Technical Memorandum 2

Transport of Trace Metals in the Magela Creek System, Northern Territory

II. Trace metal concentrations in
the Magela Creek billabongs
at the end of the 1978 dry season

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**TRANSPORT OF TRACE METALS IN THE MAGELA CREEK SYSTEM,
NORTHERN TERRITORY**

II. **Trace metal concentrations in Magela Creek billabongs
at the end of the 1978 dry season**

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DECEMBER 1981

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C O N T E N T S

SUMMARY

The concentrations of the trace metals Fe, Mn, Zn, Cd, Cu and Pb were determined in six Magela Creek billabongs near the end of the 1978 dry season (November, 1978). The billabongs selected for study represented backflow, channel and flood plain environments. There were significant limnological differences between, in particular, the backflow and flood plain billabongs, and the channel billabongs.

Compared with the total trace metal concentrations recorded during the wet season of 1978-79 (42 samples), there was an increase in the concentrations of total Fe, Zn, Cd and Cu in the backflow and flood plain billabongs. The increase was most noticeable for Fe, where the change was generally in excess of one order of magnitude; for Zn there was a two- to threefold increase, for Cd a four- to sevenfold increase and for Cu a three- to fivefold increase. An appreciable increase in the total Mn levels was only noted in Georgetown Billabong. There was no significant increase in the trace metal levels in the two channel billabongs.

The increase in total metal levels appears to be largely due to increases in suspended material. An additional increase in filterable metal levels possibly results from evaporative concentration occurring over the dry season. A model incorporating both these contributions was used with limited success to calculate the expected trace metal levels for Fe, Mn and Zn.

Variable amounts of the total trace metal concentrations were found to be in the filterable fraction. This ranged from <10% in the case of Fe, to over 90% of the Zn in some billabong waters. The proportion of this filterable fraction that is biologically available is not known.

1 INTRODUCTION

Billabongs downstream of the Ranger Uranium Mining operation at Jabiru have been identified (Fox et al. 1977) as potential deposition areas for released trace metals. Such trace metals may stay in the water column or, if incorporated into the sediments, be released at particular times of the year. Previous work in the area suggests the highest levels in the waters are to be expected at the end of the dry season since, at this time, dissolved metals will have been concentrated owing to evaporation and, additionally, metals may have been released from anoxic sediments.

For these reasons it was decided to determine the trace metal levels in a range of billabongs near the end of the 1978 dry season. Samples were taken in early November and analysed for total and filterable concentrations of Fe, Mn, Cd, Cu and Zn.

2 STUDY DETAILS

2.1 Sampling

Samples were taken from six billabongs – Georgetown, Gulungul, Mudginberri, Island, Jabiluka and Nankeen. The sample sites in each billabong are shown in Figure 1. At least one vertical profile was taken in each billabong, with water samples being taken at several depths using a tube sampler arranged as shown in Figure 2. Polyethylene or polypropylene was used for all parts of the device in contact with the sample.

Bottles for trace metal samples were cleaned by soaking in 2M nitric acid for three days, and those for alkalinity, turbidity and suspended solids determinations were washed in a strong detergent solution. After cleaning, the bottles were rinsed three times in high purity de-ionized water from a Milli-Q system and were subsequently rinsed three times with the billabong water before the sample was taken.

The samples for total trace metal analysis were preserved using 5 mL concentrated nitric acid per litre solution. Those for filterable metal analysis were filtered through a Sartorious 0.45 μm membrane filter and then acidified. The filters and polycarbonate filter units were soaked in 1M nitric acid. Immediately before use, the filter units were rinsed with 0.5M nitric acid and about 50 mL of this acid was drawn through the filter. This procedure was repeated twice with approximately 50 mL de-ionized water. The first 30-50 mL of the filtered sample was discarded.

2.2 Analytical Methods

Conductivity, temperature, dissolved oxygen, pH and Eh were determined in the field. Conductivity was determined using a YSI meter (Yellow Springs Instrument). Dissolved oxygen and temperature were determined using a YSI meter equipped with a stirrer (Yellow Springs Instruments). A Townson pH/mV meter was used for pH and Eh measurements. A combined glass electrode was used for pH determinations; a platinum (vs. Ag/AgCl) electrode was used for Eh determinations.

Turbidity and alkalinity were determined in the Jabiru field laboratory. A Hach model turbidimeter was used for turbidity measurements. The instrument was calibrated using the standards provided by the manufacturer. Alkalinity was

determined by potentiometric titration using the methods described in 'Standard Methods for the Examination of Water and Wastewater', Section 403 (APHA 1975).

Suspended solids concentrations were determined by filtration of a measured aliquot (100-500 mL) through a 0.45 μm filter.

Iron was determined by flame atomic absorption spectrophotometry (AAS). Cadmium, Cu, Pb, Mn and Zn were determined using a Varian Techtron CRA90 atomiser. The technique of standard additions was used for calibration.

3 RESULTS AND DISCUSSION

Results of the general water quality analyses for each billabong are given in Table 1 and those for the trace metal analyses in Table 2. The billabongs are discussed separately, since previous studies have shown that there are marked limnological differences between billabongs (Hart and McGregor 1980, 1981; Walker and Tyler 1979). In a later report, the billabongs will be compared with one another with respect to their trace metal chemistry.

3.1 Backflow Billabongs

3.1.1 Georgetown Billabong

The data in Table 1 show the water in Georgetown Billabong to be acidic (pH 4.9-5.4) with quite high levels of turbidity (145 NTU) and suspended solids (421-449 mg/L). The dissolved oxygen, pH and temperature data showed evidence of slight stratification between the surface layer and the rest of the billabong. The billabong waters were depleted in oxygen; at the surface, oxygen levels were around 60% saturation and decreased to 40% saturation at the bottom (site 2). Although the conductivities were relatively low (85-125 μS/cm), they were still considerably higher than those measured in Magela Creek during the wet season (10-20 μS/cm – Hart et al. 1981). There was a noticeable difference in conductivity values recorded at sites 2 and 4, which may have arisen because waters at the north and south ends of this billabong are restricted in their mixing due to a sill near the middle; at the time of sampling there was only 10 to 20 cm of water over the sill.

