AUSTRALIA

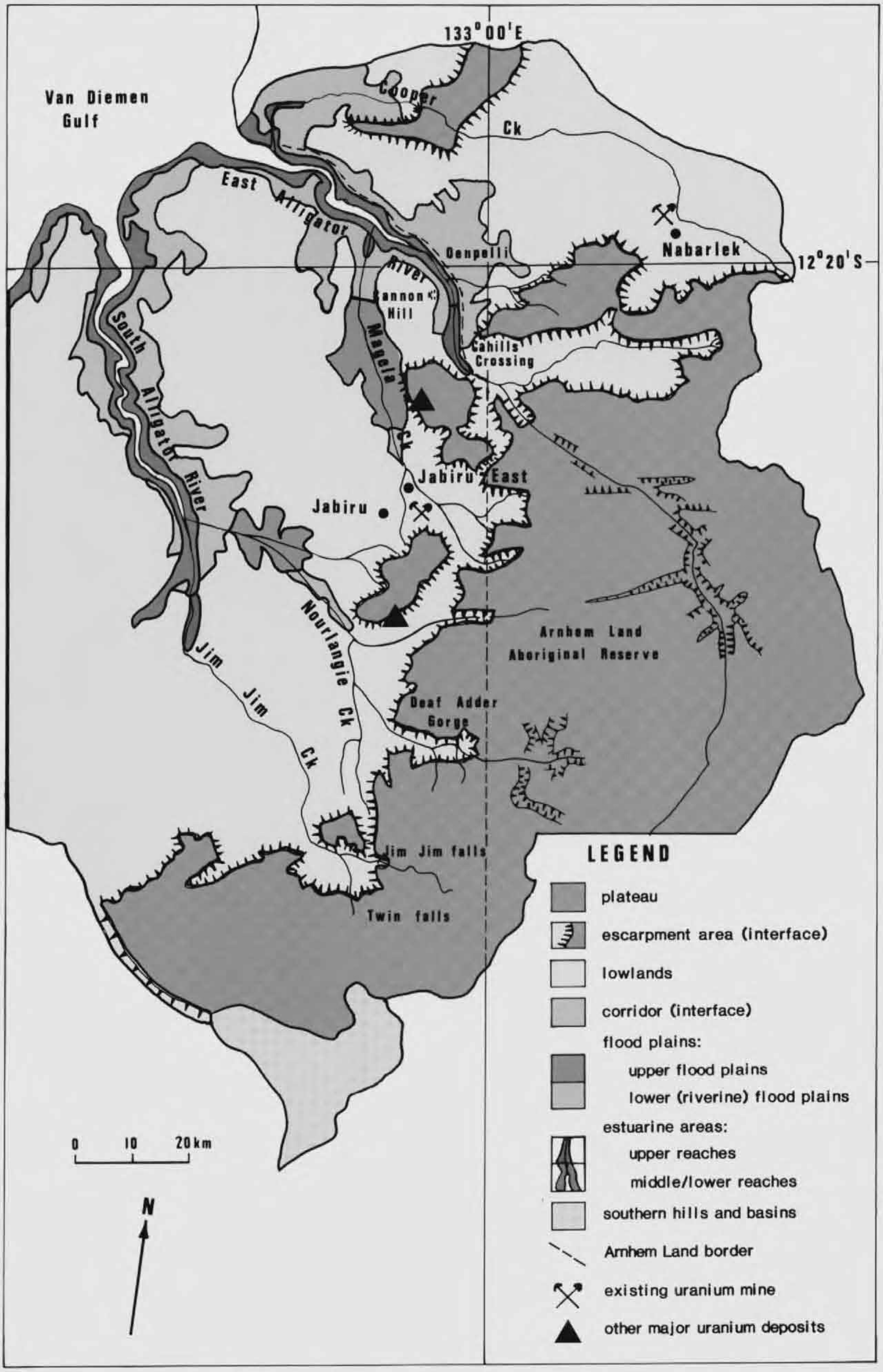
Research Report 4

Ecological studies on the freshwater fishes of the Alligator Rivers Region, Northern Territory

Volume I: Outline of the study, summary, conclusions and recommendations

K.A. Bishop, S.A. Allen, D.A. Pollard and M.G. Cook

Supervising Scientist for
the Alligator Rivers Region



Map 1. Major catchments and zones examined

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for the Alligator Rivers Region.

The manuscript, submitted in 1980, represents the results of a detailed ecological study of the freshwater fishes of the area conducted from August 1978 to December 1979. The entire work is divided into three volumes under the following titles:

Volume I: Outline of study, summary, conclusions and recommendations
Introduction to the overall study; physiography of the Region; description of aquatic habitats; materials and methods; summary; conclusions; recommendations.

Volume II: Synecology
Results and discussions of the synecological studies.

Volume III: Autecology
Results and discussions of the autecological studies, species arranged in taxonomic order.

The Supervising Scientist for the Alligator Rivers Region manages the Alligator Rivers Region Research Institute, which conducts, co-ordinates and integrates research relating to the effects on the environment of uranium mining in the Alligator Rivers Region. Research findings of projects carried out under contract to the Supervising Scientist or undertaken by the Supervising Scientist's own staff may be published in the Research Report or Technical Memorandum series. Views expressed by authors do not necessarily reflect the views and policies of the Supervising Scientist, the Commonwealth Government or any collaborating organisation.

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Dr P. McBride and Mr K. Brennan are thanked for allowing the use of their photographs in Plate 1 b and c respectively.

EXPLANATORY NOTES

Nomenclatural changes

Since this manuscript was first submitted (September 1980) a number of names of fish species and of billabongs have been revised.

Fish names

Ariidae:	*Hexanematichthys* = *Arius*
	H. australis = *A. graeffei*
Belonidae:	*Strongylura kreffti* = *S. krefftii*
Melanotaeniidae:	*Melanotaenia maculata* = *M. splendida inornata*
	Melanotaenia australis = *M. splendida australis*
Atherinidae:	*Craterocephalus marjoriae* = *C.* nov. sp.
Teraponidae:	*Pingalla* sp. = *Pingalla midgleyi*
Mugilidae:	*Liza diadema* = *L. alata*
Eleotridae:	*Hypseleotris compressus* = *H. compressa*

Place names

Baroalba crossing (coded BX) = Malabanbandju Billabong
Nourlangie Rock (NR) = Umbungbung = Anbangbang Billabong
Skull Rock (SR) = Long Harry = Namandi Garrigorry = Noarlanga
Magela bore pool (II) = Surshar Billabong

Definition of 'billabong'

The word billabong has been widely used in this report when naming waterbodies in the lowlands and flood plains of the Alligator Rivers Region.

Bayly and Williams (1973) describe a billabong thus:

> '...part of the abandoned channel is usually overdeepened and may persist as a shallow crescentic lake which in Australia is usually called a billabong. Elsewhere they are termed oxbow lakes.'

This definition is somewhat narrow in comparison to those found in recent dictionaries. There is as yet insufficient evidence to explain the name or its transfer to the current generally accepted meaning. Attempts have been made to derive it from two Aboriginal words *billa*, 'water', and *bong*, 'dead', (Wiradhuri Tribe, central NSW, 1860). *Billa* also means 'river' or 'fish' in parts of Western Australia, New South Wales and Queensland. However, the word was first noted as the Aboriginal name for the Bell River.

The definitions supplied by the Macquarie Dictionary are probably the most useful and widely accepted:

1. a waterhole in an anabranch, replenished only in flood time; and
2. a waterhole in a river or creek that dries up outside the rainy season.

These definitions of a billabong appear most applicable to the waterholes on the flood plains and those adjacent to the sandy creek channels in the lowlands of the Alligator Rivers Region affected by the regular flooding, draining and evaporative cycles of the monsoonal climate.

Names of animals and plants

Scientific and common names of fishes follow the recommendations of the Australian Museum, Sydney (but see above). Those of plants follow the recommendations of the Royal Botanic Gardens, Sydney.

Abbreviations

ARR	Alligator Rivers Region
DO	dissolved oxygen
GMSI	gonad maturity stage index
GSI	gonosomatic index
LCF	length to caudal fork
LFM	length at first maturation
RUPA	Ranger Uranium Project Area
TL	total length

Sampling method and site abbreviations will be found in the Materials and Methods section.

Aquatic seasons

The system of seasons used in this report takes into account the major changes in aquatic habitats resulting from the Wet–Dry monsoonal climate (see section 2.3). Five seasons are recognised which do not have clear time boundaries drawn between them because of the variability in the starting and ending times of 'The Wet'. Spatial variability of rainfall may also create a situation where separate catchments may be experiencing different seasons. Descriptions of the five seasons are given below and the equivalent Aboriginal names in Gundjeidmi (Maiili) language are given in parentheses.

Late-dry (*Gurrung* – early *Gunumeleng*). Usually September to October, although it sometimes begins as early as August or ends as late as November or December. Waterbodies are isolated and have contracted greatly, owing to extensive evaporation. Many waterbodies disappear altogether but the ones with considerable depth which persist and remain deep act as important refuges for aquatic animals. Temperatures and turbidities rise to high levels in the shallower waterbodies. Water persists on the flood plain only in channel waterholes.

Early-wet (*Gunumeleng*). Usually November to December, but sometimes begins as early as October or ends as late as January. Waterbodies receive first rains and surface inflows. Littoral grasses begin to grow. Temperatures in the littoral zone of the waterbodies are very high. Towards the end of this season creek channels begin to flow, interconnecting the already replenished waterbodies, and the flood plains start to fill. Animals within waterbodies can now move throughout catchments.

Mid-wet (*Gudjewg*). Usually January to March, although it can begin as early as December or end as late as April. Heavy rains induce strong flows in the channels and flooding of the surrounding forest. Waterbodies are deepest at this time of year, large expanses of water cover the flood plain and, in the upper reaches, water levels may drop and rise rapidly. There are extensive connections between fresh and estuarine waters.

Late-wet–Early-dry (*Bang-gereng* and *Yegge*). Usually April to early June, although sometimes this season begins as late as May and continues to the end of June. Rainfall slackens and water levels begin to drop in channels and waterbodies. Dissolved oxygen levels drop in waterbodies as flow-induced mixing reduces and organic matter decays. By the end of this season channel flow has reduced considerably, making it difficult for larger aquatic animals to move from waterbody to waterbody, and considerable water level draw-down occurs on the flood plain, which becomes isolated from the estuary.

Mid-dry (*Wurrgeng*). Usually late June to August; can be early June to mid-August or mid-September. Rainfall stops completely and temperatures are at their lowest. 'Trickle' flows enable small animals to move to more secure (deeper) waterbodies, but these flows usually stop in the middle of this season and the waterbodies then become isolated. Draw-down continues on the flood plain as sections become very shallow.

ABSTRACT

Bishop K. A., Allen, S. A., Pollard, D. A. and Cook, M. G. (1986). Ecological studies on the freshwater fishes of the Alligator Rivers Region, Northern Territory. Research Report 4, Supervising Scientist for the Alligator Rivers Region. Australian Government Publishing Service, Canberra.

The tropical climate of the Alligator Rivers Region of the Northern Territory has a distinctive Wet–Dry cycle resulting in seasonal flows in the creeks and rivers of its catchments. The present study, begun during August 1978, aimed at developing an ecological monitoring system that would detect changes in freshwater fish communities brought about by recent uranium mining and processing in the lowlands of the ARR. The broad objectives were:

1. to describe fish community structure at sites from a longitudinal array of habitats and show the seasonal changes in structure;
2. to collect environmental and biological information on the fish species and study sites for use in interpreting changes in community structure; and
3. to advise on the best practicable approach for detecting, predicting and minimising adverse effects on the Region's fish fauna due to uranium mining and processing operations

A large multi-dimensional matrix of information was generated from sites × habitats × seasons × habitat-structural and physico-chemical variables × species × lengths × weights × gonad weights and stages × stomach contents and fullness × presence of macroparasites.

Distinctive fish communities were present in the upper reaches of the Arnhem Land escarpment and the lower reach floodplain zones. These zones were major Dry season refuge habitats for fish. Distinctiveness was most likely the result of the substrate preferences (including aquatic plants) of some species and allowed recognition of migrations of fish between the escarpment and flood plains as Wet season flows across the lowlands linked the zones. The community structure of lowland habitats in the Wet season showed a flux between the community structures of the two Dry season refuges. In the Wet season the lowlands were very important breeding and feeding areas. Fish movement in the ARR appeared to be a classic response to temporal and spatial patchiness of resources.

1 Introduction

1.1 Background

The environmental consequences of uranium mining operations in Australia are receiving much more attention than they did in the past. The Rum Jungle uranium mining project was planned in 1953, and subsequent mining and milling operations attracted much criticism on environmental grounds. It became increasingly apparent that knowledge of the precise extent of environmental pollution in the Rum Jungle area and of the mechanisms underlying the spread of contaminants was inadequate.

Uranium extraction on a large scale had been planned in the climatically similar Alligator Rivers Region of the Northern Territory since the early 1970s, and a study by the Australian Atomic Energy Commission and the Department of Northern Australia (Davy 1975) was undertaken to obtain background information from the Rum Jungle area. The study was designed to assist in assessing the environmental consequences of the new developments in the Region and to facilitate plans to minimise any adverse effects.

Such interest in the Region has given rise to the possibilities of conflict between different land uses and of lasting environmental damage. These risks can be reduced by careful planning, based on adequate knowledge of the Region, involving the formulation in advance of environmental protection measures. In May 1972 these considerations led to an agreement being reached, between companies with mineral exploration licences in the area and the Commonwealth Government, to initiate an environmental fact-finding study of the catchments of the East Alligator River together with the area between those catchments and the South Alligator River.

A public inquiry, the Ranger Uranium Environmental Inquiry (Fox et al. 1977), into the environmental effects of the proposed development of the uranium deposits in the Alligator Rivers Region by Ranger Uranium Mines Pty Ltd, utilised information gathered in the above study and summarised the reasons for the increasing interest in the Region as a consequence of both its natural resources and its great environmental value.

Following the Ranger Inquiry the Government established the Office of the Supervising Scientist for the Alligator Rivers Region and the Alligator Rivers Region Research Institute managed by the Supervising Scientist. The research described in this report was carried out from August 1978 to December 1979 as part of the initial research program of the Supervising Scientist.

1.2 Tropical freshwater fish ecology

Lowe-McConnell (1975) gathered widely spread information on the distribution, ecology and evolution of fish communities in tropical freshwaters and pointed to gaps in the knowledge of this subject:

> Although the study of ecological processes is of fundamental importance for man's continued existence and well-being, tropical studies are still in their infancy, and theories about tropical communities are based on few hard data. Fish have been investigated more than any other vertebrate group in the tropics ... they are so important as food throughout the tropics, but the results have generally been published in specialist reports not readily available to the general ecologist and a wider public ... Tropical ecosystems are now being changed so fast by man, that it is of paramount importance to study the complex web of interrelationships in order to avoid irreparable damage to the environment and its faunas.

Lowe-McConnell (1975) noted that the tropical belt included four main landmasses with their enclosed freshwaters: South and Central America (Neotropical zoogeographic region [z.r.]); Africa (Ethiopian z.r.); tropical Asia and islands on the adjacent continental shelf (Oriental z.r.); and New Guinea and northern Australia (Australian z.r.). Tropical freshwater fish communities are noted for their high diversity (the Amazon system has over 1300 known species of fish, and the Zaire [Congo] nearly as many) compared with those of temperate areas (192 fish species for the whole of Europe or 250 for the Mississippi system [Lowe-McConnell 1975]). Jackson (1975) and Pollard et al. (1980) have noted that the mainland Australian freshwater fish fauna is a depauperate and unique one by world standards. Pollard (1974) and Midgley (1973) showed that the freshwaters of the Alligator Rivers Region of tropical Northern Australia contained around 45 native freshwater fish species; Lake (1966) showed that the Murray–Darling River system which drains most of inland temperate south-eastern Australia contains only about 19 native fish species.

1.3 Ecological conditions of tropical seasonal rivers

Tropical, seasonally flooding rivers are also found in Africa, South America and Asia. Like those of the northern coastlands of the Northern Territory, such rivers inundate immense areas seasonally on scales not known in the temperate regions, and dry out each year to leave flood plains interspersed with creeks, pools and swamps, many of which persist between Wet seasons. Although our studies of the ecology of northern Australian rivers are in their infancy, enough is known about other tropical areas to enable us to draw a general picture of the annual cycle of ecological events. In Africa studies have been made on the Niger, rivers around Lake Chad, the Zambezi, and the Barotse flood plain; in South America rivers both north and south of the equator have been studied; in Asia there is considerable literature available on rivers of the Indian peninsula and the Mekong.

