	0.6	1.1	0.3	0.3
Cd in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	0.7	1.3	1.8	1.6	1.2	14	1.6	1.6	1.4	2.1
Cr in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	24	4.2	<u>3.0</u>	<u>3.4</u>	2.4	8.2	<u>14</u>	<u>16</u>	12	<u>15</u>
Cr in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	56	18	18	10	23	57	35	24	54	105
Cu in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	<u>97</u>	312	12	63	10	9.1	35	30	27	<u>40</u>
Cu in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	<u>228</u>	1,345	73	<u>192</u>	97	62	87	44	124	283
Pb in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	<u>42</u>	35	<u>25</u>	<u>17</u>	<u>9.1</u>	19	<u>34</u>	<u>58</u>	<u>149</u>	<u>122</u>
Pb in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	97	150	148	53	86	128	85	<u>86</u>	686	861
P in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	147	<u>148</u>	<u>125</u>	<u>244</u>	<u>87</u>	<u>133</u>	<u>745</u>	<u>1,571</u>	537	330
P in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	344	640	746	748	823	911	1,845	2,315	2,474	2,329
Zn in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	133	214	37	39	40	160	114	142	184	300
Zn in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	<u>311</u>	923	<u>221</u>	119	<u>377</u>	1,097	<u>282</u>	<u>210</u>	850	2,115

Sample	Industrial				Residential			
	RT3	RT2	RT1	RT8	RT4	RT5	RT6	RT7
Cd in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	1.2	<u>1.6</u>	<u>2.5</u>	0.9	<u>2.1</u>	<u>1.7</u>	<u>3.0</u>	1.2
Cd in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	14	<u>9.0</u>	12	13	<u>5.0</u>	<u>4.5</u>	<u>5.0</u>	7.5
Cr in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	30	<u>28</u>	35	35	<u>60</u>	<u>40</u>	<u>67</u>	<u>23</u>
Cr in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	344	161	162	537	144	105	113	141
Cu in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	<u>48</u>	<u>110</u>	<u>68</u>	20	<u>100</u>	<u>60</u>	<u>61</u>	<u>40</u>
Cu in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	542	633	314	307	<u>240</u>	159	102	243
Pb in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	105	832	152	94	269	<u>157</u>	<u>81</u>	<u>59</u>
Pb in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	1,189	4,769	704	1,458	645	419	<u>136</u>	363
P in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	268	609	681	471	728	510	<u>531</u>	285
P in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	3,040	3,492	3,153	7,313	1,747	1,359	887	1,740
Zn in <2.00 mm fraction ($\mu\text{g g}^{-1}$)	323	593	693	326	897	442	509	231
Zn in mud and plant organic fractions ($\mu\text{g g}^{-1}$)	3,669	3,397	3,211	5,063	2,153	1,177	851	1,414

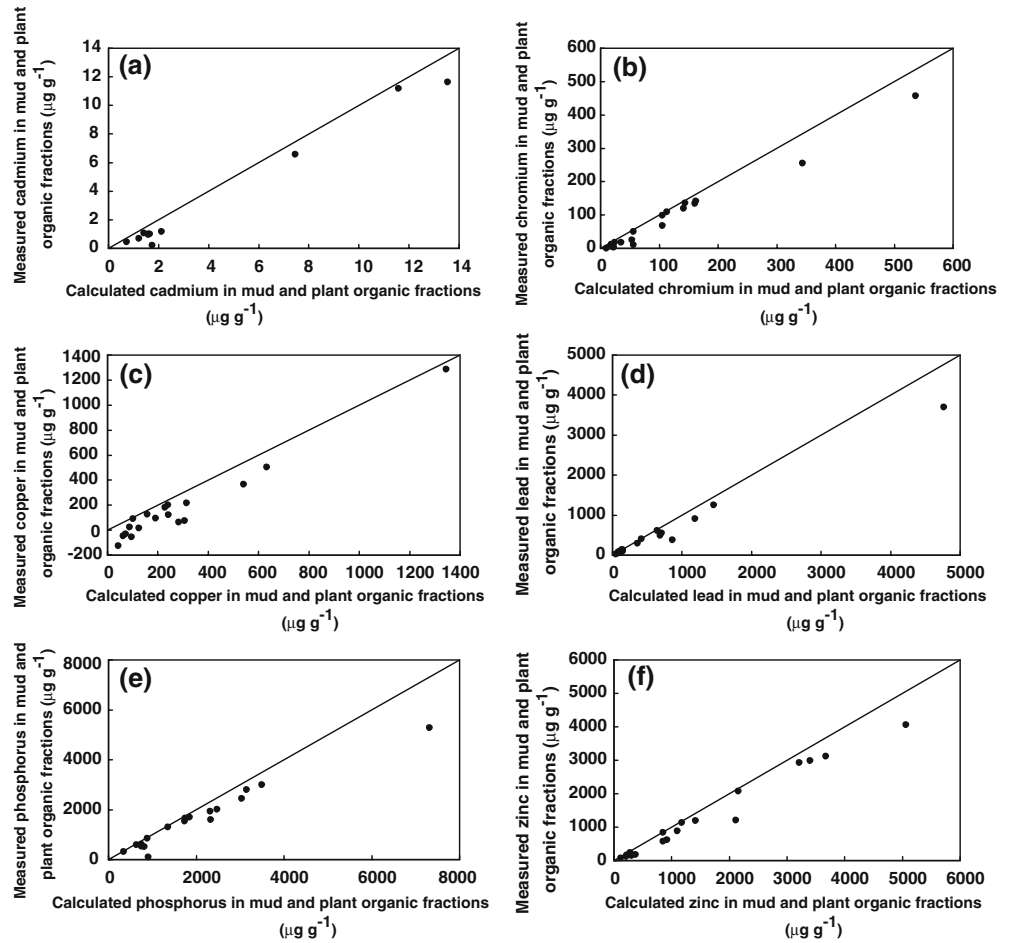
Underlined figures denote analyses that exceed the national 'trigger' values for sediment quality. Bold figures represent analyses that exceed the national 'high' guidelines for sediment quality, those at which ecological damage is deemed to have already occurred. The land use classification follows the scheme of McCaskill (1986)

