Research Report 11

Bioaccumulation of radionuclides in traditional Aboriginal foods from the Magela and Cooper Creek systems

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Abstract

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Activity concentrations of the radionuclides ^{210}Pb, ^{210}Po, ^{226}Ra, ^{238}U, ^{234}U, ^{232}Th and ^{230}Th were measured in edible flesh of a number of traditional Aboriginal food items from the Magela and Cooper Creek systems in the tropical Northern Territory of Australia. Some results for ^{227}Ac were also obtained. Food items studied were fish, buffalo, pig, magpie goose, filesnake, goanna, turtle, freshwater shrimp, freshwater crocodile and two types of plant roots. Water and soil activity concentrations were also measured to enable the calculation of concentration factors.

For most edible flesh samples, activity concentrations followed the approximate order: ^{210}Po >> [^{226}Ra~^{210}Pb] > [^{234}U~^{238}U] > [^{230}Th~^{232}Th]. The ^{210}Po/^{210}Pb activity ratio was particularly high (greater than 100) for pig flesh. The highest soft tissue activity concentration recorded was 45000 ± 2000 mBq/kg wet weight for ^{210}Po in one sample of turtle liver.

Concentration factors for fish species fall into three groups. Group 1 (bony bream and sleepy cod) had factors about five times higher than for Group 2 (eight other species including barramundi). Some smaller fish species (Group 3) are eaten whole and hence have relatively high concentration factors. Variability with location and season was small in comparison with inter-group variability. Measured factors for fish in groups 1 and 3 were generally significantly higher than IAEA default values.

Factors for turtle flesh were similar to those for fish in group 1, but were about a factor of 10 higher for liver. Factors for magpie goose, filesnake, freshwater shrimp, goanna and crocodile flesh were also of the same order as for fish in groups 1 or 2.

Bioaccumulation of radionuclides in traditional Aboriginal foods from the Magela and Cooper Creek systems

1 Introduction

The Alligator Rivers Region, comprising an area of approximately 28 000 km^2, is broadly defined by the catchments of the East, South and West Alligator Rivers (fig 1). The climate is tropical with distinct Wet (November–April) and Dry (May–October) seasons. The Ranger uranium mine is located adjacent to the Magela Creek, a tributary of the East Alligator River. Mining and the commercial production of uranium concentrate has been underway at Ranger since 1981. The Nabarlek uranium mine is located near Cooper Creek, also a tributary of the East Alligator River. All of the small, high-grade orebody at Nabarlek was mined during the 1979 Dry season and its processing was completed by June 1988; the site is presently undergoing rehabilitation.

In 1984 the Environmental Research Institute of the Supervising Scientist (ERISS)[1] submitted to the supervising authorities recommended standards for release of waste waters from the Ranger and Nabarlek uranium mining operations (Brown et al 1985). These recommendations used a dose assessment model which included the dispersion of radionuclides in surface waters, bioaccumulation in aquatic and terrestrial animals and plants, the diet of the critical group (taken to be a group of Aboriginal people living downstream of the minesite and eating traditional bush foods), and the conversion of the intake of radionuclides to committed effective dose. Bioaccumulation of radionuclides was initially estimated using a concentration factor approach based on data from the general literature and from previous work in the Alligator Rivers Region (ARR). Six radionuclides (^{226}Ra, ^{210}Pb, ^{210}Po, ^{238}U, ^{234}U and ^{230}Th) were included in the assessment.

Although based on the best evidence available at the time, it was recognised that the bioaccumulation estimates needed improvement for two reasons. Firstly, in a number of cases concentration factors based on ARR data were not available, and figures based on default values or on other species had to be used. In addition, those factors for which local data were available were generally based on a few data points only. These factors came primarily from three sources: Davy & Conway (1974), Koperski & Bywater (1984) and early ERISS data. Secondly, the concentration factor approach is based on a number of assumptions and hence may be over-simplistic, especially in the case of those dietary items delivering the greatest dose.

[1] Until 1994, ERISS was called the Alligator Rivers Region Research Institute (ARRRI).

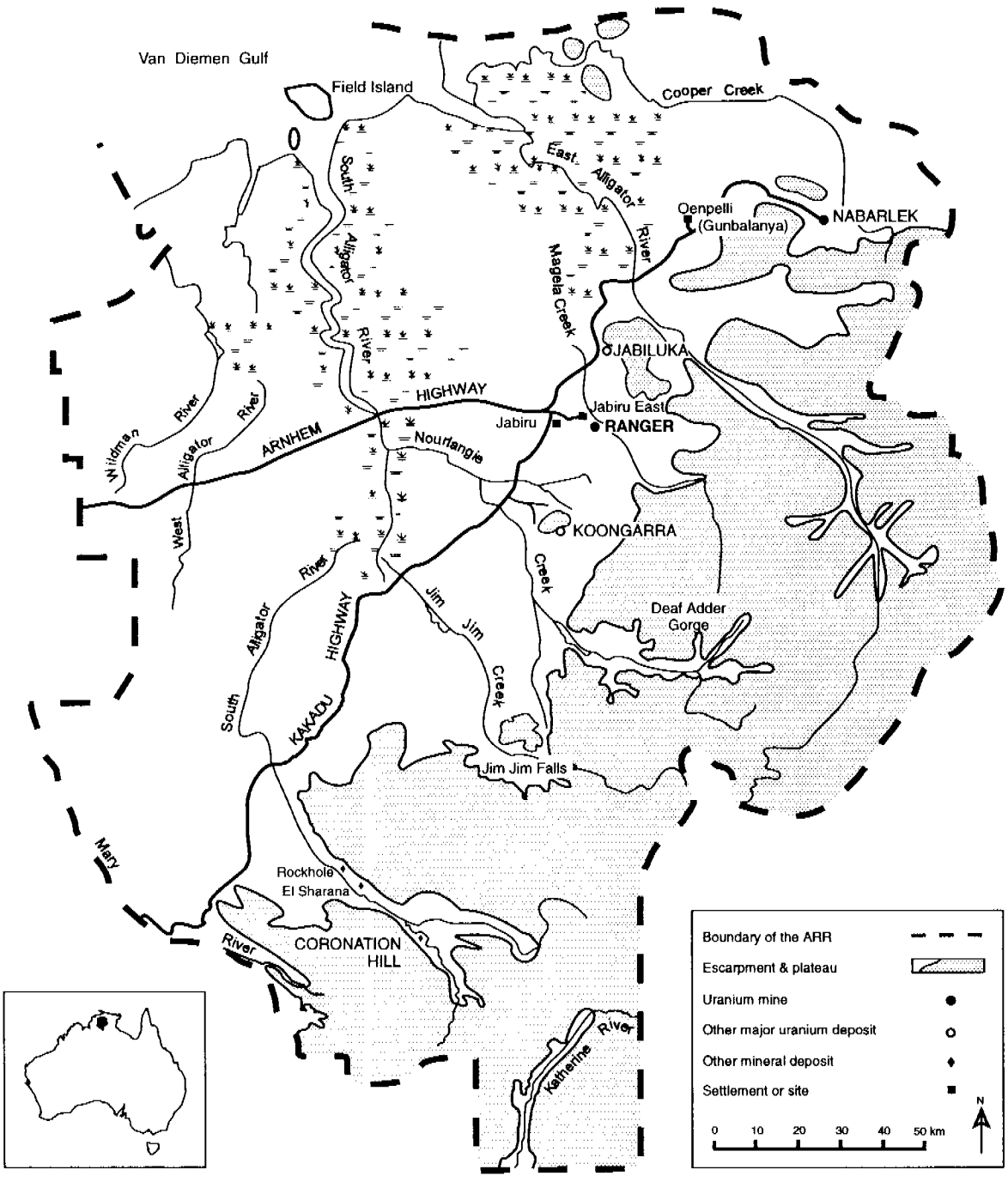

Figure 1 The Alligator Rivers Region

A sensitivity analysis was carried out for all the variables of the dose assess-ment model to determine which variables were the most significant in the estimation of radiation exposure resulting from release of Retention Pond 2 (RP2) water from Ranger. The sensitivity parameter, S_i, was defined for each variable, v_i, as:

$$S_i = (v_i/D)(dD/dv_i)$$

where D is the estimate of total dose resulting from the discharge. The results obtained for the sensitivity to the weight consumed of each of the diet components and to the concentration factors are given in table 1. Only those concentration factors for which the sensitivity parameter is greater than 0.02 are listed.

Of the dietary components, the model shows by far the greatest sensitivity to freshwater mussel consumption. Of the concentration factors, that of radium in mussels is five times more significant than any other concentration factor. For this reason, a separate study of bioaccumulation mechanisms in mussels, with special emphasis on uptake of radium, has been undertaken (Johnston et al 1984a,b, 1985, 1987a,b).

Of the remaining concentration factors, those for fish and water lily were found to be the most significant. The water lily (*Nymphaea violacea*) has been the subject of separate studies and the results reported elsewhere (Pettersson 1990; Pettersson et al 1993; Twining 1993). The work detailed here deals with concentration factors for the remaining significant dietary items. As a result of the above sensitivity analysis, fish has been the most extensively studied item. A number of other items were also studied, however, particularly where local (ARR) data were not available (eg filesnake) or where organs such as liver or kidney were known to be consumed (eg buffalo).

2 Concentration factors

The concentration factor for a nuclide in an organism is defined as the activity of the nuclide per unit fresh weight (or 'wet weight') of the organism, divided by the activity of the same nuclide per unit weight of substrate, where the substrate is the physical medium (eg water, food or soil) from which the organism obtains the nuclide. Hence the units for concentration factors are (Bq/kg) organism/(Bq/kg) substrate. The concentration factor (CF) method of dose assessment has been discussed in detail in ICRP (1978) and IAEA (1982). Application of the method is based on a number of assumptions, including:

a Nuclides are assumed to reach a steady-state concentration in the organism where rate of uptake is equal to rate of removal. In other words, the biological half-life of the nuclide is assumed to be short in comparison with the release period. In general this assumption gives rise to an over-estimate of uptake and hence conservative (high) estimates of committed dose.

b Radionuclides measured in the organism are assumed to have originated in the substrate. This assumption does not hold if there is a substantial degree of ingrowth of a nuclide from its precursor (radioactive parent) in the flesh of the organism. In the present work, the nuclide most likely to be affected in this way is ^{210}Po (daughter of ^{210}Pb; radioactive half-life of ^{210}Po is 138 days). If the biological half-life of ^{210}Po resulting from decays of ^{210}Pb in

the organism's flesh were known to be comparable with or greater than its radioactive half-life, it would be necessary to correct the measured ^{210}Po activity by subtraction of the ^{210}Pb activity. The biological half-life of ^{210}Po in the organisms studied is not known, and the conservative assumption has been made that the observed ^{210}Po concentrations arise primarily from direct uptake. If subtraction of ^{210}Pb concentrations were carried out, this would reduce the ^{210}Po concentration factors by, in most cases, 10% or less.

c The activity concentration measured in the substrate is assumed to represent that activity available for transfer to the flesh of the organism. The choice of substrate for aquatic and terrestrial organisms is discussed in the next two sections.

d Concentration factors under the conditions of a release are assumed to be identical to those during the study period. This assumption refers to the effect of the elemental composition of the substrate on uptake, and is a reason why local (ARR) data are to be preferred where available. Application of the recommended receiving water standards to the Ranger or Nabarlek mines would give rise to relatively small increases in the concentrations of most constituents in the Magela and Cooper Creeks (respectively) and hence it has been assumed that the effects of the release itself on radionuclide uptake mechanisms will be negligible. However, relatively large increases in concentrations of some constituents (eg calcium) may arise in the short term; these could have an effect on uptake of some radionuclides (eg radium).

A further consideration in dose assessment is the effect of cooking on radionuclide concentrations in food. The most common Aboriginal method of cooking involves roasting over an open fire. This method could result in the volatilisation of a portion of the ^{210}Po and possibly ^{210}Pb activities from the flesh (Martin & Blanchard 1969). In addition, some loss of radionuclides may occur in discarded fats or juices (Halford 1987). For a number of reasons, including the highly variable nature of cooking methods and temperatures and the fact that losses could only be expected to result in a decrease in the committed dose, the effect of cooking was not investigated in this study.

In summary, by making a number of simplifying assumptions, the concentration factor approach enables a dose assessment to be made where the number of food items and radionuclides involved is too large to enable detailed studies of all relevant bioaccumulation mechanisms. The approach taken by ERISS has been to use a sensitivity analysis to determine which dietary items are of most significance to the dose assessment and hence may require more detailed study. In general, a conservative approach has been taken where the validity of the underlying assumptions is in doubt.

2.1 Choice of substrate: Aquatic organisms

Organisms regarded as aquatic in the ERISS dose assessment model include fish, magpie goose, filesnake, goanna, turtle, freshwater shrimp and freshwater crocodile. The information available in this report enables the calculation of concentration factors based either on total or filtered water activity concentrations. Though it is normally assumed that the filtered water activity is the better approximation of the biologically available activity, this may not

always be the case, particularly when the particulate matter in the water sample has a large organic component. One possible method for distinguishing between the two options is to compare the relative standard deviations of concentration factors calculated using total and filtered samples respectively. The method that produces the lower relative standard deviation would be assumed to be the appropriate method.