1.4 Ichthyological studies in the freshwaters of the Australian tropical zoogeographic region

New Guinea is Australia's nearest neighbour and is included in the Australian tropical zoogeographic region. The most notable ichthyological surveys completed in New Guinea were those on the Laloki River (Berra et al. 1975), Fly River (Roberts 1978) and Purari River (Haines 1979) systems. Reynolds (1978) also studied the population dynamics of the commercially important species *Lates calcarifer* in southern New Guinea.

Williams (1971) noted that Australia remains the only scientifically developed nation with a marked lack of financial support for fundamental studies on its freshwater systems, despite the importance to the country of water as a basic and relatively scarce resource. Certainly, very little work has been published on the ecology of our freshwater systems, and Lake (1971), in his book on the freshwater fishes and rivers of Australia, highlighted how little is known about our rivers and the fauna they contain.

The tropical freshwaters of Australia have been investigated in even less detail than the temperate freshwaters. Lake (1971, 1978) listed fish species present in northern Australian drainage basins and gave brief notes on the life histories of some of these species. Beumer (1976) studied the fishes of the Black–Alice rivers system in northern Queensland with emphasis on *Therapon (Leiopotherapon) unicolor* and *Nematocentris (Melanotaenia) splendida.* Allen (1975), from a biological survey of the Prince Regent River Reserve, north-west Kimberley, Western Australia, described the freshwater fish communities in that area. Midgley (pers. comm.) has completed extensive freshwater fish surveys in tropical northern Australia, and this information exists in the form of internal reports to the Queensland and Northern Territory Governments and the Office of the Supervising Scientist. Jeffree and Williams (1975) examined the fish communities of the Finniss River, Northern Territory, as possible biological indicators of pollution from the now closed Rum Jungle uranium mine. Hoese and Larson (pers. comm.) in early 1978 surveyed the fish communities of the Victoria River, Northern Territory.

1.5 Previous ichthyological studies in the Alligator Rivers Region

R. R. Miller in 1948 conducted the first significant survey of fishes in the Region during the American–Australian Scientific Expedition to Arnhem Land. The results of Miller's survey, which covered both freshwater and marine fishes in a number of localities in Arnhem Land, were eventually published by Taylor (1964).

As part of the original Alligator Rivers Environmental Fact-finding Study, Pollard (1974) carried out a comprehensive survey and inventory of the freshwater fish species in the Magela Creek catchment of the ARR during the 1972 Dry season. Such a baseline survey was deemed necessary to evaluate the effects of any possible future pollution of these river systems which might result from changing land use associated with uranium mining and processing. The main emphasis of Pollard's survey was on the Magela Creek catchment, the area containing most of the known uranium mineralisation.

A more general survey of the fishes of the 'Uranium Province' was carried out by Midgley (1973), for the Department of the Northern Territory, between September 1972 and July 1973. Dames and Moore (1979) have sampled fish at a number of sites in the Nourlangie Creek system near Koongarra whilst preparing an environmental impact statement for Noranda Australia Pty Ltd on proposed uranium mining and processing in that area. R. Pengilly (pers. comm.) of the Conservation Commission of the Northern Territory (Wildlife Research Section) undertook extensive sampling of small fish species in several shallow backflow billabongs in the area of the Jabiru East township between 1975 and 1978.

A list of the fishes so far collected by previous workers and by us in the Region is presented in Table 1.

1.6 The present study in the ARR

As the reports of Pollard (1974) and Midgley (1973) were primarily on taxonomy and distribution, it was emphasised by Fox et al. (1977) that existing biological and ecological information on the freshwater fishes of the Alligator Rivers Region was inadequate to predict the effects of uranium mining and processing on the fauna, and also any long-term effects on aquatic ecosystems. Further research was required to provide basic background information on the environmental requirements, life histories and

Table 1. Fish species collected in the Alligator Rivers Region (past and present studies)
Please note that some of the names listed here have recently changed — see Explanatory Notes.

Class ELASMOBRANCHII	
Order LAMNIFORMES	
Carcharhinidae	
Carcharhinus leucas[a]	River whaler shark
Order PRISTIFORMES	
Pristidae	
Pristis leichhardtii[a]	River sawfish
Order MYLIOBATIFORMES	
Dasyatidae	
Dasyatis fluviorum[a]	Brown river stingray
Class TELEOSTOMI	
Order ELOPIFORMES	
Megalopidae	
Megalops cyprinoides	Tarpon or ox-eye herring
Order CLUPEIFORMES	
Clupeidae	
Nematalosa erebi	Bony bream
Nematalosa come	Bony bream
Dorosomatidae	
Stoleophorus sp. [a]	Anchovy
Order OSTEOGLOSSIFORMES	
Osteoglossidae	
Scleropages jardini	Saratoga
Order CYPRINIFORMES	
Ariidae	
Hexanematichthys leptaspis	Lesser salmon catfish
Hexanematichthys proximus	Forktailed catfish
Hexanematichthys australis	Forktailed catfish
Plotosidae	
Anodontiglanis dahli	Toothless catfish
Tandanus ater	Narrow-fronted tandan or butter jew
Neosilurus hyrtlii	Hyrtl's tandan
Porochilus rendahli	Rendahl's tandan
Porochilus obbesi	Obbes catfish
Order ATHERINIFORMES	
Hemirhamphidae	
Zenarchopterus caudovittatus[a]	Garfish
Belonidae	
Strongylura kreffti	Long tom
Melanotaeniidae	
Melanotaenia nigrans	Black-banded rainbow-fish
Melanotaenia maculata	Chequered rainbow-fish
Melanotaenia australis	Red-tailed rainbow-fish
Atherinidae[b]	
Craterocephalus marjoriae	Marjorie's hardyhead
Craterocephalus stercusmuscarum	Fly-specked hardyhead
Pseudomugil tenellus	Dainty blue eye
Order SYNBRANCHIFORMES	
Synbranchidae	
Ophisternon gutturale	One-gilled eel
Order PERCIFORMES	
Centropomidae	
Ambassis agrammus	Sail-fin perchlet
Ambassis macleayi	Reticulated perchlet
Ambassis elongatus	Yellow-fin perchlet
Ambassis sp. A	Toothed perchlet
Denariusa bandata	Penny fish
Lates calcarifer	Silver barramundi
Teraponidae	
Amniataba percoides	Black-striped grunter
Hephaestus fuliginosus	Black grunter or bream
Leiopotherapon unicolor	Spangled grunter
Syncomistes butleri	Sharp-nosed grunter
Pingalla sp.	Black-blotched anal-fin grunter
Apogonidae	
Glossamia aprion	Mouth almighty
Sparidae	
Acanthopagrus berda[a]	Pikey bream
Sciaenidae	
Collichthys lucidus[a]	Jewfish
Nibea sp.[a]	Jewfish
Toxotidae	
Toxotes lorentzi	Primitive archer fish
Toxotes chatareus	Common archer fish
Toxotes jaculator	Archer fish
Scatophagidae	
Scatophagus sp.	Butter fish
Mugilidae	
Liza diadema	Ord River mullet
Liza dussumieri[a]	Green-backed mullet
Liza macrolepis	Mullet
Squalomugil nasutus[a]	Mud mullet
Polynemidae	
Polydactylus sheridani[a]	Threadfin salmon

Table 1. Fish species collected in the Alligator Rivers Region (past and present studies) continued

Gobiidae		Periophthalmidae	
Glossogobius giurus	Flat-headed goby	*Periophthalmus* sp.[a]	Mudskipper
Glossogobius aureus	Goby	Kurtidae	
Oxuderces dentatus[a]	Goby	*Kurtus gulliveri*[a]	Nursery fish
Eleotridae[c]		Order PLEURONECTIFORMES	
Hypseleotris compressus	Northern carp gudgeon	Soleidae	
Mogurnda mogurnda	Purple-spotted gudgeon	*Aseraggodes klunzingeri*[a]	Tailed sole
Oxyeleotris lineolatus	Sleepy cod	*Brachirus salinarum*[a]	Salt-pan sole
Oxyeleotris sp.	Black-banded gauvina	*Cynoglossus heterolepis*[a]	Tongue sole
Prionobutis microps[a]	Small-eyed sleeper		

[a] in tidal and estuarine waters only
[b] *Pseudomugil gertrudae* was recorded in 1981.
[c] *Oxyeleotris nullipora* was recorded in 1984.

general biology of the freshwater fishes of the area, their sensitivities to contaminants, and the ecological interactions between species.

The present study had two primary aims: to collect basic background information on the freshwater fish species in the Region (presented in Volume III – Autecology) and to collect information on the environment and community structure – and the seasonal changes in these – of the various freshwater fish communities of the Region, as a means of developing field detection (monitoring) methodologies (presented in Volume II – Synecology). Its secondary aims were to collect information that would provide a useful basis for future predictive experimentation (waste water toxicity studies) and to advise on the best practicable approaches to minimise adverse effects on the fish fauna of the Region due to uranium mining and milling operations.

The objectives of the study were thus:

1. (*Background information*:) to collect and interpret basic biological, synecological and autecological data on the freshwater fishes of the ARR for use in evaluating the effects of possible changes associated with future uranium mining and processing in the area;
2. (*Detection methodologies*:) to attempt to delineate those biological and ecological features of the fish fauna and variables of the aquatic environment that are most sensitive to these human-induced changes and that are likely to prove of greatest value in a continuing monitoring program, and to indicate how they can be most reliably sampled and usefully measured;
3. (*Prediction*:) to gather more detailed biological and ecological data on selected fish species for use in the interpretation of data from future waste water toxicity studies; and
4. (*Advice*:) to advise, on the basis of the experiences of fisheries protection organisations and the local data collected, on the best practicable ways of minimising adverse effects on the fish fauna that might result from uranium mining and milling operations in the ARR.

1.7 Other studies in the ARR

CSIRO, in conjunction with the Northern Territory Fisheries Division, had a Barramundi Research Team (T. Davis and D. Grace) studying the population dynamics and general biology of *Lates calcarifer* in the Region from early 1978. To avoid overlap with the work of this team intensive sampling of *L. calcarifer* was not undertaken during the present study.

Since late 1978, Pancontinental Mining Limited has had a fish ecology study group sampling billabongs in the lower Magela Creek catchment, adjacent to its proposed mining and processing sites. Many of the sites examined by this study group are included in our standard sampling sites. Following consultation with us, the Pancontinental study group developed similar sampling methods and formats for data recording and analysis.*

*The Pancontinental study was discontinued in 1983 – ed.

2

The study area

2.1 Geographical position

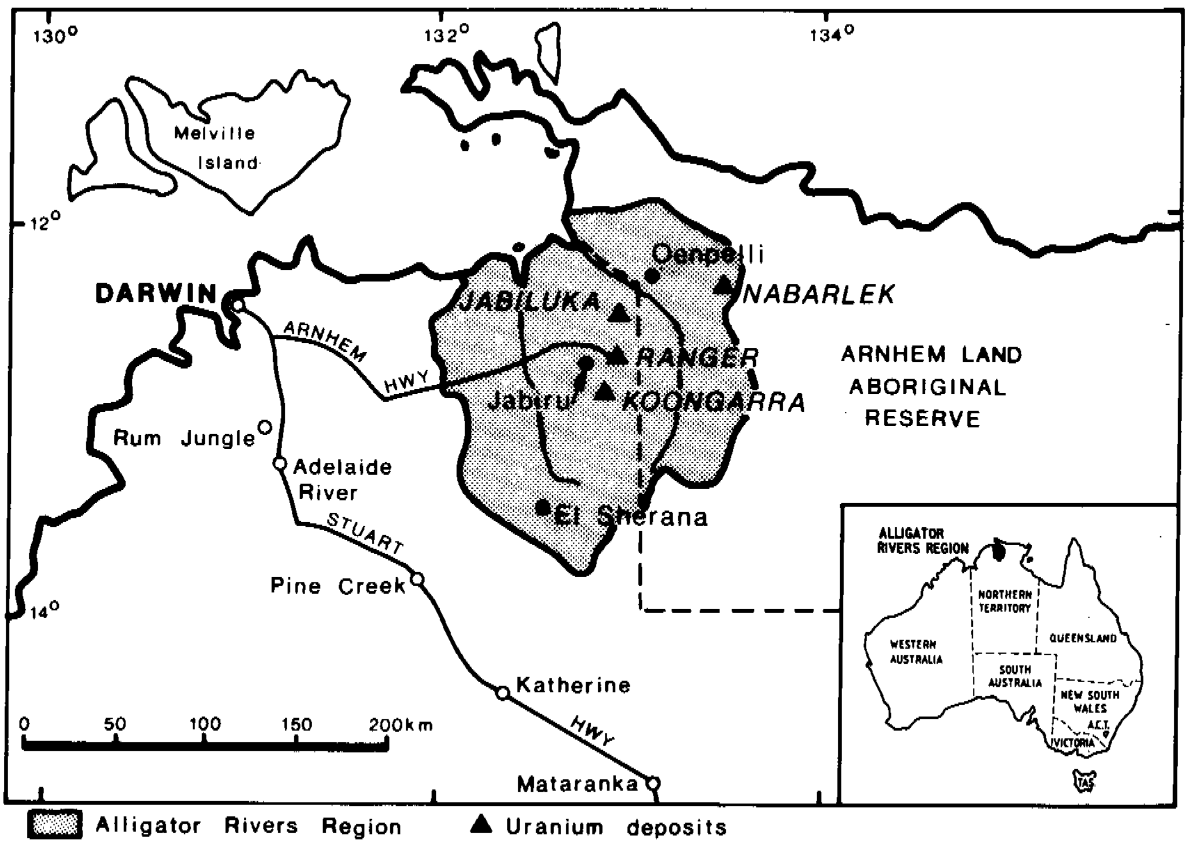
The study area lies within the area defined by Fox et al. (1977) as the Alligator Rivers Region in the tropical northern coastlands, or 'Top End', of the Northern Territory, Australia (Map 3). Distribution of freshwater fish in the ARR lies within Australia's tropical northern coastal drainage system (Pollard et al. 1980); this system includes Whitley's (1947) 'Leichhardtian fluvifaunulae' and Lake's (1971) north-eastern slopes, Gulf of Carpentaria, Timor Sea and Indian Ocean drainages. The fish fauna of this northern drainage system has close zoogeographic affinities with the fauna of southern New Guinea (Pollard 1974).

The present study is mainly concerned with the catchments of the East Alligator River including Cooper Creek, and the South Alligator River. These catchments drain, in a generally north-westerly direction, a total area of 19 920 square kilometres into the Arafura Sea via Van Diemen Gulf, and are located between approximately 200 and 300 kilometres east of Darwin (lat. 12°20′S; long. 131°00′E). Magela Creek is a northward-flowing tributary of the East Alligator River and drains an area of approximately 1700 km^2 in and adjacent to western Arnhem Land. The Alligator Rivers catchments contain a diverse range of aquatic habitats which were, until recently, virtually pristine in character except for the influence of the feral water buffalo.

2.2 Physiography and aquatic habitat types

Details of the physiography of the Region have been given by Story et al. (1969), Fox et al. (1977) and Christian & Aldrick (1977).

The Region comprises five distinct subregions: the plateau, lowlands, flood plains, tidal flats, and southern hills and basins (Christian & Aldrick 1977). The present study was chiefly concerned with the first three subregions; however, some attention was afforded the tidal areas. Further subdivisions of these four subregions resulted in catchments being examined according



Map 3. Location of the Alligator Rivers Region in Australia

to the following eight zones: plateau, escarpment (interface zone), lowlands, corridor (interface zone), upper flood plains, lower (riverine) flood plains, estuarine upper reach areas and estuarine middle and lower reach areas (Map 1). Aquatic habitat subdivisions are also indicated in the following sections.

Plateau habitats

The plateau is a massive sandstone formation towering up to 250 metres above the adjoining lowlands. Its rocks are nearly 2000 million years old. It once covered a much larger area but erosional forces have caused a gradual retreat in a south-easterly direction to its present position, leaving some outliers and exposing uranium mineralisation in the adjacent lowlands.

The plateau is mainly composed of bare rock and thin soils with a scanty vegetation cover of spinifex (*Triodia*) and shrubs. All major streams in the Region have their headwaters in the plateau, most of which is made inaccessible to the aquatic fauna of the lowlands by many high vertical drops at the escarpment in the courses of the rivers and streams.

Escarpment area habitats (Plate 1 a–d)

The irregular edges of the plateau, and the intruding gorges, sometimes along fault lines, form an escarpment area which drops abruptly and is scenically striking. The escarpment is over 600 km long and extends southwards from the East Alligator River to near Katherine, and eastwards into the Arnhem Land Aboriginal Reserve (Map 1).