1989; Loring and Rantala 1992; Working Group on Marine Sediments in Relation to Pollution 2000). The fluctuations in concentration resulting from variations in the sand component of each sediment are thereby avoided. The results expressed in this way are given in Table 2. The assumption upon which this calculation is based was tested by separating the sand fraction of each sample, determining its chemistry and using these data to calculate the actual chemistry of the mud and plant organic components of the sediments. The measured values of each element are compared with the calculated values in Fig. 2. In interpreting these results, it should be noted that the sand fractions were separated from the remainder of the <2.00 mm fraction by wet sieving. It is thus possible that traces of fine material still adhered to the sands that were digested for chemical analysis. It is also possible that contaminants may be associated with iron and manganese oxide and oxyhydroxide coatings on the sand grains. In addition, while the <2.00 mm fractions were ground by hand using a pestle and mor-

tar, the 63 μm –2.00 mm fractions were broken down mechanically using a disc mill. The sand fractions were therefore comminuted to a finer state than the <2.00 mm fractions, possibly liberating trace amounts of elements associated with the sand minerals. For these reasons, the calculated mud and organic fraction concentrations would be anticipated to be slightly higher than the measured ones. Figure 2 shows that this is true in every case. However, for none of the elements considered is there much difference between the two sets of figures. This supports the general thesis that inorganic pollutants are largely confined to the mud and plant organic fractions of sediments.

In the following discussion, the elemental concentrations normalised by reference to the proportion of mud and plant organic matter in the sediments have been employed. One reason for this is that in the case of some elements (cadmium, for example) the concentration in the sand fraction was often below the analytical detection limit, making it impossible to calculate the

Fig. 2 The *calculated elemental content* of the mud and plant organic fractions of the fluvial sediments in the River Torrens catchment, South Australia was determined by correcting the concentration in the total (<2.00 mm) sample using the proportion of sand in the <2.00 mm sample, making the assumption that none of the elements analysed is present in the sand. The *measured elemental content* of the mud and plant organic fractions was determined by correcting the concentration in the total (<2.00 mm) sample using the measured concentration in the sand fraction. Measured concentration is plotted as a function of calculated concentration for **a** cadmium, **b** chromium, **c** copper, **d** lead, **e** phosphorus and **f** zinc. The line represents equivalence of calculated and measured values



chemistry of the mud and plant organic fractions. Secondly, in the case of copper, some elemental concentrations were so low that the concentrations calculated on the basis of sand fraction chemistry lay slightly below zero. Most importantly, as explained earlier, the methods employed to separate and prepare the sand fractions are likely to have yielded elemental concentrations that are slightly inflated by comparison with those of the <2.00 mm fractions as a whole.

Discussion

Introduction

The downstream variation in the concentration of each element studied is shown in Figs. 3, 4, 5, 6, 7, 8. Each of the sampling sites has been classified according to the dominant land use in the vicinity, employing the classificatory scheme of McCaskill (1986). In applying the scheme, the Cleland Conservation Park has been included in the rural land use zone. In addition, three sites immediately downstream of land use boundaries have

been classified as lying within the upstream land use zone. These are FC10 (in public open space immediately downstream of residential land), RT3 [in public open space immediately downstream of the former sites of the Government Slaughter House, the Cattle Market and the Sewage Storage Yard (Surveyor General's Office 1881)] and RT8 (in land used for public purpose immediately downstream of the main industrial region of the catchment). Thus, sites FC1–FC8 lie within the rural zone, sites FC9, FC10 and RT4–RT7 are in residential areas and sites RT1–RT3 and RT8 are industrial.

