Technical Memorandum 9

Textural Characteristics and Heavy Metal Concentrations in Billabong Sediments from the Magela Creek System

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Thomas, P.A. and Hart, B.T. (1984). Textural characteristics and heavy metal concentrations in billabong sediments from the Magela Creek system, Northern Australia. Supervising Scientist for the Alligator Rivers Region, Tech. Mem. 9.

The objective of this study was to assess the usefulness of Magela Creek billabong sediments to monitor the potential buildup in heavy metals as a result of the Ranger uranium mining operation and the regional township at Jabiru.

Major differences were found in the physical characteristics of the sediments both between billabongs and, in some cases, within the same billabong. The billabong sediments were found to reflect closely the hydrological characteristics during the Wet Season. The sediments in the backflow billabongs were fine-grained, being mostly silt and clay, and rich in organic matter (~20%). The floodplain billabongs also contained predominantly fine-grained sediments but the organic content was considerably lower (6 to 7%). The channel billabongs contained essentially sandy sediments although deeper sections and slower flowing areas contained some silt and clay. The textural characteristics of the Mayamarleprard Waterhole system (Y-shape and Island billabongs) were found to vary widely over the two billabongs.

The sediments in Hidden and Leichhardt billabongs were considerably different from the other billabongs. They consisted of a sticky, grey clay material. This same material appears to underlie much of Island Billabong and the Mudginberri Corridor area.

A large number of sediments from Magela Creek billabongs were analysed for iron, manganese, cadmium, copper, chromium, lead, zinc and mercury. From these data three main points emerge:

(i) The concentrations of all metals in the less than 63 μm fraction are very low when compared with published values for unpolluted sediments.

(ii) The metals were evenly distributed over fractions less than 63 μm in size.

(iii) A digestion procedure involving extraction of the sediments with H_2O_2 and HNO_3 has proved to be most effective. Comparison with the results obtained using a complete digestion procedure ($H_2O_2/HNO_3/HF$) showed that most of the chromium (63%), much of the zinc (46%), but only 25 to 36% of the iron, manganese, copper and lead were associated with the mineral phase of the sediments and would be unavailable to the biota.

1 INTRODUCTION

Sediments can concentrate a wide range of toxic contaminants including heavy metals and organic compounds such as pesticides, polycyclic aromatics and halogenated hydrocarbons, and because of this, sediment analysis can provide a useful method of monitoring potentially harmful buildup of contaminants in aquatic systems (Forstner & Wittmann 1981). Forstner & Salomons (1980) have recently suggested the two main uses of sediment analysis as 'i) the identification, monitoring and control of pollution sources, and ii) the evaluation of the environmental impacts of polluted sediments, particularly with respect to the biological effects of dredged material on agricultural lands'.

Heavy metals may enter the sediments either by direct adsorption from the water column or by deposition of enriched suspended solid particles including dead algae. Once incorporated into the sediment phase, changes in pH or redox conditions cause some metals to be remobilised into the interstitial water phase and from there to the water column. Resuspension of sediment particles may also create conditions where metals are more easily released to the water column. It is possible for heavy metals to be directly taken up from contaminated sediments by bottom feeding biota. All these mechanisms may result in food chain accumulation of heavy metals.

The Ranger Uranium Environmental Inquiry (Fox et al. 1977) identified the sediments from the Magela Creek system as a potentially useful medium for monitoring any possible adverse impacts from the Ranger uranium operation. The research project reported here had the following aims:

(i) to characterise texturally and chemically the sediments from representative billabongs in the Magela Creek system,

(ii) to determine the present concentrations of heavy metals in these sediments,

(iii) to assess the potential usefulness of these billabong sediments in monitoring heavy metal buildup and to recommend the best monitoring sites,

(iv) to provide information on the heavy metal transportation processes operative in the Magela Creek system.

Results of an earlier investigation (Thomas et al. 1981) had suggested that subsequent work should be concentrated in the Mudginberri Corridor. In this region Magela Creek changes from a well defined stream channel to a flood plain which is 1 to 2 km wide and some 7 km in length (we consider here only the southern corridor area extending from Mudginberri crossing to the northern end of Island Billabong (Fig. 1)). During the Wet Season the flooded corridor region contains extensive macrophyte stands which appear to be efficient in 'filtering' out any suspended particulate matter. This, together with the reduction in water velocity, means that suspended solid deposition and heavy metal accumulation could occur in the corridor region.

As a result of the radiocarbon dating of paperbark leaves (dated to be 3500 years old) recovered from a drill hole 1.5 m below the surface we have been able to estimate an average annual sedimentation rate of 0.43 mm/year on the Mudginberri Corridor. Hart et al. (1981) have

estimated the annual transport of suspended matter by Magela Creek to be 5300 tonnes (this assumes an average annual flow of 500 x 10^6 m^3). If it is assumed that all this is deposited evenly over the corridor area (estimated to be 10.5 km^2) the average deposition rate would be 0.50 mm. This is quite close to the value calculated on the basis of radiocarbon dating and lends support to the hypothesis that much of the suspended material transported by Magela Creek is trapped in the corridor area.

Here we report the results of analyses of sediment samples collected from a range of billabongs in October 1979. These data, together with those previously reported (Thomas et al. 1981), are used to draw conclusions and to make recommendations relating to the above aims. Investigations into heavy metal uptake and release mechanisms have also been undertaken and will be reported.

2 METHODS

2.1 Sampling

Sediment samples were taken from thirteen billabongs in October 1979. Billabongs sampled were (Fig. 1) :

- four backflow billabongs; Gulungul (GL), Georgetown (GT), Corndorl (CD) and Anseranas (AN).
- five channel billabongs; Mudginberri (MG), Boomerang (BM), Y-shape (YS), Island (IS) and Three-croc.
- four floodplain billabongs; Hidden (HD), Leichhardt (LC), Jabiluka (JB) and Nankeen (NK).

Details of the billabong characteristics and location of sampling sites are given in Section 3. The general limnological characteristics of these billabong classes have been given by Walker and Tyler (1979) and Hart and McGregor (1980).

All sediment samples were obtained by combining two Ekman grab samples in a clean plastic bag, mixing well, and transferring a subsample to an acid-washed clear plastic jar. The jars were then taken to the laboratory and kept frozen until analysed.

Core samples were collected from Gulungul, Corndorl, Island and Hidden billabongs and analysed for particle size distribution and concentrations of heavy metals. The cores, obtained using clear perspex tubing, were sectioned in the field, placed in Whirl Paks, and frozen until analysed.

2.2 Size Separation Procedure

The sediment samples for heavy metal analysis were separated into four fractions: Sand+Organics, Silt+Clay, Fine Silt+Clay and Clay (see Section 2.3 below for definitions of the fractions).

The Silt+Clay fraction was obtained by sieving 50 g of wet sediment (10-20 g dry sediment) through a 63 µm nylon sieve using approximately 300 mL of ultrapure water. Prior to sieving the samples were dispersed by sonication, a process that has some effect on the particle size

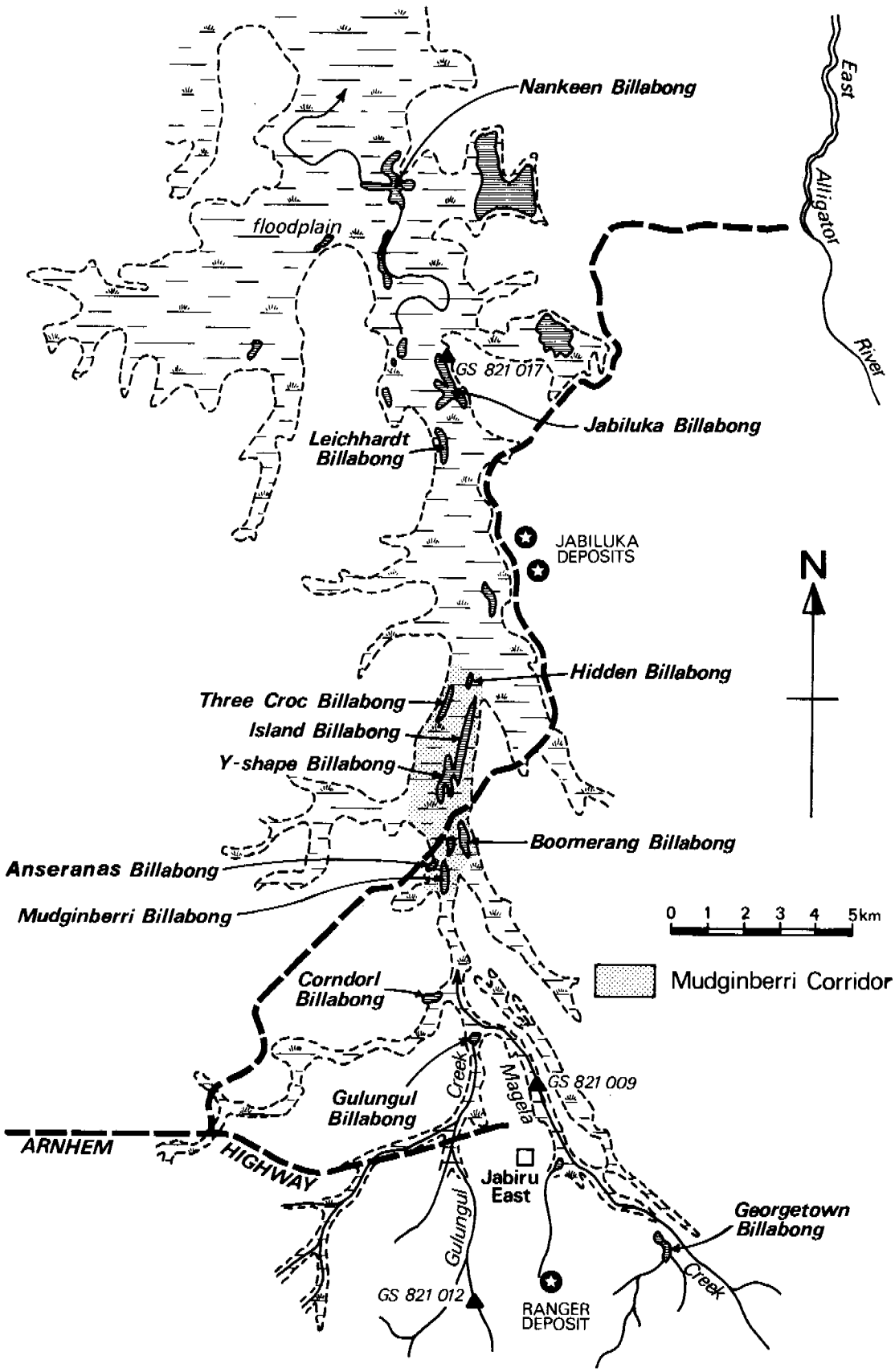

FIGURE 1 MAGELA CREEK SYSTEM.