Most of the channels and streams in the escarpment area are scoured by floodwaters, and some banks are frequently inundated during the Wet season. Waters in this zone are relatively cool and clear, though phytoplankton populations generally build up towards the end of the Dry season.

Main-channel waterbodies. The escarpment contains many large waterbodies, which may be up to 1.5 km in length and up to 7 m deep, along the main channels within deep gorges. The gorges usually terminate upstream in rockpools, which, though usually less than 100 m in diameter, may be up to 15 m deep, into which waterfalls and cascades drop from the plateau (Plate 1 a). Erosional forces are active in the upper bedrock reaches of the escarpment gorges, resulting in the deposition of sand and sometimes shingle at the lowland mouths of the gorges where the waters are slower flowing. In places the banks of the waterbodies are steep and generally covered by thick rainforest vegetation (Plate 1 b); in other places shelving or vertical bedrock outcrops predominate. Submerged fallen timber is often associated with the rainforest vegetation.

Seasonal feeder streams. Small feeder streams, generally less than 4 m wide, enter the main channels during the Wet season. These streams are transformed into a series of small isolated rock pools during the Dry season. Rainforest vegetation often surrounds these habitats.

Perennial streams. The flow in small (generally less than 4 m wide) spring-fed perennial streams (Plate 1 c) persists all year round in these habitats onto the lowlands for a few kilometres, or to main-channel escarpment waterbodies. In the Dry season these streams arise from groundwater trapped in aquifers underneath the plateau, then flow over bedrock and boulder substrates and through the extensive, exposed root systems of the dense rainforest vegetation which encloses most of these habitats.

Lowland habitats (Plates 2, 3, and 4)

The present land surface of this zone has been formed by erosion and deposition of eroded materials from the escarpment and the plateau. This is an undulating zone with low hills and ridges, where the soils are sandy or loamy and highly susceptible to erosion if disturbed. Terrestrial vegetation is either open *Eucalyptus* forest, woodland or scrub. Tall grasses grow in the Wet season, and fires usually sweep through these in the following Dry season.

Sandy creek bed pools/channels. All creek beds in this zone are scoured by Wet season flows, have shifting sandy substrates, and are surrounded by rainforest and lowland flora (Plate 2). Heath (1978) noted that the seeds of some of the rainforest genera wash down from the escarpment country in times of Wet season flow and establish themselves along the creek banks. In some areas along the creeks there is an intermingling with typical lowland plant communities such as those of *Melaleuca* and *Pandanus*, but in general the rainforest elements have a greater overall dominance. During the Wet season hydrophytes abound around the submerged clayey banks of the creeks.

In the Wet season there is continuous flow along each creek channel, but in the Dry season the channel dries out to leave a series of isolated pools.

Backflow billabongs. Muddy billabongs with shelving clay banks exist in the lowlands on tributaries and on some anabranches of the main creek channels (Plates 3 and 4). Most of these waterbodies are near the mouths of tributaries or in depressions behind levees beside the main channels. Depending upon the distribution of rainfall in the catchments during the Wet season, water either flows through to the main stream, or 'backflows' from the main channel to the billabongs and up the tributaries. Backflow tends to deposit fine sediments and organic matter. Thick hydrophyte growth occurs in most of these billabongs in the Wet season as their banks, wooded with *Melaleuca* spp. and sometimes *Barringtonia acutangula*, are submerged by floodwaters.

Corridor habitats (Plate 5 a)

This zone contains a series of large (up to 1 km in length), deep (up to 5 m) stream channels and waterholes which effectively funnel waters between the lowlands and the upper flood plains. These waterbodies are well flushed each Wet season by the main creek flow and remain relatively cool and clear for most of the year. The steep banks are thickly covered by *Pandanus aquaticus*, *Brachiaria mutica* and *Melaleuca* spp. and the sediments of the billabongs are very sandy. Hydrophytes are only found in slow-flowing waters around edges. Hart & McGregor (1982) indicated that these habitats probably receive seepage from surrounding sandy aquifers for some time after the creek flow stops.

Upper flood plain billabong habitats (Plate 5 b and c)

Williams (1979) indicated that the substrate in these areas was probably formed when clay and mud material was deposited in river estuaries. These floodplain areas then emerged from the estuary as a result of a rise in land surface or a drop in sea level. Williams noted that the floodplain portion of the Magela Creek system covers about 150 km^2 of the 1700 km^2 of catchment, and consists of poorly drained *Melaleuca* swamps, open perennial and annual swamps, billabongs and grass/sedge herb fields. The billabongs on the flood plains are deep (up to 6 m) and have mud/clay bottoms with shelving clay banks. It is unlikely that they are significantly scoured by Wet season flows, which appear to travel relatively slowly over the flood plains (Hart & McGregor 1982). Depressions around the margins of the flood plains may first receive water from runoff from adjacent catchments or from spillover from the main streams. Williams (1979) noted that an unusual feature of the Magela Creek flood plain is that it has no continuous channels, and so the manner of water movement across it is not readily discernible. He concluded that the Magela flood plain forms a large freshwater 'lagoon' isolated from the East Alligator River at the end of the Wet season. The hydrophyte types present are direct indicators of water depth within the 'lagoon', the capacity of which is approximately 60×10^6 m^3. The average daily input during the Wet season is approximately 3% of the total 'lagoon' volume. During the Dry season the billabongs that remain contain only about 5×10^6 m^3 of water.

The vast expanses of water across the flood plains and the lush growth and diversity of hydrophytes are notable features in the Wet season. The declining water level and the corresponding demise of these hydrophytes result in increasing concentrations of suspended matter in the water. Turbidity increases owing to wind action on the sediments, especially after the mat-like cover of hydrophytes has decreased, allowing wind-generated currents to penetrate the water column (Walker & Tyler 1979). Water buffalo and Magpie Geese also contribute to the increase in turbidity by stirring up bottom sediments in these habitats.

Lower (riverine) flood plain billabong habitats (Plate 6 a)

Habitats examined in this zone were restricted to the riverine flood plain of the East Alligator River. The Magela Creek flood plain was found to be enclosed by the higher elevation flood plain of the East Alligator River. This barrier has been maintained by sediment deposition from East Alligator floodwaters. Within this riverine flood plain area is a series of large (up to 5 km in length), deep (up to 7 m) billabongs, usually found at the base of escarpment outliers; these billabongs lose their identity during the Wet season as water from the East Alligator River spreads over the plains and covers them. Some of the billabongs are well flushed in wet years, as they become active channels for the East Alligator floodwaters. The vegetation on these flood plains consists of forest and perennial herbs. Thick vegetation in some areas surrounds these billabongs, but generally this vegetation is not nearly as well established as in some of the upper flood plain billabongs. Seasonal trends in the development of hydrophytes and turbidity appear to be similar to those in the upper flood plain. During the Dry season salt intrusion into the riverine flood plain may occur from the estuarine reaches of the East Alligator River.

Estuarine habitats (Plate 6 b–d)

An estuary is an aquatic habitat in which fresh water from streams or rivers mixes with salt water from oceans or seas. An estuary is therefore an area subject to regular tidal flushing and is essentially a transitional zone (ecotone) between two habitats. Estuaries are characterised by wide variation in salinity, tidal and stream current turbulence, and turbidity and siltation; seasonal and daily fluctuations in these factors are among the greatest found in any habitat.

Upper reaches. Habitats examined were restricted to the main channel and anabranches of the East Alligator River. A road ford across the river at Cahill's Crossing, 95 km upstream from the river mouth (Map 1), reduces the tidal influence from the estuary upstream from this point. However, tidal variation above the ford may reach 2 m (as water flows upstream over the ford at high tide), and the water in this area in the Dry season could be described as brackish. During the Wet season, the limit of incursion of brackish water is displaced downstream as East Alligator floodwaters thoroughly scour the channel and overflow on to its plain. Substrates near the ford are estuarine silts, and these are nearly completely replaced by sands within 2 km upstream. Above the ford, a channel, about 5 m deep and less than 50 m wide, with small hydrophyte-rich first-order feeder streams is impounded; the banks are steep and covered with rainforest, and much associated fallen timber is submerged.

The river ceases to flow in the Dry season except under the influence of spring tides, but close to the limit of tidal influence it has a sandy bed about 200 m wide. Associated with this section of the river are a number of anabranches, up to 2 km long and 6 m deep, which are connected to the main river by narrow channels. Hydrophytes are rare in these habitats and the banks are steep and mainly rocky, and in places fringed with *Pandanus* and *Melaleuca.* The water in these anabranches remains clear for most of the year and becomes brackish by the end of the Dry season; the anabranches are thoroughly flushed by fresh water in the Wet season.

Middle and lower (meandering) reaches. Fox et al. (1977) noted that the substrates in these reaches consisted of marine clays and muds and some low beach ridges with coarse sandy soils. Their vegetation consists mostly of sedges and salt-tolerant species with areas of mangroves and semi-deciduous forest. Most of this area is regularly inundated by brackish to marine water. Williams (1979) noted that the East Alligator River is estuarine at its junction with Magela Creek, and in the Dry season the tide flows into small stream systems in this area. The velocity of tidal flow in the main channel and the larger tributaries of these stream systems may exceed 1 m/s. Two features of these small stream systems near the Magela Creek mouth are firstly that their channels are incompetent (Morisawa 1968), and secondly that although stream channels are present, they are discontinuous between the estuary and the freshwater flood plain.

2.3 Generalised seasonal cycle

The general sequence of events in tropical seasonal rivers is similar throughout the tropics in Africa, South America, parts of South-East Asia, India and Australia, and both north and south of the equator. However, the floods come at different times of the year and are of different intensities.

Climate

Rainfall. The Alligator Rivers Region, in common with much of far northern Australia, has a monsoon-like climate. The Dry season lasts from about May to September, and virtually the entire annual rainfall occurs in the Wet season, which varies in length but is generally confined to the November–March period. October and April appear to be transitional months (Fox et al. 1977). For the present study a more detailed identification of season was often needed, and a system of five seasons was used, as outlined in the Explanatory Notes. The names used for these five seasons — Late-dry, Early-wet, Mid-wet, Late-wet–Early-dry and Mid-dry — show their relationship to the major division of the year into Wet and Dry seasons.

The equatorial or monsoonal troughs and the organised convection system often produce widespread rain. Tropical cyclones produce intensive rain over restricted areas; local convection systems result in thunderstorms and showers, the intensities of which may be high for short periods. Easterly disturbances intervene to extend the rainfall season in some years (Christian & Aldrick 1977).

Average monthly rainfalls for Jabiru during the 9 year period from 1971 to 1979 are shown in Fig. 1 together with actual monthly rainfalls during each Wet season from 1971–72 to the end of the study period.

The total rainfall (1490 mm) of the 1978–79 Wet season within the study period was slightly less than average (1560 mm). This Wet season also appeared to start earlier than average, as did the 1971–72, 1974–75 and 1975–76 Wet seasons. The monthly rainfall peaked only once (in January) during the 1978–79 Wet season, unlike the years 1972–73, 1973–74, 1976–77 and 1977–78. Seasons such as 1971–72 and 1974–75, which also peaked only during one month, had most of their rainfall in February or March. The 1978–79 season appeared to end earlier and more abruptly than other years, as April 1979 had the lowest rainfall for that month on record. Similar early ending of the rains occurred in the 1971–72 and 1977–78 seasons. Extended rains occurred during the 1973–74 and 1976–77 seasons.

The 1979–80 Wet season commenced later and at its beginning was less intense than average.

Temperature and evaporation. A prominent feature of the Region's climate is the high temperature sustained throughout the year. The mean annual temperature is approximately 27°C and the range of mean monthly temperatures is only 5.6°C. A mean monthly maximum of 38°C occurs in November, and a mean monthly minimum of 18°C occurs usually in July.

Estimated mean evaporation in the Region is about 100 mm in February, but rises to 260 mm in October at the end of the Dry season. The mean annual evaporation is about 2200 mm (Christian & Aldrick 1977).

Hours of sunshine. A small range in day length occurs at this latitude, the shortest day (11.2 h) occurring on June 21, and the longest (12.7 h) on December 21. The mean hours of sunshine, however, vary inversely to this; during the Dry season they range between 9.7 and 10.2 hours per day, but in the generally overcast Wet season the number drops to between 4.5 and 7.5 hours per day (Christian & Aldrick 1977).

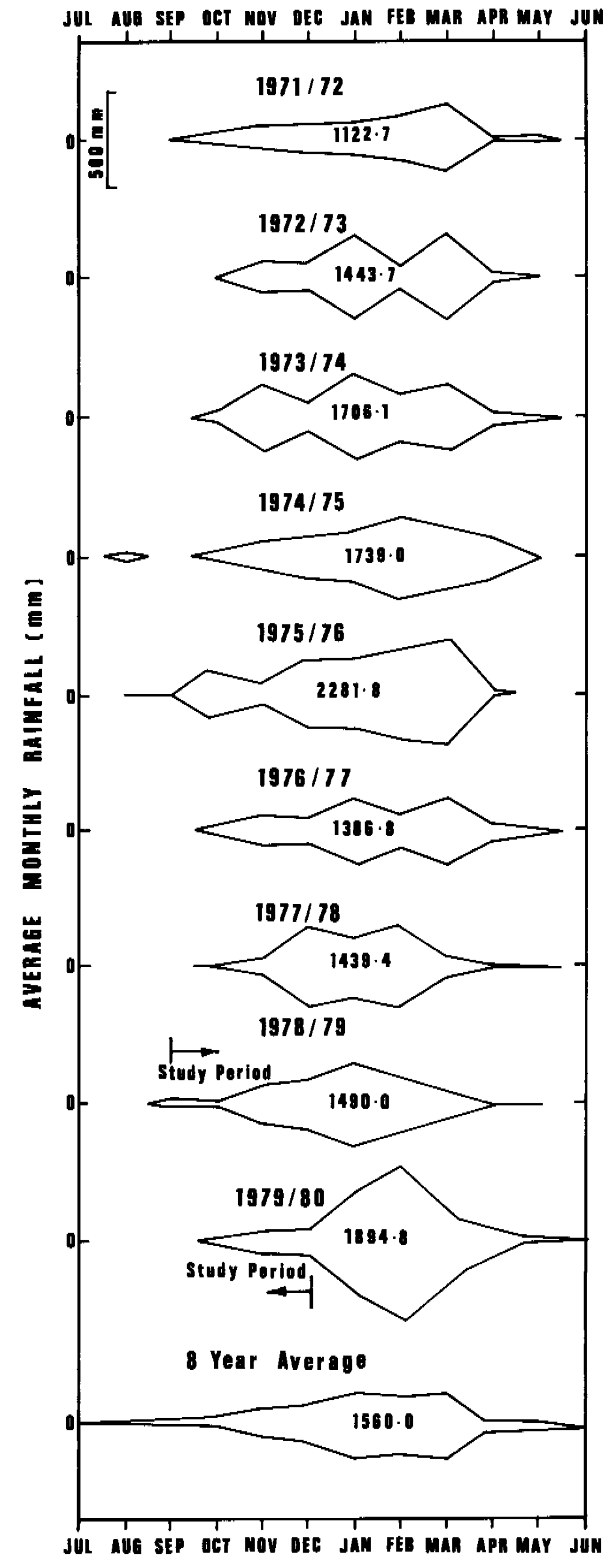


Figure 1. Rainfall distribution at Jabiru during each Wet season 1971–72 to 1979–80

Hydrological regime

The seasonal rainfall pattern of the Region causes great variations in the hydrological regime of its rivers and creeks. The area and volume of the total aquatic environment thus fluctuate seasonally, and may vary considerably from year to year. Such variations may have important effects on fish growth and survival (Lowe-McConnell 1975).

The Region's rivers and their tributaries flow in the Wet season when a series of flood peaks is superimposed on a base flow which begins in an average year during mid December and ceases about the end of June (Hart & McGregor 1982). In most rivers, the flood peaks occur well after the rains have started, the time of which may also vary from year to year. The flow increases the diversity of the aquatic environment; large areas, notably flood plains and lowlands, take on a quite different appearance when the Wet season follows after months without rain. Upstream escarpment habitats are relinked with all downstream habitats in their respective catchments. The rising waters first run down the channels and creeks on to the flood plains, connecting ponds and swampy areas that were isolated in the Dry season. Water floods over banks which delineate the channels and billabongs, and on to the flood plain, forming a vast sheet of water a few metres deep and of variable extent – for example, in the flood plains of Magela Creek about 200 km^2 are flooded in most years and it is estimated that, on average, the area flooded may extend to more than 300 km^2 once in ten years and to nearly 500 km^2 once in 100 years (ANPWS 1980). Decreased runoff and channel storage effects result in lower flood peaks on the flood plains than further upstream (Galloway 1976).