Such a comparison was made between the two methods for fish species bony bream, fork-tailed catfish, barramundi, long tom and saratoga (these being the species for which three or more analyses are available). The results are given in table 2. Thorium isotopes were not included as the extremely low activity concentrations measured gave rise to large analytical uncertainties. Note that the unweighted mean CF values derived in table 2 are not necessarily the same as the weighted means given elsewhere in this report.

For most isotopes, there was no significant difference in the ratio of the standard deviation to the mean between factors calculated on the basis of filtered water concentrations and those relating to total water concentrations. For ^{210}Po, filtered water gave lower ratios for all species shown in table 2 suggesting that for this isotope at least, filtered water concentration is the more appropriate parameter. Concentration factors given elsewhere in this report are, therefore, calculated on the basis of filtered water concentrations. This needs to be taken into account in any application of these concentration factors.

2.2 Choice of substrate: Terrestrial organisms

Organisms regarded as terrestrial in the ERISS dose assessment model are water buffalo, pig and non-aquatic fruits and vegetables. Buffalo and pig forage predominantly on or at the margins of waterways, especially floodplain areas.

For terrestrial herbivores, the most important radionuclide transfer pathways are uptake from pasture vegetation, ingestion of soil, ingestion of water, and inhalation of airborne dust. For omnivores such as pig, uptake via flesh foods may also be important. In a traditional dose assessment, separate concentration factors would be used to predict transfer via each pathway before summing to obtain a final radionuclide concentration increase in the animal tissue (eg IAEA 1982). However, this method is likely to be unreliable when applied to wild animals because of the difficulty of obtaining the information required for each pathway (in particular information on the range and relative amounts of foodstuffs eaten, concentration factors for radionuclide uptake by those foodstuffs from soil or water, and soil ingestion rates).

An alternative approach is to take as the substrate the soil over which the animals forage (Bondietti et al 1979; Linsalata et al 1989, 1991). This method assumes that uptake from each of the pathways mentioned above is linearly related to the soil concentration. Practical application of the method also requires that the animal forage area is reasonably well defined and average soil concentrations known, and that the radionuclide activity which is present on the soil as a result of a practice (in this case as a result of release of mine waste waters into the creek system) acts in a similar manner to that activity naturally present.

This last requirement is particularly important because a non-conservative (low) estimate of uptake may be obtained where a higher proportion of the radionuclides originating from the waste water are in a biologically available

form than those measured in the derivation of concentration factors. For this reason, the term 'concentration ratio' has been used here for uptake related to total soil concentration, and application of these ratios to a dose assessment will require the question of relative availability to be addressed.

The few data which have been published on the chemical forms of radionuclides on the Magela Creek floodplain show that for ^{226}Ra and uranium between 45 and 90% of the activity is present in an 'extractable' form (Williams 1983; Willett 1992). The excess of ^{210}Pb over ^{226}Ra on Magela floodplain soils (table 4) indicates that at least 40% of ^{210}Pb and ^{210}Po originate from rainwater, and so were not originally bound in the soil mineral matrix. Hence for radium, uranium, ^{210}Pb and ^{210}Po, application of these concentration ratios would not be expected to result in an underestimate of uptake of more than a factor of two. Given that this pathway is currently predicted to result in less than 1% of the total dose resulting from discharge, further refinement of these ratios is not warranted at this stage.

3 Methods

3.1 Radionuclide analysis

Samples of edible flesh were weighed into an aluminium tray, dried for several days in an oven at 60°C, reweighed after cooling to room temperature to determine the dry:wet ratio, and the sample ground to a fine powder in a ring mill prior to analysis. Alpha-particle spectrometry was chosen as the method of analysis for the majority of samples, as the low activity concentrations present in most of the tissue and water samples demanded that a method of high sensitivity be used. The analysis techniques have been described in detail in Research Report 7 (Martin & Hancock 1992). In brief, a known activity of a tracer isotope of the element being analysed is added to the sample and the sample digested using nitric and hydrofluoric acids.

Chemical separation techniques are then used to separate the element of interest from the rest of the sample matrix and from other alpha-emitting radionuclides. The radionuclides to be measured are deposited onto a suitable metal disc, and the activity of each isotope measured using a silicon surface barrier detector. The measured activity is related to the activity of the tracer isotope, giving both the activity concentration of each isotope and the overall chemical yield. The method of background subtraction used is discussed in detail in the section on analytical uncertainties.

Lead-210 is a beta-emitting isotope and cannot be measured directly using alpha-particle spectrometry. Consequently, a method utilising two separate analyses of the sample for the daughter ^{210}Po, separated by a period for ingrowth and decay of the daughter, was used. The ^{210}Po and ^{210}Pb activity concentrations in the sample on the date of sample collection can then be calculated using the Bateman's equations for ingrowth and decay. The first ^{210}Po analysis was performed within 2–4 weeks of sample collection. For water samples, the second analysis was performed after approximately 6–12 months. For tissue samples, the ^{210}Po activity concentration was invariably found to be greater than that of ^{210}Pb, usually by at least an order of magnitude, and a longer

ingrowth period of 2–3 years was required. Ingrowth from ^{226}Ra was also allowed for, assuming a ^{222}Rn retention in the sample of 50 ± 30 %.

3.2 Analytical uncertainties

Uncertainties quoted in this report are one standard deviation due to counting statistics only. An additional uncertainty in the activity concentration is that due to errors in calibration of the tracer solution. This uncertainty is estimated to be approximately 3–4%. For the majority of samples, a corresponding water sample was collected and analysed using the same tracer solution as that used for the tissue sample, in which case the tracer calibration error cancels out in the calculation of the concentration factor.

Since many of the activity concentrations measured were extremely low, the method of background subtraction is important in a consideration of analytical uncertainties. The background count rate observed in alpha-particle spectrometry has three major components:

a Counts due to contamination on the detector, counting chamber, etc.

b Counts due to the inevitable presence of some activity of the isotope of interest in the reagents used in sample digestion and element separation.

c Counts due to accidental contamination of the sample or sample digest by, for example, dust particles present in the air, sample cross-contamination, or the use of contaminated glassware.

The first component is relatively stable and easily determined by a background count immediately before or after counting the sample source.

The second component is reasonably predictable within each batch of samples, but is likely to vary with time as new reagent solutions are prepared. For this reason, a blank source was prepared with each batch of samples analysed.

Blank sources were prepared alongside samples using the same amount of each reagent as was used for the samples. These sources were then counted immediately before or after counting the sample sources to give the total background activity. This method of background subtraction is reasonably reliable in accounting for the first two components of the background mentioned above.

Although good housekeeping in the laboratory can reduce the incidence of the third component, it can never be eliminated entirely. It is in the nature of this source of contamination that its magnitude is unpredictable, so that although gross effects are usually noticed and the result checked by a repeat analysis, occasionally affected results will be accepted. Unfortunately, the magnitude of error of this type in accepted results is difficult to estimate. The error will be of greatest importance for analyses of low activities. Over a number of sample analysis batches, the error due to the third background component should be non-systematic provided the blank source has the same probability of contamination as the sample sources, though this is not true within each batch of analyses.

For the majority of edible flesh samples, radioisotope activity concentrations were found to follow the following approximate order: $^{210}Po >> [^{226}Ra \sim ^{210}Pb] > [^{234}U \sim ^{238}U] > [^{230}Th \sim ^{232}Th]$. Consequently, the majority of results with large analytical errors were obtained for thorium and uranium isotope analyses. As the study progressed, the analysis sample size was

increased in an attempt to improve the statistical uncertainties for these isotopes, but there is a limit to the amount of sample which can be used before chemical recoveries are significantly affected.

Wherever possible the result obtained has been reported together with its estimated analytical uncertainty (± 1 standard deviation based on counting statistics only) rather than the use of a detection limit and reporting of less-than values. This has been done to enable a weighted mean to be calculated in a consistent manner. In calculation of the weighted mean, each observation was given a weight proportional to the reciprocal of the square of the estimated analytical uncertainty (Topping 1962).

3.3 Water radionuclide activity concentrations

Water sample results are summarised in the Appendix. Two water samples of 20 litres each were collected in acid-washed plastic containers from a depth of approximately 10–30 cm. One sample ('filtered') was filtered through a cartridge-type filter (nominal size 0.45 μm, Brunswick Technetics, Filterite DFNT .45–10 UN), followed by acidification to 1% by volume with concentrated HNO_3. The second sample ('total') was acidified without pre-treatment.

For water samples BD7002, GN8006, MI8001 and MI8006, only one 20 litre sample was collected. These samples were then filtered through a 0.45 μm cellulose acetate filter (Sartorius 11106–142–N) and the filter digested and analysed to give a measure of particulate (>0.45 μm) activity. The total activity concentration may be obtained by addition of the filtered and particulate results.

For some water samples, no result is available for some radioisotopes. In these cases, a figure has been used based upon results for the same sampling site from samples collected between 1984 and 1988. Since Bowerbird and Mudginberri Billabongs do not show strong seasonal variations in radionuclide activity concentrations, for these billabongs the means for all filtered samples analysed between 1984 and 1988 has been used (table 3).

No ^{226}Ra measurement is available for filtered water from Georgetown Billabong on 12.07.85 (sample GN5015). Measurements made in other years show that ^{226}Ra activity concentrations vary from year to year for July in this billabong (8 ± 2 mBq/L and 1.54 ± 0.08 mBq/L were recorded for 12.07.84 and 16.07.87 respectively). This prevents calculation of a concentration factor for ^{226}Ra for sample GN5019.

One water sample collected in February 1988 from Mudginberri Billabong (MI8001) was unusual in having high ^{210}Pb and ^{210}Po activity concentrations (460 ± 20 and 19 ± 2 mBq/L respectively for filtered water). The particulate value for ^{210}Po was also high for this sample (24.1 ± 0.9 mBq/L). It is possible that these high measurements are due to contamination from the sample container or during sample filtration. An alternative explanation is that an intense rainstorm may have occurred shortly before sampling. Rainwater is known to contain high levels of ^{210}Pb and ^{210}Po and rainwater samples collected at Jabiru and Jabiru East have shown radionuclide activity concentrations similar to those measured in this sample. Although rainstorm events are unlikely to change activity concentrations significantly in Mudginberri Billabong as a whole, they may have an influence on the surface layer of the billabong from which the sample was collected. Whether the high values

obtained are due to contamination or a transient phenomenon in the billabong, the resulting concentration factor is unlikely to be valid and hence factors for specimens collected on this date have been calculated using the means for Mudginberri given in table 3.

3.4 Soil radionuclide activity concentrations

Concentration ratios for buffalo and pig have been calculated relative to soil dry weight activity concentrations (section 2.2). Specimens of these species were collected from the Magela Creek floodplain. Since these animals are highly mobile, soil samples were not taken at the place of capture as they could not reasonably be expected to represent the animal's entire foraging area. Rather, sediment activity concentrations representative of the floodplain as a whole were used in the calculation of concentration ratios.

Activity concentrations of the uranium and thorium series radionuclides in Magela Creek floodplain sediments have been studied in detail at ERISS (Johnston et al 1987c; Wasson 1992). ^{238}U activity concentrations were found not to vary substantially with distance from the beginning of the floodplain (ie distance from the outlet of Mudginberri Billabong). ^{226}Ra and ^{210}Pb activity concentrations both decrease by a factor of approximately four between the Mudginberri outlet and the floodplain outlet. Most of this decrease, especially in the case of ^{226}Ra, occurs in the first few kilometres below Mudginberri Billabong. As this area represents only a small fraction of the area of the Magela floodplain, it is not likely to have contributed significantly to the diet of the animals sampled and has been ignored.

Table 4 shows average activity concentrations (in Bq/kg dry weight) for samples collected from four sites on the Magela floodplain (Rainer Marten, pers comm), with means derived for the radionuclides of interest. As these data were obtained via gamma-ray spectrometry, direct measures of ^{232}Th, ^{234}U, ^{230}Th and ^{210}Po are not included. ^{232}Th activity concentrations have been calculated as the mean of the daughters ^{228}Th and ^{228}Ra, based on the fact that the two daughters are in secular equilibrium in these soils. ^{210}Po has been assumed to be in equilibrium with its parent ^{210}Pb, based on the relatively short ^{210}Po half-life ($t_{1/2}$ = 138 days).

Few data are available on ^{234}U and ^{230}Th activity concentrations in Magela floodplain sediments. Results are reported by Wasson (1992, tables 3.10 and 3.15) for two sites (MX1 and MX2) in the Mudginberri corridor. $^{234}U/^{238}U$ activity ratios for these two sites were 1.30 and 1.31 respectively, while the $^{230}Th/^{238}U$ activity ratios were 0.94 and 0.82. The mean values of each of these ratios have been used to derive ^{234}U and ^{230}Th activity concentrations from the ^{238}U mean value given in table 4.

4 Results

With the exception of section 4.1.1, all edible portion activity concentrations given in the following sections are in mBq/kg of wet flesh. Dry/wet weight ratios for each sample are given in the sample summary tables to enable the calculation of activity concentrations on a dry weight basis if desired.