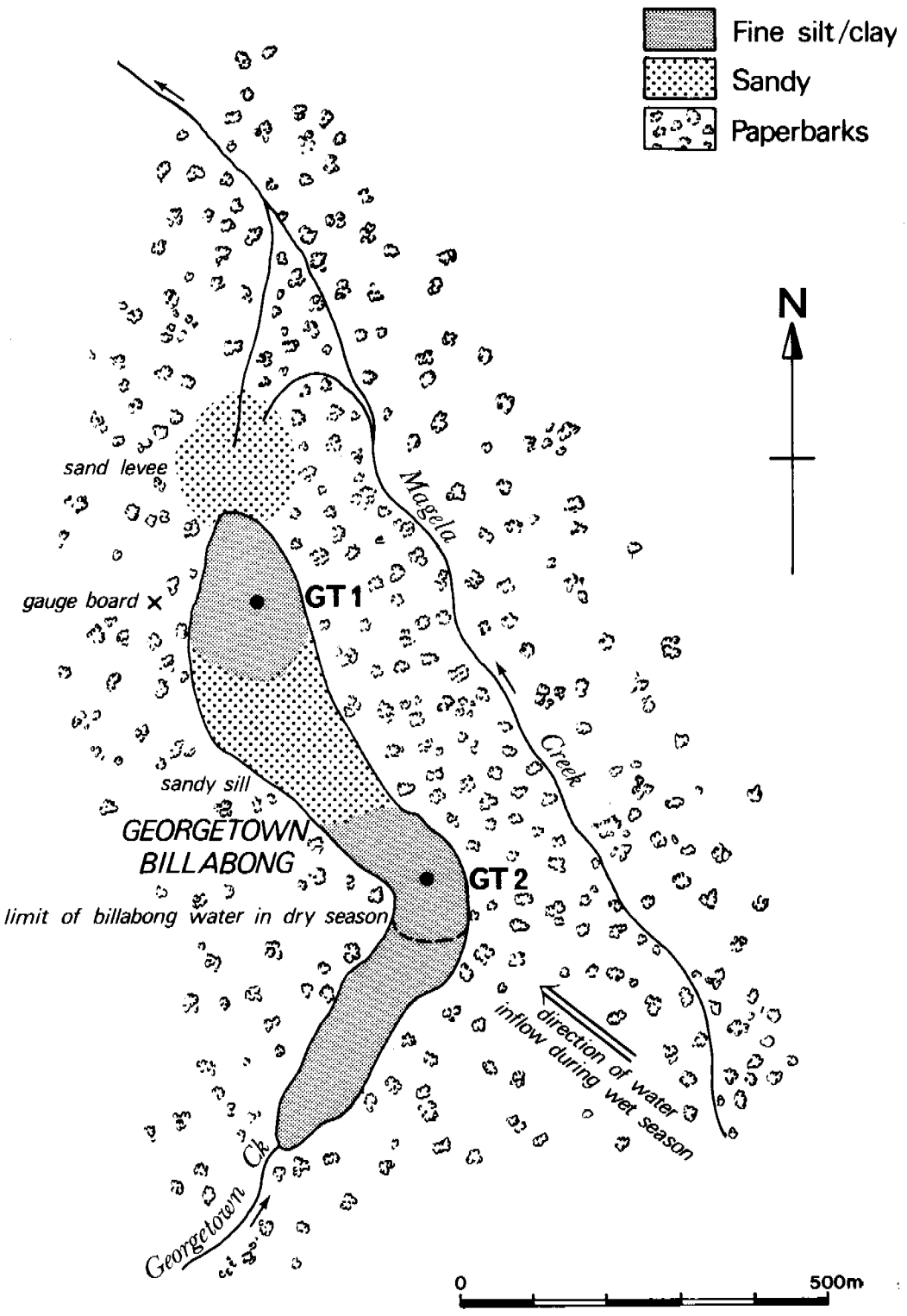

FIGURE 2 GEORGETOWN BILLABONG SHOWING THE SAMPLING LOCATIONS.

distribution. The material that did not pass through this sieve is described as the Sand+Organic fraction. The Fine Silt+Clay fraction was obtained by wet sieving another 50 g of wet sediment through the same 63 µm nylon sieve into a 1 L measuring cylinder. This was made up to volume (1 L) with ultrapure water, the cylinder inverted continuously for one minute and then allowed to stand. After the calculated time (Appendix A, Guy 1969) the top 500 mL of the suspension was removed and oven dried at 80°C to give the Fine Silt+Clay fraction. The Clay fraction was obtained in an independent separation using the above method but with a different settling time (Appendix A).

The particle size distributions for all billabong sediments analysed are given in Table 1.

Triplicate sediment samples were collected from one site in Georgetown Billabong (GT2) (Fig. 2) and separately analysed for particle size distribution and concentration of heavy metals to provide a measure of the homogeneity of sediment samples collected from a single site. Results (Table 2) showed that while the ratio of Silt+Clay to Sand+Organic varied considerably the ratio of Fine Silt+Clay to Silt+Clay remained relatively constant. Thus at this sampling site the fractions less than 63 µm in size were reasonably homogenous in distribution and could be reproducibly separated while the larger sized Sand+Organics fraction was quite variable in composition between the three samples.

2.3 Definition of Size Fractions

The Fine Silt+Clay and Clay fractions obtained using the separation technique described above require comment.

With the classical sedimentation (pipette) technique based on Stoke's law, a small aliquot is removed at a specified depth (d) after a calculated sedimentation time. This small volume will contain particles less than a defined size that are representative of the total sediment particle size distribution. The separation procedure used here differs from the pipette technique in that the total volume above d was removed to obtain sufficient material for analysis. This fraction, which will contain all particles less than a defined size, will have a distribution of particles that is biased toward the finer size particles. Since the actual distribution is not known a correction can not be made for this bias.

Therefore, although the size fractions obtained could be described as greater or less than a specific size, it is preferable to describe them as follows:

Sand+Organics	- total fraction greater than 63 µm (sieve separation)
Silt+Clay	- total fraction less than 63µm (sieve separation)
Fine Silt+Clay	- fraction less than approximately 20 µm (sedimentation separation)
Clay	- fraction less than approximately 2 µm (sedimentation separation).

TABLE 1 PARTICLE SIZE DISTRIBUTION, PER CENT MOISTURE AND PER CENT ORGANIC CONTENT OF SEDIMENT SAMPLES.

Billabong	Site[a]	% of Total Sediment		% of Silt+Clay Fraction		% Moisture	% Organic Content	
		Sand + Organics[b]	Silt + Clay[b]	Fine Silt+Clay[b]	Clay[b]		Sand+Organic Fraction	Silt+Clay Fraction
Georgetown	GT1	6	94	83	36	59	27	11
	GT2 B	31	69	87	36	57		11
Gulungul	GL2	25	75			79	37	19
Corndorl	CD					73		21
Mudginberri	MG	84	16			17		19
Boomerang	BM	37	63	91	40	66		17
Y-Shape	YS1	38	62	79	23	76	21	15
	YS2	98	2			30	1	15
Island	IS1	75	25	88	28	71	15	21
	IS2	4	96	96	10			17
Hidden	HD	52	48	77	22	75		14
Leichhardt	LC1-top			78	27	74	51	13
	LC1-bottom	3	97	84	18	53		5
	LC2	8	92	81	20	77	28	11
Jabiluka	JB	21	79	54	36	71	21	6
Nankeen	NK	12	88	61	36	70	20	6

[a]See Figs 1-5 for locations.

[b]See Section 2.3 for explanation of size fractions.

TABLE 2 PARTICLE SIZE DISTRIBUTION OF SEDIMENT SAMPLES FROM GEORGETOWN BILLABONG.

Sample	% of Total Sediment that is Sand+Organics[b]	Silt+Clay[b]	% of the Silt+Clay Fraction that is Fine Silt+Clay[b]
GT2 A[a]	16	84	87
GT2 B	31	69	87
GT2 C	26	74	83

[a]See Fig. 2 for location.
[b]See Section 2.3 for discussion of particle size fractions.

2.4 Organic Carbon and Moisture

The method used to determine organic carbon was identical to that reported in Thomas et al. (1981). Five to 10 g of sediment was dried to constant weight at 100°C. After ignition at 400°C for 7 hours the sample was desiccated overnight, weighed and the percent weight loss on ignition calculated. Under these conditions the dominant contribution to the weight loss would be oxidation of organic matter (Jaffe & Walters 1979) and we will refer to these results as 'organic content'.

The organic content in all sediments is recorded in Table 1. The per cent moisture content of the sediments, also recorded in Table 1, was obtained by oven drying sediments at 110°C for eight hours.

2.5 Concentrations of Heavy Metals

Concentrations of heavy metals were determined after the sediment sample had been digested with hydrogen peroxide and nitric acid. The detailed procedure was as follows: approximately 1 g (determined to constant weight) of dry, ground sediment was placed in an acid-washed Teflon beaker with 3 mL of ultrapure water (Milli-Q system). Ten mL of 30% H_2O_2 was then added slowly and the beaker capped and allowed to stand overnight. The unreacted H_2O_2 was removed by heating on a waterbath until effervescence ceased. This was followed by the addition of 10 mL Suprapur HNO_3 that was heated to fuming on a hot plate until reduced to a small volume. The contents of the beaker were then quantitatively transferred to a 50 mL volumetric flask and made up to volume with ultrapure water. The solution was then transferred to an acid-washed, clear plastic centrifuge tube and centrifuged at 3000 rpm for 15 minutes. The clear supernatant was decanted and stored in 100 mL acid-washed, plastic bottles (final pH 1-2).

Iron, manganese, cadmium, copper, chromium, lead and zinc were determined in the final digest using flame atomic absorption spectroscopy (Varian AA6 with background correction). The AA6 operating conditions have been reported by Thomas et al. (1981). Although the AA conditions were the same as in the previous work, the solution matrices differ since there were differences in the digestion techniques used (in previous work an additional HF/H_3BO_3 digestion was used). The method of standard additions was used to verify that these matrix differences were not significant.

TABLE 3 CONCENTRATIONS OF HEAVY METALS DETERMINED IN NATIONAL BUREAU OF STANDARDS (NBS) STANDARD SAMPLES[a].