Trace metal concentrations are given in Table 2. Iron was found to exist almost entirely in particulate forms, the total Fe levels (13-16 mg/L in surface waters) being higher than in the other billabongs studied.

Iron concentrations in the particulate matter were around 32 000-43 000 μg/g. These values are similar to the Fe levels found in the sediments from this billabong (29 400-33 600 μg/g in <20 μm fraction). At sites 2 and 4, the total Fe levels were higher at depth, but this may simply represent the stirring up of sediments during sampling. This is supported by the fact that suspended solids levels were also found to be higher at depth at these sampling sites (Table 1).

Manganese, in contrast to the Fe, was present almost entirely in filterable forms. There was considerably more particulate Mn in the bottom waters, but again this may be due to the higher levels of suspended solids in these bottom waters. The Mn concentrations in the particulate matter varied between <2 and 30 μg/g and were somewhat lower than found in the sediments (latter values approx. 100 μg/g, but using $HNO_3/H_2O_2/HF$ digestion).

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The total Zn concentrations were found to be less than 10 µg/L (6.5-9.7 µg/L) with between 30 and 60% in filterable forms. The higher filterable Zn concentrations in the bottom waters suggest that Zn may be released from bottom sediments.

The levels of total Cd, Cu and Pb were all found to be very low.

3.1.2 Gulungul Billabong

Table 1 shows that, at the time of sampling, Gulungul Billabong waters were acidic (pH 5.2-5.5) and quite turbid (SS 148-172 mg/L, turbidity 220-240 NTU). The high conductivity (approx. 170 µS/cm) indicated that some concentration due to evaporation had probably taken place; this increase in conductivity could also be partly due to inflow of high salinity groundwaters. There was little evidence of stratification in this billabong at the time of sampling, 0930 hours, but it should be noted that the DO levels were low (36-60% saturation) over the whole billabong.

It is interesting to compare the turbidity and suspended solids levels recorded in this billabong with those in Georgetown Billabong (Table 1). While the suspended solids levels in Georgetown were around three times higher than those in Gulungul, the turbidity levels in Georgetown were only one half those in Gulungul. This suggests that the suspended matter in these two billabongs is very different. The composition of the sediments and suspended solids in both these billabongs is contained in another report (Thomas et al. 1981).

The total Fe concentrations in Gulungul Billabong (Table 2) were found to be quite high (approx. 4-5 mg/L), with most (95%) associated with the particulate matter. The Fe concentrations in the particulate matter were in the range 24 000-28 000 µg/g.

The total Mn concentrations were fairly uniform over the billabong and were around one-third those in Georgetown. Only 30-50% of the total Mn was filterable. Manganese concentrations in the particulate matter were 25-35 µg/g.

Total Zn concentrations were found to be fairly uniform (7.2-8.8 µg/L) with 30-50% present in filterable form. Evidence for Zn release from the sediments would be difficult to obtain in this well mixed billabong. Zinc concentrations in the particulate matter were 18-23 µg/g.

The concentrations of Cd, Cu and Pb were all found to be very low and close to the analytical detection limit.

3.2 Channel Billabongs

3.2.1 Mudginberri Billabong

Mudginberri Billabong waters (Table 1) were near neutral, very clear, with low suspended solids and low turbidity. They had low conductivity. There was little evidence of temperature stratification, even though the sampling was conducted at 1400 hours. Dissolved oxygen concentrations were considerably lower in the bottom waters (approx. 50% saturation) than in the top waters; this was confirmed by the Eh values which indicated that slightly reducing conditions existed near the bottom.

Total Fe concentrations (Table 2) were comparatively low (0.13-0.23 mg/L) and most (>90%) was in particulate forms. There was some evidence that the concentration increased slightly with depth.

The total Mn concentrations were quite low (2.3-3.8 μg/L) and relatively uniform over the billabong. Between 60 and 100% was in filterable forms.

Total Zn levels were also very low (0.6-1.0 μg/L) with 63 to 86% in filterable forms. There was no evidence of a significant increase in Zn concentrations with depth. However, in view of the very sandy nature of the sediments in this billabong, the release of sediment-bound trace metals would not be expected to be very important, even under anoxic conditions.

The concentrations of total Cd, Cu and Pb were all below the analytical detection limit.

3.2.2   Island Billabong

The waters of Island Billabong were low in conductivity and suspended solids. This billabong is known to sustain a high primary productivity (Walker and Tyler 1979). The data in Table 1 bear this out. Even at 1000 hours on the day of sampling there was obvious intense algal activity, resulting in high surface pH (7.5) and DO (110% saturation). Below 1.0 m depth, however, the DO and pH both diminished rapidly, so that the bottom waters were reducing (DO approx. 23% saturation, Eh 30 mV) and slightly acidic (pH 5.9).

The total Fe concentrations in this billabong were quite low (Table 2), although a little higher than the levels found in Mudginberri Billabong. There was some evidence of higher total Fe levels in the bottom waters, but this was not reflected in correspondingly higher levels of filterable Fe. In common with other billabongs, most of the total Fe in Island Billabong was in particulate forms. The particulate matter in this billabong appeared to be somewhat different from that in the other billabongs sampled, in that it contained particularly high concentrations of Fe (69 000-98 000 μg/g), Mn (500-1200 μg/g) and Zn (200 μg/g). It seems likely that this particulate material consisted predominantly of algal matter, which is known to be able to concentrate trace metals. The Fe concentration in the particulate matter from Mudginberri Billabong was similar to that in Island Billabong particulate matter (50 000-82 000 μg/g), but somewhat lower for Mn (150-343 μg/g) and Zn (26-91 μg/g). This aspect warrants further study, but probably reflects the different composition of the particulate matter from these two billabongs.