Rural sites

Although sites FC1–FC8 all lie within areas classified as rural, there is a distinct change of land use downstream of FC5. Above this point, the sites lie within the woodland of the Cleland Conservation Park. Downstream, roads, housing and agriculture play a larger role in the landscape. Considering first those sites within the Conservation Park, the concentrations of copper, lead and zinc are all rather higher than would normally be

Fig. 3 The concentration of cadmium in the mud and plant organic fractions of bed sediment with distance downstream along First Creek and the River Torrens, South Australia

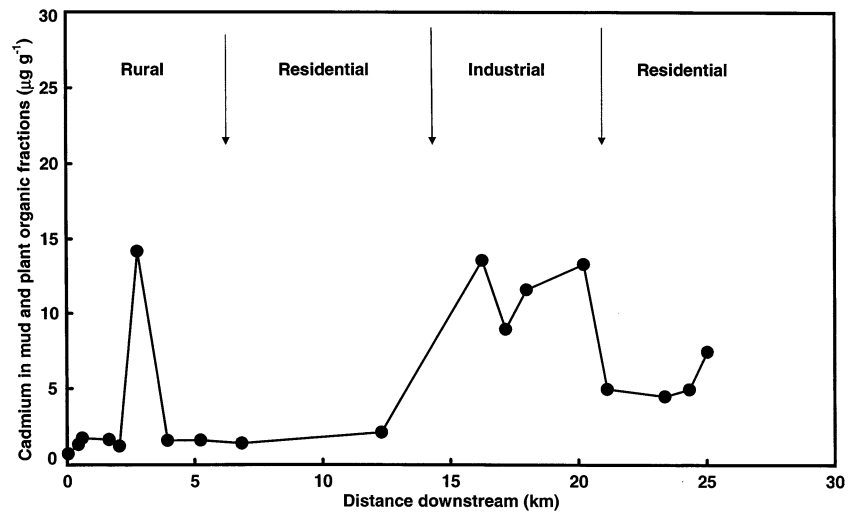


Fig. 4 The concentration of chromium in the mud and plant organic fractions of bed sediment with distance downstream along First Creek and the River Torrens, South Australia

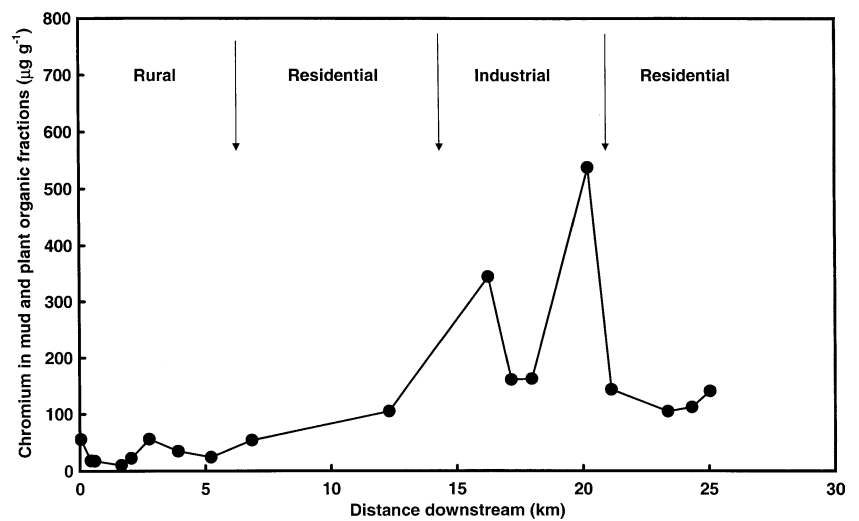


Fig. 5 The concentration of copper in the mud and plant organic fractions of bed sediment with distance downstream along First Creek and the River Torrens, South Australia