Sample		Concentration (μg/g dry wt)				
		Mn	Cd	Cu	Pb	Zn
River Sediment						
Replicate	1		7	97	711	1523
	2		9	102	790	1690
	3		10	109	741	1660
Mean ± S.D.			9±2	103±6	747±40	1620±90
Certified Value			10.2±5	109±19	714±28	1720±169
Orchard Leaves						
Replicate	1	80	<1	13	47	25
	2	86	<1	11	50	25
	3	86	<1	12	41	22
Mean ± S.D.		84±3	<1	12±1	46±5	24±2
Certified Value		91±4	<1	12±1	45±3	25±3

[a] H_2O_2/HNO_3 digestion procedure used.

TABLE 4 CONCENTRATIONS OF HEAVY METALS DETERMINED IN A COMPOSITE SEDIMENT SAMPLE[a].

Replicate	Concentration (μg/g dry wt)					
	Fe	Mn	Cu	Cr	Pb	Zn
1	25 200	ND[b]	25	35	19	64
2	26 600	387	26	37	20	65
3	25 200	380	25	40	21	66
4	26 000	385	24	35	24	62
5	25 400	376	24	40	21	63
6	24 400	374	25	37	25	63
Relative Standard Deviation (%)	3	1	3	6	10	2

[a] Chisholm Institute of Technology secondary standard sediment.
[b] Not determined.

2.6 Accuracy

Two National Bureau of Standards (NBS) samples, river sediment and orchard leaves, were analysed to ascertain the accuracy of the H_2O_2/HNO_3 digestion procedure. The results are given in Table 3 along with the certified values. Good agreement with the certified values was obtained in all cases except for manganese in the orchard leaves where the result obtained was slightly less than the certified value.

2.7 Repeatability

As a quality control check, a composite sediment sample was analysed at regular intervals throughout this project. Table 4 shows the concentrations of heavy metal obtained in six separate digestions. The relative standard deviation was less than 3% for iron, manganese, copper and zinc, 6% for chromium and 10% for lead.

As well as determining the analytical variability, it is necessary to test the variability of the concentration of heavy metal in grab samples taken from essentially the same position in a billabong. If billabong sediments are to be used to monitor long-term changes in metal concentrations, the variability between samples taken at the one site must be small. To test this, three separate sediment grab samples were taken from an area of approximately 10 m radius in Georgetown Billabong (GT) (Fig. 2). They were then size separated and analysed. Concentrations of heavy metals in the Silt+Clay and Fine Silt+Clay fractions are given in Table 5. The *in situ* variability in the concentrations of heavy metals associated with these finer sediment fractions was very low. These data, coupled with those reported by Forstner & Wittmann (1981), suggest that the finer fractions of the sediment samples may be used with some confidence in monitoring increases in the concentrations of heavy metals that may result from the Ranger uranium mining operation or from the regional township.

2.8 Comparison of Digestion Techniques

Until October 1979 all sediment samples were digested using an $H_2O_2/HNO_3/HF$ digestion procedure (see Thomas et al. 1981). Since that time a procedure using only H_2O_2/HNO_3 has been used. This latter digestion technique should give a better estimate of the environmentally significant concentration of each heavy metal (Forstner and Wittmann 1981) since the HF digestion step would dissolve the mineral phase and release metals that are unlikely to be available to the biota.

The Fine Silt+Clay fraction of each of the October 1979 samples was analysed by both techniques (Table 6). The results provide information on the way in which the metals are distributed within the sediments since the difference between the metal concentrations given by the two digestion procedures will give a measure of the amount associated with the mineral phase.

The major portion of the chromium (mean 63% over all billabongs) was associated with the mineral phase as was much of the zinc (mean 46%). With the other metals analysed - iron, manganese, copper and lead - only 24-36% was associated with the mineral phase as between two-thirds and three-quarters was extracted by H_2O_2/HNO_3.

More detailed analysis of the data indicates a number of differences between the billabongs (Table 6). Hidden Billabong sediments, for example, have generally less metal associated with the mineral phase, this was particularly so for iron and manganese. By comparison the sediments from Jabiluka and Nankeen Billabongs contained a greater fraction of these metals in association with the mineral phase (Table 6).

3 RESULTS AND DISCUSSION

To assist the following discussion of results, each billabong has been given one of three broad classifications: backflow, channel or floodplain billabong. The physical characteristics and associated heavy metal concentrations of sediments from each are discussed. The concentrations of heavy metals in the Silt+Clay, Fine Silt+Clay and Clay fractions from each sediment are given in Tables 8 and 9 and these results are summarised in Table 10.

3.1 Backflow Billabongs

3.1.1 Georgetown Billabong (GT)

Georgetown Billabong consists of two shallow basins which are less than 1 m deep by the end of the Dry Season and are separated by a sill (Fig. 2). The sediments in each basin are predominantly Fine Silt+Clay and that on the sill is higher in sand. The two sample positions (GT1 and GT2) are close to the centre of the two respective basins (Fig. 2). Sample GT1 contained a greater amount of Silt+Clay but at both sites this fraction consisted predominantly of Fine Silt+Clay (GT1 83%, GT2 83-87%; Table 1). Approximately one third of the Silt+Clay fraction was clay which was composed mainly of chlorite, kaolinite and illite with a small amount of expandable clay (Table 7).

TABLE 5 CONCENTRATIONS OF HEAVY METALS IN TWO SIZE FRACTIONS SEPARATED FROM REPLICATE SEDIMENT SAMPLES TAKEN FROM GEORGETOWN BILLABONG.

Fraction	Sample[a]	Concentration (µg/g dry wt)[b]					
		Fe	Mn	Cu	Zn	Cr	Pb
Silt+Clay	GT2 A	21 200	123	37	11	55	15
	B	20 500	116	39	13	61	17
	C	21 000	120	38	11	61	16
Fine Silt	GT2 A	18 800	115	33	9	49	15
	B	20 300	118	39	12	58	16
	C	19 400	118	35	11	53	18

[a] See Fig. 2 for location.
[b] H_2O_2/HNO_3 digestion procedure used.

TABLE 6 CONCENTRATIONS OF HEAVY METALS EXTRACTED FROM THE FINE SILT+CLAY FRACTION OF SEDIMENT SAMPLES USING TWO DIGESTION PROCEDURES - A : H_2O_2/HNO_3 B : $H_2O_2/HNO_3/HF$[a].

Billabong		Site	Concentration (µg/g dry wt)											
			Fe		Mn		Cu		Cr		Pb		Zn	
			A	B	A	B	A	B	A	B	A	B	A	B
Georgetown		GT1	17 900	26 900	103	158	46	46	56	122	17	23	13	28
		GT2	18 800	27 700	115	178	33	54	49	127	15	25	9	25
Gulungul		GL2	9 100	15 200	114	142	22	29	36	80	17	24	10	18
Boomerang		BM	15 600	25 100	146	195	26	38	35	103	12	20	14	17
Y-Shape		YS1	15 700	25 000	144	203	20	29	45	94	13	22	20	35
Island		IS1	24 000	36 200	169	205	22	30	32	87	13	18	24	43
		IS2	25 100	35 400	160	201	19	27	38	101	13	17	22	38
Hidden		HD	36 000	40 000	246	237	18	24	32	91	ND[c]	ND[c]	30	41
Leichhardt	top	LC1	29 000	39 400	139	180	15	18	35	122	11	23	30	68
	bottom	LC1	26 100	39 900	240	300	8	12	36	107	16	29	27	53
		LC2	22 200	32 000	115	158	13	17	38	107	13	21	27	42
Jabiluka		JB	16 800	30 600	72	117	8	14	27	94	12	20	19	37
Nankeen		NK	24 100	39 300	128	184	7	12	40	112	14	20	22	44
Mean Ratio (%)[b]			67		76		70		37		64		54	
Relative Standard Deviation (%)			9		11		8		6		9		10	

[a]See Section 2.5 for details of digestion procedures.

[b]$\Sigma \frac{A}{B} \times 100 / n$

[c]Not determined.

Early in the Wet Season Georgetown Billabong fills by water backflowing from Magela Creek over a sand bar at the northern end of the billabong. Visual observations indicated that high water velocities occur here at such times. The billabong also receives water from Georgetown Creek (catchment area 10 km^2). As the Wet Season progresses and the water level in the billabong rises, the main flow into Georgetown is from Magela Creek at the southern end of the billabong (Fig. 2). This is consistent with the observation that site GT2 has a higher sand content than site GT1.

Thomas et al. (1981) reported that eight sediment samples taken longitudinally along Georgetown Billabong varied in organic matter from 0.1% to 10.7%, the highest values occurred in sediments taken from the basin regions. The latter result was confirmed by the present study where it was found that the organic content in both samples was 11% (Table 1).

The most noticeable feature of the sediments in Georgetown Billabong was the high concentration of copper in the Silt+Clay fraction (33-37 µg/g, Table 8). These were the highest in the billabongs tested in the study.

TABLE 7 CLAY MINERALOGY OF SEDIMENT AND SUSPENDED SOLIDS SAMPLES[a].

p = present, x = absent, tr = trace; d = some doubt that quartz present. If present, it is only in trace quantities

Sample	Chlorite	Kaolinite	Illite	Quartz	Expandable
Sediment:[b]					
Georgetown	p	p	p	d	tr
Gulungul	p	p	x	d	x
Corndorl	p	p	x	d	x
Jabiluka	p	p	p	d	x
Nankeen	p	p	p	d	tr
Suspended Solids:[c]					
Georgetown	p	p	p	p	p
Gulungul	x	p	p	p	p
Island	p	p	p	p	p
Jabiluka	p	p	p	p	p
Nankeen	p	p	p	p	p

[a] Suspended solids samples collected by filtering billabong water through a 0.4 µm Nuclepore filter. All samples were less than 2 µm and were digested with H_2O_2.

[b] XRD analysis by Dr B.T. Hart while at Institute for Sedimentology, University of Heidelberg, Heidelberg, F.R.G.

[c] XRD analysis by Dr M. Muller-Monmoos, E.T.H., Zurich, Switzerland.

There was little difference in the levels of copper in the Silt+Clay fraction from the two sampling sites at opposite ends of the billabong. All particle sizes less than 63 μm had high copper concentration, no enrichment being noted in the smaller size fractions (Table 9).

High concentrations of copper are often correlated with high organic content in sediments (Forstner & Wittmann 1981). However this does not appear to be the case in Georgetown Billabong since these sediments had relatively low organic contents and yet had high copper concentrations. Georgetown samples excluded, a reasonable linear correlation existed between the copper concentration in the Silt+Clay fraction and the organic

TABLE 8 CONCENTRATIONS OF HEAVY METALS IN THE SILT+CLAY FRACTION FROM BILLABONG SEDIMENT SAMPLES.