In most tropical seasonal habitats flood peaks are of great importance to fish because their breeding activity is usually limited to the few first flood peaks of the Wet season flow. The main feeding, growing and fattening season for fish is during high water or peak flooding periods when most of the usually dry land is submerged. Fish movement is also at its maximum during this period (Lowe-McConnell 1975).

As the rainfall decreases towards the end of the Wet season, a much reduced flow continues for a few months into the Dry season and the flood plains remain extensively flooded for many months. In the Dry season some water remains in rock pools in the plateau and escarpment areas and in billabongs in the lowlands and flood plains. The number of waterholes that persist throughout the Dry season varies from year to year, as does the amount of water left in permanent aquatic habitats. In some unusually wet seasons a number of creeks may flow along their entire courses all the year; such all-year flow is otherwise limited to escarpment reaches of some streams.

Peak flood discharges of the rivers and creeks of the Region for various years have been calculated by the Water Division of the Northern Territory Department of Transport and Works. Mean daily water flows in Magela Creek near Jabiru East (Gauge Station GS 821009) from

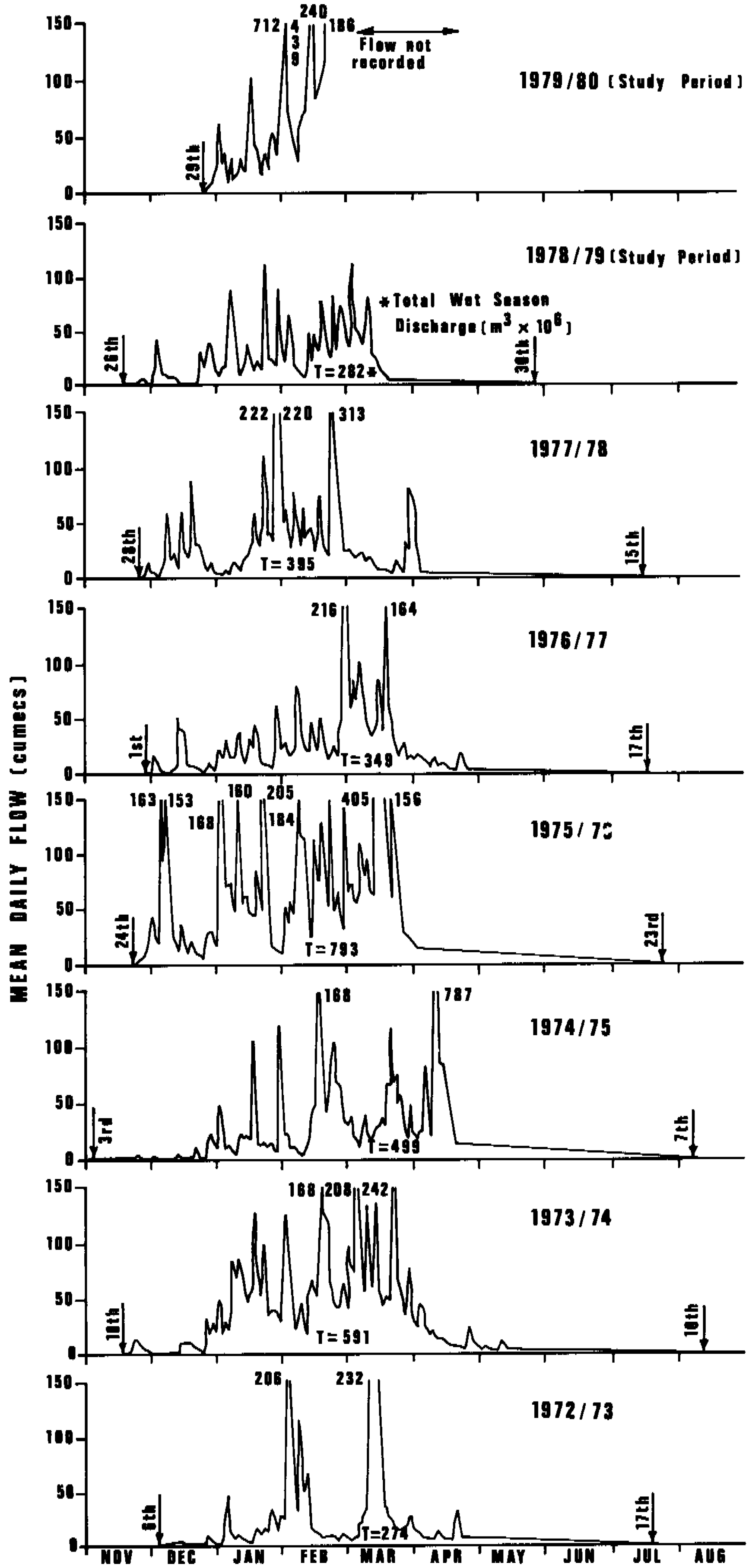


Figure 2. Hydrological regime of Magela Creek during each Wet season 1972–73 to 1979–80 measured at GS 821009 (near Jabiru)

water years 1972–73 to 1978–79 (the study period Wet season) are shown in Fig. 2.

The total discharge of Magela Creek during the 1978–79 Wet season, which fell in the study period, was 282 × 10^6 m^3. This was much lower than average (approx. 450 × 10^6 m^3) and nearly the lowest for any season on record. Flow in the creek commenced on 26 November; this timing appears to be fairly typical of the Wet seasons recorded. The flow comprised a series of flood peaks, most of which were small compared with earlier years, and ceased on 30 May, six weeks to two months earlier than average. The maximum flow in the 1978–79 season was approximately 110 cubic metres per second, a rate that had been exceeded during all water years between 1972–73 and 1977–78. Thus the 1978–79 Wet season in the Magela Creek catchment was much drier than usual and may be considered atypical.

In the 1979–80 Early-wet season (the end of the study period), no major flows had commenced in the systems examined by 15 December. However, flows in escarpment areas in Magela Creek reached to just upstream of the Ranger Uranium Project Area (RUPA) and then the flow front began to recede. Some billabongs within RUPA received some local runoff during this month.

2.4 Waterbody classification schemes

Three separate study groups (Davy & Conway 1974; Hart & McGregor 1982*; Walker & Tyler 1979) have developed classification schemes for waterbodies in the Magela Creek catchment using as criteria characteristics such as influence of groundwater input, productivity, bottom substrate, bank inclination and vegetation, water depth, temperature and clarity, and the nature and extent of surface water inflow. Table 2 summarises these classifications.

Davy & Conway (1974) divided the waterbodies into Class I and Class II, corresponding respectively to the channel and backflow billabongs of both the Hart and the Walker studies. The Class II waterbodies of Davy and Conway were subdivided into those hydrologically isolated, and those associated with perched water tables. Walker and Tyler (1979) followed this subdivision of backflow billabongs. However, they defined a third backflow type as being highly productive.

Hart & McGregor (1982) defined floodplain waterbodies and Walker & Tyler (1979) subdivided these into Class A (non-eutrophic, muddy bottom) and Class B (eutrophic, firm clay bottom, muddy margin). Walker & Tyler (1979) defined escarpment billabongs as a fourth general waterbody type.

The present study followed the broad classification system developed by Walker & Tyler (1979) and Hart & McGregor (1982), i.e. channel, backflow, floodplain and escarpment waterbody types. Habitats other than these four were also examined (see Section 2.2).

2.5 Artificial changes to the environment

Uranium mining and processing

The locations of existing uranium mining and processing developments and of other major uranium deposits in the Region are shown in Map 1 (see also Fox et al. 1977).

Ranger project. The layout of the Ranger Uranium Project Area (RUPA) in relation to the Magela Creek drainage system is shown in Map 4.

Construction and operation of the mine and mill might be expected to have various ecological effects about the mine site, along service routes, and in the adjacent and downstream areas of the Magela Creek drainage system. The removal and disturbance of vegetation and substrate could lead to erosion and sedimentation of streams, and the mining of sand from creek beds could result in the destruction of habitat. Changes in the local water flow regime and seepage patterns could also occur, depending on the extent of the above disturbances and the success of control measures.

A much larger area could be affected by discharges and/or seepage of waste water. The main substances contained within waste waters are likely to be copper, zinc, manganese, uranium and radium. Discharges of aqueous wastes from retention ponds and seepage from these ponds and the tailings dam could affect the whole Magela drainage system downstream of Jabiru East, including the flood plains and the East Alligator River estuary, and possibly also underground waterbodies. The degree to which these areas might be affected would depend largely on the extent and nature of the environmental control measures adopted.

Air pollution, mainly in the form of sulphur dioxide emissions from the acid treatment plant and radon and dust from the mining and milling operations, would have its main influence within the mineral lease, and its extent would be generally determined by wind direction and speed.

Other uranium mining projects. It may be assumed that the mining development by Queensland Mines Limited at Nabarlek and the developments proposed by Pancontinental Mining Limited and Noranda Australia Ltd at Jabiluka and Koongarra respectively, would have ecological effects similar in kind to those of Ranger. Such effects would vary according to the size of the projects and their rate of production, their location, the nature of the site and the orebody, and the water management and tailings disposal systems adopted.

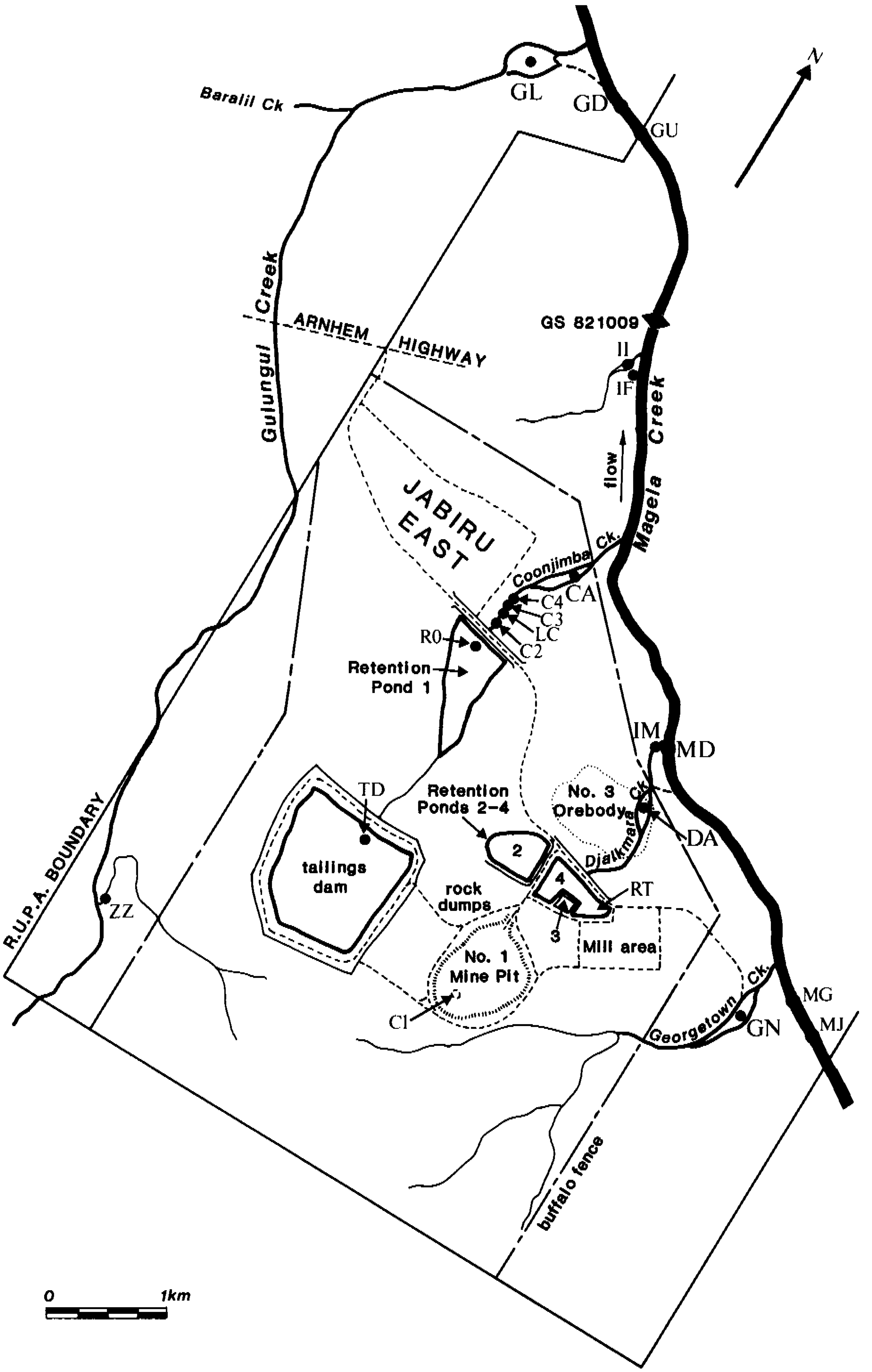
Jabiluka is on the edge of the Magela flood plain downstream from Jabiru, and hence any wastes discharged to the adjacent waters would add to those reaching that area from Jabiru.

*Report published since this manuscript was written — ed.

Table 2. Classification of waterbodies

Feature	*Davy & Conway (1974)*			*Hart & McGregor (1982)*			*Walker & Tyler (1979)*						
	Class I	*Class II*		*Channel*	*Backflow*	*Floodplain*	*Channel*[a]	*Backflow*			*Floodplain*		*Escarpment*
		Subclass A	*Subclass B*					*Class A*		*Class B*	*Class A*	*Class B*	
								Subclass I	*Subclass II*				
Groundwater inflow	–	Isolated	Associated with perched water table	Sandy aquifers	–	–	Sandy aquifers	Isolated	Associated with perched water table	–	Suspected groundwater seepage		–
Production	–	–	–	–	–	–	–	Low (plankton low)		High (plankton high)	–	Eutrophic	–
Substrate	Sand	Fine, impervious black clay		Sand	Fine silt and organic material	Muddy	Sand	Fine black clay			Muddy	Firm clay, muddy margins	Rock and sand
Bank	Steep	Gradually sloping		Steep	Shelving clay banks	Shelving	Steep	Shelving			Shelving		Rocky
Bank vegetation	–	–	–	Well vegetated	Little present	Some present	–	–	–	–	–	–	–
Depth	–	–	–	Deep	Shallow (1–2 m)	Deep (3.3–4.4 m)	Deep	Shallow			Deep		Deep
Temperature	Cool	Hot, may reach 40°C		–	–	–	Cool	Hot, may reach 40°C			Hot, may reach 40°C		Cool
Clarity	Clear	Becomes very turbid		Clear	Becomes very turbid		Clear	Becomes very turbid			Becomes very turbid		Clear
Surface inflow/ outflow	–	–	–	Well flushed	Tributary catchment or channel (backflow)	Loses identity as channel spreads over plain	–	Varying periods of backflow			–	–	Permanent

[a] called corridor in the present study



Map 4. Layout of the Ranger Uranium Project Area in relation to the Magela Creek drainage system, showing locations of sampling sites not included on Map 2. Regular sampling sites are identified by larger type, occasional sites by smaller.

Nabarlek is in the Cooper Creek catchment of the East Alligator River, and Koongarra is in the Nourlangie Creek catchment of the South Alligator River.

Other land uses

Regional urban centre. Increased numbers of people in the proposed township could have undesirable ecological effects in this previously very sparsely populated area. Over-fishing of local creeks and waterholes may occur once large numbers of people become established in the Region. Sewage and other wastes, and runoff and drainage likely to contain fertilisers, pesticides and other chemicals, would affect some areas. The treated sewage effluent and drainage from the township would enter Barralil and Corndorl creeks*, and thence reach the main channels of the Magela system.

Pastoral industry. The ecological effects of pastoral development on Mudginberri and Munmarlary stations include interference with wildlife habitats because of grazing and trampling of the vegetation by buffalo. Feral buffalos have already caused damage in and around, and pollution of, waterbodies and drainages in the lowland country and on the flood plains (Christian & Aldrick 1977). Fertilising of improved pastures and the use of pesticides and other agricultural chemicals could also contribute to water pollution.

Artificial waterbodies

Costeans. A costean is a small pit which remains after topsoil and subsoil have been removed by heavy machinery. Costeans are constructed to expose rock formations at mineral prospecting sites and usually fill with water in the Wet season from sheet runoff. A number of water-filled costeans were present in the Ranger Uranium Mines lease area over areas of extensive uranium mineralisation.