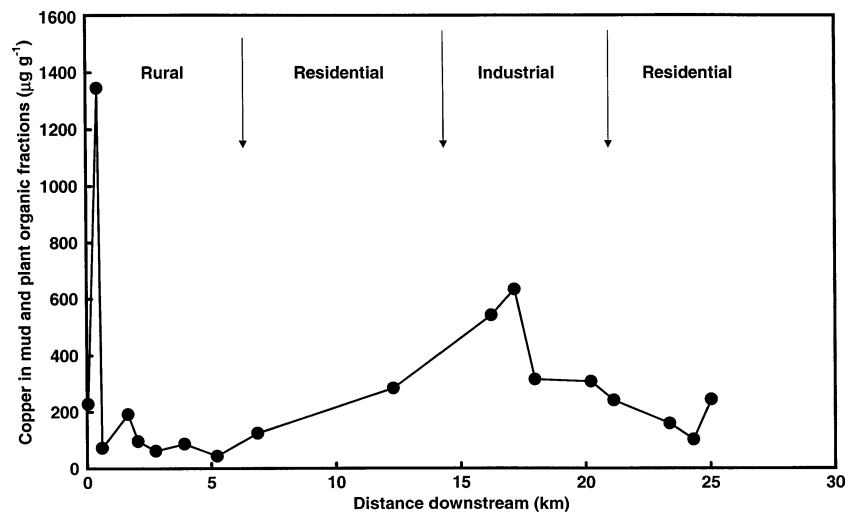


Fig. 6 The concentration of lead in the mud and plant organic fractions of bed sediment with distance downstream along First Creek and the River Torrens, South Australia

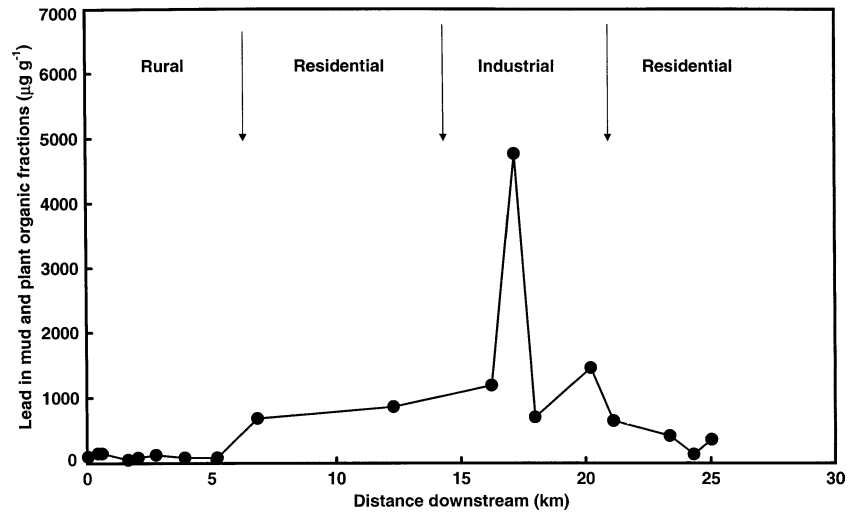


Fig. 7 The concentration of phosphorus in the mud and plant organic fractions of bed sediment with distance downstream along First Creek and the River Torrens, South Australia

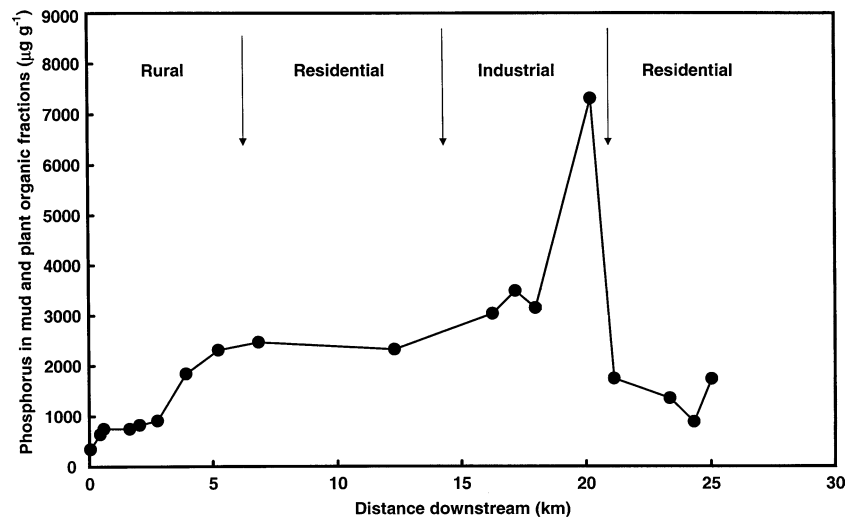
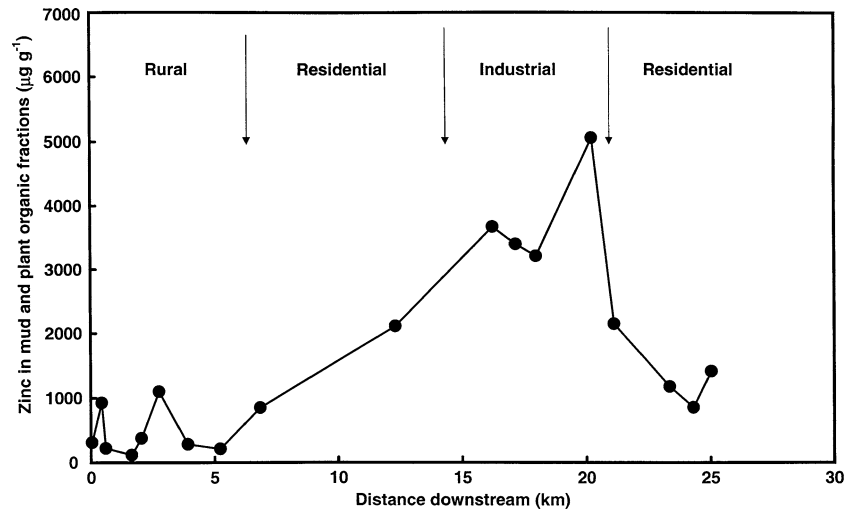