Water activity concentrations are in mBq/L. The results for billabong water samples are summarised in the Appendix. Where the activity concentration for a particular water sample is not available, values based on all measured samples from the same location collected between 1984 and 1988 have been used (section 2.3).

4.1 Fish

Samples of the larger fish species were collected using a gill net of 100 mm mesh. The net was set perpendicular to the bank and checked every few minutes. Checkered rainbowfish and spangled grunter were collected using a seine net.

If a concentration factor approach is to be used, it should be demonstrated that the factor is independent of variables such as location and season. Two species of fish were chosen for such a detailed study: the bony bream (a bottom detritus feeder) and the fork-tailed catfish (a carnivore feeding on smaller fish).

Variability in the concentration factor within a group of individuals exposed to the same water was estimated by analysing the flesh of three fork-tailed catfish collected from Mudginberri Billabong in December 1985 (section 4.1.2). Flesh activity concentrations for ^{210}Po in the three fish gave an unweighted mean of 200 mBq/kg with a standard deviation of 55 mBq/kg, the standard deviation being of approximately the same magnitude as the analytical uncertainties in the measurements (table 9). The situation is similar for ^{210}Pb and ^{226}Ra measurements for these fish, implying that individual variability is not large at least for fork-tailed catfish. Nevertheless, in order to minimise the influence of this variable, on most occasions the flesh of fish caught at the same location and on the same date were combined. The number of fish represented in each sample is given in the sample summary table given in each section. Variation of concentration factor with location was investigated by collecting fish from three billabongs:

Georgetown Billabong on the Magela Creek

Sample code: GN

This billabong is filled during the Wet season predominantly by back-flow from the main creek. It has a gentle contour; aquatic plants grow thick during the Wet season, producing a waterbody relatively still except during times of high flood. Evaporation over the course of the Dry season results in retreat of the billabong to a small waterhole with a high suspended solids load. Samples were collected from the area near the gauge board at the downstream end of the billabong (fig 2).

Mudginberri Billabong on the Magela Creek

Sample code: MI

This is a steep-sided, relatively deep billabong lying on the main Magela Creek channel. During the Wet season the billabong is charged predominantly from the creek inlet at the southern end. The edges of the billabong are thick with trees, particularly *Pandanus aquaticus* and paperbarks, but the waterbody itself is clear of aquatic plants. Samples were collected at a small inlet on the eastern side of Mudginberri (fig 2). The mouth of the inlet is steep-sided and relatively deep, and fish and water samples were collected at this point. Further into the inlet the water-body becomes shallower and the banks have a gentler slope; water lilies grow towards both banks of the inlet and were collected from this area.

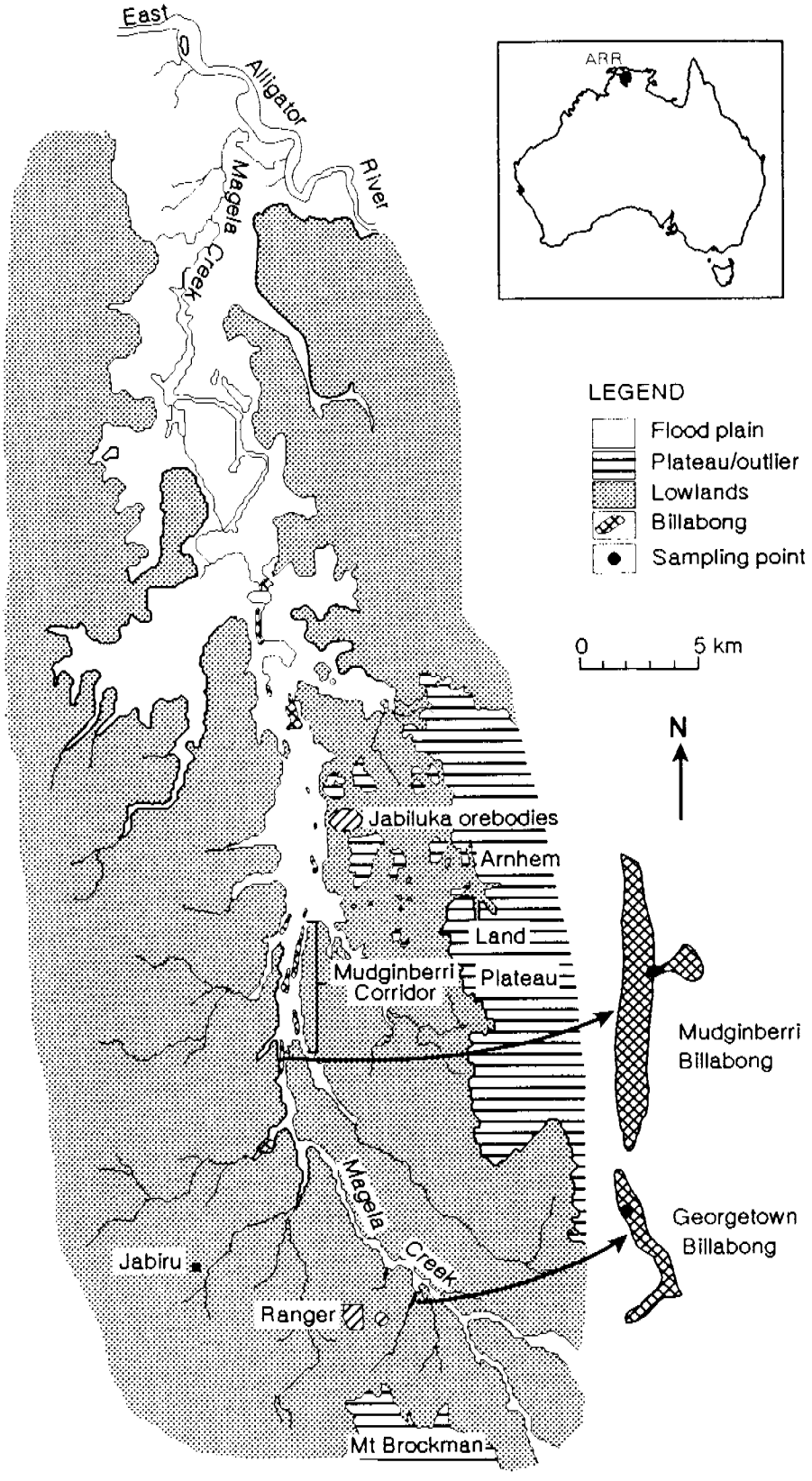

Figure 2 Location of sampling points for Mudginberri and Georgetown Billabongs on the Magela Creek

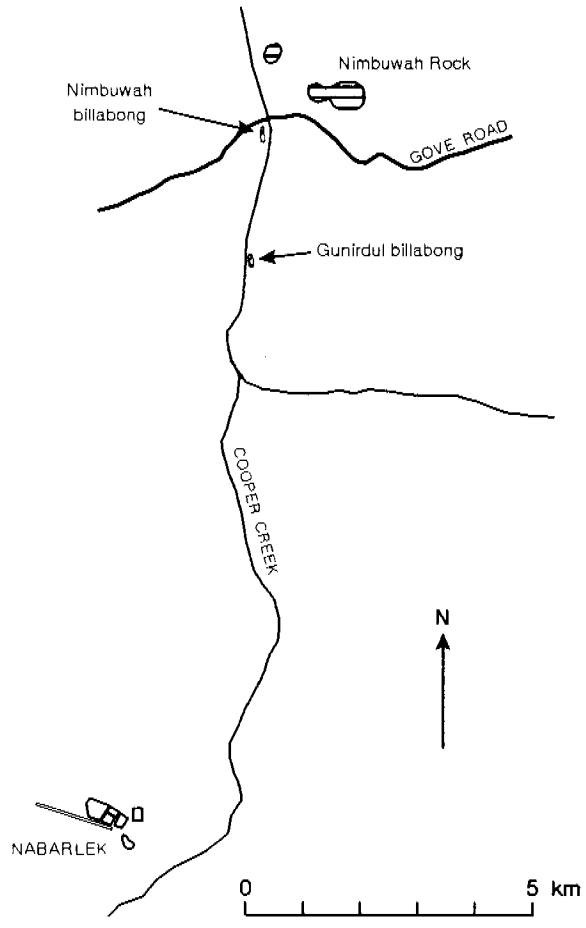

Figure 3 Location of Gunirdul Billabong on the Cooper Creek

Gunirdul Billabong on the Cooper Creek

Sample code: GU

This is a small billabong on the eastern side of the main Cooper Creek channel (fig 3). During the Wet season it is charged both from the creek and from run-off from higher ground to the eastern side. The sides are steep except for the northern end.

Fish are highly mobile during the Wet season, so that the length of time prior to sampling that fish have been in a billabong cannot be known. However, for the majority of analyses reported here the fish were collected during the Dry season, and the billabong sampled had been isolated for some months.

4.1.1 Whole fish

For the larger fish species, present Aboriginal practice is to eat flesh only, but for at least two of the smaller species (checkered rainbowfish and spangled grunter), fish are eaten whole (Beck 1986). Quantities eaten are known to be smaller than for the larger fish (Zigi Madycki & Wilfred Braubrau pers comm), but quantitative estimates of consumption are not available. Concentration factors for these species can be expected to be higher than for the other species

studied due to the inclusion of bone, skin and organs such as liver (Pentreath et al 1979; Pettersson et al 1990; Swanson 1983).

Data are available for whole fish of these species from samples collected in March 1984 from three waterbodies: two of Ranger Uranium Mines retention ponds [samples RT4003 from retention pond 2 (RP2) and R44002 from retention pond 4 (RP4)] and checkered rainbowfish collected where the Magela Creek crosses the Oenpelli road (MX4001).

The mean Magela Creek concentrations given in Murray et al (in press) were used in calculation of the concentration factors for the Magela crossing sample. Note that the activity concentration in the fish is given in Bq/kg wet weight in tables 6 and 7.

The concentration factors obtained for ^{210}Po in checkered rainbowfish from the retention pond samples were higher by an order of magnitude than that obtained for the Magela crossing sample, while for ^{226}Ra the Magela crossing sample gave a higher concentration factor. The final concentration factors listed in table 57 for ^{210}Po and ^{226}Ra are those for the Magela crossing sample, as these are more likely to represent the situation in the creeks when release occurs than are the retention pond sample results.

4.1.2 Fork-tailed catfish (*Arius leptaspis*)

Results are given in tables 8 to 11 for fork-tailed catfish flesh. Concentration factors for sample MI8003 have been calculated using mean water concentrations for Mudginberri Billabong as the water sample MI8001 had unusually high ^{210}Pb and ^{210}Po activity concentrations (see section 2.3).

4.1.3 Bony bream (*Nematalosa erebi*)

Results are given in tables 12 to 15 for bony bream flesh. Concentration factors for sample MI8005 have been calculated using mean water concentrations for Mudginberri Billabong as the water sample MI8001 had unusually high ^{210}Pb and ^{210}Po activity concentrations (section 3.3).

4.1.4 Other fish species

Results are given in tables 16 to 19 for a number of other fish species. As with fork-tailed catfish and bony bream, fish flesh only was analysed.

The ^{210}Pb activity concentration measured for sample MI5049 (freshwater mullet) was greater than that for ^{210}Po. This was the only flesh sample in this study for which this was the case, and the result for ^{210}Pb has been rejected as possibly due to contamination.

4.1.5 Fish species: Summary

Table 20 summarises concentration factors, rounded to two significant figures, for all fish species for which only flesh is eaten. The fish species studied here appear to fall into two groups, with bony bream and sleepy cod in group 1 and all other species in group 2. Concentration factors for the group 1 species are higher than those for group 2 by factors of about three to ten, while within each group there is surprisingly little variation. For ^{210}Po in group 2, for example, the (unweighted) mean of the concentration factors for the eight species studied

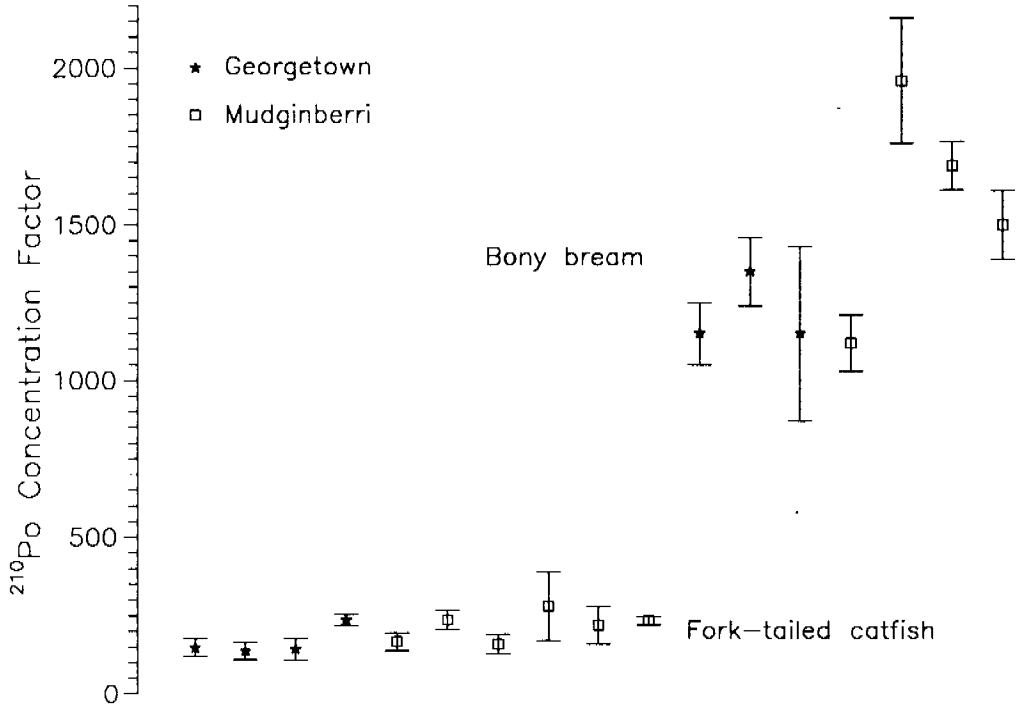

Figure 4 Individual measurements of ^{210}Po concentration factors for fork-tailed catfish and bony bream. Uncertainties are one standard deviation due to counting statistics only

was 170 with a standard deviation of 60; for bony bream and sleepy cod the factor obtained was 1300 for both species. Figure 4 shows the individual measurements for ^{210}Po concentration factors for fork-tailed catfish and bony bream, illustrating the significant difference between these two species.