Billabong	Site	Concentration (μg/g dry wt) Fe	Mn	Cu	Cr	Pb	Zn	% Org. Cont.
Georgetown	GT1	18 200	10	37	54	16	15	11
	GT2	20 900	120	33	59	16	11	11
Gulungul	GL2	9 300	113	22	36	17	10	19
	GL/Core[a]	7 700	109	25	28	19	11	21
Corndorl	CD/Core	11 400	172	27	52	19	13	21
Anseranas	AN/Core	11 800	121	24	33	12	41	24
Mudginberri	MG	35 900	260	29	62	16	31	19
Boomerang	BM	16 000	152	25	38	9	13	17
Y-Shape	YS1	16 100	152	24	43	14	23	15
Island	IS1	27 700	173	30	35	13	30	21
	IS2	25 800	161	28	46	11	26	17
	IS2/Core	27 100	150	24	36	20	36	19
Hidden	HD	48 200	294	19	35	13	29	14
	HD/Core	39 200	234	9	31	15	21	10
Leichhardt								
top	LC1	27 900	139	14	41	14	29	13
bottom	LC1	27 000	246	9	48	14	26	5
	LC2	25 100	126	12	41	11	29	11
Jabiluka	JB	13 900	51	7	25	9	18	6
Nankeen	NK	20 800	110	7	33	10	19	6
Mean		29 900	160	22	41	13	23	15
Standard deviation		10 400	60	9	10	4	9	6
Relative standard deviation (%)		46	38	42	25	32	39	38

[a]Top 3 cm of core analysed.

content. This relationship can be expressed by the equation:

$$Cu\ (\mu g/g) = 1.26 \times org.\ cont.\ (\%) + 1.14 \qquad (r = 0.87).$$

This equation predicts a copper concentration of 15 µg/g for Georgetown Billabong sediments which is much lower than the actual value of 35 µg/g.

The other metals tested showed minimal differences in concentration between the size fractions from sampling sites GT1 and GT2.

3.1.2 Gulungul Billabong (GL)

Gulungul Billabong is situated at the confluence of Gulungul and Magela Creeks (Fig. 3). Water enters the billabong either from Gulungul Creek (catchment area 110 km^2) or by backflow from Magela Creek; the billabong is separated from the main Magela channel by a sand levee although a defined channel exists through this sand levee. The balance of water flow into Gulungul Billabong from Magela Creek and Gulungul Creek is not well understood. Rhodamine dye experiments have shown that on a falling hydrograph in Magela Creek, Gulungul Creek has a major flow path through the billabong although some dye was detected in all areas of the billabong and at all depths (Smith et al. 1979).

This billabong will be an important monitoring site since drainage from the regional township and contaminants from the Ranger operation may enter it via Gulungul and Magela Creeks.

Sediments were previously found to be relatively consistent throughout this billabong (Thomas et al. 1981). They were predominantly Fine Silt and Clay (70-75% Fine Silt), unconsolidated and had a high content of organic matter (16-20% in the less than 63 µm fraction, dry wt basis). The Clay fraction from this sediment appeared to consist almost entirely of chlorite and kaolinite (Table 7). The aquatic vegetation known to grow prolifically in this billabong during the Wet Season contributes to the high organic content of the sediments. The macrophytes could also be a major contributor to the high organic content (37%) found in the fraction greater than 63 µm for sediments collected in October 1979 (Table 1).

Previous work on these sediments has shown that the heavy metal levels are similar irrespective of where in the billabong the samples were taken, with no evidence of enrichment in the smaller particle size fractions (Thomas et al. 1981). In this present study, where a different digestion procedure was used (H_2O_2/HNO_3 vs $H_2O_2/HNO_3/HF$), the heavy metals were also found to be distributed evenly over all fractions less than 63 µm in size. Some 20-40% of the iron, manganese, copper, lead and zinc, and 55% of the chromium in the Fine Silt+Clay fraction was associated with the mineral phase and would not be environmentally significant.

Iron was the only metal in Gulungul sediments to show any major difference when compared with the mean concentrations of heavy metals for all sediments. Iron was approximately one half the mean level in all fractions less than 63 µm (Tables 8 and 9).

A core sample showed that the sediments from this billabong were very well mixed. There was essentially no difference down the 25 cm profile in either moisture content, organic content or the concentrations of heavy metals (Fig. 7, Appendix B).

TABLE 9 CONCENTRATIONS OF TRACE METALS IN THE FINE SILT+CLAY AND CLAY FRACTIONS FROM BILLABONG SEDIMENT SAMPLES.

Billabong	Site	Fine Silt+Clay							Clay						
			Concentration (µg/g dry wt)							Concentration (µg/g dry wt)					
		%[a]	Fe	Mn	Cu	Cr	Pb	Zn	%[b]	Fe	Mn	Cu	Cr	Pb	Zn
Georgetown	GT1	83	17 900	103	36	56	17	13	36	17 400	94	34	56	17	10
	GT2	86	19 500	117	36	53	16	11	36	20 700	125	37	54	17	11
Gulungul	GL2	96	9 100	114	22	36	17	10	56	10 600	120	23	37	ND[c]	14
Boomerang	BM	91	15 600	146	26	35	12	14	40	14 500	133	25	47	12	12
Y-Shape	YS1	79	15 700	144	20	45	13	20	23	13 000	165	19	54	11	19
Island	IS1	88	24 000	169	22	32	13	28	28	24 800	128	13	41	8	29
	IS2	96	25 100	160	19	38	13	22	10	23 300	164	16	54	15	22
Hidden	HD	77	41 200	262	19	32	13	29	22	28 700	207	19	41	8	30
Leichhardt															
top	LC1	81	29 000	139	15	35	14	30	27	24 800	146	22	33	14	26
bottom	LC1	78	30 800	255	10	49	14	28	18	27 200	216	7	49	11	25
	LC2	84	22 200	115	13	38	13	27	20	17 400	103	16	43	12	31
Jabiluka	JB	54	16 800	72	8	27	12	19	36	20 800	83	9	33	13	25
Nankeen	NK	61	24 100	128	7	40	14	22	36	24 200	150	8	40	13	24
Mean			22 400	148	19	40	14	21		20 600	141	19	45	13	21
Standard deviation			8 200	55	9	9	2	7		5 600	40	9	8	3	7
Relative standard deviation (%)			37	37	48	22	12	34		27	28	49	18	23	35

[a]% of Silt+Clay that is Fine Silt+Clay; [b]% of Silt+Clay that is Clay; [c]Not determined.

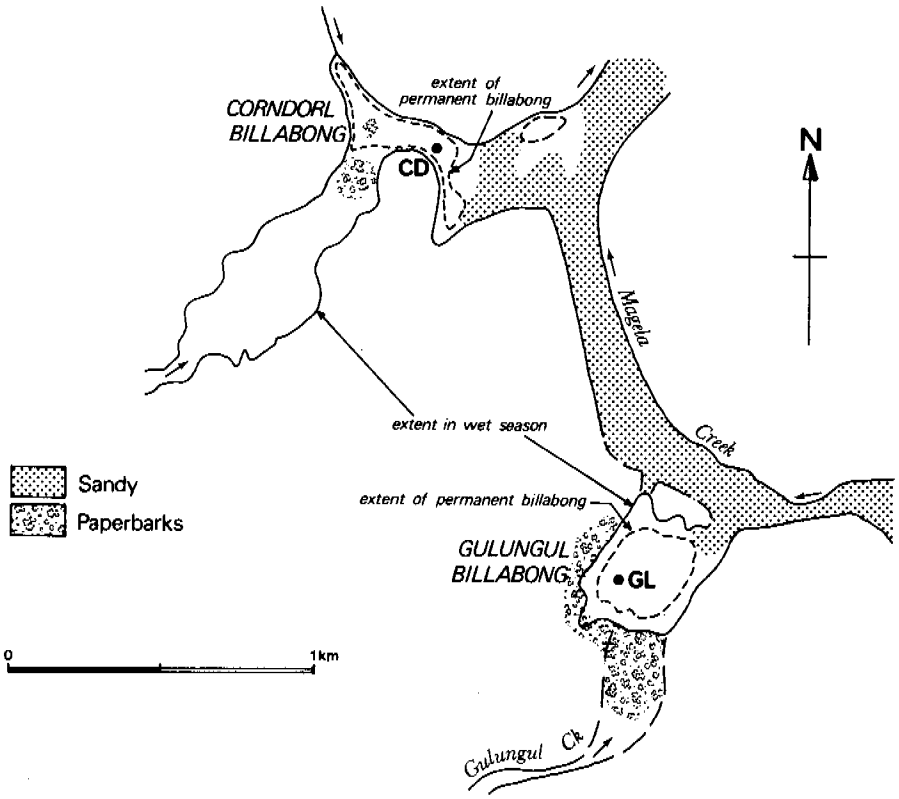

FIGURE 3 GULUNGUL AND CORNDORL BILLABONGS SHOWING THE SAMPLING LOCATIONS.

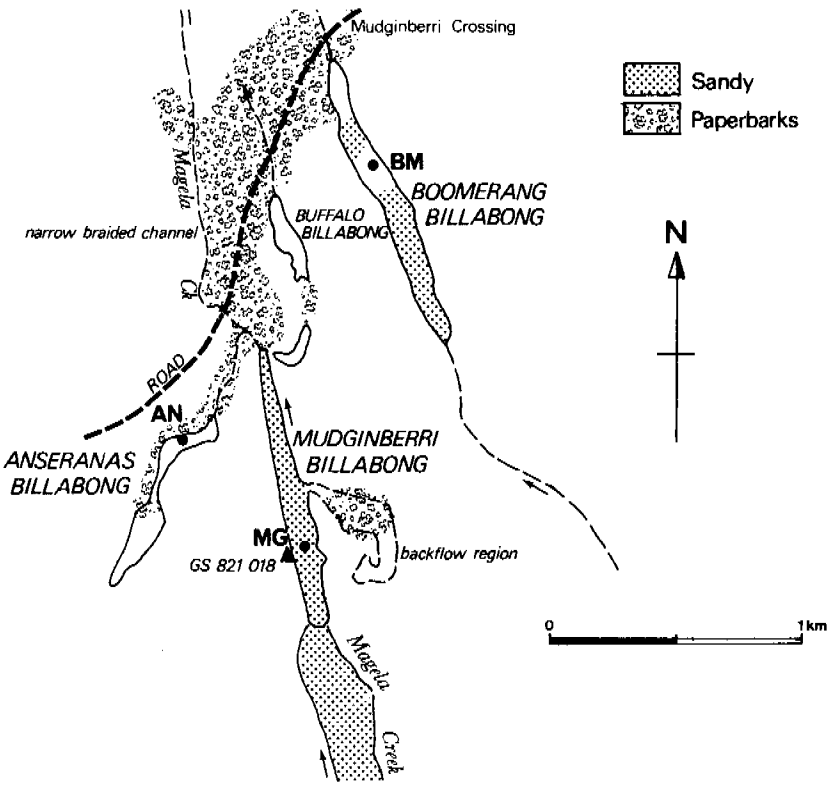

FIGURE 4 MUDGINBERRI, ANSERANAS AND BOOMERANG BILLABONGS SHOWING THE SAMPLING LOCATIONS.