Fig. 8 The concentration of zinc in the mud and plant organic fractions of bed sediment with distance downstream along First Creek and the River Torrens, South Australia



anticipated under natural conditions. (For comparison, see the typical elemental concentrations of uncontaminated Australian regolith materials listed in Table 3, though such values should be taken as no more than indicative.) This is likely to be a consequence of the extensive copper–lead–zinc mineralisation of the underlying Proterozoic rocks of the Stonyfell Quartzite and Saddleworth Formation between sites FC1 and FC8 (Forbes 1980).

Although the bedrock contribution to sediment chemistry is likely to be maintained downstream of FC5 as First Creek continues to flow over the Saddleworth Formation, other factors begin to play a role beyond this point. The dramatic increases in the concentration of phosphorus above background levels, for example,

are unlikely to be explicable other than by reference to human activities. The presence of phosphorus in a rural environment is likely to indicate inputs from fertiliser, sewage, animal excrement or detergent. During the nineteenth century, numerous market gardens and orchards lay along the reach between FC6 and FC8 (Warburton and Warburton 1977), and it is likely that manures were applied intensively and extensively on the hillslopes bordering the stream. It is equally likely that the newly cleared slopes experienced high rates of erosion, carrying both soil and manure into the channel. Interestingly, the highest rural values of phosphorus lie immediately downslope of a vineyard. In this case at least, the phosphorus may come largely from the erosion of superphosphate-enriched soils.

Table 3 Typical elemental concentrations in uncontaminated Australian regolith materials. There are wide variations between the data sets in terms of the size fractions analysed, the analytical methods used and the range of results obtained. These must all be taken into consideration when referring to this table

Element	Arithmetic mean, geometric mean or median concentration ($\mu\text{g g}^{-1}$)	Material	Sample size	Source of data
Cadmium	0.0045 ^a	Unfertilised soils	$n = 4$	Williams and David (1973)
	0.045 ^a	Unfertilised soils	$n = 6$	Williams and David (1976)
	0.048 ^a	Uncropped soils	$n = 5$	Williams and David (1976)
	0.97 ^a	Unfertilised rural soils, 0–25 mm depth	$n = 38$	Hanson (1988) in McLaughlin et al. (1996)
	0.51 ^a	Unfertilised rural soils, 0–100 mm depth	$n = 38$	Hanson (1988) in McLaughlin et al. (1996)
	0.11 ^a 0.09 ^c	Soils never used for agriculture, 0–50 mm depth	$n = 69$	Merry and Tiller (1991)
	0.06 ^a 0.04 ^c	Soils never used for agriculture, 50–100 mm depth	$n = 66$	Merry and Tiller (1991)
Chromium	< 0.5 ^a < 0.5 ^b	Undisturbed rural soils, 0–150 mm depth	$n = 120$	Olszowy et al. (1993)
	0.2 ^c	Laterites	$n \geq 1,072$	Reimann and Caritat (1998)
Copper	8.3 ^a 5.9 ^b	Undisturbed rural soils, 0–150 mm depth	$n = 120$	Olszowy et al. (1993)
	80.5 ^c	Laterites	$n \geq 1,072$	Reimann and Caritat (1998)
Lead	15.5 ^a 9.0 ^b	Undisturbed rural soils, 0–150 mm depth	$n = 120$	Olszowy et al. (1993)
	14 ^c	Laterites	$n \geq 1,072$	Reimann and Caritat (1998)
Phosphorus	14 ^a	Uncontaminated soils		Nriagu (1978)
	16.4 ^a 13.1 ^c	Soils never used for agriculture, 0–50 mm depth	$n = 69$	Merry and Tiller (1991)
	9.6 ^a 6.4 ^c	Soils never used for agriculture, 50–100 mm depth	$n = 66$	Merry and Tiller (1991)
	14 ^a 12 ^b	Undisturbed rural soils, 0–150 mm depth	$n = 120$	Olszowy et al. (1993)
	21 ^a	Pre-European Holocene lake sediments	$n = 12$	Gale et al. (1995)
Zinc	14 ^c	Laterites	$n \geq 1,072$	Reimann and Caritat (1998)
	175 ^a	South Australian soils, some may have been fertilised	$n = 540$	Wild (1958)
	17 ^a	Unfertilised soils	$n = 4$	Williams and David (1973)
	693 ^a 368 ^b	Undisturbed rural soils, 0–150 mm depth	$n = 120$	Olszowy et al. (1993)
	276 ^a	Pre-European Holocene lake sediments	$n = 12$	Gale et al. (1995)
	218 ^c	Laterites	$n \geq 1,072$	Reimann and Caritat (1998)
Zinc	215 ^a	Pre-European Holocene beach ridge sediments	$n = 14$	Gale and Carden (2005)
	8.3 ^a	Unfertilised soils	$n = 6$	Williams and David (1976)
	21 ^a 13 ^b	Undisturbed rural soils, 0–150 mm depth	$n = 120$	Olszowy et al. (1993)
	24 ^c	Laterites	$n \geq 1,072$	Reimann and Caritat (1998)