In a study of ^{226}Ra, ^{210}Pb and ^{TOTAL}U in fish from the Beaverlodge Lake area, Saskatchewan, Swanson (1983) observed higher radionuclide concentrations for bottom-feeding species than for piscivorous fish. It is tempting to ascribe the high concentration factors observed for bony bream to the fact that it is a bottom detritus feeder. However, this leaves open the question of why sleepy cod, which is an opportunistic carnivore feeding mainly on crustaceans, insects and small fish (Pollard 1974) should have similar concentration factors.

Table 21 shows a comparison of concentration factors obtained for ^{226}Ra, ^{210}Pb, ^{210}Po and uranium in fork-tailed catfish and bony bream from Georgetown and Mudginberri Billabongs. Factors for Georgetown Billabong samples are lower than those for Mudginberri, although the difference for ^{210}Po is small. Since mean water concentrations for Georgetown are about a factor of ten higher in Georgetown than in Mudginberri, the differences in CFs imply that the biological half-lives for radium, lead and uranium are large, and that use of these factors will result in an overestimate of dose for short-term water releases.

Table 22 shows a comparison of IAEA default values for freshwater fish (IAEA 1982, Table XXII) with the values obtained from this study. The IAEA values are based on unfiltered water concentrations, and so for a valid comparison the ARR values must be reduced by about a factor of two. Even allowing for this, values for radium, polonium and uranium in group 1 fish are higher than the default values by up to an order of magnitude, illustrating the importance of obtaining local values whenever possible. It is interesting that the IAEA default values for lead are higher than those for polonium, as this order was reversed in the results obtained from this study. Pettersson et al (1990) obtained flesh concentration factors for fish from central and northern Sweden in the range 20–270 for uranium, 100–250 for ^{226}Ra and 200–1600 for ^{210}Pb. These results agree with those for ARR fish for uranium and ^{226}Ra, but are more in line with the IAEA default value for ^{210}Pb.

Since bony bream is a fine-boned fish, there was some concern that the high concentration factors observed here might be due to the inclusion of some bone with the flesh sample. This is considered unlikely for a number of reasons. Samples were dissected carefully to avoid inclusion of bones and skin. Sleepy cod, which is placed in group 1, is not particularly fine-boned, whereas tarpon (group 2) has extremely fine bones. In addition, concentration factors were observed to be high in group 1 fish not only for ^{226}Ra and ^{210}Pb, which are known to accumulate in bone, but also for ^{210}Po.

Finally, if inclusion of bone had occurred, it could be expected to vary considerably from sample to sample. Table 2 shows that the standard deviations divided by the means for observed concentration factors for ^{210}Pb, ^{210}Po, ^{226}Ra and ^{238}U in bony bream were of the same order as those for the other fish species studied.

Nevertheless, in order to investigate this possibility, ten samples were analysed for calcium concentration (table 23). Templeton and Brown (1964) determined calcium concentrations in freshwater brown trout and obtained values between 42 and 290 µg/g wet weight for flesh and between 48 000 and 80 000 µg/g wet weight for bone. The higher concentration of calcium in bone should enable gross contamination of flesh to be detected by this method. However, the results of Templeton and Brown (1964) show that there is considerable variation in flesh concentrations even for one species, and so comparison between species is likely to be difficult.

Calcium concentrations observed for fork-tailed catfish, long tom, barramundi and saratoga were similar to those observed by Templeton and Brown (table 23). Concentrations observed in bony bream and one sample of sleepy cod were higher, but within the range observed by Sharif et al (1993) for ten species of freshwater fish of Bangladesh (they observed variations between 5.2 and 29.5 mg/g dry weight). Although not conclusive, the low calcium concentration for sleepy cod sample GN8008 combined with its high ^{210}Po concentration factor suggests that inclusion of bone is not a significant factor.

4.2 Buffalo (*Bubalus bubalis*)

Buffalo specimens were obtained from areas on the Magela Creek floodplain. Animals were shot with a high-powered rifle, then bled by cutting of the throat. After removal of the skin, samples of flesh were cut from the hindquarter and

internal samples cut from sections of the major organs. All knives were stainless steel and the portions were placed in clean plastic bags. Immediately upon return to the laboratory all samples were thoroughly washed with tap water, then rinsed in distilled water. Contents of stomach and intestine samples were removed during the washing process.

The soil activity concentrations used in the calculation of concentration ratios are discussed in section 3.4. All concentration ratios in the tables have been multiplied by 10^3, eg the concentration ratio for ^{226}Ra in buffalo flesh is 0.22×10^{-3}.

The concentration ratio results obtained here for ^{226}Ra, uranium and thorium are in broad agreement with those reported by Linsalata et al (1989) for liver, kidney and flesh of beef cattle raised in New York and with those of Linsalata et al (1991) for muscle tissue from steer from the Pocos de Caldas plateau, Brazil. Of interest are the high kidney ^{210}Po activity concentrations (approximately ten times those in liver) and $^{210}Po/^{210}Pb$ ratios.

4.3 Pig (*Sus scrofa*)

Three pig specimens were taken at a creek on the western Magela floodplain. All three animals were adult sows. Sample collection and preparation procedures were as described for buffalo. Flesh samples, taken from the hindquarter, were analysed.

The soil activity concentrations used in the calculation of concentration ratios are discussed in section 3.4. All concentration ratios in the tables have been multiplied by 10^3, eg the concentration ratio for ^{226}Ra in pig flesh is 0.28×10^{-3}. Of interest are the high ^{210}Po activity concentrations and very high $^{210}Po/^{210}Pb$ ratios (all greater than 100) obtained for these samples.

The flesh concentrations obtained for ^{226}Ra, ^{238}U, ^{234}U and ^{230}Th were similar to those obtained by Linsalata et al (1991) for pig from the Pocos de Caldas plateau, Brazil. However, since the soil concentrations reported by Linsalata et al were higher than those for the Magela floodplain, their derived concentration ratios were lower by about a factor of five.

4.4 Magpie goose (*Anseranas semipalmata*)

Three magpie goose specimens were taken on the western Magela floodplain. Approximately equal quantities of breast and leg flesh were combined and analysed. Water concentrations used are the means of those obtained for five samples collected from Mine Valley Billabong on the Magela floodplain between November 1984 and May 1985.

4.5 Filesnake (*Acrochordus arafurae*)

Filesnakes were collected by setting unbaited fyke nets in shallow water (<1 m depth) perpendicular to the bank of the billabong (Shine 1984). Attempts to capture filesnakes from Gunirdul Billabong were unsuccessful, but specimens were obtained from Georgetown and Mudginberri Billabongs. Flesh only was analysed minus skin, bones and viscera.

Two specimens of filesnake were collected from Georgetown Billabong in November 1984 and three from Mudginberri Billabong in July 1985. Of these samples, only one (GN4013/1) was female. Since adult females are much larger

than males their diets differ both in prey species and prey size (Shine 1984), and it is possible that they have different radionuclide concentration factors. The activity concentrations recorded here for radium, uranium and thorium isotopes in the female specimen were substantially higher than for the male from the same location, suggesting that concentration factors may be higher for females.

The Georgetown Billabong water sample activity concentrations were very high, a result of the sample being collected at the end of the Dry season. As the filesnake flesh activity concentrations for the male specimen from Georgetown were not substantially different from the Mudginberri samples, the concentration factors obtained for the Georgetown sample were considerably lower. The results for the Georgetown samples are therefore rejected here on the basis that they are due to a transient phase in Georgetown water concentrations and not representative of the situation in the creeks when release is likely to occur. The final concentration factors listed in table 57 are the weighted means of the results obtained for the three Mudginberri samples only.

4.6 Goanna

Shine (1984) studied the abundances of sand goannas (*Varanus panoptes* and *Varanus gouldii*) and water goannas (*Varanus mertensi* and *Varanus mitchelli*) in the Magela Creek system, and their utilisation by Aboriginal people in the region. He found that the water goannas are of negligible importance as a food source by Aborigines, and that their habitat selection (mainly up minor creeks) makes them unlikely to be exposed to contaminants from any release of mine waters. Of the sand goannas, *V. panoptes* is the more common and consumes a higher proportion of aquatic prey than *V. gouldii*, and is therefore likely to be the most important goanna species in terms of contaminant transfer.

Calculation of concentration factors for goannas is complicated by the fact that they do not live entirely in the aquatic environment. The approach taken here is to calculate the factor based upon the proportion (by weight) of prey that is of aquatic origin. Table 40 shows data for the Magela system taken from Shine (1984).

One goanna sample only was collected for analysis. This was a fresh road kill found in the vicinity of Baralil Creek. As the creek was dry, no water sample could be taken; previous analyses show that Baralil Creek has a similar radionuclide composition to Magela Creek, and the mean Magela Creek concentrations given in Murray et al (in press) were used in calculation of the concentration factors.

4.7 Turtle (*Elseya dentata*)

Two turtle samples were collected from Bowerbird Billabong, upstream of Magela Creek. Unfortunately, sample BD4004 suffered some fluid loss before dissection due to the failure of the freezer in which it was stored; flesh and liver samples were nevertheless analysed and radionuclide results reported here based on the dry/wet weight ratios obtained for BD7003.

As was found for buffalo, radionuclide concentrations were considerably higher in liver than in flesh. In both samples, liver represented a considerable fraction of the turtle soft tissue (60 g of liver and 160 g of muscle flesh were

obtained from sample BD7003, though this underestimates the mass of muscle flesh somewhat as this was more difficult to remove quantitatively).

4.8 Freshwater shrimp (*Macrobrachium rosenbergii*)

One specimen of *M. rosenbergii* was collected from Georgetown Billabong and five were collected from Gunirdul Billabong (table 47) in November 1984. The results are given here in two tables, one for the Georgetown sample (48) and one for the Gunirdul samples (49). The Georgetown Billabong water sample activity concentrations were very high, a result of the sample being collected at the end of the Dry season. As the shrimp flesh activity concentrations were not substantially different from the Gunirdul samples, the concentration factors obtained for the Georgetown sample were considerably lower. The results for the Georgetown sample are rejected here on the basis that they are due to a transient phase in Georgetown water concentrations and not representative of the situation in the creeks when release is likely to occur.

4.9 Freshwater crocodile (*Crocodylus johnstoni*)

Crocodile forms a part of present-day Aboriginal diet, the intestines and organs being highly prized food items. As large quantities were not believed to be consumed, it was not originally intended to include crocodile in this study. However, a freshwater crocodile was accidentally drowned after becoming entangled in a fyke net at Gunirdul Billabong, and this animal was dissected and analysed. The animal was a male, weight 6 kg, length 1.425 m, head length 24.6 cm, snout-vent length 0.75 m. Portions analysed included bones and lung; although these portions are not believed to be eaten, the activity concentration results are included here (table 51).

4.10 Vegetable foods

The aquatic plant considered most important in terms of contaminant transfer was the water lily (*Nymphaea violacea*). This plant has been the subject of separate studies and the results reported elsewhere (Pettersson 1990; Pettersson et al 1993; Twining 1993).

Radionuclide uptake by terrestrial plants is a relatively unimportant pathway for water release into the creek system, but will need to be considered in assessing options for rehabilitation of the minesite. For example, current dose assessments of the Ranger Land Application area (a 35 ha plot of bushland on the Ranger site to which contaminated water has been applied) estimate ingestion of fruit and vegetables from the site to be a more important pathway than inhalation of ^{222}Rn and progeny and inhalation of dust, and only slightly less important than the dose from external irradiation (Moroney 1992; Carter et al 1994).

The large number of plant species used as Aboriginal food items made it impossible to include a comprehensive study as part of this project. Two root samples only, collected at Deaf Adder Creek as part of a study of Aboriginal diet (Beck 1986), were analysed. Soil samples collected from around the roots were also analysed. Soil activity concentrations are on a dry weight basis. All concentration ratios in the tables have been multiplied by 10^3, eg the concentration ratio obtained for ^{226}Ra in sample DR5001 was 14×10^{-3}.