3.1.3. Corndorl Billabong (CD)

Corndorl Billabong is similar to Gulungul Billabong, being a backflow billabong separated from the main Magela channel by an extensive sand levee (Fig. 3). Sediments are fine-grained (65% of the total sediment was less than 63 μm) and high in organic matter (20% in the Silt+Clay fraction) (Table 1). Most of the greater than 63 μm fraction was organic matter. The clay fraction consisted almost entirely of chlorite and kaolinite and in this respect was similar to Gulungul (Table 7).

A core sample indicated that sediments from this billabong may be slightly more consolidated than those from Gulungul. The moisture content in this core noticeably decreased with depth (Fig. 7) and suggests that only the top 15 cm of the sediment at this site was mixed.

The concentrations of heavy metals in the Silt+Clay fraction of the surface sediment from Corndorl Billabong were similar to those in Gulungul Billabong. Exceptions, for which we have no explanation, were manganese and chromium which were considerably higher in Corndorl Billabong. There was an apparent increase in the copper and lead concentrations between 3 and 6 cm depth and an increase in the zinc concentration between 10 and 15 cm in the core sample taken from this billabong (Fig. 7).

3.1.4 Anseranas Billabong (AN)

This is a relatively small backflow billabong situated close to the northern end of Mudginberri Billabong (Fig. 4). The sediments were similar to those from Gulungul and Corndorl billabongs, being fine-grained and high in organic matter (24% of the Silt+Clay fraction). When sampled in October 1979 the water was very shallow (20 cm) and the sediments had a strong sulphide smell.

With the exception of zinc, the concentrations of heavy metals in the Silt+Clay fraction were similar to those in Gulungul Billabong sediments. The zinc concentration (41 μg/g) in this size fraction was the highest of any of the billabongs surveyed (mean of all billabongs 21±7 μg/g, Table 10). The elevated zinc levels may arise from activities at the adjacent Mudginberri Station.

TABLE 10 CONCENTRATIONS OF HEAVY METALS IN THREE SIZE FRACTIONS FROM BILLABONG SEDIMENTS.

Fraction	Number of Samples[a]	Concentration (μg/g)						Org. Cont. (%)
		Fe	Mn	Cu	Cr	Pb	Zn	
Silt+Clay	13	22800±9600	149±63	21±9	41±9	13±3	21±7	3±5
Fine Silt+Clay	13	22400±8200	148±55	19±9	40±9	14±2	21±7	-
Clay	13	20600±5600	141±40	19±9	45±8	13±3	21±7	-

[a]Samples used: GT1, GT2, GL2, BM, YS1, IS1, IS2, HD, LC1-top, LC1-bottom, LC2, JB, NK.

3.2 Channel Billabongs

The channel billabongs are characteristically deep with relatively clear water and extensive fringe vegetation. Previous work on two of these billabongs - Mudginberri and Island - has shown that the sediments are sandy with little organic matter (Thomas et al. 1981).

3.2.1 Mudginberri Billabong (MG)

Mudginberri Billabong (Fig. 4) is a deep, clear billabong with very sandy sediments. Water velocities through Mudginberri during the Wet Season are probably sufficient to prevent accumulation of fine sediments except on parts of the eastern bank where eddies have been observed (Smith et al. 1979; C. Humphries, pers. comm.). A grab sample taken in October 1979 consisted of 84% Sand+Organics (mostly sand) and 16% Silt+Clay. This latter fraction contained approximately 19% organic matter (Table 1) and elevated levels of iron, manganese, copper, chromium and zinc (Table 8). The iron, manganese and chromium levels in particular were considerably higher than mean values in the Silt+Clay fraction from the other billabongs.

3.2.2 Boomerang Billabong (BM)

Boomerang Billabong is a large billabong (approximately 2 km long at the end of the Dry Season) situated to the north-east of Mudginberri Billabong (Fig. 4). The billabong is fed by water from a different catchment (area 80 km^2) and almost certainly does not receive water from Magela Creek. For this reason it may prove to be a useful 'control' billabong.

A series of grab samples taken along the length of the billabong indicated that the sediments were mainly sandy with accumulations of fine sediment and organic detritus in the deeper areas. The sediment sample taken for analysis was from a deeper area; it contained 73% Silt+Clay and 37% Sand+Organic matter. The Silt+Clay fraction contained approximately 50% Fine Silt+Clay, 50% Clay and 17% organic matter.

With the exception of zinc, the levels of heavy metals in the Silt+Clay fraction were similar to those in Island Billabong (Table 8). The zinc concentration (13 µg/g) was low and resembled the levels observed in the backflow billabongs. This low zinc level may be characteristic of this billabong and its catchment. In common with the other sediments from the Magela system heavy metals in Boomerang Billabong sediments were distributed evenly over particles in the less than 63 µm size range.

3.2.3 Mayamarleprard Waterhole

Mayamarleprard Waterhole is the name given to two connected billabongs, Island (IS) and Y-shape (YS) (Fig. 5). Island Billabong is the large billabong on the east side of the floodplain area known as the Mudginberri Corridor, whilst Y-shape Billabong is on the western side. Y-shape Billabong is situated approximately 1 km downstream of where Magela Creek changes from a relatively fast-flowing stream confined to a narrow channel into a less defined stream dispersed over a flood plain 1 to 2 km wide.

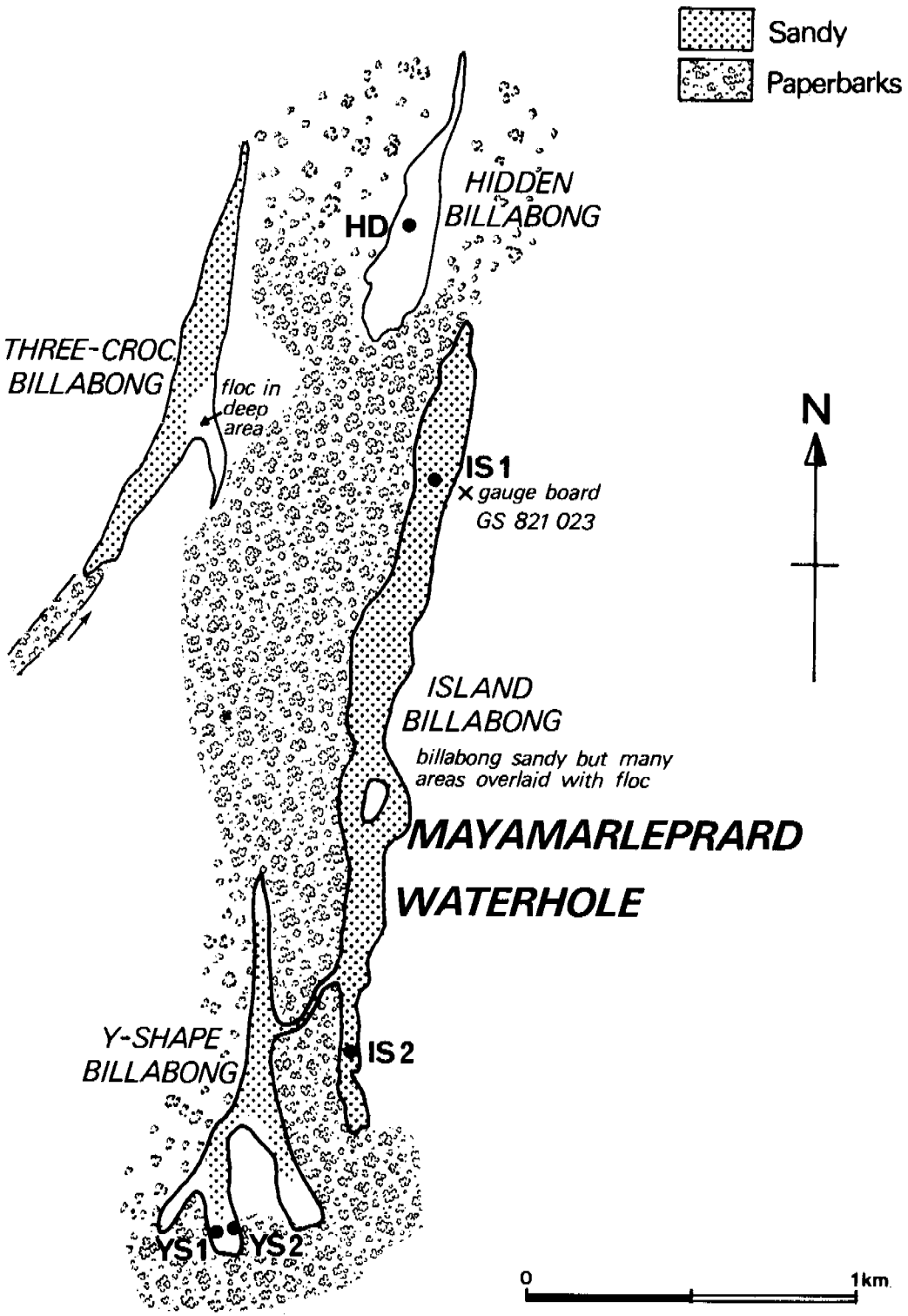

FIGURE 5 MAYAMARLEPRARD WATERHOLE (ISLAND AND Y-SHAPE BILLABONGS) AND HIDDEN AND THREE-CROC BILLABONGS SHOWING THE SAMPLING LOCATIONS.

The sediments from these billabongs showed considerable variation in texture but generally may be described as sandy with varying amounts of silt and clay. For example, the percentage of Silt+Clay in the October 1979 samples ranged from 96% at IS2 to 2% at YS2. Sample YS2 was taken close to a small sand island in Y-shape Billabong. Whitehead and Hickey (1980) also found sandy sediments in the main channels of Island and Y-shape billabongs with increasing amounts of silt towards the banks.