Retention ponds. A functioning uranium mine and mill produce large amounts of potentially contaminating water within the mine site. This water would include runoff and seepage from the ore stockpiles and waste rock dump, water pumped from the mine pits, seepage and runoff from the tailings dam, and runoff from other parts of the site. Essential features of the proposed waste water management scheme for the Ranger development (Map 4) are four retention ponds to impound catchments that drain the mine site. These ponds were constructed towards the end of the study period during the 1979 Dry season. The largest pond has a surface area of approximately 0.2 km^2 and a present maximum depth of 5.5 m (1980). All trees and topsoil were removed before the retention ponds filled.

Tailings dam. The tailings dam at the Ranger development was also constructed towards the end of the present study period. The storage area is approximately 1 km^2, with a total embankment length of 4 km and a height above ground level ranging between 16 and 30 m. A water depth of 2 m over the solid tailings will be maintained where possible.

Other waterbodies. Other artificial waterbodies in the area include silt traps constructed adjacent to roadways and drainage channels, a sewage treatment works, and a proposed† artificial lake near the new regional urban centre.

*In October 1980 a sewage release point was constructed on the western bank of Magela Creek, just upstream of sites GL (Gulungul Billabong) and GD.

†Completed 1980 – ed.

Materials and methods

3.1 Sampling design

Sampling sequence

Fish were collected during eight sampling periods, including that of the pilot survey (Pollard & Bishop 1978), in the course of the study, which lasted from August 1978 to December 1979. These *regular* sampling periods were timed to coincide with periods of maximum biological activity, based on the Wet–Dry seasonal cycle of events rather than on a fixed time interval approach. The relationships between sampling period, the Wet–Dry seasonal cycle, water flow and date are given in Table 3. The 1979 end of Wet and beginning of Dry season samplings were merged to form one sampling period (No. 4: Late-wet–Early-dry), as flow subsided very rapidly in the watercourses at the end of the 1978–79 Wet season. This period (No. 4) therefore appeared to be representative of the time when the flow was subsiding, and fish communities were becoming isolated in Dry season habitats.

Sites sampled on an *occasional* basis gave valuable information on the continuity of fish distributions. Regular sampling at these sites was impossible owing to difficulty of access and the resultant incompatibility with established sampling schedules.

Sampling sites

The ecological effects of any controlled or uncontrolled releases of wastes from the Ranger Uranium Mines Pty Ltd development near Jabiru would be expected to become apparent first in Coonjimba, Gulungul, Georgetown and Djalkmara creeks and their associated waterbodies in the Magela Creek system. An intensive program to sample regularly the freshwater fishes in these areas was thus undertaken as a part of a wider monitoring program for the whole Magela Creek system. Upstream 'control' sites representative of habitats present downstream of the Ranger site were also sampled regularly. The fish faunas of sites adjacent to the other three major uranium deposits (Jabiluka, Koongarra and Nabarlek) were sampled occasionally, as were other sites outside the Magela catchment, in order to provide additional information on fish distributions.

A list of all sites sampled during the study is shown in Table 4. This table gives for each site the following information: drainage system; site name and code; geographic zone; distance to creek mouth at estuarine reaches; stream order; elevation; map name and number with grid reference; and latitude and longitude.

A summary list of regular and occasional sampling sites (site codes only), grouped separately according to drainage systems and habitat types, is shown in Table 5. The locations of occasional and regular sampling sites are shown in Maps 2 and 4.

3.2 Recording of environmental data

Habitat-structural and physico-chemical variables were recorded at each of the sampling locations outlined in the previous section. Values were recorded on data cards A and E (see Appendixes 1 and 2) in the field at the beginning of each fish sampling operation.

The date, starting time, sampling location code, sampling method, and mesh size provided a unique reference code for each sample (see Appendix 1).

Table 3. Relationship between sampling season, water flow and sampling period

Sampling season	*Flow condition*	*Period no.*	*Dates*
Mid-dry 1978	No flow	P[a]	5–23.viii.78
Late-dry 1978	No flow	1	6.ix.–22.x.78
Early-wet 1978-79	Flow commenced	2	1–22.xii.78
Mid-wet 1978-79	Peak flow	3	3.ii.–9.iv.79
Late-wet–Early-dry 1979	Flow subsiding	4	2.iv.–10.v.79
Mid-dry 1979	No flow	5	9–27.vii.79
Late-dry 1979	No flow	6	27.ix.–16.x.79
Early-wet 1979-80	No flow, rains	7	26.xi.–11.xii.79

[a] P = pilot study.

Table 4. List of sampling sites with associated information
Abbreviations in column 1: Bb. = Billabong; Ck = Creek.
Abbreviations in column 3: EL = estuarine middle and lower reaches; EU = estuarine upper reaches; LFP = lower flood plains; UFP = upper flood plains; C = corridor; L = lowlands; E = escarpment (valleys and gorges); P = plateau.
Abbreviations in column 5: A = anabranch; FP = flood plain; I = impoundment; ? = stream order undetermined.

Site name	*Site code*	*Zone*	*Distance to estuary (km)*	*Stream order*	*Elevation above sea level (m)*[a]	*Map and no.*[b]	*Grid reference*	*Latitude S*	*Longitude E*
EAST ALLIGATOR RIVER CATCHMENT									
East Alligator River									
Magela mouth	MMa	EL	0	2	5	East Alligator 5473	680425	12°16′	132°52′
Tidal creek	MMb	EL	0	1	5	East Alligator 5473	791360	12°21′	133°56′
Western Red Lily Bb. (on anabranch)	WL	LFP	1	FP	7	East Alligator 5473	791327	12°22′	133°58′
Cannon Hill Bb. (on anabranch)	CH	LFP	4	FP	7	East Alligator 5473	773313	12°22′	133°57′
Cahills Crossing	CC	EU	0	?	20	East Alligator 5473	787252	12°26′	132°58′
Rock Hole	RH	EU	2	?	20	East Alligator 5473	801215	12°28′	132°59′
Cooper Creek system									
Cooper Creek									
Maybangul Bb.	MY	L	120	5	40	Oenpelli 5573	197485	12°13′	133°20′
Bullwidgi Bb.	CD	L	121	5	40	Oenpelli 5573	194473	12°14′	133°20′
Adgibongololo Creek									
Adgibongololo Ck	AU	L	133	3	40	Oenpelli 5573	173367	12°20′	133°19′
Nabarlek Dam	AM[c]	L	134	3 (I)	60	Oenpelli 5573	166362	12°20′	133°19′
Birraduk Creek	BC	L	122	4	40	Oenpelli 5573	122403	12°18′	133°16′
Magela Creek system									
Magela Creek									
Nankeen Bb.	NN	UFP	21	FP	2	East Alligator 5473	675252	12°26′	132°52′
Jabiluka Bb.	JA	UFP	25	FP	2	East Alligator 5473	687215	12°28′	132°52′
Leichhardt Bb.	LT	UFP	27	FP	2	East Alligator 5473	688193	12°29′	132°52′
Ja Ja Bb.	JJ	UFP	32	FP	5	Cahill 5472	703150	12°31′	132°53′
Island Bb.	ID	C	36	6	5	Cahill 5472	697108	12°34′	132°53′
Magela Crossing	MX	C	38.5	6	20	Cahill 5472	691080	12°35′	132°52′
Buffalo Bb.	BO	C	39	6	20	Cahill 5472	693081	12°35′	132°53′
Mudginberri corridor	MI	C	40	6	20	Cahill 5472	692071	12°36′	132°53′
Magela bed	GD	L	44.5	6	20	Cahill 5472	706032	12°38′	132°53′
Magela bed	GU	L	45.5	6	20	Cahill 5472	713027	12°38′	132°53′
Magela bore pool	II[c]	L	47.5	A	20	Cahill 5472	719007	12°39′	132°54′

Magela riffle	IF[c]	L	47.5	A	20	Cahill 5472	719007	12°39′	132°54′
Magela bed	MD	L	50.5	6	20	Cahill 5472	738984	12°40′	132°55′
Magela bed	MG	L	52.5	6	20	Cahill 5472	754977	12°41′	132°56′
Magela bed	MJ	L	53	6	20	Cahill 5472	755976	12°41′	132°56′
Magela upstream	MU	L	62	5	40	Howship 5572	843925	12°43′	133°01′
Magela upstream	UU	L	64.5	5	40	Howship 5572	856908	12°44′	133°01′
Bowerbird Bb.	BD	E	70	5	40	Howship 5572	876868	12°47′	133°03′
Magela Falls base	BF	E	79	5	100	Howship 5572	939857	12°47′	133°06′
Magela Falls top	TF	P	79.5	5	220	Howship 5572	943856	12°47′	133°06′
Corndorl Creek									
Corndorl Bb.	CL	L	43.5	3	20	Cahill 5472	688039	12°37′	132°52′
Gulungul Creek									
Gulungul Bb.	GL	L	44	4	20	Cahill 5472	701028	12°38′	132°53′
Goanna Bb. (on Baralil Ck)	GA	L	47	3	20	Cahill 5472	687000	12°39′	132°52′
Bore site	ZZ[c]	L	52	4	20	Cahill 5472	702961	12°42′	132°53′
Radon Springs	RS	E	60.5	3	60	Cahill 5472	723892	12°45′	132°54′
Radon Falls	RF	E	61	3	80	Cahill 5472	720890	12°45′	132°54′
Coonjimba Creek									
Coonjimba Bb.	CA	L	49	1	20	Cahill 5472	725994	12°40′	132°54′
Coonjimba 4	C4	L	49.5	1	20	Cahill 5472	725993	12°40′	132°54′
Coonjimba 3	C3	L	49.5	1	20	Cahill 5472	723992	12°40′	132°54′
Little Coonjimba	LC	L	50	1	20	Cahill 5472	722984	12°40′	132°54′
Coonjimba 2	C2	L	50	1	20	Cahill 5472	722983	12°40′	132°54′
Retention Pond 1	RO[c]	L	50	1 (I)	20	Cahill 5472	721985	12°40′	132°54′
Tailings dam	TD[c]	L	51	1 (I)	40	Cahill 5472	713963	12°42′	132°53′
Djalkmara Creek									
Indium Bb.	IM	L	50.5	1 (A)	20	Cahill 5472	727984	12°40′	132°55′
Djalkmara Bb.	DA	L	51	1	20	Cahill 5472	740980	12°40′	132°55′
Retention Pond 2	RT[c]	L	52	1 (I)	20	Cahill 5472	741974	12°41′	132°55′
Georgetown Creek									
Georgetown Bb.	GN	L	52.5	4	20	Cahill 5472	753973	12°41′	132°56′
Costean 1	C1[c]	L	53	?	40	Cahill 5472	738970	12°42′	132°52′
Unnamed tributary									
Fishless Bb.	FS	L	62.5	1	40	Howship 5572	838925	12°43′	133°00′
SOUTH ALLIGATOR RIVER CATCHMENT									
Nourlangie Creek system									
Nourlangie Creek									
Nourlangie 2	N2	C	15	7 (A)	10	Cahill 5472	451886	12°46′	132°39′
Nourlangie 3	N3	C	16	7 (A)	10	Cahill 5472	462882	12°47′	132°40′
Nourlangie crossing 1	NY	L	29	7	20	Cahill 5472	548822	12°49′	132°44′
Nourlangie crossing 2	NC	L	29	7	20	Cahill 5472	545818	12°49′	132°44′
Muriella Park	MA	C	33	7	20	Cahill 5472	563779	12°52′	132°40′

Table 4. List of sampling sites with associated information continued

Site name	*Site code*	*Zone*	*Distance to estuary (km)*	*Stream order*	*Elevation above sea level (m)*[a]	*Map and no.*[b]	*Grid reference*	*Latitude S*	*Longitude E*
Skull Rock	SR	C	36	7	20	Cahill 5472	590769	12°52′	132°45′
Flying Fox	FX	C	39	7	20	Cahill 5472	592737	12°54′	132°47′
Nourlangie East	NE	C	42	7	20	Cahill 5472	590711	12°55′	132°47′
Baroalba Creek									
Baroalba crossing	BX	L	26.5	3 (A)	20	Cahill 5472	557878	12°46′	132°45′
Baroalba stream	BY	E	42	4	40	Cahill 5472	695808	12°50′	132°53′
Baroalba Springs	BS	E	42	3	40	Cahill 5472	694808	12°50′	132°53′
Mt Brockman	BM	P	51	2	170	Cahill 5472	735844	12°46′	132°55′
Koongarra Creek									
Nourlangie Rock	NR	L	38	3	20	Cahill 5472	607768	12°52′	132°49′
Noranda pools (on Noranda Ck)	NS	E	46	2	60	Cahill 5472	664773	12°52′	132°51′
Hickey Creek									
Sawcut Gorge	ST	E	57	4	40	Cahill 5472	755718	12°55′	132°56′
Tributary pools	SY	E	57	2	80	Cahill 5472	755716	12°55′	132°56′
Tributary pools	SZ	E	58	2	100	Cahill 5472	755717	12°55′	132°56′
Deaf Adder Creek									
Deaf Adder	DR	L	61	2	20	Jim Jim 5471	683552	13°03′	132°51′
Camp 1 (on Kolondjarluk Ck)	CP	E	72	6	40	Jim Jim 5471	761497	13°06′	132°56′
Camp 2 (on Kolondjarluk Ck)	SD	E	72.5	6	40	Jim Jim 5471	763494	13°06′	132°56′
Kolondjarluk (on Kolondjarluk Ck)	KD	E	74	6	80	Jim Jim 5471	763484	13°08′	132°56′
Jim Jim Creek									
Jim Jim Falls base	JD	E	68	5	60	Jim Jim 5471	658316	13°16′	132°50′
Twin Falls	TW	E	70	4	60	Jim Jim 5471	595265	13°19′	132°47′

[a] Vertical datum is mean sea level, Van Diemen Gulf; where recorded elevation is a multiple of 10, actual elevation has been rounded up to the next contour line value. [b] Bureau of Mineral Resources geological maps, 1:100 000; [c] artificial structure.

Table 5. Regular and occasional sites grouped according to drainage systems and habitat type
See Table 4 for site codes.

	Regular sites		*Occasional sites*			
ZONE *Habitat*	*Magela Creek*	*Nourlangie Creek*	*East Alligator River*	*Cooper Creek*	*Magela Creek*	*Nourlangie Creek*
PLATEAU	–	–	–	–	TF,BM	–
ESCARPMENT						
Main-channel waterbodies (incl. terminal)	BD[a]	ST[a]	–	–	BF	CP,KD,SD, JD[b],TW[b]
Seasonal feeder streams	–	SZ[c]	–	–	–	SY,NS,BY
Perennial streams	RS[a]	BS[a]	–	–	RF	–
LOWLANDS						
Sandy creek bed habitats	GD,MD	NC[a]	–	AU	GU[d],UU[a], ZZ,MG[a], MJ[a,d],MU	NY[a]
Backflow billabongs (shallow or channel)	CL,GL,IM,DA, GA,CA,GN,FS[a]	NR[a],BX[a]	–	MY,CD,BC	LC,II,IF, C2,C3,C4	DR
CORRIDOR	MI,BO,ID	–	–	–	MX	N2,N3,SR, FX,MA,NE
FLOODPLAIN BILLABONGS						
Upper	JJ,LT,JA,NN	–	–	–	–	–
Lower (riverine)	–	–	WL,CH	–	–	–
ESTUARINE HABITATS						
Upper reaches	–	–	RH,CC	–	–	–
Middle and lower reaches	–	–	MMa,MMb	–	–	–
ARTIFICIAL	–	–	–	AM	C1,R0, TD,RT	–

[a] Control sites; [b] Jim Jim Creek drainage; [c] This site was accessible only on three occasions; [d] GU, MU and MJ were originally intended to be regular sites, but became occasional sites because the waterbodies dried up early in the Dry season; [e] NY was used as a substitute site for NC in the Mid-wet season, when NC was inaccessible.

Environmental variables

Type A cards were used to record and describe the environment in the immediate fishing area rather than the whole waterbody. Appendix 1 presents a key to the codes used to describe variables in the immediate fishing environment.

Finishing time was recorded so that the time taken for a sampling operation could be determined. Zone, habitat category and habitat subtype were used to develop a waterbody classification system. The method notes recorded the approach or positioning of a particular sampling gear (usually seine net), from which quantitative data could be gathered in reference to dimensions A and B (see section 3.3: Seine nets, and Appendix 1). Water levels were recorded from gauge boards which were located in a number of the sampling sites by the Northern Territory Water and Sewerage Division.