The total Mn concentrations were low (2.0-5.3 μg/L). The proportion in filterable form was quite variable, ranging from less than 3% to 53%. The highest concentrations of filterable Mn were found in waters at 1 m depth.

Total Zn concentrations were low, with around 50-60% in particulate forms.

In the one sample tested, the levels of Cd, Cu and Pb were below the analytical detection limits.

3.3 Flood Plain Billabongs

3.3.1   Jabiluka Billabong

Jabiluka Billabong waters were turbid, slightly acidic (pH 5.7-6.3) and contained moderate levels of dissolved salts (conductivity 230-260 μS/cm). Although dissolved oxygen was depleted in the bottom waters (approx. 30% saturation), Eh measurements indicated that oxic conditions existed.

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Total Fe concentrations were high, with almost all in particulate forms; the Fe concentration in the particulate matter was 20 000-22 000 μg/g. The Fe concentration varied little throughout the billabong, although there was some evidence of an increase in the filterable Fe concentration in the very bottom waters. Manganese showed a similar increase in filterable form in bottom waters. Filterable Mn made up 50-77% of the total Mn, with the higher proportions found to occur in bottom waters. The Mn content of the particulate matter was quite low at around 9 μg/g.

Between 60 and 90% of the total Zn was in filterable forms. Concentrations of filterable Zn were comparable to those in the two backflow billabongs tested. It appears that some Zn may be released by the sediments or the suspended solids, since there was a slight increase in the level in the bottom waters.

The total Cd concentrations were higher than in the channel or backflow billabongs, but this may simply reflect the higher suspended solids levels in Jabiluka.

3.3.2 Nankeen Billabong

Nankeen Billabong was similar to Jabiluka; the waters were turbid, contained high levels of suspended solids and were slightly acidic. There was a very obvious stratification in this billabong, with significant oxygen depletion in all but the very surface layer. Eh measurements indicated that the very bottom waters were reducing. This did not appear to affect the trace metal levels significantly, since there was little evidence of increasing levels of Fe, Mn or Zn with depth.

In general, the trends in both the concentrations and forms of the trace metals noted for Jabiluka Billabong were also found in Nankeen Billabong.

3.4 Comparison of Trace Metal Concentrations

The previous discussion has shown that there are significant limnological differences between the three classes of billabongs studied. More detailed discussions on the differences are contained in the reports by Hart and McGregor (1981) and Walker and Tyler (1979). These limnological differences would be expected to significantly influence the behaviour of the trace metals, and any worthwhile attempt to discuss trace metal chemistry in billabongs will need to consider each billabong separately. The limited data obtained for each billabong during this study preclude a detailed discussion. However, it is possible to make some general observations relating to the trace metal levels found in the billabongs at the end of the 1978 dry season. For convenience, the data have been collected together in Table 3. To assist in making comparisons between the wet and dry season data, Table 3 also contains the total trace metal levels found during the 1978-79 wet season (Hart et al. 1981) and the levels reported for Jabiluka Billabong by Morley (1979).

Perhaps the most noticeable trend was the high levels of all trace metals in the backflow (Georgetown, Gulungul) and flood plain (Jabiluka, Nankeen) billabongs compared with the levels in the two channel billabongs (Mudginberri, Island). In fact, the last two billabongs showed no significant increase in trace metal levels over those recorded in Magela Creek during the wet season. The greatest increases in metal levels in the backflow and flood plain billabongs were for total Fe, where changes in excess of one order of magnitude were recorded. For total Mn there was a one- to fivefold increase, for total Zn a two- to threefold increase, for total Cd a

four- to sevenfold increase and for total Cu a three- to fivefold increase. Morley's (1979) data suggest similar increases in Jabiluka Billabong between wet and dry seasons.

A simple model may be postulated to account for these observed increases in total trace metal levels.

(i) Over the dry season, evaporation would result in concentration of the 'dissolved' components present in the billabong waters. An example of this effect is the increase in conductivity found to occur in each billabong. Such evaporative concentration would also result in an increase in the filterable metal concentrations, provided the trace metals behave in a conservative manner.

(ii) The very marked increases in the suspended solids concentrations through the dry season, particularly in the backflow and flood plain billabongs, should produce an increase in particulate (and hence total) trace metal levels.

These two effects may be expressed mathematically as :

$$M^d = M_f^w \times CF + SS^d \times M_s \times 10^{-3} \qquad (\mu g/L)$$

where M^d = total metal concentration at end of dry season ($\mu g/L$)

M_f^w = filterable metal concentration during wet season ($\mu g/L$)

M_s = metal concentration in sediments ($\mu g/g$)

CF = concentration factor due to evaporation

SS^d = suspended solids concentration at end of dry season (mg/L).

This model has been used to calculate end-of-dry-season concentrations for Fe, Mn, Cu and Zn, based on the data recorded in Table 4. The CF values used were estimated on the basis of the ratio of total dissolved solids (TDS) recorded in October 1978 to those recorded in April 1978 (Walker and Tyler 1979), and will be subject to the uncertainties noted below. The filterable metal concentrations for the wet season (M_f^w) are the mean values found by Hart et al. (1981) during the 1978-79 wet season. The metal concentrations assumed for the particulate matter (M_s) were based on sediment values reported by Thomas et al. (1981). As noted in Table 4 (footnote d), the particulate metal levels found experimentally and those assumed on the basis of work by Thomas et al. (1981) are not directly comparable, since slightly different extraction procedures were used; however, it is unlikely that the values will differ by more than a factor of two.

The calculated and actual total trace metal levels for four of the billabongs tested are given in Table 5. The model appears to work reasonably well for Fe, which possibly reflects the fact that essentially all the Fe is present in particulate forms. The agreement between calculated and actual values is less satisfactory for the other three metals. In all cases, the model predicts higher values than were actually found experimentally.