The cheeky yam roots (DR5001) were peeled before analysis, but the Anbulubi roots (DR5003) were washed only. The inclusion of the skin may be the reason that the concentration factors obtained for Anbulubi were greater than those for cheeky yam.

4.11 Actinium-227

^{227}Ac is a member of the ^{235}U series, and a parent of ^{227}Th and ^{223}Ra. This series is only naturally present as 4.6% of the activity of the ^{238}U series, and so the ^{227}Ac activity in most environmental samples is extremely low. However, the radiotoxicity of ^{227}Ac is high, and the annual radioactivity limits of ingestion are a factor of 80 lower than ^{238}U, and a factor of 10 lower than ^{226}Ra (ICRP 1991).

The determination of ^{227}Ac concentration factors was not one of the original aims of this project, and hence samples were not analysed for this isotope. However, in those cases where ^{226}Ra is determined using ^{224}Ra as the tracer isotope, the sample ^{223}Ra activity is also obtained. From approximately 6 months after sample collection, ^{227}Ac and ^{223}Ra will be in secular equilibrium in the sample, and hence for samples analysed after this period the ^{223}Ra activity measured will be in fact a measure of ^{227}Ac. Table 55 summarises the information available from this project. As expected, the ^{227}Ac activity concentrations are very low for all samples analysed.

IAEA (1982) gives no default value for actinium concentration factors in aquatic foods, while factors for beef and food crops are taken to be the same as those for americium. This situation is probably due to the paucity of data on actinium concentrations in the environment. The results obtained here show that the measurement of concentration factors would require a technique capable of measuring concentrations down to at least 1 mBq/kg flesh and probably even lower.

5 Conclusions

The concentration factors obtained from this study, rounded to two significant figures, are summarised in tables 56 and 57. For the majority of food items, values decrease in the following approximate order:

^{210}Po>^{226}Ra>[^{210}Pb~uranium]>thorium.

In general, organs such as liver and kidney have higher concentration factors than muscle flesh, particularly high values being obtained for ^{210}Po in turtle liver and buffalo kidney. The ^{210}Po concentration ratio obtained for pig flesh was also very high.

Factors for fish have been given in three groups, where groups 1 and 2 relate to flesh only and group 3 (for checkered rainbowfish and spangled grunter) to whole fish. Where a concentration factor for a species in group 1 or group 2 is missing, use of the weighted mean value for the group is reasonable, as variation within each group is generally not substantially greater than the analytical uncertainties in the measurements.

There are some gaps remaining in these tables. The most significant of these are probably those relating to whole fish (fish group 3), since this group has higher concentration factors than those for fish in the two flesh-only groups.

However, since no quantitative data are known to the authors on what proportions of fish eaten come from which group, it is difficult to gauge the relative importance of these factors.

Data for filesnake in table 57 were obtained from male specimens only. There is some evidence that concentration factors may be greater for females (section 4.5). Shine (1984) reported that for two sets of filesnake captured by Aborigines as part of his study, females substantially outnumbered males (88 females to 42 males), so that the preponderance of male results here is unfortunate.

Despite the gaps, the data presented here represent the most detailed study of radionuclide concentration factors for Aboriginal dietary items currently known to the authors. Considering the large uncertainties involved in applying the concentration factor approach, it would appear most appropriate to concentrate any further effort in bioaccumulation studies on detailed studies of the most important dietary items, rather than further refinement of concentration factor values. Such studies would need to consider rates of radionuclide uptake, especially when considering short-term release conditions.

Tables

Table 1 Sensitivity parameters for variables of the dose assessment model; results for masses of diet components and concentration factors

Diet component	Sensitivity	Concentration factor *	Sensitivity
Freshwater mussel	0.60	Ra/mussel	0.48
Fish	0.23	Ra/fish	0.09
Water lily	0.10	U/water lily	0.09
Magpie goose	0.030	U/fish	0.09
Water	0.016	Pb/mussel	0.06
Goanna	0.015	Po/mussel	0.05
Filesnake	0.004	Po/fish	0.03
Turtle	0.003	Pb/fish	0.02
Buffalo	0.0006		

* Concentration factors for which the sensitivity is less than 0.02 are not listed.

Table 2 Comparison of concentration factors obtained using total and filtered water concentrations

	Species				
	Bony bream	F/T catfish	Long tom	Barramundi	Saratoga
Uranium - 238					
n	5	3			
Total					
Mean (s.d.)	200 (140)	16 (24)			
s.d./mean	0.69	1.50			
Filtered					
Mean (s.d.)	300 (220)	15 (21)			
s.d./mean	0.74	1.39			
Radium - 226					
n	5	7			
Total					
Mean (s.d.)	330 (210)	55 (30)			
s.d./mean	0.65	0.54			
Filtered					
Mean (s.d.)	1010 (570)	230 (150)			
s.d./mean	0.57	0.63			
Lead - 210					
n	5	7	3		
Total					
Mean (s.d.)	77 (53)	18 (11)	22 (19)		
s.d./mean	0.69	0.59	0.83		
Filtered					
Mean (s.d.)	156 (120)	35 (22)	29 (27)		
s.d./mean	0.77	0.64	0.96		
Polonium - 210					
n	7	10	3	3	3
Total					
Mean (s.d.)	579 (368)	82 (31)	78 (16)	80 (43)	98 (58)
s.d./mean	0.64	0.38	0.20	0.54	0.59
Filtered					
Mean (s.d.)	1410 (350)	195 (53)	110 (17)	240 (115)	237 (76)
s.d./mean	0.25	0.27	0.16	0.48	0.32

Table 3 Mean (standard deviation) and number of determinations for total and filtered water concentrations measured between 1984 and 1988

Billabong	^{238}U	^{234}U	^{232}Th	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po
Total							
Bowerbird	0.33 (0.27)	0.59 (0.29)	0.10 (0.03)	0.28 (0.17)	2.4 (1.0)	2.9 (1.4)	2.7 (0.7)
	11	11	9	9	8	8	12
Georgetown	23 (30)	24 (31)	5.9 (7.8)	16 (20)	39 (48)	52 (64)	26 (29)
	12	12	12	12	12	11	13
Gunirdul	1.8 (1.9)	2.2 (2.1)	1.8 (2.3)	1.8 (2.0)	4.2 (3.7)	5.0 (4.6)	4.1 (5.2)
	12	12	12	12	11	12	12
Mudginberri*	0.87 (0.64)	1.13 (0.65)	0.56 (0.45)	0.90 (0.56)	2.8 (1.7)	4.7 (3.5)	3.9 (1.9)
	13	13	13	13	12	11	15
Filtered							
Bowerbird	0.22 (0.06)	0.42 (0.12)	0.03 (0.02)	0.22 (0.14)	1.05 (0.79)	1.54 (0.81)	1.31 (0.64)
	10	10	8	8	4	8	11
Georgetown	6.6 (9.5)	6.8 (9.9)	1.5 (2.8)	4.1 (6.8)	7.3 (10.6)	18. (30.)	7.7 (12.3)
	14	14	14	14	13	11	14
Gunirdul	0.61 (0.47)	0.81 (0.56)	0.34 (0.61)	0.40 (0.31)	0.92 (0.69)	1.3 (1.0)	1.3 (1.5)
	12	12	11	11	10	12	12
Mudginberri*	0.43 (0.28)	0.64 (0.37)	0.14 (0.11)	0.37 (0.46)	0.71 (0.46)	1.24 (0.68)	1.40 (0.70)
	13	13	13	13	13	10	15

* Sample MI8001 has been excluded.

Table 4 Average activity concentrations (Bq/kg dry weight) for samples collected from four sites on the Magela floodplain

	JA	NN	FM	GS	Mean
^{238}U	70	60	50	65	61
^{226}Ra	80	81	54	59	68
^{210}Pb	200	85	62	59	102
^{228}Ra	62	60	69	69	65
^{228}Th	60	60	69	69	64

Site codes: JA Jabiluka; NN Nankeen (Magela Point); FM between NN and GS; GS Gauging Station Magela outlet

Table 5 Whole fish: Sample summary

Species	Sample code	Date	No. of animals	Dry/Wet ratio	Water sample	Date
Checkered rainbowfish (*Melanotaenia splendida inornata*)						
	RT4003/2	13.03.84	39	0.2809	RT4002	20.03.84
	R44002/2	12.03.84	6	0.2501	R44001	20.03.84
	MX4001	24.03.84	58	0.3045		
Spangled grunter (*Leiopotherapon unicolor*)						
	RT4003/1	13.03.84	11	0.2777	RT4002	20.03.84
	R44002/1	12.03.84	3	0.2321	R44001	20.03.84

Table 6 Whole fish: Uranium activity concentrations and concentration factors

Sample	Fish concentration		Water concentration		Concentration factor	
	^{238}U (Bq/kg)	^{234}U (Bq/kg)	^{238}U (mBq/L)	^{234}U (mBq/L)	^{238}U	^{234}U
Checkered rainbowfish						
RT4003/2	136 ± 2	137 ± 2	430 ± 10	430 ± 10	320 ± 10	320 ± 10
Spangled grunter						
RT4003/1	72 ± 6		430 ± 10		170 ± 10	

Table 7 Whole fish: ^{226}Ra, ^{210}Pb and ^{210}Po activity concentrations and concentration factors

Sample	Fish concentration		Water concentration		Concentration factor	
	^{226}Ra (Bq/kg)	^{210}Po (Bq/kg)	^{226}Ra (mBq/L)	^{210}Po (mBq/L)	^{226}Ra	^{210}Po
Checkered rainbowfish						
RT4003/2	177 ± 1	1300 ± 100	450 ± 20*	45 ± 8	400 ± 20	29000 ± 6000
R44002/2		380 ± 30		8.6 ± 0.9		44000 ± 6000
MX4001	3.1 ± 0.3	11.1 ± 0.8	1.2 ± 0.1	3.2 ± 0.3	2600 ± 300	3500 ± 400
Spangled grunter						
RT4003/1	96.6 ± 0.7	410 ± 30	113 ± 2**	45 ± 8	850 ± 20	9000 ± 2000
R44002/1		560 ± 60		8.6 ± 0.9		65000 ± 10000

* Water concentration from sample RT5007, collected 18/4/85

** Water concentration from sample R46003, collected 24/7/86

Table 8 Fork-tailed catfish: Sample summary

Sample code	Date	No. of animals	Dry/Wet ratio	Water sample
GN5012	22.05.85	5	0.1994	GN5011
GN5023	29.08.85	1	0.2035	GN5020
GN8003	10.02.88	2	0.1762	GN8001
GN8007	08.04.88	9	0.2031	GN8006
MI5037	24.05.85	3	0.2024	MI5035
MI5048	27.08.85	1	0.1997	MI5045
MI5052/1	05.12.85	1	0.2000	MI5055
MI5052/2	05.12.85	1	0.2052	MI5055
MI5052/3	05.12.85	1	0.1847	MI5055
MI8003	17.02.88	2	0.2037	MI8001

Table 9 Fork-tailed catfish: ^{226}Ra, ^{210}Pb and ^{210}Po activity concentrations and concentration factors

Sample	Flesh activity concentration			Concentration factor		
	^{226}Ra (mBq/kg)	^{210}Pb (mBq/kg)	^{210}Po (mBq/kg)	^{226}Ra	^{210}Pb	^{210}Po
GN5012	85 ± 9	19 ± 8	490 ± 90	55 ± 8	6 ± 3	150 ± 30
GN5023	410 ± 30	27 ± 9	310 ± 60	240 ± 30	10 ± 4	140 ± 30
GN8003			530 ± 30			140 ± 30
GN8007			420 ± 20			230 ± 20
MI5037	150 ± 20	30 ± 10	480 ± 80	260 ± 50	40 ± 20	170 ± 30
MI5048	95 ± 8	53 ± 8	290 ± 30	160 ± 120	70 ± 10	240 ± 30
MI5052/1	30 ± 20	50 ± 20	140 ± 30	110 ± 80	50 ± 20	160 ± 40
MI5052/2	80 ± 40	40 ± 20	250 ± 100	300 ± 200	40 ± 20	300 ± 100
MI5052/3	140 ± 20	27 ± 9	200 ± 50	500 ± 100	30 ± 10	220 ± 60
MI8003			330 ± 20			200 ± 100

Table 10 Fork-tailed catfish: Uranium activity concentrations and concentration factors

Sample	Flesh activity concentration		Concentration factor	
	^{238}U (mBq/kg)	^{234}U (mBq/kg)	^{238}U	^{234}U
GN5012	5 ± 1	8 ± 2	2.1 ± 0.4	3 ± 1
GN5023	11 ± 4	13 ± 7	4 ± 2	5 ± 3
MI5048	19 ± 3	18 ± 3	40 ± 8	35 ± 7

Table 11 Fork-tailed catfish: Thorium activity concentrations and concentration factors

Sample	Flesh activity concentration		Concentration factor	
	^{232}Th (mBq/kg)	^{230}Th (mBq/kg)	^{232}Th	^{230}Th
GN5012	0.3 ± 2.7	-0.2 ± 4	0.9 ± 7.7	-0.3 ± 5
GN8003	0.7 ± 2.0	13 ± 5	4 ± 11	18 ± 7
GN8007	2 ± 2	2 ± 2	10 ± 10	2 ± 2
MI8003	9 ± 5	-9 ± 6	60 ± 60	-20 ± 30