Habitat-structural variables

Bank inclination, vegetation type, substrate type, bank cover and flow were all qualitatively assessed.

Physico-chemical variables

Surface and bottom water samples were taken just before fish sampling, using a 4.5 L sample bottle which could sample surface and bottom waters directly in an inner 250 mL narrow-mouthed, ground-glass-stoppered bottle. Water temperature was measured to the nearest 1°C. Conductivity and pH were determined to the nearest 2 μS/cm and 0.1 pH unit, respectively, in the field using meters. These meters were calibrated before each reading. The inner glass bottle was taken out of the water sampling bottle and the dissolved oxygen within its contents was fixed with magnesium sulphate and alkaline iodide solutions for later (up to a few days) dissolved oxygen (DO) determinations to the nearest 0.1 mg/L using the Winkler technique. Concentrated sulphuric acid was added to the samples just before titration with 0.01 N sodium thiosulphate. Turbidity (or 'visibility') was assessed by using a Secchi disc to measure Secchi depth to the nearest 5 cm (or to the nearest 1 cm when Secchi depth was less than 5 cm).

General habitat variables

Type E cards were used to record and describe the environment of the whole waterbody, rather than that in the immediate fishing area (Appendix 2 presents a key to variables used). Each card line contained the sample reference number corresponding to that on the environmental card (type A).

Average length (except in the case of streams) and width of the waterbody were estimated to give a rough indication of its expansion and contraction throughout the Wet–Dry cycle. Bank inclination, aquatic and bank vegetation, vegetation zonation, vegetation cover above and below the water, density of bank vegetation, herbivore damage to aquatic plants, condition of vegetation, and presence of epiphytic, benthic or surface algae and phytoplankton were subjectively assessed (see Appendix 2 for details).

Stream order was assessed according to Abell (1961): 1st-order streams are streams shown on 1:100,000 topographic maps which have no tributaries; where two 1st-order streams meet they form a 2nd-order stream; where two 2nd-order streams meet they form a 3rd-order stream, and so on. Where a 1st-order stream meets a 2nd-order stream, the resulting stream is still only a 2nd-order stream, and so on.

For each sampling site latitude, longitude, altitude and distance to estuarine reaches were measured from 1:100,000 topographic maps.

3.3 Collecting and observation of fishes

A variety of sampling methods was used to collect fishes, and in some sampling locations a combination of several techniques was employed in an effort to get a representative sample of as much of the fish community at each site as possible; see Volume II. Two standard netting methods, multiple-mesh-sized monofilament gillnets (gn) and seine nets (sa), were used widely as regular repeatable methods. Underwater observations were also used as standard methods in escarpment sites where netting methods would be likely to create an undesirable fishing pressure. Variables such as time of day, mesh size and sampling locations in particular waterbodies were kept constant wherever possible. The following collecting and observation methods were used:

Multiple-mesh-sized monofilament gillnets

A 35 × 2 m length of multiple-mesh-sized gillnet (gn) was used to sample the larger size ranges of fish inhabiting the sites. In order to catch a wide size range, the net incorporated seven 5 m panels, each with a different mesh size (26, 44, 58, 76, 100, 132 and 150 mm meshes, knot to knot) arranged sequentially by increasing mesh size. The catch of each panel of the net was regarded as a separate sample. This net was usually set at right angles to the bank for a period of one hour so that sunset occurred approximately in the middle of the set. The placement of the net in the waterbody was recorded at each site in the Method notes (Appendix 1).

The gillnet was set only during the day at some floodplain sites in the Wet season, as water access to these sites at dusk was hazardous due to navigational problems and crocodiles. This net could be successfully set in flowing channels during the Wet season, either in backwaters or large eddy currents. This procedure was followed in the use of all other types of gillnets.

Multifilament gillnets

A 20 × 3 m length of heavy gauge (10 ply) multifilament 150 mm (knot to knot) gillnet (bn) was used occasionally to sample very large predatory fish species. These nets were originally confiscated by the Northern Territory Fisheries Division from people fishing illegally for barramundi (*Lates calcarifer*). These nets are known locally as 'barramundi nets'.

Seine nets

sa: A 10 m long seine net, with a 10 mm mesh (knot to knot) and a depth of 1.5 m, was used to sample small fish in the littoral zones (maximum depth 1.5 m) of the sampling sites.

The direction relative to the bank(s) in which the seine was pulled at each site was recorded in the Method notes (Appendix 1). The mouth width (distance between the two ends of the seine net) of each haul was recorded with another critical dimension (dependent on method of hauling – see Appendix 1, dimensions A and B) in order that the area of water seined at each station could be estimated. This procedure was followed in the use of all types of seine nets.

sb: A 30 m long seine net, with a 10 mm mesh (knot to knot) and a depth of 1.5 m, was used occasionally to sample small fish from large backwaters.

sc: A 12 m long seine net, with a 24 mm mesh (knot to knot) and a depth of 2 m, was used infrequently to sample larger-sized littoral-dwelling fish species.

sd: A 5 m long seine net, with a 2 mm mesh (knot to knot) and a depth of 2 m, was used frequently to sample larval and post-larval fishes.

sz: A 10 m long seine net, with a 5 mm mesh (knot to knot) and a depth of 2 m, was used infrequently to sample some littoral-dwelling fish species.

Dipnets

Circular hoop (35 cm diameter) and triangular (25 cm sides) dipnets (dn) with a mesh of 2 mm (knot to knot) were used to sample sites inaccessible to seine nets. Dipnets were frequently used in small escarpment streams when searching for rare types and/or sizes of fish species.

Underwater observations

Underwater observations (ob) of fish, using mask and snorkel in clear water escarpment streams (e.g. RS, BS, SY; see Table 4), were valuable in assessing the composition of fish communities in these habitats. At these sites two divers would survey a standard course in a standard time. Each diver recorded all fish species present within the area, along with relative sizes and abundances. Results were later combined for analysis.

Spears

Spears (sp) were infrequently used underwater in clear water escarpment habitats when searching for rare types and/or sizes of fish species.

Lines

Longlining (ll), baited hooks (hl), and lures (rl) were infrequently used to obtain larger samples of particular species when their capture rates were low using gillnets and seine nets. These fishing methods were used mainly to capture *Hephaestus fuliginosus* (black grunter or bream) in escarpment habitats.

Cast net

A 28 mm mesh (knot to knot) monofilament cast net (cn) with a 2 m drop was used infrequently to capture rare and elusive types and/or sizes of fish species.

Poisoning

This method (pn) was used only rarely in situations where all other methods of fish capture listed above were ineffective. Where lotic waters entered larger lotic waters (e.g. feeder streams or small anabranches) a rotenone-based ichthyocide (Chemfish Regular) was used for sampling the fish. Such sampling areas were delineated by upstream and downstream stopnets, each of mesh size 10 mm (knot to knot). After thorough mixing (for 10 minutes) in a small volume of water, the ichthyocide was introduced immediately above the upstream net. The sampling area was then searched (using a face mask where necessary) and fish were collected with a dipnet. The search was ended when no further specimens could be found. Rocks and debris large enough to conceal dead fish were either removed or dislodged.

Use of natural fish kills

Natural fish kills (fk) were recorded when observed at the sampling sites. The number of fish of each species and length frequency data on them were recorded at each fish kill. Post mortems were conducted on some freshly dead specimens, and notes were made on the behaviour of live fish. Collections were made with dipnets and seines in the fish kill zone. Water quality measurements were more intensively taken at some fish kill sites.

3.4 Recording of fish catches

Field procedures

The fish obtained from the sampling operations outlined above were listed by species name and number on data card B (see Appendix 3) in the field. Voucher samples of these species will be lodged with the Northern Territory Museum of Arts and Sciences, Darwin. Each card line contained the sample reference number corresponding to that on the environmental card (type A) and the general habitat card (type E).

Samples of smaller fish species (less than about 60 mm in length) collected with seine nets and by other methods were then preserved intact in 10% (v/v) formalin, with the body cavities of fishes greater than 60 mm in length first being slit to aid preservation of the stomach contents. Where practical, samples of larger fish species collected with gillnets were deep frozen overnight and processed later in the laboratory (see next paragraph) after thawing – usually the following day. Larger fish species which could not be deep frozen (e.g. on extended field trips) were preserved in 10% formalin.

Laboratory and data analysis procedures

Fish from samples were either thawed or rinsed to remove formalin and the following details were recorded: length in millimetres (length to caudal fork, LCF, for fish with forked tails, or total length, TL, for fish with rounded tails); weight (to the nearest 1 g, or 0.1 g for small fish species); gonad weight (0.01 g, or 0.001 g for small fish species); gonad stage on a seven point scale after Pollard (1972) (variations from this method are noted in the text); stomach fullness (on a five point scale after Ball 1961); and an identification number for each fish, were recorded on a separate card line on data card C (see Appendix 4). This card line also contained the sample reference number and the species name and code so that biological information from a given fish could be related to the species and environmental data. The above data were summarised for each species on card B where the total number of fish caught, their total weight (g), and maximum and minimum lengths (mm LCF or TL) were recorded.

Species diversity indices (Vol. II)

The sampling unit in all diversity analyses was the catch of fish collected in a sampling period at a site using both standard sampling techniques. The richness, evenness and heterogeneity components of species diversity were calculated. Each of these concepts and related indices are explained in detail by Peet (1974). Richness is the concept of the relative wealth of species in a community. Evenness measures the distribution of the abundance of individuals among species. Maximum evenness occurs when all species occur in the same abundance and minimum evenness occurs when a few species are very abundant and the other species are represented by only a few individuals. Heterogeneity is a measure of both richness and evenness combined.

Heterogeneity (H) was measured by the Shannon-Weaver Index (hereafter referred to simply as the Shannon Index):

$$H = -\sum_{i=1}^{s} \frac{n_i}{N} \ln \frac{n_i}{N}$$

where: s = number of species in the sample
n_i = abundance of species i in the sample
N = abundance of all individuals in the sample

Evenness (E) was measured with the scaled Shannon Index:

$$E = \frac{H}{\ln s}$$

Richness (R) was measured by the Gleason Index:

$$R = \frac{(s-1)}{\ln N}$$

Size composition (Vol. III)

Length frequency. The length increments used in the length frequency distribution (either 10, 5 or 2 mm LCF or TL) were decided on for each species according to mean length of specimens captured during the study. The increments used for each species are apparent on the respective length frequency distribution figures.

Condition factor. Relative condition factors (K) were calculated for seasonal collections of fish using the equation:

$$K = W_s/aL_s^b$$

where W_s and L_s are the mean lengths and weights (geometric means were used as log-normality was assumed) for season s, a is the constant and b is the exponent in the overall length–weight relationship.

Environmental requirements — definition of terms (Vol. III)

Quarters. For each environmental variable (e.g. pH, temperature, DO), the mean value associated with each fish species (or colour form in the case of the plotosid catfishes) was calculated. The 36 species studied were then ranked for that environmental variable in ascending order of these means. After ranking they were divided into four quarters: species with ranks 1–9, with the lowest mean values, constituted the lower quarter; species with ranks 10–18 formed the lower-middle quarter; those with ranks 19–27 the upper-middle quarter; and those with ranks 28–36 the upper quarter. If data were not available for all 36 species, these numbers changed accordingly.

Aquatic vegetation dominance. The amount of cover provided by four defined types of vegetation was estimated by a rank number, from 0 to 6 (see Appendix 1). A further rank number (7) was given to submerged terrestrial vegetation. The total dominance of each vegetation type was calculated using the equation:

$$TD_j = \sum_{i=0}^{5} N_{ij}\, x_i$$

where TD_j = total dominance for fish species j
Ni_j = frequency of occurrence of rank i for fish species j
i = rank number (0 to 5 only)

This total dominance score was converted to a percentage of the sum of the total dominance scores for all four vegetation types for a particular fish species j, i.e. percentage dominance (PD) of vegetation type k is given by:

$$PD = \frac{TD_{jk}}{\sum_{k=1}^{4} TD_{jk}} \times 100$$

The accuracy of this percentage dominance score decreases as sample size decreases.

No vegetation rank. This rank was obtained by dividing the number of times no vegetation was present in association with a particular species at sample sites at which it was found, by the total number of times the hydrophyte abundance was estimated for all sample sites associated with that species. Thus, the no vegetation rank effectively estimated the relative number of times the fish species was found in waters with sparse or no vegetation. The accuracy of this index decreases with smaller sample size.

Substrate dominance. As defined in Appendix 1, dominant and subdominant substrates were noted at each site sampled for a particular species, over a possible seven types of substrates. Each time a substrate was considered dominant it was given a rank of 2, and each time a substrate was subdominant it was ranked 1. These values were summed for each substrate type to give a final weighted score of total substrate dominance. This dominance total was converted into a percentage dominance figure by dividing it by the sum of total dominance for all substrate types.

Reproduction (Vol. III)

Estimation of gonad maturity stages. When a fish was first captured, gentle pressure was applied to its abdominal area to see if milt or eggs were extruded. Later at dissection the gonads were observed by cutting away the abdominal wall. A seven stage system adapted from Pollard (1972) was used, in which maturity stages were subjectively assigned according to the appearance and size of the gonads within the body cavity. As a number of unrelated species were examined, a generalised staging system to describe the development of all species was developed. Any features differing from the general system are outlined in the section on that particular species.

The changes in macroscopic appearance of the gonads are:

Stage I (immature virgin). Gonads thin and threadlike, translucent and colourless; sexes usually indistinguishable.

Stage II (developing virgin/recovering spent). Testes: thin and straplike, translucent and greyish. Ovaries: more rounded, usually translucent and colourless; eggs not visible to the naked eye.

Stage III (developing). Testes: thickening, opaque and greyish white. Ovaries: thickening, opaque; small pale yellowish eggs may be visible to the naked eye.

Stage IV (maturing). Testes: swollen, elongated, often extend 3/4 of the way along length of body cavity. Ovaries: swollen, rounded, extend 3/4 way along length of body cavity; larger opaque yellow eggs clearly visible.

Stage V (mature). Testes: may extend length of body cavity, opaque white with generally a smooth creamy texture. Ovaries: may fill body cavity and distend abdominal wall, large yellow eggs often translucent.

Stage VI (ripe). Testes: as in V, milt may be extruded from fresh specimens by pressure on abdominal wall. Ovaries: as in V, eggs translucent yellow, free from ovarian connective tissue, and may be extruded by pressure on the abdominal wall in fresh specimens.

Stage VII (spent). Testes: thin, flaccid, straplike; blood vessels and 'bruising' evident; may contain white areas of residual sperm. Ovaries: hollow, thin and flaccid; saclike; may contain both residual and undeveloped eggs; blood vessels and 'bruising' evident.

As 'bruising' subsides and residual eggs and sperm are resorbed, stage VII gonads become stage II and the maturation cycle may begin anew.

Slides of histological sections of gonad tissue stained with eosin and haematoxylin were prepared in cases where determination of gonad stage of small fish species proved difficult. Gonad staging was then confirmed or reassessed after the sections were examined under a high-power microscope.

Length at first maturation. The method for estimating the length at which fish first become sexually mature was adapted from State Pollution Control Commission (1981). Fish recorded with gonad stages later than III were considered capable of spawning during the forthcoming reproductive season. The length at first maturation (LFM) was therefore considered to be the length at which 50% of the fish examined had a gonadal maturity stage later than stage III, using the following method:

The highest percentage of fish with gonads at stages later than III in any bimonthly sample was plotted against fish length. A line of best fit was plotted by eye through the scatter points in the length range from where the percentage of stage IV–VII gonads was first greater than zero to where it consistently equalled 100%. A horizontal line was drawn from the 50% maturity level on the y-axis to intersect the line of best fit. The x co-ordinate of the intersection point was taken to give the estimated LFM. This method was used because it avoids basing the LFM on a few isolated, sexually precocious individuals. Any problems arising from this method were generally due to small sample sizes; small samples of fish captured mainly outside their breeding season may result in a biased estimate of LFM. In these cases, the position of the line of best fit was allowed to be influenced more by the scatter points for mature fish collected within the breeding season than by the scatter points for those collected outside the breeding season. Species which were aseasonal spawners would not be expected to have 100% mature individuals in any given sample; in such cases the position of the upper end of the line of best fit was determined by percentage scatter points much lower than the 100% level.

Fish smaller than the LFM for the particular species are termed 'juvenile' and fish equal to or greater than the LFM are termed 'adult'. Any fish, juvenile or adult, with a gonad stage less than IV, is termed 'immature', and may be either an immature virgin, or a fish outside the breeding season with regressed gonads.