Some possible reasons may be advanced to account for the lack of compatability between the calculated and actual trace metal concentrations.

(i) Part of the discrepancy can be explained by the fact that the calculated particulate metal levels are too high, because the sediment metal levels used in the calculations were obtained using a slightly different analytical method. If it is assumed that this could result in a maximum difference of two between calculated and actual concentrations, the data recorded in Table 5 show that still other factors must be responsible for the majority of results, which vary by more than this amount.

(ii) It is possible that only part of the assumed increase in conductivity is due to evaporation. Comparison of the relative increases in the conservative elements Na and Cl over the dry season lends support to this explanation. Thus a number of billabongs show increases in the concentrations of these elements in excess of that expected as due to evaporation (Walker and Tyler 1979). The additional increase could well be due to ingress of groundwater. The increases appear to be most noticeable in the flood plain billabongs. The possible ingress of groundwater into flood plain billabongs is also suggested by the rather marked increases in sulphate concentrations found to occur near the end of the dry season (Morley, personal communication; Walker, personal communication).

The effect upon the model calculations of an inflated concentration factor (CF) would be to increase the concentration of the calculated filterable metal fraction.

(iii) In the simple model used, it was assumed that the filterable trace metal fractions acted in a conservative manner. However, if some fractions were lost from the water column by coagulation, precipitation, adsorption or biological uptake, the actual concentration would be less than predicted.

The relatively close correspondence between calculated and experimentally observed trace metal levels in the billabongs at the end of the 1978 dry season suggests that large scale remobilisation of trace metals from the sediments into the water column did not occur at this time. This does not mean that there could not be other conditions under which trace metals could be remobilised from billabong sediments.

While discussing possible evaporative concentration, sorption and other losses from solution and remobilisation from sediments, it is interesting to compare the ratios of filterable Mn and Zn found in each billabong at the end of the dry season, with the corresponding values found during the wet season. These ratios are recorded in Table 6. Sufficient data were available only in the case of these two metals.

It is clear that both metals behave differently in Mudginberri and Island Billabongs compared with the other billabongs. The filterable Mn and Zn concentrations actually decreased over the dry season in these two billabongs, while they either remained essentially the same or increased slightly in the other four. A possible explanation for this decrease in the two channel billabongs is that these metals may be taken up by algae, and part subsequently lost from the water column in that fraction of the algae that sediments out.

The behaviour of filterable Zn appears superficially to be rather similar in the backflow and flood plain billabongs studied. There was a twofold increase in concentrations in each billabong over the dry season. This increase is less than that expected on the basis of the CFs derived from the TDS increases and may indicate that the derived CFs are incorrect, and/or that some removal of filterable Zn from the water column has occurred.

The model cannot yet be used for establishing the relative increases and decreases in trace metal concentrations. Before it can become a reliable indicator, more information must be available on the relative amounts of evaporation and groundwater input taking place for each billabong.

The rather large (sevenfold) increase in filterable Mn in Georgetown Billabong over the dry season suggests that some release under anoxic conditions may occur.

4 CONCLUSIONS

1. There were marked limnological differences between the billabongs studied. Waters in both the backflow billabongs (Georgetown, Gulungul) and the flood plain billabongs (Jabiluka, Nankeen) were turbid, with levels of suspended solids in excess of 150 mg/L. They were acidic (pH <6.0), and had elevated conductivity suggesting that evaporative concentration and possibly groundwater ingress had occurred. Definite dissolved oxygen stratification occurred in Jabiluka and Nankeen, with reduced dissolved oxygen levels also found in the backflow billabongs.

    The channel billabongs (Mudginberri and Island) contained very much clearer waters, that were somewhat lower in dissolved salts (conductivity approximately 65 and 44 μS/cm respectively) than the other billabong waters. Dissolved oxygen stratification occurred in both billabongs, but was more noticeable in Island Billabong. Algal productivity in the top 0.5 to 1.0 m of these two billabongs caused oxygen to be supersaturated and pH to be increased; again the changes were greater in Island Billabong.

2. Total Fe concentrations varied from as low as 0.13 mg/L in Mudginberri to as high as 47.2 mg/L in Georgetown. The total Fe levels appeared to reflect the amount of suspended matter in the water column, since very little Fe (<10%) was in filterable forms. There was some evidence that Fe had been released from sediments in the bottom waters of Jabiluka and Nankeen Billabongs. The total Fe levels in the backflow and flood plain billabongs were more than one order of magnitude higher than the levels recorded in Magela Creek during the 1978-79 wet season.

3. Total Mn concentrations were variable, but were highest in the four turbid billabongs. Concentrations were highest in Georgetown, with most contributed by the filterable fraction. It is possible that some release of Mn by anaerobic sediments occurred in this billabong over the dry season. The levels in Gulungul, Jabiluka and Nankeen were comparable with the mean found in Magela Creek during the 1978-79 wet season (approx. 9 μg/L). With the exception of Island Billabong, between 50% and 100% of the total Mn was filterable. In Island the percentage was lower (3-5.3%).

4. The mean total Zn concentrations were again highest in the four turbid billabongs, varying between approximately 5 μg/L in Jabiluka to 8 μg/L in Georgetown. Levels in Mudginberri and Island were considerably lower (0.9 μg/L, 1.8 μg/L respectively) and, in fact, were lower than the total Zn concentrations found in Magela Creek during the wet season. Between 30% and 90% of the total Zn was filterable. The filterable Zn concentrations in the four turbid billabongs increased by a surprisingly constant amount over the dry season, to around twice the concentration recorded in the wet season.

5. Total Cd concentrations were low, with highest values recorded in Jabiluka (0.24 μg/L) and Nankeen (0.30 μg/L); the other billabongs had concentrations generally less than 0.1 μg/L.