Table 12 Bony bream: Sample summary

Sample code	Date	No. of animals	Dry/Wet ratio	Water sample
GN5013	22.05.85	5	0.2126	GN5011
GN5022	29.08.85	4	0.2274	GN5020
GN8002	10.02.88	7	0.2033	GN8001
GU4014/1	13.11.84	4	0.1760	GU4011
MI5036	24.05.85	5	0.2352	MI5035
MI5047	27.08.85	6	0.2237	MI5045
MI8005	17.02.88	13	0.2056	MI8001
MI8007	30.03.88	11	0.2144	MI8006

Table 13 Bony bream: ^{226}Ra, ^{210}Pb and ^{210}Po activity concentrations and concentration factors

	Flesh activity concentration			Concentration factor		
Sample	^{226}Ra (mBq/kg)	^{210}Pb (mBq/kg)	^{210}Po (mBq/kg)	^{226}Ra	^{210}Pb	^{210}Po
GN5013	820 ± 60	120 ± 20	3800 ± 200	530 ± 70	38 ± 7	1100 ± 100
GN5022	1220 ± 50	190 ± 20	3100 ± 200	720 ± 90	73 ± 9	1400 ± 100
GN8002			4300 ± 200			1100 ± 300
GU4014/1	530 ± 50	160 ± 20		900 ± 1300	100 ± 20	
MI5036	520 ± 90	180 ± 30	3200 ± 200	900 ± 200	260 ± 60	1100 ± 90
MI5047	1260 ± 60	230 ± 40	2400 ± 100	2000 ± 1000	310 ± 70	2000 ± 200
MI8005			2400 ± 100			1700 ± 900
MI8007			1860 ± 60			1500 ± 100

Table 14 Bony bream: Uranium activity concentrations and concentration factors

	Flesh activity concentration		Concentration factor	
Sample	^{238}U (mBq/kg)	^{234}U (mBq/kg)	^{238}U	^{234}U
GN5013	230 ± 30	260 ± 40	100 ± 10	110 ± 20
GN5022	270 ± 20	260 ± 20	110 ± 10	93 ± 9
GU4014/1	130 ± 10	190 ± 20	650 ± 200	500 ± 90
MI5036	60 ± 20	110 ± 30	300 ± 100	400 ± 100
MI5047	170 ± 20	160 ± 20	360 ± 60	310 ± 50

Table 15 Bony bream: Thorium activity concentrations and concentration factors

	Flesh activity concentration		Concentration factor	
Sample	^{232}Th (mBq/kg)	^{230}Th (mBq/kg)	^{232}Th	^{230}Th
GN5013	20 ± 10	30 ± 30	60 ± 30	40 ± 40
GN8002	12 ± 6	20 ± 10	70 ± 40	40 ± 30
MI5036	30 ± 20	60 ± 30	200 ± 100	200 ± 100
MI8007	1 ± 2	5 ± 4	7 ± 14	30 ± 20

Table 16 Other fish species: Sample summary

Species	Sample code	Date	No. of animals	Dry/Wet ratio	Water sample
Archer fish (*Toxotes chatareus*)	GN8005	11.02.88	2	0.1963	GN8001
	GU5016	23.08.85	3	0.2614	GU5014
Barramundi (*Lates calcarifer*)	MI5053	05.12.85	1	0.2138	MI5055
	MI8002	17.02.88	3	0.2359	MI8001
	MI8009	30.03.88	2	0.2202	MI8006
Eel-tailed catfish (*Plotosidae*)	GN8004	10.02.88	3	0.1664	GN8001
Freshwater mullet (*Liza alata*)	MI5049	27.08.85	1	0.2358	MI5045
Long tom (*Strongylura kreffti*)	GN5019	13.07.85	7	0.2297	GN5015
	GN5024	29.08.85	1	0.2308	GN5020
	MI5043	16.07.85	1	0.2286	MI5040
Saratoga (*Scleropages jardini*)	MI5050	27.08.85	1	0.2373	MI5045
	MI8004	17.02.88	1	0.1870	MI8001
	MI8008	30.03.88	1	0.2199	MI8006
Sleepy cod (*Oxyeleotris lineolatus*)	GN8008	08.04.88	1	0.1827	GN8006
	GU4014/2	13.11.84	2	0.2054	GU4011
Tarpon (*Megalops cyprinoides*)	GU5015	23.08.85	1	0.2556	GU5014

Table 17 Other fish species: ^{226}Ra, ^{210}Pb and ^{210}Po activity concentrations and concentration factors

	Flesh activity concentration			Concentration factor		
Sample	^{226}Ra (mBq/kg)	^{210}Pb (mBq/kg)	^{210}Po (mBq/kg)	^{226}Ra	^{210}Pb	^{210}Po
Archer fish						
GN8005			210 ± 20			60 ± 10
GU5016	50 ± 10	40 ± 10	240 ± 50	60 ± 10	40 ± 10	190 ± 40
Barramundi						
MI5053	50 ± 7	20 ± 10	330 ± 30	180 ± 50	20 ± 10	370 ± 50
MI8002			210 ± 20			150 ± 80
MI8009			250 ± 20			200 ± 20
Eel-tailed catfish						
GN8004			670 ± 30			180 ± 40
Freshwater mullet						
MI5049	50 ± 10	(370 ± 40)*	210 ± 50	80 ± 70	(490 ± 80)*	170 ± 40
Long tom						
GN5019	240 ± 20	120 ± 10	400 ± 70		17 ± 2	90 ± 20
GN5024	140 ± 20	24 ± 8	280 ± 40	80 ± 20	9 ± 3	120 ± 20
MI5043	190 ± 20	100 ± 20	280 ± 40	600 ± 400	60 ± 10	120 ± 20
Saratoga						
MI5050	100 ± 30	60 ± 10	360 ± 50	170 ± 140	80 ± 20	290 ± 50
MI8004			210 ± 20			150 ± 80
MI8008			340 ± 20			270 ± 20
Sleepy cod						
GN8008			2260 ± 80			1260 ± 80
GU4014/2	1300 ± 100	270 ± 40	1000 ± 200	2000 ± 3000	180 ± 30	2000 ± 600
Tarpon						
GU5015	20 ± 10	20 ± 10	180 ± 40	20 ± 10	20 ± 10	140 ± 30

* Result rejected—see text.

Table 18 Other fish species: Uranium activity concentrations and concentration factors

	Flesh activity concentration		Concentration factor	
Sample	^{238}U (mBq/kg)	^{234}U (mBq/kg)	^{238}U	^{234}U
Barramundi				
MI5053	22 ± 3	26 ± 3	50 ± 30	40 ± 20
Long tom				
GN5019	9 ± 2	14 ± 3	3.0 ± 0.7	5 ± 1
GN5024	17 ± 6	10 ± 8	7 ± 2	4 ± 3
MI5043	2 ± 25	4 ± 35	5 ± 70	9 ± 70
Sleepy cod				
GU4014/2	29 ± 7	40 ± 10	140 ± 60	110 ± 30
Tarpon				
GU5015	5 ± 3	6 ± 4	20 ± 10	20 ± 10

Table 19 Other fish species: Thorium activity concentrations and concentration factors

Sample	Flesh activity concentration		Concentration factor	
	^{232}Th (mBq/kg)	^{230}Th (mBq/kg)	^{232}Th	^{230}Th
Archer Fish				
GN8005	1 ± 3	3 ± 5	6 ± 17	4 ± 7
Barramundi				
MI5053	6 ± 3	16 ± 4	70 ± 40	110 ± 40
MI8002	-11 ± 6	-13 ± 13	-80 ± 80	-40 ± 60
MI8009	3 ± 2	2 ± 3	20 ± 10	10 ± 20
Eel-tailed catfish				
GN8004	1 ± 3	1 ± 6	6 ± 17	1 ± 8
Freshwater mullet				
MI5049	2 ± 30	30 ± 40	20 ± 300	200 ± 300
Long tom				
GN5019	1 ± 2	43 ± 6	3 ± 5	22 ± 5
GN5024	2 ± 12	60 ± 30	9 ± 50	90 ± 50
MI5043	20 ± 20	100 ± 30	100 ± 100	400 ± 200
Saratoga				
MI5050	4 ± 19	30 ± 30	40 ± 200	200 ± 200
MI8004	2 ± 6	10 ± 10	10 ± 40	30 ± 40
MI8008	3 ± 2	2 ± 2	20 ± 10	10 ± 10
Sleepy cod				
GN8008	3 ± 2	5 ± 3	20 ± 10	5 ± 3
GU4014/2	6 ± 3	46 ± 5	150 ± 100	100 ± 10
Tarpon				
GU5015	1 ± 3	7 ± 4	8 ± 25	30 ± 20

Table 20 Summary of concentration factors for fish flesh

	^{226}Ra	^{210}Pb	^{210}Po	Uranium	Thorium
Group 1					
Bony bream	630	58	1300	110	29
Sleepy cod	2000	180	1300	120	14
Weighted mean	630	60	1300	110	15
Group 2					
Fork-tailed catfish	75	13	190	2	3
Archer fish	60	40	70		4
Barramundi	180	20	220	43	22
Eel-tailed catfish			180		2
Freshwater mullet	80		170		110
Long tom	80	16	110	4	13
Saratoga	170	80	270		15
Tarpon	20	20	140	20	21
Weighted mean	60	16	140	3	6

Table 21 Comparison of concentration factor weighted means for fish from Georgetown and Mudginberri Billabongs

Species	Billabong	^{226}Ra	^{210}Pb	^{210}Po	U
Fork-tailed catfish	Georgetown	67	7	180	2
	Mudginberri	250	48	200	37
Bony bream	Georgetown	600	51	1200	100
	Mudginberri	900	130	1400	330

Table 22 Comparison of fish concentration factors with IAEA default values for freshwater fish (IAEA 1982). Note that IAEA values relate to unfiltered water concentration.

	IAEA default	ARR Group 1	ARR Group 2
Radium	50	630	60
Lead	300	60	16
Polonium	50	1300	140
Uranium	10	110	3
Thorium	30	15	6

Table 23 Calcium concentrations for ten fish flesh samples. Calcium was determined by flame atomic absorption spectrometry

Sample	Ca (mg/g dry)	Ca (μg/g wet)	^{210}Po CF
Bony bream			
MI5047	9.3	2100	2000
MI8007	3.1	660	1500
Sleepy cod			
GN8008	0.43	79	1260
GU4014/2	22	4500	2000
Fork-tailed catfish			
GN5012	0.46	92	150
GN8007	0.36	73	230
MI5037	0.54	110	170
Long tom			
GN5024	1.4	320	120
Barramundi			
MI5053	0.84	180	370
Saratoga			
MI8004	0.79	150	150

Table 24 Buffalo: Sample summary

Sample code	Date	No. of animals	Subsample code	Portion	Dry/Wet ratio	Notes
DK7001	29/7/87	1	DK7001/1	heart	0.1940	1–2 year old bull
			DK7001/2	stomach wall	0.2023	Site: Drum Creek
			DK7001/3	intestines	0.2400	
			DK7001/4	kidney	0.2210	
			DK7001/5	liver	0.2957	
			DK7001/6	flesh	0.2305	
			DK7001/7	tongue	0.2964	
GS7001	5/6/87	1	GS7001/1	heart	0.2344	3–4 year old bull
			GS7001/2	liver	0.3576	Site: gauge station
			GS7001/3	kidney	0.2369	GS019
			GS7001/4	flesh	0.2534	
RS6004	9/1/86	1	RS6004/1	flesh	0.2477	3–4 year old bull
			RS6004/2	kidney	0.1809	Site: Red Lily swamp
			RS6004/3	liver	0.3038	
			RS6004/4	tongue	0.2581	
			RS6004/5	heart	0.2260	
RS6005	15/7/86	5	RS6005/1	flesh	0.1527	Site: Ant bed island
			RS6005/2	heart	0.1832	(near Red Lily swamp)
			RS6005/3	liver	0.1676	
			RS6005/4	tongue	0.2803	
			RS6005/5	kidney	0.1088	

Table 25 Buffalo: Flesh activity concentrations (mBq/kg) and concentration ratios

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
DK7001/6			270 ± 20			2 ± 2	1 ± 4
GS7001/4	20 ± 20			13 ± 6	20 ± 10		
RS6004/1	20 ± 20			-4 ± 9	3 ± 18	1 ± 7	-9 ± 10
RS6005/1	15 ± 4	16 ± 5	190 ± 20	11 ± 3	15 ± 9	2 ± 3	5 ± 5
Weighted mean	15	16	230	10	16	2	2
CR x 10^3	0.22	0.16	2.3	0.16	0.20	0.03	0.04

Table 26 Buffalo: Heart activity concentrations and concentration ratios

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
DK7001/1			440 ± 30			1 ± 2	4 ± 6
GS7001/1	9 ± 8			6 ± 5	-10 ± 20		
RS6004/5	20 ± 30	280 ± 50	410 ± 40	1 ± 7	10 ± 10	7 ± 5	9 ± 7
RS6005/2	18 ± 5	39 ± 7	300 ± 20	8 ± 4	1 ± 7	9 ± 4	7 ± 6
Weighted mean	16	44	350	6	3	3	6
CR x 10^3	0.24	0.43	3.4	0.10	0.04	0.05	0.11