Over a period of almost two years (November 1978 to October 1980) regular monitoring of sediments in Island Billabong has illustrated the changeable character of these sediments. When first sampled in November 1978, the sediment at IS2 was found to be 99% sand (Thomas et al. 1981). In May 1979, following the Wet Season, the appearance of a layer of extremely fine, unconsolidated sediment floc was noted at this site. In October 1979 an extensive survey was made of both billabongs. At site IS2 a layer of this fine sediment floc approximately 15 cm thick was found (96% was less than 63 μm, Table 1). This sediment floc contained a significant amount of relatively undegraded leaf and bark detritus. Observations made during the 1980/81 Wet Season suggest that this leaf and bark is transported down Magela Creek at times of high flow and is deposited in slower flowing waters such as those in Island and Y-shape billabongs.

A core taken at IS2 in October 1979 gave some insight to the sediment variation in Island Billabong. The core consisted of the fine sediment floc overlying approximately 15 cm of sandy material. Below this the sediment was similar to the grey, clayey material found in Hidden and Leichhardt billabongs (between 18-22 cm the Island core sediment still contained 60% sand).

The sediment in Mayamarleprard Waterhole consisted predominantly of sand over a grey clay bed material. This clay bed appears to run through much of the northern section of the Mudginberri Corridor. Two questions however remain unanswered, namely the origin of the sand layer in Island Billabong and the origin of the fine sediment floc observed.

The fine sediment floc was also found in Y-shape Billabong but only in the deeper regions. For example, site YS1 was approximately 2 m deep and contained the fine sediment floc whereas YS2, only 30 m away and less than 1 m deep, was predominantly sand (Table 1). Other areas of Y-shape Billabong contained mainly sandy sediments with a substantial amount of plant debris, particularly at the northern end. Observations in October 1980 indicated only localised accumulation of the fine sediment floc in both billabongs.

The fine sediment floc noted in areas of Mayamarleprard Waterhole during 1979 appeared to be flushed out during the 1979-80 Wet Season and the sand layer was again exposed. It is possible that this fine sediment was flushed out during one particularly large flood in February 1980. Large floods probably have a great influence on the distribution of sediments in the Magela System. Douglas (1969) and Schubel (1974) have previously noted the often profound influence of rare storms on the amounts of suspended solids transported by rivers.

The organic content in the Silt+Clay fraction of the October 1979 samples from this billabong was quite high (Table 1). The fine sediments (less than 63 μm fraction) from the backflow billabongs Gulungul, Corndorl and Anseranas also contained a high proportion of organic matter. In these

latter billabongs this was attributed to the degradation of the prolific macrophyte stands that occur in the billabongs each Wet Season. However, in the case of Mayamarleprard Waterhole, the organic input must be somewhat different, since macrophyte growth is restricted to the banks and floodplain area, the billabongs being too deep and too sandy to sustain much macrophyte growth. It is possible that organic matter is deposited in the billabong from the surrounding flood plain and upstream areas. Another source of this organic matter may be phytoplankton as this billabong sustains high algal populations (J. Kessell, pers. comm.).

The concentrations of heavy metals in the sediment fractions less than 63 µm showed little variation (Tables 8-10).

The sediment core taken at IS2 showed some variations in concentration with depth (Fig. 7). Three main observations can be made:

(i) The organic content in the Silt+Clay fraction fell with depth from 19% in the top 2 cm to around 10-11% below 15 cm depth. This trend was also observed with the copper concentration which fell from 24 µg/g in the top layer to 12-13 µg/g below 15 cm and to a lesser degree with lead which fell from 20 µg/g to 13-14 µg/g. These latter results would be explained by the close association of copper and lead with organic matter.

(ii) At 15 to 18 cm manganese increased to over double the concentration in the surface layer (380 µg/g vs 150 µg/g). The higher concentrations at depth are probably related to the influence of the clay bed material which is also found in Hidden and Leichhardt billabongs and contains manganese concentrations in the range 234 to 294 µg/g. The noticeable gradient in the manganese concentration in this core suggests that the manganese rich bed material may be an important source of manganese to the water column.

(iii) A very high concentration of zinc (79 µg/g) was noted in the Silt+Clay fraction of the sandy layer 2-15 cm below the sediment surface (the greater than 63 µm fraction was not analysed). This Silt+Clay fraction contributes only 1% of the total sediment down to 15 cm excluding the fine sediment floc that overlay the core. Similar high zinc concentrations have been noted in Island and Mudginberri Billabong sediments collected in November 1978 (Thomas et al. 1981). It was suggested then that a possible reason may be the presence of heavy materials such as ZnS.

3.2.4 Three-croc Billabong

Also investigated was a billabong close to Mayamarleprard Waterhole that we have called Three-croc Billabong (Fig. 5). This billabong is situated downstream of Y-shape Billabong and is connected to it during the Wet Season by a well defined sand channel.

Visual inspection suggested that the sediments are very similar to those in Mayamarleprard Waterhole, with sand occurring in the shallow areas and a fine, organic rich sediment in the deeper depressions. No textural or chemical analyses of these sediments have been made at this stage.

3.3 Floodplain Billabongs

Four floodplain billabongs were studied: Hidden (Fig. 5), Leichhardt, Jabiluka and Nankeen billabongs (Fig. 6). Previous work indicated that the sediments from Leichhardt Billabong were, texturally and in the concentrations of heavy metals, quite different from sediments from Jabiluka and Nankeen billabongs (Thomas et al. 1981). This finding has been confirmed and quantified in this present study.

Sediments from Hidden Billabong, situated at the northern extremity of the Mudginberri Corridor, appeared to resemble more closely those of Leichhardt Billabong than those of Mayamarleprard Waterhole. For this reason it has been classified as a floodplain billabong.

3.3.1 Hidden Billabong (HD)

Hidden Billabong is in the immediate vicinity of Island Billabong (Fig. 5) and yet the two billabongs contain quite different sediments. Sediment from Hidden Billabong was grey in colour and very fine textured. The less than 63 μm particle size fraction, which makes up almost 50% of the total, is similar in size distribution to that from Leichhardt Billabong, almost 80% was Fine Silt+Clay. The greater than 63 μm fraction was predominantly organic detritus with a small amount of sand. The organic content of the less than 63 μm fraction was 14%, again similar to that in Leichhardt Billabong sediments but significantly higher than that in the sediments from Jabiluka and Nankeen billabongs.

The concentrations of iron and manganese in sediments from Hidden Billabong were the highest of any billabong sediments sampled; these metals were more concentrated in the silt size particles. The manganese concentration was similar to that found in Leichhardt Billabong which has a similar sediment type. Concentrations of other metals were close to the mean values for all sediments from the Magela system (Tables 8 and 9).

A core sample taken from Hidden Billabong showed a slight decrease with depth in the iron and manganese concentrations but little change in organic content, or copper, lead and zinc concentrations. The core and grab samples were taken from slightly different sites in the billabong and this may account for the difference in the concentration of copper which was significantly higher in the grab sample (Table 8).

3.3.2. Leichhardt Billabong (LC)

Three sediment samples were taken from Leichhardt Billabong (Fig. 6). At site LC1, a black, unconsolidated sediment approximately 10 cm deep and smelling strongly of hydrogen sulphide overlay an extremely compacted fine grey sediment. This top layer had a very high organic content (51%) in the greater than 63 μm fraction. The sample taken at LC2 had the appearance of sediments from Jabiluka and Nankeen and consisted predominantly of Fine Silt+Clay.

The distribution of the fine, grey sediment found in Leichhardt Billabong is interesting. Similar material has now been found in a number of locations including Hidden Billabong, at a depth greater than 1.5 m in a bore hole drilled in the flood plain next to Island Billabong (opposite GS 821023) (Fig. 5), in the banks and sediments underlying the sandy bottom of Island Billabong and other areas of the Magela flood plain.

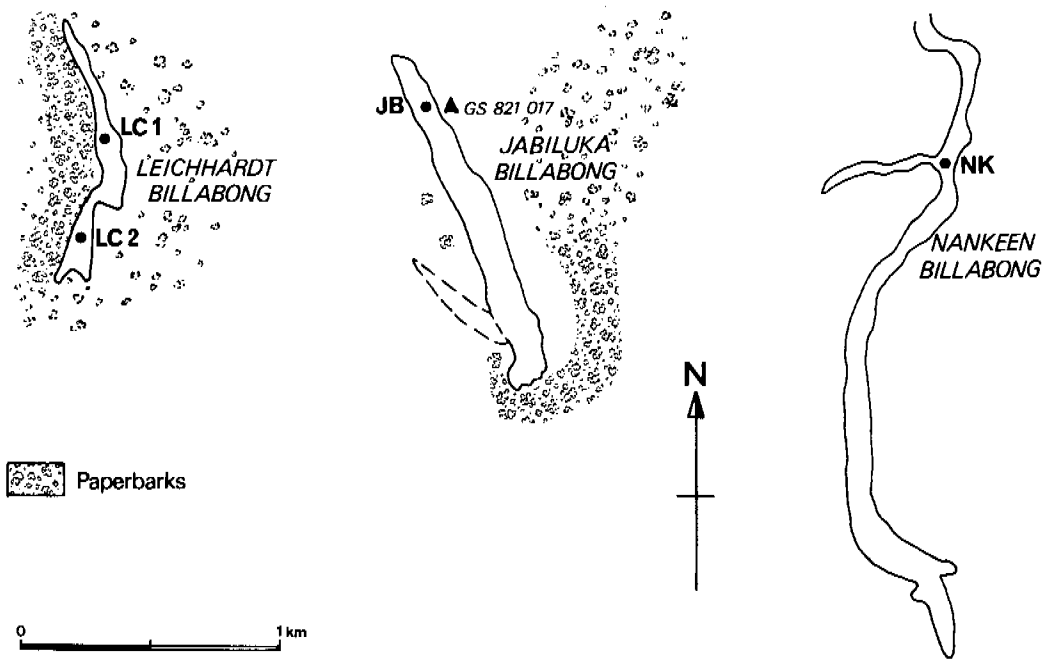

FIGURE 6 LEICHHARDT, JABILUKA AND NANKEEN BILLABONGS SHOWING THE SAMPLING LOCATIONS.

Major differences were noted in the concentrations of manganese and copper in the two sediment layers sampled at LC1. Manganese was higher in the bottom layer (246 µg/g vs 139 µg/g in Silt+Clay fraction) while the copper concentration was highest in the top layer (14 µg/g vs 9 µg/g in Silt+Clay fraction). The copper trend is explainable by the higher organic content in the top layer. The lower manganese concentration in the top sediment layer may result from this layer being periodically anaerobic (when sampled this layer smelt of H_2S) which would enable manganese oxides, MnO_x, to dissolve as Mn^{2+} and diffuse to the water column. Once in the water column the Mn^{2+} may be taken up by algae, adsorbed onto particulate matter or reoxidised to colloidal manganese oxides (MnO_x).