6. Total Cu concentrations were also quite low, varying between less than 1 µg/L in Mudginberri and Island to 2.1 µg/L in Gulungul.

7. Total Pb concentrations were less than 2 µg/L in all billabong waters.

8. Compared with the total trace metal levels recorded in Magela Creek during the 1978-79 wet season (Hart et al. 1981), increases in all metals were noted in the backflow and flood plain billabongs. There were no significant increases in the two channel billabongs. The raised total metal levels appear to be due mainly to increases in suspended material. An additional increase in filterable metal levels possibly results from evaporative concentration occurring in each billabong. The relative contribution of each of these sources is difficult to assess. Remobilisation of large quantities of trace metals from the billabong sediments did not appear to have occurred.

9. A simple model was used to calculate the trace metal concentrations in the four turbid billabongs at the end of the dry season. The model assumed each trace metal concentration to consist of two contributions: one from the filterable metal fraction which behaves in a conservative manner and is increased over wet season levels by an amount corresponding to an evaporative concentration factor; and the other from the particulate fraction which is related to the amount of suspended material in the water column and to the trace metal levels in this material. The calculated total metal concentrations were in reasonable agreement with the experimentally determined results.

   This model will be considerably more useful for predicting the relative increases (via remobilisation from sediments, algae, etc.) and decreases (via coagulation, precipitation, sorption or biological uptake) in trace metal concentrations, when there exist more precise methods for determining the amount of evaporative concentration and groundwater inflow occurring in each billabong over the dry season.

10. The greater proportion of the discussion in this report has been directed towards developing an understanding of the factors controlling the temporal variability in trace metal concentrations in the Magela Creek billabongs. However, if effective monitoring programs are to be developed, it will also be necessary to know the possible spatial variability in trace metal concentrations within each billabong. In well mixed systems, such as the billabongs studied, one would not expect to find significant spatial variability.

   For the two backflow billabongs and the two flood plain billabongs, this was generally found to be the case, with the relative standard error (RSE = (Standard error/Mean) x 100) averaging around 8% for Fe, 10% for Mn and 14% for Zn. Higher RSE values were found for Mudginberri and Island Billabongs, and this is possibly attributable to the higher productivity in these billabongs, leading to less homogeneous systems and to the generally lower trace metal levels in the billabongs.

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TABLE 1   GENERAL WATER QUALITY IN THE SIX BILLABONGS SAMPLED

Billabong	Date 1978	Site No[a]	Time (h)	Depth (m)	pH	Conduct-ivity (μS/cm)	Temp. (°C)	DO (mg/L)	DO (% sat.)	Eh (mV)	Susp. Solids (mg/L)	Turb-idity (NTU)	Alka-linity (meq/L)
Georgetown	5 Nov	2	1000	S	5.2	125	32.6	4.2	57	130	421	145	nd
				0.5	5.1	105	29.5	3.8	49	135	nd	nd	nd
				1.0	4.9	105	29.2	3.2	41	110	482	145	nd
				1.3	5.0	105	28.6	3.0	38	90	nd	nd	nd
		4	1115	S	5.4	86	33.0	4.2	58	115	449	140	nd
				0.5	5.0	85	29.8	3.7	48	100	nd	nd	nd
				0.8	5.0	85	29.5	3.6	47	100	1480	180	nd
Gulungul	8 Nov	1	0930	S	5.4	172	30.6	3.5	46	110	nd	240	nd
		2	0930	S	5.2	168	29.8	3.1	41	125	148	230	nd
				0.4	5.4	168	29.4	2.8	36	110	172	220	nd
		3		S	5.5	168	31.8	4.2	57	115	nd	230	nd
		4		S	5.5	167	31.0	4.5	60	115	nd	240	nd
Mudginberri	13 Nov	1	1400	S	7.3	64	32.8	7.2	98	220	3.3	3.3	0.08
				0.5	7.3	64	32.8	6.9	94	130	nd	nd	nd
				1.0	7.0	64	32.8	6.4	88	90	4.2	3.6	nd
				1.5	7.1	65	32.4	5.6	76	90	nd	nd	nd
				2.0	6.8	64	32.0	5.1	69	80	3.8	3.4	nd
				2.5	6.7	64	32.0	5.0	68	60	nd	nd	nd
				3.0	6.5	63	32.0	4.8	65	40	3.5	3.2	nd
				3.5	6.4	67	32.0	4.2	57	10	3.3	3.0	0.09
				3.75	nd	67	32.2	3.7	50	20	nd	nd	nd
				4.0	6.3	67	32.2	3.6	49	25	nd	nd	nd

[a] See Figure 1 for site locations;   S = surface;   nd = not determined.

TABLE 1   GENERAL WATER QUALITY IN THE SIX BILLABONGS SAMPLED (ctd)