Gonosomatic and gonad maturity stage indices. Both fish and gonad weights were used to calculate the gonosomatic index (GSI), using the formula

$$\text{GSI} = \frac{\text{gonad weight (g)}}{\text{total fish weight (g)}} \times 100$$

The gonad maturity stage index (GMSI) was calculated as the mean gonad maturity stage of all adult fish, i.e. those of length greater than or equal to the LFM. In calculating the mean, stage VII gonads (i.e. spent) were assigned the same value as stage II.

Reproductive development was assumed to be accurately delineated by changes in the mean GSI calculated for each season using adult fish. The use of GMSI to determine accurately the reproductive development period was also assumed to be valid, as discussed by State Pollution Control Commission (1981).

Estimation of reproductive development and spawning periods. Reproductive development was assessed by plotting mean GSI and GMSI (for adult fish) against sampling season. The period of reproductive development was arbitrarily defined as the period of time encompassed by obvious peaks that rise from and return to the resting level on the GMSI and GSI plots. The spawning period was defined as the range of seasons during which fish were found with gonads at maturity stage VI (ripe), or the seasons including or just prior to the capture of stage VII (spent) individuals. Data on reproductive biology are summarised in Vol. III in a composite figure for each species for which sufficient data were available.

Spawning locality. The assumed spawning localities of each species were determined by noting from which habitats fish with gonads at maturity stages VI (ripe) and VII (spent), or small juvenile fish, were collected.

Sex ratio. The numbers of identifiable males and females captured over each sampling period, and the numbers of adults of each sex (i.e. with lengths equal to or greater than their respective LFMs), were noted for each species. The sex ratios for both the total samples (i.e. all fish) and adult fish only were calculated and compared with expected values using a chi-square test (Zar 1974). Variations between these two values were examined for changes in sex ratio within each season.

Fecundity and oocyte diameter. Ovaries from stage V (mature) females were preserved for two weeks in 10% formalin and then transferred to 75% alcohol. Each preserved ovary was weighed and dissected; where both lobes of the ovary were approximately the same size, only one lobe was dissected. Often a number of different size classes of eggs were present, representing varying stages of oocyte development. Only the largest size class of eggs was counted for the fecundity estimate. Either total counts were made by teasing the eggs away from the ovarian tissue, or a smaller section of ovary was removed and weighed, the eggs in the subsample were counted, and the total fecundity was estimated by multiplying back to the original weight of the gonad.

For each ovary, diameters of ten oocytes from the largest size class were measured, and either the range or the mean and standard deviation, or both, were calculated. The mean oocyte diameter for the species was the average of the individual means if more than one ovary was dissected.

Feeding habits (Vol. III)

Stomach contents data. The stomach contents of each fish were analysed under a dissecting microscope by the points (estimated volumetric) and occurrence methods (Pollard 1973). The percentage volume of each food type in the stomach contents was recorded to the nearest 5% on card lines in data card D (see Appendix 5). Card D also contained the sample reference number, the fish species code, and the individual fish number so that stomach contents data for a given fish could be related to the biological and environmental data.

Grouping of stomach contents data. The dietary composition of each species was summarised as a series of sub-means representing an average diet of the species for all habitats and seasons combined. These sub-means were rounded off to the nearest 1%. Food items with sub-means of 1% (i.e. greater than 0.5%) or greater in the diet of a particular species were included in further analyses. In the course of rounding off percentages an error of up to $\pm 2\%$ was sometimes generated; in these instances the unidentified organic material component was adjusted (on the assumption that adjustment of this component would minimise distortion of the identifiable diet components) to absorb the $\pm$ 2% rounding-off error, thus correcting the data to make the diet total for each species 100%; this made the sub-means more useful as relative abundance data. Bait material and alimentary tract parasites were excluded from this examination and therefore the sub-means were corrected by a factor of $100/(100 - n)$, where n = % parasites and/or bait material (i.e. sub-means were again corrected to add to 100%).

Some of the rarer food items were then grouped on a taxonomic basis (though not at any particular phylogenetic level) leaving a total of 60 food groups. Emphasis in these selective groupings was given to relatively widespread occurrence of a food item amongst the different species and to items represented at high percentages in the diets of individual species. These data were then analysed to compare different species' diets using the CSIRO TAXON library programs CANMAR/MULCLAS, GROUPER, GOWER and GOWECOR.

The 60 food items were further grouped to 27 items (again on a taxonomic basis at various phylogenetic levels). These groupings were used in the preparation of pie diagrams showing the main components of the diets of each species. Emphasis in this presentation was thus given to illustrating major differences in diet between species. As a consequence the invertebrate food items are revealed in more detail than the plant or vertebrate food components (the invertebrate component of diet tended to be more varied and specialised and tended to reflect a more distinct partitioning of resources, whereas the various vertebrate and plant components tended to be less specific in stratifying the feeding preferences of the different species). The diagrams are presented in a form in which aquatic and terrestrial components of the diet are separated and the outer circles are used to group the food items (again taxonomically) for broader comparisons.

Macroscopic parasites (Vol. III)

Parasites on fish were noted during the study, and information about them was recorded so that if necessary it could be related to all levels of data collected. The position of the parasite in or on the body of the fish was noted in each case.

4

Summary of results

Detailed results and discussion of the synecological studies on the freshwater fish of the Region are presented in Volume II of this Research Report. The results and discussion of the autecological studies are given in Volume III. The following section gives a brief summary of the findings.

4.1 Synecological studies

Habitat and environmental characteristics

Many environmental characteristics showed dynamic changes seasonally and also longitudinally within the catchments. From their headwaters to their mouths, the creek systems presented a gradient of conditions. Cool, clear waters over rocky and sandy substrates in the headwaters progressed downstream to warmer, more turbid waters over muddy and clayey substrates with hydrophytes in the lower reaches. An index of these headwater characteristics could be usefully developed for sampling sites in the catchments using gradients in these conditions. Superimposed on this upstream/downstream gradient were extensive seasonal changes in waterbodies. Conditions changed from being heterogeneous and unfavourable to fish in the Dry season to being homogeneous and favourable in the Wet season. Conditions in the Wet season in general approximated or even exceeded in favourability the conditions found in the most favourable Dry season habitat (namely escarpment main-channel waterbodies). The Magela and Nourlangie Creek systems were similar in terms of geographic zonation patterns. However, the escarpment and lowland zones of the Nourlangie catchment were situated closer to the estuarine reaches than were equivalent zones in the Magela catchment; other minor topographical differences between equivalent habitats were found in these catchments – for instance, the corridor zone was longer in the Nourlangie catchment than in the Magela catchment.

The geographic arrangement of habitats along the Cooper Creek system near Nabarlek was different from that in the above catchments, owing to the great distance to estuarine reaches, the presence downstream of escarpment type habitats, and the absence of lowland shallow backflow billabongs.

Fish community structure

Information on the seasonal structure of fish communities (which showed dynamic changes seasonally and longitudinally in the catchments) in a wide range of sampling sites in the study area is presented in Volume II. Highest heterogeneity existed between communities in the Late-dry seasons and lowest heterogeneity in the Mid-wet and Late-wet–Early-dry seasons (probably corresponding to a generally increased homogeneity of the aquatic environment and conditions suitable for mixing of communities).

Twenty-one habitats were tentatively identified. Habitats were shown to have characteristic fish communities that showed marked seasonal variations. Both seasonal and annual variations would, however, need to be studied further before community structure could be used as a tool in ecological monitoring surveys. As habitat complexity is frequently correlated with fish species diversity it is desirable that some measure of this complexity be developed in the future. Furthermore, a classification key by which to define more precisely zonational and habitat types is needed for the fuller understanding of aquatic systems in the study area. Information is required on the annual variation in fish community structure in selected habitats and the factors which control it. Considerable taxonomic difficulties were encountered in identifying fishes of the family Plotosidae and, to a lesser extent, the smaller species of Centropomidae. These problems need to be resolved before species diversity indices can effectively be used for monitoring surveys.

The fish communities present in the lowland habitats in the Dry season showed a temporal flux in structure between the community structures of refuge communities present in the escarpment main-channel waterbodies and those in the corridor waterbodies and floodplain billabongs in the lower reaches of the catchment. The influence of the lower reach communities (i.e. the large Magela 'lagoon' fish community) on community structure in these intermediate habitats appeared to be much greater than that of the upper reach communities because the downstream refuge is much more extensive in area and because the inherent nature of many fish species is to move upstream when flow conditions are suitable. The main factor limiting fish movement was shown to be the insurmountable obstacles in escarpment cascade areas; this barrier to upstream movement of many species resulted in upstream habitats having distinctive communities of relatively few species.

The fish communities of the Magela and Nourlangie Creek systems differed. Five more species were found in the latter system, and differences also occurred in the distributions of some species within the two systems. The communities present in that part of the Cooper Creek catchment examined had surprisingly few species, probably because of the great distance between the sampling sites and the estuarine reaches, and because of the presence downstream of escarpment-type habitats with insurmountable cascades or waterfalls.

4.2 Autecological studies

Distribution

Twenty-four species were found to be abundant at many sites downstream of the Ranger Uranium Project Area. Seven of these species were also found to be abundant at many sites upstream of the mine, twelve were common at a few upstream sites, and five were rarely found at upstream sites.

An additional three species which were found to be abundant at upstream sites were found rarely at some sites downstream of the mine.

Size composition and condition

Information is given in Volume III on the overall and seasonal size composition (length frequency distribution and length-weight relationship) and condition of samples of 32 fish species found in the study area, together with habitat preferences of juvenile and adult fish. Additional analyses of the data should determine the extent to which the various fishing methods select for species and size of fish. Further interpretation of seasonal trends and comparisons with fish surveys undertaken in the Finniss River catchment (Rum Jungle, abandoned uranium mining site) should then be possible.

Communities of smaller juveniles (i.e. fish not yet old enough to be sexually mature) occurred at highest diversities and abundances in lowland backflow and floodplain billabongs, indicating that these two habitats are probably important nursery areas. Communities of larger-juveniles/smaller-adults were found to have highest diversities and abundances in corridor waterbodies and to a lesser extent in lowland sandy creek bed habitats. In the Wet season the latter habitats connect the fish communities of the more permanent waterbodies with those of the lowland backflow billabongs; it is therefore considered that the corridor waterbodies and the lowland creek beds may function as migration or dispersal routes for sexually maturing fish. Communities which contained the greatest number of species with large adults were found in floodplain billabongs and corridor waterbodies and, to a lesser extent, in escarpment main-channel waterbodies. These three habitats thus provide refuge areas (or 'reservoirs'), particularly in the Dry season, for large adults (as would be expected, since they contain deeper and more permanent waters).

Three types of juvenile recruitment were defined: Type A, recruitment usually limited to one discrete season; Type B, continuous recruitment with a few peaks occurring during the year; and Type C, continuous recruitment with no apparent peaks.

Type B species showed greatest secondary recruitment in the Mid-dry season, which may be due to a resurgence of macroinvertebrate communities (particularly in corridor waterbodies) noted by Marchant (1982) in this season. Annual variation in juvenile recruitment and survival was noted: it appeared that the 1979 Late-dry season was less favourable to fish than the 1978 Dry season. Factors causing such variations need to be elucidated.

Seventeen species, mainly small and widely distributed, could apparently reach breeding state in one year or less. These species have short life cycles, and abundance in catches may rapidly reflect environmental conditions conducive to spawning success.

Most species attained highest condition factor (see section 3.4 for definition) between the Mid-wet and Mid-dry seasons, with a peak occurring in the Late-wet–Early-dry season (i.e. this peak was delayed slightly past the season of greatest feeding activity). Lowest condition factor was apparently caused by breeding activity, lack of food, and harsh environmental conditions. Annual variation in condition factor was noted and showed again that the 1979 Dry season was less favourable to fish than the 1978 season. Before condition factors can be used to predict environmentally induced stress on fish species of the Region, the effects on condition of factors such as sex, size of fish and the habitat in which the fishes are captured need to be examined.

Environmental requirements

Information on the environmental requirements (habitat-structural and physico-chemical variables) of 32 fish species is presented in Volume III. Previous findings on some species were confirmed and much was learnt of the requirements of previously unstudied species. This information should be valuable in the setting up of near-natural tank conditions in future toxicity-testing experiments. Some lines of further investigation were suggested to elucidate the major importance of bank vegetation and water flow to the environmental requirements of fish.

The ranges of habitat-structural and physico-chemical variables in which the various fish species were found, reflected their distributions within the longitudinal gradient of conditions found in the catchments. For example, escarpment-dwelling species were typically found in cooler, clearer, well-oxygenated, more acidic waters with low levels of dissolved solids over rocky and sandy substrates with sparse hydrophyte growths; the opposite was true for 'lower reach' species.

Conditions became less favourable in lower reach habitats during the Dry season as water temperatures and turbidities increased, and dissolved oxygen levels and abundance and diversity of hydrophytes decreased. It was apparent that knowledge of the limits of environmental tolerance of each species would enable us to predict which species would persist in certain sites as conditions deteriorated towards the Late-dry season. Thus the information collected in this section of the study will be valuable in monitoring studies using freshwater fishes in the Alligator Rivers Region.

Reproduction

Extensive information on the reproductive biology of 23 freshwater fish species found in the study area is presented in Volume III. Thirteen of the species had well-defined breeding seasons (mainly around the Early-wet season) while the remaining 10 either had extended breeding seasons (usually through the Wet season) or bred continuously throughout the year. Three species are believed to move to estuarine environments to breed.

Each species was classified according to one of six broad, sometimes overlapping, breeding strategies, and into three broad life history stages.

Fish in breeding condition were generally not found throughout the whole preferred range of a particular species. Many species were therefore apparently selecting certain areas in which to spawn in preference to other areas. The importance of lowland backflow billabongs as potential breeding sites for many species has already been mentioned; up to five species appeared to breed exclusively in these habitats and another eight species used them as well as other spawning sites. In the Magela Creek catchment, the majority of the most important apparent breeding sites were found downstream of the Ranger Uranium Project Area.

Information is required on the annual variation of spawning success and the natural factors that may influence it. Once these factors are elucidated it may be possible to detect the effects of human-induced alterations to the aquatic environments on spawning success of fish. Fluctuations in water levels, distribution and abundance of aquatic plants and food animals, and types of substrate present in waterbodies appear to be the main factors governing the spawning success of most species. Human-induced alterations to these natural conditions should be kept to an absolute minimum.

Diet

Information on the seasonal diets of 32 fish species from various habitats in the study area is presented in Volume III. Similarities between these species' diets were examined and four broad, sometimes overlapping, trophic classes were allocated. The relative numbers of species occupying these niches are much the same as those given in several overseas studies of tropical freshwater fish.

A tentative food web for the freshwater fishes of the Region was devised. The main transfer of energy and nutrients from primary producers to the fish fauna appeared to be via aquatic invertebrates. The number of links in the invertebrate food chains and the species involved are unknown in Australian freshwater ecosystems and this area requires attention in future studies. When, for instance, *Lates calcarifer* is captured and eaten by people, humans could be placed as high as the eighth trophic level, but would be most commonly at either the fifth or sixth level, depending on the feeding habitats of the fish and prey they had consumed.

Most fish species displayed strongly opportunistic feeding habits. Analysis of the data from the present study to describe changes in feeding habits with size of fish, diurnally and annually, is required in future studies. Food availability studies should be undertaken in conjunction with this.

The mean number of species vigorously feeding (as judged by the mean fullness index of stomachs) per season per habitat increased markedly in the Early-wet season from a minimum in the Late-dry season. By the Mid-wet season feeding activity had reached a maximum and it then began to decrease slightly by the Late-wet–Early-dry season.

The mean number of species feeding vigorously per habitat per season was shown to be far greater in habitats downstream of the Ranger Uranium Project Area, particularly in lowland backflow billabongs and floodplain billabongs. These habitats are therefore very important as fish feeding areas. Lowland sandy creek bed habitats and corridor waterbodies had the lowest numbers of vigorously feeding fish species. However, most piscivores were found to be feeding in these habitats.

Parasites

Macroscopic parasites infected 23 species of fishes. Incidences were up to 60% and varied with species, season and habitat. Severe infestations could have similar effects to adverse environmental conditions on body condition, migration and reproductive success.

Predators

More information is required to accurately define how birds, amphibians, reptiles and humans fit into the aquatic food chain in the Region. Twelve fish species in the Region, of which *L. calcarifer* is the most important, are consumed by humans.

Fish movements

Recolonisation of lowland sandy creek bed habitats and lowland backflow billabongs was the most striking effect of fish movements noted in the study. Lateral movement across the inundated flood plains was also noticeable. Lowland backflow billabongs are important feeding and breeding areas. These are entered via lowland sandy creek bed channels (important migration routes in the Wet season), by fish species apparently mainly from downstream (floodplain billabongs and corridor waterbodies) and to a lesser extent by species from upstream (escarpment habitats) Dry season refuge areas.