^aArithmetic mean concentration

^bGeometric mean concentration

^cMedian concentration

Site FC6 is a hot spot for cadmium and zinc. This may be linked to the high concentration of these elements until recent times in the phosphatic fertilisers used in Australia (Walkley 1940; Williams and David 1973; Williams 1974, 1977; Merry and Tiller 1991).

Residential sites

There is a shift in the relative incidence of every element analysed as the stream enters the residential zone (Table 4; Figs. 3, 4, 5, 6, 7, 8). The most dramatic increase is in lead values. The widespread use of lead in western society over the last two centuries has been well documented. Most important has been the use of tetraethyl lead as an additive to petrol. By 1998–99, 98% of lead fallout from the atmosphere in Adelaide came either directly or indirectly from leaded fuels (Adeeb et al. 2003). This was despite the prohibition on the use of leaded petrol in South Australia by new vehicles in 1986 (Nicolson et al. 2003). The sale of leaded petrol ceased in South Australia in 2000 (Nicolson et al. 2003). However, this can have had little effect on existing reservoirs of lead in the environment, which are likely to continue to be reworked into the river system for many decades.

The increase in phosphorus at the residential sites may be a consequence of the intensive domestic use of fertilisers, although effluent from phosphatic detergents may also be important (and observation of the public park at site FC9 points to animal excrement as a major source of phosphorus). No specific sources of chromium and copper can be identified in the residential areas, and it is likely that the increase in the representation of these metals reflects their numerous domestic uses. These include their employment in alloys, metal plating, electrical products, fungicides, insecticides, piping and so on. Copper may also be the product of brake lining wear, which is thought to give rise to the high concentrations recorded in the particulate matter sampled from road runoff in Adelaide (Kumar et al. 2002).

Cadmium and zinc may have domestic sources similar to those of the other metals. However, at least part of the increase in these elements may be linked to their high incidence until recently in Australian superphosphate fertilisers. Zinc, thought to be the product of tyre wear, has also been recorded in high concentrations in the mineral matter sampled from road runoff in Adelaide (Kumar et al. 2002).

Industrial sites

With the passage of the river into the industrial zone there is a substantial increase in the concentration of the inorganic pollutants in the sediments (Table 5; Figs. 3, 4, 5, 6, 7, 8). The most notable change is in lead levels. Average concentrations are almost 20 times those found at rural sites and almost four times those of residential locations; although this figure is skewed by the value of 4,769 $\mu\text{g g}^{-1}$ from site RT2. In part, this may reflect the location of one of the busiest road junctions in Adelaide at Hindmarsh Bridge immediately upstream of site RT2, and the combination of direct fallout of tetraethyl lead from vehicle exhausts and inwashing of lead from roads and other surfaces into the river. The particulates from road runoff in metropolitan Adelaide are also very high in copper (Kumar et al. 2002) and this may contribute to the extremely high sedimentary copper levels recorded at site RT2.