Billabong	Date 1978	Site No[a]	Time (h)	Depth (m)	pH	Conduct-ivity µS/cm	Temp. (°C)	DO (mg/L)	DO (% sat.)	Eh (mV)	Susp. Solids (mg/L)	Turb-idity (NTU)	Alka-linity (meq/L)
Island	15 Nov	4	0935	S	7.5	43	33.0	8.0	110	140	4.5	7.1	0.04
			1030	0.5	7.5	43.5	32.8	8.0	109	150	nd	nd	nd
				1.0	6.7	43.5	32.4	4.3	59	135	nd	5.0	nd
				1.5	6.1	43	32.2	2.1	28	130	nd	nd	nd
				2.0	6.0	44.5	32.0	1.9	26	120	nd	3.8	nd
				2.5	5.9	44	32.0	1.8	24	110	nd	nd	nd
				3.0	5.9	44	32.0	1.6	22	100	nd	4.4	nd
				3.5	5.9	43	32.0	1.7	23	70	nd	nd	nd
				4.0	5.9	43	32.0	1.7	23	30	6.4	4.8	0.05
Jabiluka	16 Nov	3	0915	S	6.3	245	32.0	6.0	81	180	238	92	nd
				0.5	6.0	245	31.6	5.2	70	160	nd	nd	nd
				1.0	5.7	245	30.6	4.8	64	150	nd	93	nd
				1.5	5.8	245	30.2	4.1	54	135	nd	nd	nd
				2.0	5.7	235	29.6	3.0	39	130	nd	91	nd
				2.5	5.8	230	29.4	2.8	36	130	nd	nd	nd
				3.0	5.8	235	29.4	2.6	34	125	nd	96	nd
				3.5	5.8	260	29.4	2.5	32	120	276	96	nd
				4.0	5.8	260	29.4	2.1	27	90	nd	nd	nd
Nankeen	17 Nov	3	1010	S	5.5	nd	28.8	6.5	84	145	220	340	nd
				0.5	5.4	nd	28.6	2.2	28	130	nd	nd	nd
			1050	1.0	5.4	nd	27.8	1.3	16	115	nd	350	nd
				1.5	5.3	nd	27.4	1.2	15	110	nd	nd	nd
				2.0	5.6	nd	26.8	1.2	15	110	nd	360	nd
				2.5	5.6	nd	26.6	1.3	16	120	nd	nd	nd
				3.0	5.5	nd	26.4	1.3	16	20	262	370	nd

[a] See Figure 1 for site locations;   S = surface;   nd - not determined.

TABLE 2   TRACE METAL CONCENTRATIONS IN BILLABONG WATERS

Billabong	Date 1978	Site No[a]	Time (h)	Depth (m)	Fe (mg/L) tot.	Fe (mg/L) filt.	Mn (µg/L) tot.	Mn (µg/L) filt.	Zn (µg/L) tot.	Zn (µg/L) filt.	Cd tot.	Cu (µg/L) tot.	Pb tot.
Georgetown	5 Nov	1		S	13.1	nd	32	nd	9.3	nd	nd	nd	nd
		2	1010	S	13.8	0.03	34	37	6.5	2.4	0.17	1.3	<2
				1.0	20.7	0.02	42	27	8.9	5.1	nd	nd	nd
		3		S	15.7	nd	39	nd	9.7	nd	nd	nd	nd
		4	1115	S	16.2	0.01	35	39	6.5	1.9	nd	nd	nd
				0.8	47.2	0.01	44	36	7.8	4.5	nd	nd	nd
Gulungul	8 Nov	1		S	4.3	nd	12.5	nd	7.5	nd	nd	nd	nd
		2		S	4.2	0.19	10.7	5.1	7.8	3.9	0.05	2.1	<2
				0.4	4.1	0.15	12.5	3.8	8.8	2.9	nd	nd	nd
		3		S	4.2	nd	11.6	nd	7.5	nd	nd	nd	nd
		4		S	4.8	nd	11.7	nd	7.2	nd	nd	nd	nd
Mudginberri	13 Nov	1	1420	S	0.23	<0.005	2.4	1.9	1.0	0.7	<0.1	<1	<2
				1.0	0.21	0.015	2.3	2.4	0.9	0.6	nd	nd	nd
				2.0	0.20	<0.005	3.7	2.5	0.7	0.6	nd	nd	nd
				3.0	0.24	0.025	3.3	2.1	0.8	0.5	nd	nd	nd
				3.5	0.29	0.015	2.6	4.0	1.0	0.8	nd	nd	nd
		2		S	0.15	nd	2.8	nd	0.8	nd	nd	nd	nd
		3		S	0.13	nd	2.8	nd	0.6	nd	nd	nd	nd
		4		S	0.21	nd	3.8	nd	1.0	nd	nd	nd	nd

[a] See Figure 1 for site locations;   S = surface;   nd = not determined.

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TABLE 2   TRACE METAL CONCENTRATIONS IN BILLABONG WATERS (ctd)

Billabong	Date 1978	Site No [a]	Time (h)	Depth (m)	Fe (mg/L) tot.	Fe (mg/L) filt.	Mn (µg/L) tot.	Mn (µg/L) filt.	Zn (µg/L) tot.	Zn (µg/L) filt.	Cd tot.	Cu (µg/L) tot.	Pb tot.
Island	15 Nov	1		S	0.56	nd	3.9	1.5	2.1	nd	nd	nd	nd
		2		S	0.31	nd	3.0	0.4	1.8	nd	nd	nd	nd
		3		S	0.26	nd	4.3	0.4	1.7	nd	nd	nd	nd
		4	1030	S	0.31	<0.005	5.3	1.8	1.7	0.8	<0.1	<1	<2
				1.0	0.30	0.010	5.1	2.7	1.5	0.6	nd	nd	nd
				2.0	0.37	0.010	2.0	<0.1	2.1	0.9	nd	nd	nd
				3.0	0.71	<0.005	3.0	<0.1	1.8	0.7	nd	nd	nd
				4.0	0.63	0.005	3.1	0.6	2.0	1.0	nd	nd	nd
Jabiluka	16 Nov	1		S	5.2	nd	13	nd	5.0	nd	nd	nd	nd
		2		S	5.0	nd	12	nd	3.9	nd	nd	nd	nd
		3	1010	S	4.7	0.06	11	8.5	4.2	3.7	0.24	1.3	<2
				1.0	4.9	0.09	11	8.2	4.1	3.6	nd	nd	nd
			1055	2.0	5.2	0.15	12	8.2	4.7	3.2	nd	nd	nd
				3.0	5.1	<0.06	12	8.5	6.1	4.4	nd	nd	nd
				3.5	6.1	0.25	12	9.6	7.4	4.5	nd	nd	nd
		4		S	4.9	nd	14	nd	6.3	nd	nd	nd	nd
Nankeen	17 Nov	1		S	8.3	nd	8.4	nd	6.8	nd	nd	nd	nd
		2		S	8.0	nd	8.3	nd	6.3	nd	nd	nd	nd
		3	1050	S	7.1	<0.05	8.3	5.9	6.1	4.9	0.30	1.5	<2
				1.0	6.7	<0.05	8.0	6.4	5.9	4.0	nd	nd	nd
				2.0	6.7	<0.05	8.7	6.2	6.0	2.9	nd	nd	nd
				3.0	6.4	0.10	7.9	6.2	6.9	2.6	nd	nd	nd
		4		S	8.8	nd	10.7	nd	7.6	nd	nd	nd	nd

[a] See Figure 1 for site locations;   S = surface;   nd = not determined.