The concentrations of heavy metals in the Silt+Clay fraction of the top layer at LC1 and in the sediment at LC2 were very similar (Table 8).

The bottom sediment layer at LC1 had a similar appearance to the sediments in Hidden Billabong. This similarity was also observed in the concentrations of manganese, lead and zinc found in each sediment fraction. The manganese levels were higher than in any other sediment from the Magela system (246-294 µg/g in the Silt+Clay fraction) and appear to be characteristic of this sediment type. Iron and copper levels were lower in the Leichhardt sediment; copper probably because the Leichhardt sediment has a lower organic content. The lower copper concentrations in the floodplain billabong sediments may reflect the lack of particulate organic matter entering these billabongs. Macrophyte growth in these billabongs is restricted by depth.

3.3.3 Jabiluka (JA) and Nankeen (NK) Billabongs

Jabiluka and Nankeen billabongs are both situated on the Magela flood plain (Fig. 6). Their sediments are very similar to each other but quite different from those in other Magela billabongs. The Silt+Clay fraction contained approximately 60% Fine Silt+Clay whereas other sediments contained in excess of 80% (Table 1). Approximately one third of the less than 63 µm fraction of these sediments was Clay. The clay minerals consisted of chlorite, kaolinite and illite with possibly a small amount of expandable clays and clay sized quartz particles (Table 7). The Jabiluka and Nankeen sediments were also low in organic content (6%). These sediments are best described as coarse silt and clayey sediments low in organic matter.

The concentrations of heavy metals (Tables 8-10) in the less than 63 µm fraction reflect these characteristics. The copper levels were the lowest of any sediment analysed (7 µg/g). The concentrations of iron and manganese were also somewhat less than in the other floodplain sediments.

3.4 Mercury Analysis

Unfractionated wet sediments were digested using an HCl/HNO_3 mixture and the resultant digest analysed for mercury. This work was done by Mr B. Bycroft, Chemistry Department, Monash University.

Triplicate portions of the wet sediment, each equivalent to 0.2 g dry weight were individually analysed. Each wet sediment had sufficient distilled water added to it to make the total volume of water up to 5 mL. Aristar HCl (3.8 mL) and HNO_3 (1.2 mL) were added and the sample heated on a boiling water bath for 5 minutes. Following this 50 mL of distilled water and 15 mL of 5% $KMnO_4$ were added and similarly heated for a further 30 minutes. The resulting solution was then stoppered and allowed to stand overnight at room temperature. Hydroxylamine hydrochloride was added to dissolve MnO_2 and the solution made up to volume and analysed by flameless atomic absorption spectroscopy. The method of standard additions was used to quantify results.

The results are given in Table 11 and indicate that all sediment samples from the Magela Creek system contain very low concentrations of mercury.

4 CONCLUSIONS

As a result of work carried out over the past eighteen months and reported both here and in Thomas et al. (1981), a number of conclusions can now be drawn regarding the textural characteristics and concentrations of heavy metals in billabong sediments from the Magela Creek system.

There are major differences in the physical characteristics of sediments between billabongs and, in some cases, within the same billabong. Factors influencing the sediment characteristics include waterflow pattern, limnological characteristics of the billabong, relative position of the billabong in the Magela Creek system (i.e. channel, backflow or floodplain), and sedimentological and geomorphological history of the area.

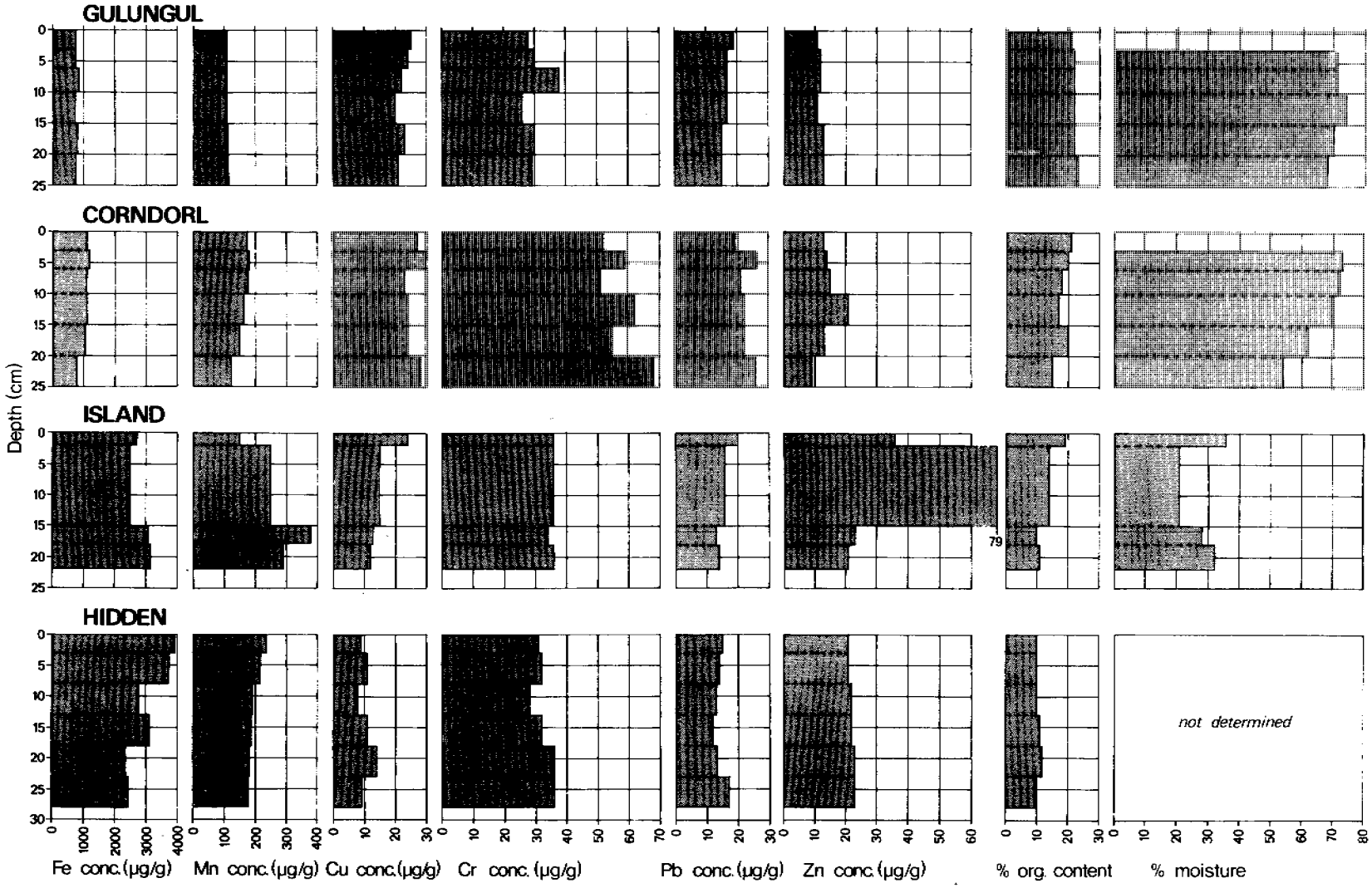

FIGURE 7 CONCENTRATIONS OF HEAVY METALS, ORGANIC CONTENT AND PER CENT MOISTURE IN THE SILT+CLAY FRACTION OF CORE SAMPLES.

TABLE 11 CONCENTRATIONS OF MERCURY IN UNFRACTIONATED SEDIMENT SAMPLES[a].

Billabong	Sample Code	Mercury Concentration[b] (µg/g dry wt)
Georgetown	GT 1	0.08
Gulungul	GL 2	0.06
Y-Shape	YS 1	0.03
Island	IS 2	0.07
Hidden	HD	0.08
Leichhardt	LC 2	0.06
Jabiluka	JB	0.03

[a]Analytical results supplied by Mr B. Bycroft, Monash University.
[b]Standard deviation ± 0.03 µg/g.

The sediments in the backflow billabongs were generally fine-grained and rich in organic matter. The Silt+Clay fraction (i.e. less than 63 µm in size) was generally in excess of 70% of the sediment with most of it less than 20 µm in size. The organic content of the Silt+Clay fraction was high (approximately 20%) except for Georgetown Billabong (10%). The Sand+Organic fraction consisted of varying amounts of sand and detrital organic matter. The backflow billabongs are typically shallow at the end of the Dry Season (less than 1 m deep) and as a result the sediments are well mixed to depths of around 25 cm as for example in Gulungul Billabong.

These results generally accord with these billabongs being:

(i) poorly flushed because of their position relative to Magela Creek,

(ii) able to support considerable macrophyte growth over the Wet Season,

(iii) shallow and well mixed.

As a general rule sediments from the channel billabongs were sandy. However, depending on the position within the billabong some large variations in sediment texture were noted. This was particularly so for the Mayamarleprard Waterhole system where the sand fraction ranged from 4%-98% in Island and 38%-98% in Y-shape Billabong. These billabongs are generally well flushed during most Wet seasons and this probably accounts for the small accumulations of silt and clay. This is also consistent with the observation that accumulation of silt and clay mostly occurs in the deeper regions of this billabong type.

During 1979 a layer of fine sediment floc 10 to 20 cm deep was found to overlay the more consolidated, very sandy sediment. This fine sediment floc occurred principally in Island and Y-shape billabongs and appeared to be flushed out during the 1979-80 Wet Season leaving a sandy surface layer. The origin of this sediment floc is unknown. It could possibly arise from the settling out of dead phytoplankton, the washing of

macrophyte matter into the billabong in the latter stages of the Wet Season, scouring of the billabong banks or transport and sedimentation of suspended matter by Magela Creek. Suspended matter transported through Boomerang Billabong could contribute to this floc in Island Billabong. In fact, in March 1981 during a very high flow a slug of reddish coloured water (perhaps reflecting a higher clay content) was observed to pass through Boomerang Billabong and enter Island Billabong. This slug was not observed in Magela Creek.

A core taken in Island Billabong (at IS2) provided some insight into the sediments underlying the sand. Down to 18 cm the sediment material was predominantly sand. However, between 18 and 22 cm the sand content dropped to less than 60% and the physical appearance resembled the sticky, grey, clayey sediment observed in Hidden and Leichhardt billabongs. A bore hole put down in the flood plain adjacent to Island Billabong and opposite the gauging station also yielded a similar material at around 1.5 m depth.