The general increases in lead and the other metallic pollutants along this stretch of the river are also likely to be related to the former presence of a string of metal-processing industries along the reach downstream of RT2. In addition, a dozen or more metal-working concerns were located in the streets behind the river (Needham and Thomson 1987). Those alongside the river included the metal foundry of Mason & Cox. This was established in 1917 adjacent to site RT2, where it remained until the firm was progressively removed to a new location during the years 1966–76. The foundry

Table 4 Comparison of elemental concentrations in the mud and plant organic fractions of fluvial sediments from rural and residential sites in the River Torrens catchment, South Australia

Element	Mean concentration at rural sites ($\mu\text{g g}^{-1}$)	Standard deviation at rural sites ($\mu\text{g g}^{-1}$)	Mean concentration at residential sites ($\mu\text{g g}^{-1}$)	Standard deviation at residential sites ($\mu\text{g g}^{-1}$)	Increase in mean concentration from rural to residential sites
Cadmium	1.4 ^a	0.4 ^a	4.3	2.2	×3.0
Chromium	30	18	110	33	×3.7
Copper	112 ^b	70 ^b	192	73	×1.7
Lead	104	34	518	261	×5.0
Phosphorus	1,046	671	1,756	593	×1.7
Zinc	443	361	1,427	588	×3.2

The standard deviations should be taken only as an indication of the dispersion of values; they do not necessarily signify that the population from which each sample was drawn is normally distributed

^aDoes not include site FC6

^bDoes not include site FC2

Table 5 Comparison of elemental concentrations in the mud and plant organic fractions of fluvial sediments from rural and industrial sites in the River Torrens catchment, South Australia

Element	Mean concentration at rural sites ($\mu\text{g g}^{-1}$)	Standard deviation at rural sites ($\mu\text{g g}^{-1}$)	Mean concentration at industrial sites ($\mu\text{g g}^{-1}$)	Standard deviation at industrial sites ($\mu\text{g g}^{-1}$)	Increase in mean concentration from rural to industrial sites
Cadmium	1.4 ^a	0.4 ^a	11.9	2.1	×8.4
Chromium	30	18	301	179	×10.1
Copper	112 ^b	70 ^b	449	164	×4.0
Lead	104	34	2,030	1,853	×19.5
Phosphorus	1,046	671	4,249	2,051	×4.1
Zinc	443	361	3,835	840	×8.7

The standard deviations should be taken only as an indication of the dispersion of values; they do not necessarily signify that the population from which each sample was drawn is normally distributed

^aDoes not include site FC6

^bDoes not include site FC2

made brass and steel castings and used chromium in the manufacture of steel alloys (Sandercock 1963; Needham and Thomson 1987). The Union Engineering Company's heavy engineering works shifted to a riverside location in the first decade of the twentieth century (Payne 1996). F.W. Hercus, an engineering and machine tool company, moved to premises in Anderson Street, Southwark in 1938, remaining there until 1994 (F.W. Hercus Pty. Limited c. 1970; Payne 1996). In addition, not far from the river was W. Brown & Sons, manufacturers and suppliers of ingots of brass, copper, lead and zinc (Anon 1963). Although numbers have declined in the last few decades, several small-scale metallurgical concerns still operate in the area.

The pharmaceutical company of F.H. Faulding and Co. Ltd acquired a riverside site just upstream of RT1 in 1910, though new buildings were not erected here until 1915. In addition to manufacturing a wide range of pharmaceutical products, the factory made soap, pesticides and a range of poisons, and may have contributed to the high levels of many of the pollutants found downstream of the site. The company operated until 1990, when it moved to a new location to the north of the city (Donovan and Tweddell 1995).

Other possible sources of pollution hereabouts include the public rubbish dumps located on either side of the river between RT1 and RT8.

The increase in phosphorus concentrations along this stretch of the river is likely to be at least partly associated with effluent from the Adelaide Chemical Works Company. This was established in 1881 or 1882 for the manufacture of phosphatic fertiliser and acetic, hydrochloric, nitric and sulphuric acids (Jack 1919; Johnstone 1957; Cor < tin > to Cuming 1968), remaining in operation until at least c. 1956 (Smith c. 1956). The factory was located upstream of site RT8 (Anon 1928; Smith c. 1956), where phosphorus concentrations reach their highest value along the entire length of the river, 7,313 $\mu\text{g g}^{-1}$, over twice the concentration of any other

site (Fig. 7). The peaks in zinc and cadmium concentrations at this site (Figs. 3, 8) may also reflect the introduction of waste from the fertiliser plant into the river. In addition, the chemical works may have been responsible for the high sedimentary lead levels downstream of the plant. This is because sulphuric acid was manufactured using the lead-chamber process (Jack 1919), in which the reactions that form the acid take place in large lead-lined chambers and towers (Pauling 1956).