Table 27 Buffalo: Tongue activity concentrations (mBq/kg) and concentration ratios

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
DK7001/7			270 ± 20			1 ± 2	11 ± 5
RS6004/4	30 ± 30	60 ± 60	770 ± 70	47 ± 9	40 ± 10	28 ± 9	30 ± 10
RS6005/4	22 ± 6	10 ± 8	960 ± 70	13 ± 4	4 ± 7	16 ± 6	16 ± 8
Weighted mean	22	11	350	19	16	4	15
CR x 10^3	0.32	0.11	3.4	0.31	0.20	0.06	0.28

Table 28 Buffalo: Kidney activity concentrations (mBq/kg) and concentration ratios

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
DK7001/4			31000 ± 1000			7 ± 5	11 ± 8
GS7001/3	130 ± 20			12 ± 6	20 ± 10		
RS6004/2	260 ± 20			1 ± 8	10 ± 10	8 ± 4	4 ± 7
RS6005/5	174 ± 8	140 ± 20	7000 ± 200	3 ± 2	4 ± 5	4 ± 2	7 ± 3
Weighted mean	180	140	8000	4	8	5	7
CR x 10^3	2.6	1.4	78	0.07	0.10	0.08	0.13

Table 29 Buffalo: liver activity concentrations (mBq/kg) and concentration ratios

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
DK7001/5			5500 ± 600			12 ± 8	-3 ± 14
GS7001/2	60 ± 20			7 ± 10	-10 ± 20		
RS6004/3	50 ± 20			-2 ± 11	4 ± 22	5 ± 6	10 ± 10
RS6005/3	20 ± 4	320 ± 20	830 ± 40	5 ± 4	2 ± 8	1 ± 3	6 ± 4
Weighted mean	23	320	850	5	1	3	6
CR x 10^3	0.34	3.1	8.3	0.08	0.01	0.05	0.11

Table 30 Buffalo: Stomach wall activity concentrations (mBq/kg) and concentration ratios

	^{210}Po	^{232}Th	^{230}Th
DK7001/2	360 ± 30	13 ± 7	1 ± 11
CR x 10^3	3.5	0.2	0.02

Table 31 Buffalo: Intestines activity concentrations (mBq/kg) and concentration ratios

	^{210}Po	^{232}Th	^{230}Th
DK7001/3	1140 ± 70	50 ± 10	40 ± 10
CR x 10^3	11	0.8	0.7

Table 32 Pig: Sample summary

Sample code	Date	No. of animals	Dry/Wet ratio
TK5001/1	20/6/85	1	0.2743
TK5001/2	20/6/85	1	0.2579
TK5001/3	20/6/85	1	0.3069

Table 33 Pig: Activity concentrations (mBq/kg) and concentration ratios

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
TK5001/1	20 ± 20	15 ± 9	5700 ± 300	6 ± 3	3 ± 4	9 ± 4	2 ± 4
TK5001/2	6 ± 11	7 ± 5	3600 ± 200	7 ± 3	8 ± 5	3 ± 2	11 ± 4
TK5001/3	60 ± 20	40 ± 10	5600 ± 300	29 ± 6	25 ± 7	17 ± 3	24 ± 5
Weighted mean	19	14	4600	9	8	8	11
CR x 10^3	0.28	0.14	45	0.15	0.10	0.12	0.20

Table 34 Magpie goose: Sample summary

Sample code	Date	No. of animals	Dry/Wet ratio
RS6001	8/1/86	1	0.2807
RS6002	8/1/86	1	0.2618
RS8003	8/1/86	1	0.2592

Table 35 Magpie goose: Activity concentrations (mBq/kg) and concentration factors

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
RS6001	30 ± 10	60 ± 10	250 ± 30	4 ± 3	4 ± 6	8 ± 3	9 ± 4
RS6002	30 ± 10	48 ± 6	650 ± 40	4 ± 3	12 ± 5	5 ± 3	3 ± 4
RS6003	30 ± 10	41 ± 9	410 ± 30	3 ± 3	8 ± 4	4 ± 3	10 ± 5
Weighted mean	30	49	400	4	8	6	7
Water	0.37	1.37	1.19	0.48	0.64	0.13	0.15
CF	80	36	340	8	12	46	47

Table 36 Filesnake: Sample summary

Sample code	Date	No. of animals	Dry/Wet ratio	Water sample	Sex
GN4013/1	2/11/84	1	0.1711	GN4008	Female
GN4013/2	2/11/84	1	0.1627	GN4008	Male
MI5044/1	17/7/85	1	0.1660	MI5040	Male
MI5044/2	17/7/85	1	0.1641	MI5040	Male
MI5044/3	17/7/85	1	0.1594	MI5040	Male

Table 37 Filesnake: ^{226}Ra, ^{210}Pb and ^{210}Po activity concentrations and concentration factors

Sample	Flesh activity concentration			Concentration factor		
	^{226}Ra (mBq/kg)	^{210}Pb (mBq/kg)	^{210}Po (mBq/kg)	^{226}Ra	^{210}Pb	^{210}Po
GN4013/1	240 ± 20			6.2 ± 0.7		
GN4013/2	60 ± 9	62 ± 8	1400 ± 100	1.5 ± 0.3	0.8 ± 0.1	31 ± 3
MI5044/1	33 ± 7	52 ± 8	820 ± 50	100 ± 80	29 ± 5	340 ± 30
MI5044/2	20 ± 10	20 ± 20	1690 ± 90	60 ± 50	10 ± 10	710 ± 60
MI5044/3	40 ± 8	40 ± 10	1020 ± 60	120 ± 90	22 ± 6	430 ± 40

Table 38 Filesnake: Uranium activity concentrations and concentration factors

Sample	Flesh activity concentration		Concentration factor	
	^{238}U (mBq/kg)	^{234}U (mBq/kg)	^{238}U	^{234}U
GN4013/1	230 ± 20	260 ± 20	6.9 ± 0.6	7.3 ± 0.6
GN4013/2	64 ± 8	45 ± 9	1.9 ± 0.2	1.3 ± 0.3
MI5044/1	12 ± 4	12 ± 6	30 ± 10	30 ± 10
MI5044/2	30 ± 10	-9 ± 18	80 ± 30	-20 ± 40
MI5044/3	22 ± 5	19 ± 8	60 ± 10	40 ± 20

Table 39 Filesnake: Thorium activity concentrations and concentration factors

Sample	Flesh activity concentration		Concentration factor	
	^{232}Th (mBq/kg)	^{230}Th (mBq/kg)	^{232}Th	^{230}Th
GN4013/1	70 ± 10	180 ± 20	7 ± 1	7.9 ± 0.8
GN4013/2	14 ± 5	53 ± 8	1.4 ± 0.5	2.3 ± 0.4
MI5044/1	4 ± 2	38 ± 4	30 ± 20	140 ± 50
MI5044/2	25 ± 10	60 ± 20	180 ± 80	200 ± 100
MI5044/3	20 ± 20	60 ± 30	150 ± 150	200 ± 100

Table 40 Percentages of prey of aquatic origin eaten by varanids (taken from Shine 1984, table 17)

Species	Prey of aquatic origin (% by weight)
V. panoptes	29.2
V. gouldii	1.4
V. mertensi	39.7
V. mitchelli	44.1

Table 41 Goanna: Sample summary

Species	Sample code	Date	No. of animals	Dry/Wet ratio	Notes
V. panoptes	BL9001	20/6/89	1	0.2641	Total weight 741 g, total length (tip nose to tip tail) 83 cm

Table 42 Goanna: Activity concentrations (mBq/kg) and concentration factors

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
Flesh	76 ± 8	91 ± 8	4900 ± 300	35 ± 5	28 ± 5	9 ± 2	23 ± 3
Water	1.2 ± 0.1	2.1 ± 0.8	3.2 ± 0.3	1.3 ± 0.2	1.5 ± 0.3	0.4 ± 0.1	1.2 ± 0.6
CF	18 ± 2	13 ± 5	450 ± 50	8 ± 2	5 ± 1	7 ± 2	6 ± 3

Table 43 Turtle: Sample summary

Sample code	Date	No. of animals	Water sample	Subsample code	Portion	Dry/Wet ratio
BD4004	26.11.84	1	BD4005	BD4004/1	flesh	
				BD4004/2	liver	
BD7003	08.10.87	1	BD7002	BD7003/2	liver	0.3629
				BD7003/3	flesh	0.1735

Table 44 Turtle: ^{226}Ra, ^{210}Pb and ^{210}Po activity concentrations and concentration factors

Sample	Flesh activity concentration			Concentration factor		
	^{226}Ra (mBq/kg)	^{210}Pb (mBq/kg)	^{210}Po (mBq/kg)	^{226}Ra	^{210}Pb	^{210}Po
Flesh						
BD4004/1	200 ± 20			200 ± 100		
BD7003/3	120 ± 10	98 ± 6	1210 ± 60	300 ± 100	120 ± 20	1000 ± 100
Liver						
BD4004/2	1800 ± 90			2000 ± 1000		
BD7003/2	180 ± 20	890 ± 40	45000 ± 2000	400 ± 200	1100 ± 200	38000 ± 4000

Table 45 Turtle: Uranium activity concentrations and concentration factors

Sample	Flesh activity concentration		Concentration factor	
	^{238}U (mBq/kg)	^{234}U (mBq/kg)	^{238}U	^{234}U
Flesh				
BD4004/1	2 ± 3	2 ± 5	10 ± 15	7 ± 17
BD7003/3	12 ± 2	14 ± 3	39 ± 8	28 ± 6
Liver				
BD4004/2	130 ± 20	180 ± 20	650 ± 200	600 ± 100
BD7003/2	59 ± 9	80 ± 10	190 ± 40	160 ± 20

Table 46 Turtle: Thorium activity concentrations and concentration factors

Sample	Flesh activity concentrations		Concentration factor	
	^{232}Th (mBq/kg)	^{230}Th (mBq/kg)	^{232}Th	^{230}Th
Flesh				
BD4004/1	6 ± 4	4 ± 5	200 ± 200	18 ± 25
BD7003/3	3 ± 1	9 ± 2	150 ± 90	45 ± 10
Liver				
BD4004/2	70 ± 10	60 ± 20	1800 ± 900	100 ± 40
BD7003/2	6 ± 4	29 ± 7	300 ± 250	140 ± 40

Table 47 Freshwater shrimp: Sample summary

Sample code	Date	No. of animals	Dry/Wet ratio	Water sample
GN4014	2/11/84	1	0.2073	GN4008
GU4014/A	13/11/84	1	0.1351	GU4011
GU4014/B	13/11/84	1	0.1924	GU4011
GU4014/C	13/11/84	1	0.2015	GU4011
GU4014/D	13/11/84	1	0.1880	GU4011
GU4014/E	13/11/84	1	0.2054	GU4011

Table 48 Freshwater shrimp (Georgetown Billabong): Activity concentrations (mBq/kg) and concentration factors

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
GN4014	530 ± 70	40 ± 30	800 ± 600	30 ± 10	40 ± 20	1 ± 30	2 ± 50
Water	39 ± 3	78 ± 5	44 ± 2	33 ± 1	36 ± 1	9.9 ± 0.5	23.3 ± 0.9
CF	14 ± 2	0.5 ± 0.4	20 ± 15	0.9 ± 0.3	1.1 ± 0.6	0.1 ± 3	0.1 ± 2

Table 49 Freshwater shrimp (Gunirdul Billabong): Activity concentrations (mBq/kg) and concentration factors

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
GU4015/A	380 ± 50	180 ± 30	800 ± 200	150 ± 20	130 ± 30	20 ± 20	110 ± 30
GU4015/B	120 ± 40	50 ± 20	500 ± 300	5 ± 12	6 ± 30	30 ± 20	20 ± 30
GU4015/C	80 ± 20	20 ± 30	800 ± 200	20 ± 10	10 ± 20	3 ± 12	-10 ± 20
GU4015/D	130 ± 20	30 ± 10	700 ± 200	15 ± 9	9 ± 15	15 ± 8	-3 ± 10
GU4015/E	70 ± 20	10 ± 40	300 ± 800	10 ± 10	20 ± 20	20 ± 20	9 ± 20
Weighted mean	110	43	720	21	23	14	7
Water	0.6 ± 0.9	1.5 ± 0.1	0.5 ± 0.1	0.20 ± 0.06	0.38 ± 0.06	0.04 ± 0.02	0.47 ± 0.05
C.F.	180	29	1400	100	60	350	15

Table 50 Freshwater crocodile: Sample summary

Sample code	Date	No. of animals	Subsample code	Portion	Dry/Wet ratio	Water sample
GU4016	13/11/84	1	GU4016/6	flesh		GU4011
				(breast muscle)	0.2040	
			GU4016/3	heart	0.1706	
			GU4016/2	liver	0.2257	
			GU4016/10	stomach lining	0.1825	
			GU4016/5	intestines	0.1890	
			GU4016/4	lung	0.1394	
			GU4016/7	bones	0.4255	

Table 51 Freshwater crocodile: Activity concentrations (mBq/kg) and concentration factors