Thus the sediments from Mayamarleprard Waterhole consist of a thin layer of sand (up to 20 cm thick) overlying a largely impermeable, sticky clay material. It is of interest to speculate about the origin of the sand layer. There is a very large store of sand in the main channel of Magela Creek and this could be transported down and deposited in the Mudginberri Corridor billabongs. However if this were so it is difficult to explain why more sand is not deposited in the floodplain regions immediately to the north of the Mudginberri crossing, that is, between the Magela channel and Y-shape and Island billabongs. It may be that the sand is only transported under flow conditions that are so great that deposition does not occur until the open waters of the billabongs are reached. Alternatively the sand may be from a relic channel of Magela Creek.

The sediments in the floodplain billabongs were characteristically silt/clay in nature; greater than 80% of the particles were less than 63 µm in size. The organic content in the Silt+Clay fraction was low (~14%) possibly as a result of the small autochthonous input from phytoplankton (Hart and McGregor 1980). This is not the case for Leichhardt Billabong which sustains a high level of phytoplankton and had a very high organic content (51%) in the greater than 63 µm fraction of the top layer of sediment at site LC1. There would be limited organic matter contributed by macrophytes since these floodplain billabongs are quite deep.

Sediment samples were taken from twelve billabongs in the Magela Creek system and fractionated into Silt+Clay (less than 63 µm), Fine Silt+Clay (less than 20 µm) and Clay (less than 2 µm) size fractions. These fractions were analysed for iron, manganese, cadmium, copper, chromium, lead and zinc after H_2O_2/HNO_3 digestion. The unfractionated sediment was also separately analysed for mercury.

The concentrations of metals, except iron, are lower in Magela Creek billabongs than in other unpolluted sediments (Table 12). They are also very much lower than the levels reported for standard shale.

Previous work on these sediments has shown major differences in the concentrations of heavy metals associated with different particle size fractions (Thomas et al. 1981). These earlier results were obtained using a complete extraction method involving $H_2O_2/HNO_3/HF$. In this current work, using a H_2O_2/HNO_3 mixture to extract only the most 'environmentally

significant' metal fraction, it was found that the heavy metals were almost equally distributed over the finer sediment fractions less than 63 µm in size (Tables 8-10). This is very different to the situation existing in most polluted systems where it is generally found that the metals are more concentrated in the very small clay-sized particles (Forstner & Wittmann 1981).

This finding is of significance since future sediment monitoring work can now proceed on the basis of the analysis of the less than 63 µm fraction (Silt+Clay) without the need to separate samples into finer fractions. This has important implications regarding the time required to prepare and analyse each sample.

Recently Forstner and Salomons (1980), after a review of the world literature, suggested that standardisation was needed with regard to the sediment fraction analysed and considered that there was an advantage in using the sieve fraction less than 63 µm in size. They recommended the less than 63 µm fraction because:

(i) heavy metals have been found to be present mainly in silt/clay particles.

(ii) this fraction is most nearly equivalent to the material carried in suspension (by far the most important transport mode of sediments).

(iii) sieving does not alter metal concentrations by remobilisation (particularly when water of the same system is used).

(iv) numerous metal studies have already been performed on the suggested less than 63 µm fraction.

Any heavy metal contaminants added to the Magela system will most likely associate with the finer sediment fractions. Because of this it is recommended that the clay size fraction be analysed once per year to determine the magnitude of any build-up.

Some comments can also be made about the differences in concentrations of the individual heavy metals in sediments from the Magela Creek system. The following discussion will refer only to the concentrations in the Silt+Clay fraction (i.e. the less than 63 µm fraction, Table 8).

Iron. Concentrations were highest in Hidden, Mudginberri, Island, Leichhardt and Y-shape billabong sediments. It is not yet possible to be definitive about the factors influencing the concentrations of iron in the sediments. However two factors that appear to be important are:

(i) the organic content - there may be an inverse correlation between iron and organic content since low iron concentrations were found in Gulungul, Corndorl and Anseranas Billabong sediments and these had high organic content,

(ii) the redox potential - low iron levels may occur in billabong sediments which become anaerobic at times, resulting in the release of ferrous iron (Fe^{2+}) to the water column (e.g. Jabiluka and Nankeen).

Manganese. The highest manganese levels were found in the grey, clayey sediments from Hidden and Leichhardt billabongs. The other high value was in Mudginberri Billabong sediments and this is probably due to the continuous aerobic state of this billabong. The manganese levels in

TABLE 12 CONCENTRATIONS[a] OF HEAVY METALS IN THE PELITIC FRACTION OF SEDIMENTS FROM THE MAGELA CREEK SYSTEM AND IN FOSSIL AND RECENT AQUATIC SEDIMENTS.

Metal	Fossil Lake Sediment (Ries-Lake)[b,c]	Recent Lake Sediment (mostly from remote areas (n = 87))[b]		Fossil River Sediment (Rhine)[b,d]	Shale Standard[e]	This Study[f]
Iron	18 200	43 400	(11 500-67 300)	32 350	46 700	20 600
Manganese	406	760	(100-1800)	960	850	141
Copper	25	45	(20-90)	51	45	19
Lead	16	34	(10-100)	30	20	13
Zinc	105	118	(50-250)	115	95	21
Chromium	59	62	(20-190)	47	90	45
Cadmium	0.2	0.4	(0.10-1.50)	0.3	0.3	-
Mercury	0.5	0.35	(0.15-1.50)	0.2	0.4	0.06[g]

[a] Concentration in µg/g.
[b] Forstner and Wittmann, 1981.
[c] Mean 25 values.
[d] Mean 4 values.
[e] Turekin and Wedepohl, 1961.
[f] Mean 13 billabong samples, see Table 8 for actual results.
[g] Mean 7 total sediment samples, not fractionated.

TABLE 13 RECOMMENDED SEDIMENT MONITORING SITES.

Billabong	Site	Reason for Selection
Georgetown	GT1	Receives little runoff from the Ranger site
Gulungul	GL	First billabong downstream of both Ranger and Jabiru township
Boomerang	BM	Control billabong in a catchment adjacent to Magela Creek
Island	IS1	Likely depositional area in Mudginberri corridor
	IS2	" " " " "
Y-shape	YS1	" " " " "
Hidden	HD	Different sediment type[a]
Leichhardt	LC1	Considerable flow through this billabong in the Wet, may be a depositional area
Jabiluka	JA	Opposite side of corridor to Leichhardt, downstream of the proposed Jabiluka operation.

[a]Recommend that this site be included for a period of three years after which time the results should be reviewed.

Jabiluka Billabong sediments were low, possibly because the redox conditions at times allowed the manganese to dissolve as Mn^{2+}.

Copper. Concentrations in sediments appeared to be positively correlated with the organic content. A simple linear regression produced the following relationship for predicting the concentration of copper in the sediment on the basis of the organic content:

$$Cu\ (\mu g/g) = 1.26 \times Org.\ Cont\ (\%) + 1.14 \qquad (r = 0.87,\ n = 18).$$

Thus the backflow billabong sediments (excluding Georgetown) which were high in organic matter had high concentrations of copper and the floodplain sediments which were low in organic content had low concentrations of copper. Copper is obviously bound differently in the sediments from Georgetown Billabong as levels were high in spite of the low organic contents.

Zinc. Concentrations were generally lowest in the backflow billabongs and increased in the Mudginberri Corridor billabongs. The very low concentration found in Boomerang Billabong may reflect a low zinc input from the catchment of this billabong.

Lead. Concentrations were generally low and showed little change through the system (range 9-19 µg/g). There was some evidence that the lead levels may be positively correlated with the organic content.

The results of this present study indicate that sediments can be very effectively used to monitor the potential buildup in heavy metals in the Magela Creek system.

It is recommended that sediment analyses for monitoring purposes be conducted on the less than 63 μm fraction using a H_2O_2/HNO_3 digestion procedure. Samples should be collected twice yearly, at the end of the Wet (May-June) and again at the end of the Dry (November), from the nine sites listed in Table 13. Some analyses of the clay fraction (<2 μm) should also be carried out at less frequent intervals.

This study has made no attempt to determine the relationship between the metal extracted with H_2O_2/HNO_3 and the biological availability. In view of the very low metal concentrations present naturally in these sediments, the investigation of such a relationship hardly seems worth pursuing at this stage. It will however be more relevant if metal concentrations in the billabong sediments are shown to increase over the next few years.

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APPENDIX A

SETTLING TIME FOR PARTICLE SIZE SEPARATION[a].

Sample	Time[b]	Volume[c] (mL)	Depth (cm)
Fine Silt+Clay (< 20 μm)	7 m 20 s	500	17
Clay (< 2 μm)	7 h 36 m	300	10

[a]Guy 1969. [b]Temperature 23° C.
[c]Sample volume removed from 1 L measuring cylinder.

APPENDIX B

PARTICLE SIZE DISTRIBUTION AND CONCENTRATIONS OF HEAVY METALS IN THE SILT+CLAY (< 63 μm) FRACTION FROM CORE SAMPLES.

Billabong	Depth (cm)	Concentration (μg/g dry wt)						Particle Size (μm) Distrib.			
		Fe	Mn	Cu	Cr	Pb	Zn	>63	<63	2-20[a]	<2[a]
Gulungul	0-3	7 700	109	25	28	19	11				
	3-6	7 700	110	24	30	17	12				
	6-10	8 300	111	22	38	17	12	4	96	42	50
	10-15	7 600	108	20	26	17	11	9	91	43	46
	15-20	8 000	110	23	30	15	13	11	89	44	43
	20-25	7 600	118	21	29	15	13	14	86	41	44
Corndorl	0-3	11 400	172	27	52	19	13				
	3-6	12 200	181	30	59	26	14				
	6-10	11 200	179	23	51	21	15				
	10-15	11 300	166	24	62	22	21	32	68	31	34
	15-20	10 500	152	24	55	22	13	28	72	29	40
	20-24	8 000	123	28	68	26	9	20	80	23	54
Island	0-2	21 700	150	24	36	20	36	99			
	2-15	25 400	250	14	36	16	79	99			
	15-18	30 500	380	13	34	13	23	87			
	18-22	31 900	290	12	36	14	21	58			
Hidden	0-3	39 200	234	9	31	14	21				
	3-8	37 400	213	11	32	14	21				
	8-13	27 700	190	8	28	13	22				
	13-18	31 200	188	11	32	12	22				
	18-23	23 700	184	14	36	13	23				
	23-28	24 400	175	9	36	17	23				

[a]Determined using conventional pipette technique.

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