Interestingly, Gell et al. (1999) have argued that the high nutrient-phosphorus status of the River Torrens is mainly a product of 'subsoil derived native phosphorus'. This is phosphorus reworked into the river in association with sediments derived from gullyng and bank collapse. Such an explanation is difficult to credit given the generally low phosphorus content of Australian regolith materials (Table 3), the close association of high phosphorus values and human activity along the length of the river and the high levels of cadmium and zinc associated with phosphorus in the river sediments (and the close links between these three elements in local phosphatic fertilisers).

The environmental impact of inorganic pollution of the river sediments

With the exception of chromium, the concentration of every metal investigated in this study lies above the national trigger value for sediment quality at some point along the course of the river (Table 2). In general, the rural sites show little cause for concern and the high values of copper and zinc probably reflect natural background conditions rather than pollution. By contrast, the lead content of every residential site exceeds either the trigger value or (at site RT4) the value at which ecological damage is deemed to have already occurred. Similarly, the zinc content of every residential

site but one lies above the relevant trigger value or (at sites RT4, RT5 and RT6) the value at which ecological damage is assessed to have already taken place. The cadmium content of residential sites RT4, RT5 and RT6, immediately downstream of the industrial zone, is also above that at which intervention is judged to be required to protect the ecosystem.

Within the industrial zone, every site exceeds the trigger values for lead and zinc. Site RT2 (in the case of lead) and sites RT1 and RT2 (in the case of zinc) lie far beyond the level at which ecological damage is thought to have occurred. Two sites (RT1 and RT2) exceed the trigger value for cadmium, and one site (RT1) exceeds that for copper.

These threshold values are based on analyses made on the entire <2.00 mm fraction of the sediments. However, if the process of deposition involves sediment sorting and if this were to result in high silt and clay concentrations at particular sites, the guideline concentrations for the total sediment may be exceeded. In such circumstances it is appropriate to assess the sediment on the basis of analyses of the <63 μm fraction (ANZECC and ARMCANZ 2000). If this is done, the picture is far more serious. For every metal analysed, every site from the start of the industrial zone to the mouth of the river lies above the relevant trigger value (Table 2). In the case of lead and zinc, every industrial site lies above the threshold for ecological damage. For all the metals analysed, at least one of the industrial sites lies above this threshold.

In the residential zone, the zinc concentration of all sites and the lead concentration of all but one of the sites lie above the level at which ecological damage is deemed to have occurred. The situation is not quite so bleak for the other metals, though every residential site downstream of the industrial area and most of those above it lie above the relevant trigger value.

The rural sites present a more favourable picture, though site FC6 is a focus for cadmium and zinc, perhaps a consequence of overindulgent application of fertiliser in the neighbouring gardens. Most of the relatively high metal values in this zone are likely to reflect the background mineralisation of the bedrock and it is possible that the ecology of the river is little affected as a consequence.

Although there are no national guidelines against which to assess the phosphorus content of the sediments, there is strong evidence that human activities have had a significant impact on phosphorus levels in the river. There have been major cyanobacterial blooms along the lower Torrens, both in the recent past (for example,

1998–2002) and at present (early 2005). These have been linked to the release of nutrients from the sediments (Patawalonga & Torrens Catchment Water Management Boards 2002). Phosphorus concentrations in the water have also reached dramatic levels. Thus, the South Australian Environment Protection Authority reported a mean total phosphorus content of 0.439 mg l⁻¹ in the River Torrens during the period June 1995 to January 1997 (Environment Protection Authority 1998). This is far above the relevant default trigger value for South Australian lowland rivers (ANZECC and ARMCANZ 2000).

Conclusions

The claim that Adelaide lies on the dirtiest river of any capital city in Australia (Hodge 2003) is difficult to assess. Some of the pollution in the headwater streams is likely to be natural, the product of copper–lead–zinc mineralisation of the underlying rocks. It is clear, however, that the sediments of the Torrens downstream of its junction with First Creek are badly contaminated by cadmium, lead, phosphorus and zinc. Levels of chromium and copper are also of concern. Pollution at every site along the trunk stream is such that immediate investigation is required if ecological damage is to be prevented and, in the case of lead and zinc, several sites already exceed the threshold beyond which damage must have occurred. It is likely that much of this contamination is a response to past pollution practices, whether the result of industries intentionally or unintentionally discharging waste into the river or the product of long-term reservoirs of contaminants being reworked into the channel. Unfortunately, these problems are likely to persist. There is little evidence that bed sediments are being moved downstream and flushed out of the system or that they are being diluted by mixing with relatively uncontaminated sediments. Indeed, the close association between pollution peaks in the river and likely sources of pollution would suggest that little mobilisation of sediment has taken place since deposition first occurred. This is not surprising. The chains of weirs, sluices and reservoirs along the river must have reduced the magnitude of the flood flows that would have entrained the sediments under natural conditions, while simultaneously acting as sediment traps to prevent pollutants from being transported downstream.

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