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
Activity concentrations							
Flesh	120 ± 20	34 ± 8	1200 ± 100	8 ± 4	1 ± 6	1 ± 6	-6 ± 10
Heart	400 ± 70	360 ± 80	1900 ± 500	30 ± 30	-30 ± 60	-20 ± 40	-10 ± 80
Liver				40 ± 10	50 ± 20	30 ± 10	30 ± 20
Stomach lining	110 ± 40			8 ± 3	11 ± 5	16 ± 5	9 ± 6
Intestines	70 ± 20			15 ± 5	1 ± 10	3 ± 2	5 ± 4
Lung	130 ± 30			4 ± 8	-8 ± 20	1 ± 11	-1 ± 20
Bones	25000 ± 1000	4100 ± 600	4800 ± 500	50 ± 10	60 ± 20	70 ± 50	40 ± 100
Concentration factors							
Flesh	200	23	2400	40	3	20	<40
Heart	700	250	3900	150	<300	<2000	<350
Liver				200	130	750	60
Stomach lining	180			40	29	400	20
Intestines	120			75	3	75	10

Table 52 Yam and Anbulubi roots: Sample summary

Species	Sample code	Date	Dry/Wet ratio	Soil sample	Dry/Wet ratio
Cheeky yams (*Dioscorea bulbifera*)	DR5001	24.05.85	0.2788	DR5002	0.9866
Anbulubi roots (*Eriosema chinense*)	DR5003	21.05.85	0.4303	DR5004	0.9505

Table 53 Cheeky yams: Activity concentrations and concentration factors (x 10^3)

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
Root (mBq/kg)	260 ± 20	42 ± 9	210 ± 90	20 ± 20	60 ± 30	50 ± 40	70 ± 80
Soil (Bq/kg)	18.4 ± 0.3	31 ± 5	29 ± 2	11.2 ± 0.8	10.9 ± 0.8	5.9 ± 0.6	5.1 ± 0.6
C.R. (x10^3)	14 ± 1	1.4 ± 0.4	7 ± 3	2 ± 2	6 ± 3	8 ± 7	14 ± 16

Table 54 Anbulubi roots: Activity concentrations and concentration factors (x 10^3)

	^{226}Ra	^{210}Pb	^{210}Po	^{238}U	^{234}U	^{232}Th	^{230}Th
Root (mBq/kg)	1190 ± 90	1700 ± 100	1600 ± 200	30 ± 10	60 ± 20	30 ± 10	310 ± 30
Soil (Bq/kg)	1.5 ± 0.4	52 ± 6	42 ± 3	7.2 ± 0.7	8.2 ± 0.8	22 ± 3	14 ± 2
C.R. (x10^3)	55 ± 4	33 ± 4	38 ± 5	4 ± 1	7 ± 3	1.4 ± 0.5	22 ± 4

Table 55 Actinium-227 activity concentrations

Sample	Sample code	^{227}Ac (mBq/kg)	Sample	Sample code	^{227}Ac (mBq/kg)
Buffalo			*Goanna*	BL9001	3 ± 8
flesh	RS6005/1	2 ± 2			
heart	RS6005/2	0 ± 2	*Turtle*		
liver	RS6005/3	7 ± 5	flesh	BD4004/1	6 ± 5
tongue	RS6005/4	1 ± 4		BD7003/3	1 ± 2
			liver	BD4004/2	24 ± 14
Fish				BD7003/2	9 ± 7
F/T catfish	GN5012	2 ± 2			
	MI5048	3 ± 2	*Magpie goose*	RS6001	0 ± 9
Barramundi	MI5053	2 ± 2			
Long tom	GN5019	5 ± 3	*F/W crocodile*		
			heart	GU4016/3	17 ± 14
Filesnake	GN4013/1	6 ± 3	lung	GU4016/4	9 ± 12
F/W shrimp	GN4014	30 ± 20	*Anbulubi roots*	DR5003	30±13
	GU4015/A	0 ± 20			
	GU4015/B	0 ± 15			
	GU4015/C	50 ± 15			
	GU4015/D	0 ± 5			

Table 56 Concentration ratios (x 10^{3*}) relative to total soil activity concentrations

		^{226}Ra	^{210}Pb	^{210}Po	Uranium	Thorium
Buffalo	flesh	0.22	0.16	2.3	0.18	0.04
	heart	0.24	0.43	3.4	0.07	0.08
	tongue	0.32	0.11	3.4	0.26	0.17
	kidney	2.6	1.4	78	0.08	0.10
	liver	0.38	3.1	8.3	0.04	0.08
	stomach wall			3.5		0.11
	intestines			11		0.8
Pig		0.28	0.14	45	0.12	0.16
Cheeky yams		14	1.4	7	3	9
Anbulubi roots		55	33	38	4	2

* For example, concentration ratio for ^{226}Ra in buffalo flesh is 0.22×10^{-3}

Table 57 Concentration factors relative to filtered (<0.45 μm) water activity concentrations

		^{226}Ra	^{210}Pb	^{210}Po	Uranium	Thorium
Fish group 1 (flesh only)						
Bony bream		630	58	1300	110	29
Sleepy cod		2000	180	1300	120	14
Weighted mean		630	60	1300	110	15
Fish group 2 (flesh only)						
Fork-tailed catfish		75	13	190	2	3
Archer fish		60	40	70		4
Barramundi		180	20	220	43	22
Eel-tailed catfish				180		2
Freshwater mullet		80		170		110
Long tom		80	16	110	4	13
Saratoga		170	80	270		15
Tarpon		20	20	140	20	21
Weighted mean		60	16	140	3	6
Fish group 3 (whole fish)		2600		3500	270	
Magpie goose		80	36	340	10	46
Filesnake*		80	24	420	40	60
Freshwater shrimp (*M. rosenbergii*)		180	29	1400	80	180
Goanna** (*Varanus panoptes*)		18	13	450	6	7
Turtle (*Elseya dentata*)	flesh	250	120	1000	28	40
	liver	460	1100	38000	180	120
Freshwater crocodile	flesh	200	23	2400	20	20
	heart	700	250	3900	150	<350
	liver				160	400
	stomach lining	180			34	200
	intestines	120			40	40

* Results for filesnake obtained from male specimens only. See section 4.5.

** Results for the goanna (*Varanus panoptes*) have been multiplied by a factor of 0.292, this being the proportion of prey of aquatic origin for the Magela system obtained by Shine (1984). See section 4.6.

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Appendix 1

Billabong water sample results

Total Sample	Date	^{238}U	^{234}U	^{232}Th	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po
BD4005	841126	0.29 ± 0.05	0.61 ± 0.08	0.15 ± 0.03	0.11 ± 0.08	3.29 ± 0.29	3.70 ± 0.26	3.78 ± 0.32
GN4008	841102	76.3 ± 3.6	82.5 ± 3.8	16.8 ± 2.8	47.8 ± 5.2	103.3 ± 6.3	156 ± 10	95.1 ± 4.4
GN5011	850522	3.71 ± 0.22	3.77 ± 0.23	0.64 ± 0.10	7.72 ± 0.39	5.29 ± 0.79	11.3 ± 0.5	8.36 ± 0.34
GN5015	850712	4.22 ± 0.20	4.80 ± 0.22	0.82 ± 0.08	2.44 ± 0.18	4.94 ± 0.33	7.07 ± 0.48	5.88 ± 0.25
GN5020	850829	3.87 ± 0.17	3.82 ± 0.18	0.40 ± 0.08	1.06 ± 0.13	4.20 ± 0.36	3.33 ± 0.25	4.00 ± 0.21
GN8001	880210	1.28 ± 0.10	1.93 ± 0.14	0.75 ± 0.08	1.30 ± 0.10	4.59 ± 0.22	5.76 ± 0.92	14.6 ± 0.7
GU4011	841113	0.51 ± 0.07	0.64 ± 0.08	0.32 ± 0.04	0.67 ± 0.07	2.36 ± 0.52	2.89 ± 0.22	0.44 ± 0.20
GU5014	850823	0.43 ± 0.04	0.61 ± 0.06	0.32 ± 0.07	0.33 ± 0.16	1.66 ± 0.22	1.62 ± 0.16	1.25 ± 0.10
MI4005	841106	0.56 ± 0.07	0.64 ± 0.08					5.12 ± 0.26
MI5035	850524	0.28 ± 0.04	0.42 ± 0.06	0.25 ± 0.03	0.39 ± 0.05	1.92 ± 0.14	1.50 ± 0.15	3.67 ± 0.18
MI5040	850716	0.60 ± 0.05	0.68 ± 0.06	0.22 ± 0.04	0.76 ± 0.11	1.46 ± 0.18	2.20 ± 0.18	2.93 ± 0.17
MI5045	850827	0.43 ± 0.05	0.68 ± 0.06	0.21 ± 0.03	0.62 ± 0.06	1.81 ± 0.12	1.64 ± 0.16	2.22 ± 0.15
MI5055	851205			0.24 ± 0.03	0.59 ± 0.06	2.54 ± 0.15	1.86 ± 0.18	2.57 ± 0.15
Filtered (<0.45µm)								
BD4005	841126	0.20 ± 0.04	0.29 ± 0.05				2.61 ± 0.19	0.89 ± 0.10
BD7002	871008	0.31 ± 0.04	0.50 ± 0.04	0.02 ± 0.01	0.20 ± 0.03	0.44 ± 0.21	0.79 ± 0.15	1.19 ± 0.13
GN4008	841102	33.3 ± 1.1	35.7 ± 1.1	9.87 ± 0.48	23.3 ± 0.9	38.9 ± 2.8	78.4 ± 4.7	44.5 ± 2.2
GN5011	850522	2.37 ± 0.12	2.43 ± 0.12	0.35 ± 0.04	0.77 ± 0.07	1.55 ± 0.16	3.16 ± 0.18	3.33 ± 0.24
GN5015	850712	3.01 ± 0.15	3.08 ± 0.15	0.37 ± 0.06	1.92 ± 0.28		6.89 ± 0.39	4.28 ± 0.21
GN5020	850829	2.45 ± 0.13	2.80 ± 0.14	0.22 ± 0.04	0.65 ± 0.07	1.69 ± 0.21	2.62 ± 0.18	2.28 ± 0.14

Appendix 1 Billabong water sample results (cont'd)

Total Sample	Date	^{238}U	^{234}U	^{232}Th	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po
GN8001	880210	0.91 ± 0.08	1.19 ± 0.11	0.18 ± 0.04	0.72 ± 0.08	2.97 ± 0.18	0.4 ± 1.0	3.76 ± 0.88
GN8006	880408			0.18 ± 0.03	0.95 ± 0.06			1.79 ± 0.10
GU4011	841113	0.20 ± 0.06	0.38 ± 0.06	0.04 ± 0.02	0.47 ± 0.05	0.6 ± 0.9	1.46 ± 0.12	0.49 ± 0.11
GU5014	850823	0.24 ± 0.03	0.37 ± 0.04	0.12 ± 0.03	0.23 ± 0.08	0.86 ± 0.14	1.07 ± 0.13	1.25 ± 0.11
MI4005	841106	0.32 ± 0.05	0.39 ± 0.07	0.07 ± 0.02	0.28 ± 0.05	1.65 ± 0.45		0.86 ± 0.17
MI5035	850524	0.22 ± 0.03	0.28 ± 0.05	0.14 ± 0.03	0.30 ± 0.05	0.58 ± 0.09	0.68 ± 0.12	2.90 ± 0.17
MI5040	850716	0.38 ± 0.04	0.47 ± 0.05	0.14 ± 0.03	0.28 ± 0.10	0.34 ± 0.26	1.81 ± 0.15	2.38 ± 0.15
MI5045	850827	0.47 ± 0.05	0.51 ± 0.06	0.09 ± 0.04	0.16 ± 0.04	0.60 ± 0.47	0.75 ± 0.10	1.23 ± 0.10
MI5055	851205			0.09 ± 0.03	0.15 ± 0.04	0.28 ± 0.06	0.95 ± 0.10	0.90 ± 0.08
MI8001	880217	0.76 ± 0.07	0.88 ± 0.08	0.20 ± 0.03	0.94 ± 0.07	3.13 ± 0.16	465. ± 16.	19.2 ± 1.5
MI8006	880330			0.14 ± 0.02	0.19 ± 0.03			1.24 ± 0.08
Particulate (>0.45μm)								
BD7002	871008	0.82 ± 0.04	0.82 ± 0.05	0.02 ± 0.01	0.04 ± 0.02	0.53 ± 0.04	0.74 ± 0.05	1.51 ± 0.11
GN8006	880408			0.22 ± 0.03	1.49 ± 0.09	1.79 ± 0.16		3.99 ± 0.21
MI8001	880217	0.20 ± 0.02	0.24 ± 0.03	0.15 ± 0.02	0.25 ± 0.03	0.58 ± 0.05	0.4 ± 0.6	24.11 ± 0.94
MI8006	880330			0.19 ± 0.03	0.23 ± 0.04			2.95 ± 0.15

Supervising Scientist for the Alligator Rivers Region

Research publications

Alligator Rivers Region Research Institute Research Report 1983
Alligator Rivers Region Research Institute Annual Research Summary 1984–85
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