TABLE 3　　　TOTAL TRACE METAL CONCENTRATIONS IN SURFACE BILLABONG WATERS COMPARED
WITH VALUES RECORDED IN MAGELA CREEK DURING 1978-79 WET SEASON[a]

Billabongs	Fe (mg/L)	Mn	Zn (µg/L)	Cd	Cu	Pb
Georgetown	14.70 ± 1.50	35.0 ± 2.9	8.0 ± 1.7	0.17	1.3	<2.0
Gulungul	4.40 ± 0.30	11.6 ± 0.7	7.5 ± 0.2	<0.10	2.1	<2.0
Mudginberri	0.18 ± 0.05	3.1 ± 0.6	0.9 ± 0.2	<0.10	<1.0	<2.0
Island	0.36 ± 0.14	4.1 ± 1.0	1.8 ± 0.2	<0.10	<1.0	<2.0
Jabiluka	5.00 ± 0.21	13.0 ± 1.3	4.9 ± 1.1	0.24	1.3	<2.0
Nankeen	8.10 ± 0.70	8.9 ± 1.2	6.7 ± 0.7	0.30	1.5	<2.0
Magela Creek[b]　total	0.28 ± 0.12	7.8 ± 3.3	2.8 ± 0.7	0.04 ± 0.02	0.41 ± 0.16	<0.5 - 0.8
filt.	(<0.01 - 0.035)	(4.7 ± 1.6)	(1.9 ± 0.4)	(0.04 ± 0.01)	(0.30 ± 0.09)	-
Jabiluka　dry[c]	-	150	6.0	0.3	1.5	1.5
wet	-	15	1.0	0.05	0.8	0.5

[a] Fe, Mn and Zn results tabulated as mean ± S.E., n = 4.
Cd, Cu and Pb, single result only.

[b] Source : Hart et al. (1981), n = 42.

[c] Source : Morley (1979). Mean values reported (number of samples not given).

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TABLE 4   DATA USED IN CALCULATION OF TOTAL TRACE METAL LEVELS

Billabong	CF^a	SS^b (mg/L)	M_f^w [c] (μg/L)				M_s [de] (μg/g)			
			Fe	Mn	Zn	Cu	Fe	Mn	Zn	Cu
Georgetown	2	420	0	5	2	0.3	20 000	110	13	33
Gulungul	5	150	0	5	2	0.3	10 000	100	13	20
Jabiluka	6	240	0	5	2	0.3	20 000	75	20	10
Nankeen	6	220	0	5	2	0.3	23 000	130	20	8

CF = concentration factor;   SS = suspended solids; M_f^w = filterable metal concentration during wet season; M_s = metal concentration in sediments.

[a] Based on ratios (TDS Oct 1978)/(TDS April 1978) (see Walker and Tyler 1979).

[b] Based on values recorded Oct 1978 (see Table 1).

[c] Based on mean values for 1978-79 wet season (see Hart et al. 1981).

[d] Based on values for <20 μm fraction of billabong sediments reported by Thomas et al. (1981).

Note: Sediment concentrations relate to H_2O_2/HNO_3 extraction procedure. Particulate metal concentrations (see below) relate to sample brought to approx. pH 1 with HNO_3. These should approximate each other, but will not be equal. Sediment metal concentrations are expected to be higher.

[e] Mean concentrations (in μg/g) found in particulate matter transported by Magela Creek during 1978-79 wet season, using HNO_3 extraction (Hart and Davies 1981):
    Fe = 25 500;   Mn = 294;   Zn = 90;   Cu = 16.

TABLE 5   CALCULATED AND ACTUAL TRACE METAL LEVELS

		Georgetown	Gulungul	Jabiluka	Nankeen
Fe	calculated	8	1	5	5
(mg/L)	actual	13.8	**4.4**	5.0	8.1
Mn	calculated	56	**40**	**48**	**59**
(μg/L)	actual	35	**12**	**13**	**9**
Zn	calculated	10	11	17	16
(μg/L)	actual	8.0	7.6	**4.9**	**6.7**
Cu	calculated	**15**	5	4	4
(μg/L)	actual	**1.3**	**2.1**	**1.3**	**1.5**

Bold type indicates a greater than twofold difference between calculated and actual values.

TABLE 6   RATIO OF MEAN TOTAL METAL CONCENTRATION AT END OF 1978 DRY SEASON TO MEAN TOTAL METAL CONCENTRATION IN WET SEASON

Metal	Billabong					
	Georgetown	Gulungul	Mudginberri	Island	Jabiluka	Nankeen
Mn [a]	7	1	0.5	0.3	2	1
Zn [a]	2	2	0.3	0.4	2	1

[a] Mean wet season concentration (μg/L): Mn = 4.7; Zn = 1.9 (Hart and Davies 1981).

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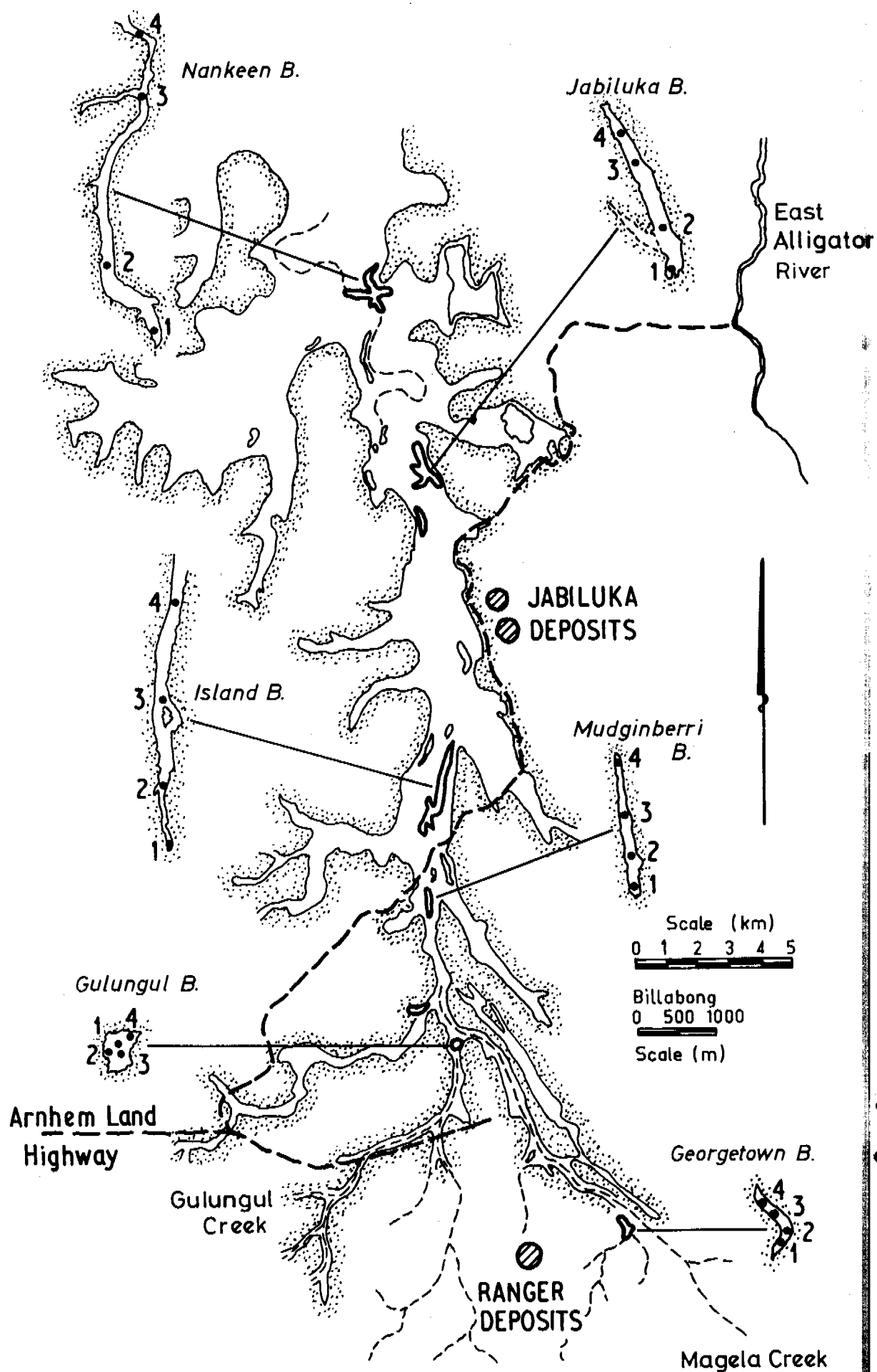
FIG. 1   MAP SHOWING LOCATIONS OF BILLABONGS SAMPLED AND SAMPLING SITES
         WITHIN EACH BILLABONG

To hand vacuum pump

Sample line

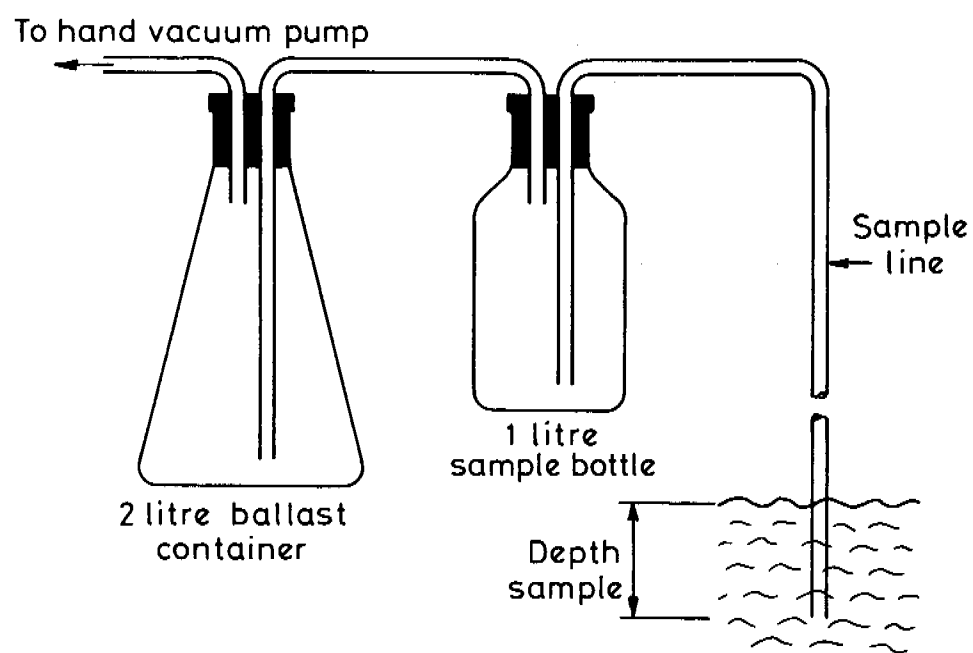1 litre sample bottle

2 litre ballast container

Depth sample

FIG. 2   SCHEMATIC DIAGRAM OF WATER SAMPLING DEVICE

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