Upstream movements of fish species are detectable in escarpment perennial streams in the Wet season. Reactions of fish to water flow are complex and have as yet been little investigated by researchers.

Migratory behaviour is probably one of the most important survival strategies of fishes in the study area. Unless migration patterns are more precisely defined, the usefulness of the ecological monitoring surveys on freshwater fish in the Wet season may be questionable. The extent of dependence of fish populations in control sites upstream of the Ranger Uranium Project Area (RUPA) on those present downstream of RUPA should be determined.

Mortality

Some small fish species showed a marked seasonal mortality among adults. Fish kills observed in the 1978–79 Early-wet season were probably caused by low dissolved oxygen levels as Wet season flows displaced anoxic bottom waters in some floodplain billabongs. This is only one possible mechanism bringing about natural fish mortality and it is stressed that it may be very difficult to differentiate between natural fish kills and those induced by human activity, owing to our scant knowledge of factors and mechanisms affecting fish survival in such waters (see Vol. III).

5

General conclusions

Interpretation of the biological and ecological data presented in this report is limited to some extent by the short-term nature of the study. A large array of biological and ecological features of the fish fauna and variables of the aquatic environment has been delineated and should prove to be of value in any continuing monitoring program. It is difficult at this stage to specify which features or variables will be most sensitive to changes associated with future uranium mining and processing in the area. However, the most sensitive features or variables would be expected to have been included in such a comprehensive array. Fish species most suitable for future toxicity experiments have been delineated, as have a range of sites suitable for a mobile toxicity-testing laboratory.

It is also difficult to specify which habitats are likely to be most susceptible to damage from changes that might result from uranium mining activity, because in almost all ecosystems complex webs of interdependence exist, and it has not been possible to identify or quantify these in this study. Habitats which require careful protection (and surveillance) from possible human-induced changes, because of their apparent importance to the fish ecology of the entire Magela Creek catchment, are detailed in Table 6.

The Magela Creek catchment area was the one most intensively sampled during the study period and hence conclusions drawn in this report are most applicable to this catchment. Although differences in environmental conditions and fish faunas between the Magela Creek and other catchments (e.g. the Nourlangie, Jim Jim and Cooper Creek systems), the information gathered in this report can be readily applied to these latter creek systems. The information should also be relevant to the Finniss River system (the fish fauna and aquatic environment of which were described by Jeffree & Williams [1975]) and other catchments with similar fish faunas, for example the coastal drainages of northern Australia and of southern New Guinea (Pollard 1974).

During the period of the present study, management policies for waters containing mining wastes for both existing and proposed future uranium mining operations in the Region shifted towards 'no release' systems. The Supervising Scientist (1979) indicated that there would nevertheless still be a need for water research because of possible seepage of wastes in surface waters via groundwater, and in case waters of a quality not necessarily inimical to life, but containing foreign compounds and natural substances at concentrations greater than those presently found in the environment, were to be released from the retention ponds within RUPA. The release of such water is often regarded as good environmental practice, as with long-term storage the water becomes more heavily loaded with wastes owing to cumulative evaporation and potentially becomes more hazardous, increasing problems of decommissioning.

Table 6. Aquatic habitats that are ecologically important to fish and are potentially vulnerable to mining operations

Habitat	*Ecological importance to fish*	*Reason for potential vulnerability*
Lowland backflow billabongs	Feeding and breeding areas	Close proximity to mining sites means that these billabongs may receive effluent seepage as well as released effluents from backflowing creeks.
Lowland sandy creek bed habitats	Migration routes	May receive releases of effluents. Concentrations of wastes in the mixing zone may be high. These areas are also centres of actual and potential sand mining activity.
Corridor waterbodies	Dry season refuge areas and migration routes	May receive releases of effluents.
Upper flood plain billabongs	Dry season refuge areas and feeding and breeding areas	May receive releases of effluents (cumulative in Magela Creek if Pancontinental Mining Limited commences mining).

The ideal management goal for most aquatic ecosystems is non-restriction of use, whether this is for propagation of fish and wildlife, for public water supplies, for recreational purposes, or for agricultural, industrial and other legitimate uses. Hence industrial management goals should be minimisation of environmental change and optimisation of beneficial use.

The Supervising Scientist (1979) indicated that standards need to be set to define the maximum concentrations at which substances present in mine wastes should be allowed to be present in surface waters to which any release might be made. One of the most effective methods for determining these standards appears to be by experimental studies of the toxicity of potential complex effluents to aquatic organisms of the Region. However, Clark (1978) indicated that the interpretation of the impact of pollution in the field has lagged behind the development of experimental testing procedures. Hence it is important to recognise that it is very difficult to determine the true ecological implications of experimental test data; they must therefore be interpreted with care.

Implementation of strict environmental management measures (based on hindsight from Rum Jungle environmental studies and information gained from research workers in the ARR) by uranium mining companies in the Region should ensure minimal environmental change to exposed aquatic and terrestrial habitats (the definition of 'minimal' is the basis of many philosophical arguments). It is thus quite likely that the environmental degradation noted by Jeffree & Williams (1975) – 'the aquatic fauna of the east-branch of the Finniss River has been almost wholly destroyed in the 10 km section downstream of the mined area [Rum Jungle]' – will never be repeated for catchments that may be exposed to mining wastes in the ARR.

Whitton (1975) noted that it was quite evident that in river basin management, technological developments are further advanced than the social-political changes necessary for their successful implementation, and that biologists and ecologists would do well to see that the information needed to allow a balanced decision to be made reaches both decision-makers and the general public.

6 Recommendations

This report is intended to be used as a general reference on the freshwater fishes of the Alligator Rivers Region by persons involved in the planning of future developments in the Region. However, it is stressed that the biology and ecology of previously unstudied and diverse tropical fish communities are extremely complex and not to be fully disclosed by a one-and-a-half-year field study. After referring to this report, those involved in the planning of water management in the area should consult relevant authorities and experts to determine if there are any species-specific or site-specific considerations which have become apparent since the preparation of this document.

6.1 Development of field detection methodologies

Annual variation in fish community structure has not been examined in detail, so sampling studies at specific sites may be necessary to verify that the fish communities at a site are representative of those associated with its habitat type as delineated in this report. Detailed analyses and studies of what can be identified as potentially critical components of the Region's ecosystems, in relation to the mining activity, will also be needed. If water management strategies are adopted in the future that result in the release of mining wastes into the aquatic environment, we believe it is essential that field detection experiments should have advanced to a point where natural changes can readily be distinguished from mining-induced changes. Only with this knowledge will it be possible to determine whether a release procedure has been successful in minimising adverse environmental effects.

Thus, for example, monitoring of fish kills and associated aquatic physico-chemical variables may be useful in the future (especially during Early-wet seasons) to enable us to discriminate between human-induced and natural fish kills.

To monitor effects of uranium mining and processing activities on the freshwater fishes of the Region, an *ecological model* which can predict fish community structure for given sites could be developed. More analyses are required on the database of the present study and further field studies should be carried out in order to determine the predicting variables.

Data analyses to aid in development of the ecological model

1. Testing of the seasonal relationship between type of habitat and fish community structure.
2. Development of a more precise system of classifying zonational and habitat types.
3. Development of an index of headwater environmental characteristics (based on topographical, physico-chemical and habitat-structural variables) for sampling sites examined in the catchments.
4. Development of some measure of habitat complexity to relate to fish species diversity.

Studies to aid in development of the ecological model

1. Further information is required to delineate annual variations in fish community structure and their causes.
2. Migratory phases of fish should be more precisely determined to provide further understanding of variation in fish community structure observed during the Wet seasons. With such information at hand, the extent to which fish populations in control sites upstream of the Ranger Uranium Project Area are dependent on those in downstream areas may be ascertained.

6.2 Background information on species

Further analyses

1. Because of the importance of migratory behaviour as a survival strategy for the majority of fishes in the Region, it would be advantageous to further investigate the importance of bank vegetation and water flow, to add to present known information on environmental requirements of fish.
2. Population trends at sites within the study area need to be more carefully analysed. The existing data could be better interpreted if the extent of selectivity of fishing method for species and fish size were taken into account. In addition, comparisons could be made with fish surveys that have been performed in the Rum Jungle area and other northern Australian catchments (see Introduction – section 1).
3. Changes in diets of fish with size and sex should be analysed in an attempt to further understand causes of variability observed.

4. Changes in condition factors of fish according to fish size, sex, maturation state, the incidence of parasite infestations and the habitat in which specimens were captured should be analysed in an attempt to further understand variability observed.

Further studies

1. Considerable taxonomic problems exist with fish of the family Plotosidae and to a lesser extent with the smaller Centropomidae. These require attention before species compositions can be accurately assessed and species diversity indices be most effectively used. The taxonomic status of the *Glossogobius* species and *Pseudomugil tenellus* also require further attention.
2. Annual variations in juvenile recruitment, spawning success, diets and feeding activities should be further investigated in order to determine the reproducibility of observed seasonal patterns.
3. If emphasis is given to food-chain studies in the future, with regard to the transfer and bioaccumulation of potential hazardous constituents from either released or seepage waters from the mine sites, the the following studies are recommended:
   a) Diurnal patterns in feeding activity would need to be determined so that food consumption rates could be ascertained.
   b) The composition of food-chain linkages between primary producers and invertebrate-feeding fish species would require elucidation to more accurately define the range of trophic levels occupied by fish.
   c) More information would be required on the extent of the dependence on aquatic food chains by major predators such as reptiles, amphibians, birds and humans.
   d) Information on current heavy metal and radionuclide levels in tissues of various fish from the study area would be required so that in the future authorities may be in a position to differentiate between natural and human-induced enhancement of levels of these substances.

6.3 Predictive experimentation

Details of species suitable for future toxicity experiments are presented in section 7. This information has been presented on the assumption that in the future emphasis will be given to toxicity experiments which aim to predict 'safe' dilution levels of waters that are to be released or that seep from the mine sites. Further, on the assumption that some of this experimentation can be carried out in the field, details of sites suitable for an experimental mobile toxicity-testing laboratory are also presented in section 7.

A straightforward study which could determine which fish species are more sensitive to potential effluents would involve the close monitoring of fish communities in retention ponds (particularly Retention Pond No. 2) within the Ranger Uranium Project Area. Sensitive species would be those which disappear from fish communities in the ponds as waste levels build up.

6.4 Advisory

The following recommendations flow on from data and interpretation in this report and are offered in the hope that they will assist in the development of a scientifically based method of establishing practical approaches for minimising adverse effects to the fish fauna of the ARR resulting from uranium mining operations. These recommendations also reflect the experience of fisheries protection organisations in this regard and relevant policies of NSW State Fisheries.

Releases and seepage

The primary mechanism by which the fish fauna of the ARR could be adversely effected by uranium mining operations is by the transfer of waste waters from the mine sites into the aquatic environment of the surrounding creek systems. This water transfer could be via controlled releases or seepage. Transfer by releases is more manageable than transfer by seepage because a small section of the aquatic environment can be chosen as the receiving site and the time interval and rate of release can be controlled. For this reason emphasis will be placed on releases in the first part of this section.

At the present time, mining companies that have commenced mining or propose to mine in the Region have adopted a policy of not releasing waste waters into the aquatic environment. This policy would certainly ensure a minimisation of adverse effects to the fish fauna. If this policy could practically be maintained it would be wise for it to be fully supported. However, in case this policy becomes impossible to maintain, a contingency plan must be available so that the fauna can be protected by suitable release controls which take into account the spatial and temporal utilisation of the aquatic environment by the species.

Regulations relevant to the release of wastes into the aquatic environment are presented in the N.S.W. Clean Waters Regulations, 1972, Part II Classification of Waters, Class P, C and R Waters (N.S.W. Government 1972). These regulations state:

> Wastes are not to be discharged if the resulting concentration of the wastes in the waters:
>
> (i) is or is likely to be harmful, whether directly or indirectly, to aquatic life or water-associated wildlife; or
>
> (ii) gives rise to or is likely to give rise to abnormal concentrations of the wastes in plants or animals.

If well thought out and accepted water release standards are not available, it will be necessary to ensure that point (i) is adhered to by undertaking non-toxic behavioural and subchronic and chronic toxicity studies on the complex wastes in question. A controlled release rate could maintain dilution levels above this 'safe' level in the aquatic environment.

Depending on the confidence given to these laboratory-derived 'safe' dilution levels, it would be prudent to give careful thought to the choice of the receiving site and the timing of releases so as to avoid areas and times heavily utilised by the fish fauna. A number of commonsense recommendations arise from this:

1. To ensure maximal and rapid dilution of released wastes, releases should be made in the lowland sandy creek bed habitat during the Mid-wet season (see Fox et al. 1977 for recommendations regarding fish avoidance and inhibition of movements in the mixing zone in respect to released wastes).
2. Because lowland backflow billabongs are heavily utilised by fish as nursery areas and for feeding during this season, it is important to minimise the probability that wastes might enter these habitats. This could be achieved by releasing during periods when water is running out of these habitats (i.e. after peak floods occur) into the lowland sandy creek bed habitat.
3. Releases should not be made in the Early-wet season when the billabongs are filling (or have just filled), as this is the period when vast numbers of fish of many species enter these waterbodies to breed and feed. It is important that this recommendation be adhered to after extreme Dry seasons, as these are the times when reproductive success may be most important so that depleted populations can receive essential recruitment of juveniles.

Physical change to habitats

The fish fauna could be adversely affected by physical change to habitats. Mining operations could physically change habitats by processes such as earth moving, sedimentation, impoundment of catchments etc. Recommendations relevant here are:

1. As migration appears to be one of the most important survival strategies of many fishes, and as this is centred on lowland sandy creek bed habitats in the Region, it is essential that conditions in these habitats be maintained as close to natural as possible, or at least to the extent that there is good assurance that movement of fish will not be inhibited. Shelter from high water velocities for migrating fish species is essential and in these habitats it is provided by fringing bank and mid-channel vegetation. Particular care is required with regard to sand mining activities in these habitats. These activities should not be allowed to interfere to any extent (directly or indirectly) with such vegetation communities. Access roads to sand mining sites (particularly clay-based roads which in the Wet season form small dams across anabranches of creeks) should be removed before Wet season flows commence.
2. Habitat characteristics of waterbodies in the Region such as substrate type, turbidity, abundance and distribution of hydrophytes, and (to an uncertain extent) the occurrence of fringing bank vegetation, appear to be important environmental requirements of many fish species in the Region. It is thus highly desirable that these characteristics are not significantly or suddenly changed by human activities from their present state.

Recreational activity of people associated with mining operations

The arrival in the Region of large numbers of personnel associated with uranium mining activities could have adverse effects on fish fauna if recreation activities of these personnel were strongly oriented towards freshwater fishing. Recommendations relevant here are:*

1. Increases in amateur fishing pressure owing to the arrival in the area of personnel associated with uranium mining activities should be monitored and their effects on fisheries watched.
2. Following on from the recommendation above, in particular, amateur recreational fisheries based on *Hephaestus fuliginosus*, an easily fished species in some escarpment main-channel habitats, should be managed very carefully. Good management will depend on careful interpretation of information obtained from specific creel censusing and population dynamics studies.
3. Because of the unique nature of escarpment perennial stream habitats and their fish communities, they should be protected and preserved from all future developments, and strict limitations on public access should be imposed. Careful control of scientific research in these areas is also important.
4. It is important that the restrictions on faunal collection imposed by the Australian National Parks and Wildlife Service (ANPWS) in the Kakadu National Park be enforced as stringently for aquatic animals as for terrestrial animals. This applies particularly to the collection of the primitive archer fish (*Toxotes lorentzi*)† by aquarists; this fish may be considered the rarest and potentially the most endangered species in the Region.

*These recommendations are of particular relevance to bodies other than the Supervising Scientist for the Alligator Rivers Region — ed.

†Sporadic large collections of this fish have been made at many sites in the five years since the preparation of this report.

Co-ordination

Recommendations regarding the protection of monitoring sites and minimising sampling interference and overlap:*

1. If mining companies intend altering any freshwater sites inside or outside their respective Project Areas, the Supervising Scientist should be consulted, for these sites could function as essential sampling areas for field monitoring surveys.
2. Biologists commencing field studies in the Region should consult with field-based research workers from the ANPWS and with the Supervising Scientist in order to minimise interference or overlap with long-term fish monitoring studies and/or related field experiments. Sampling methods should be uniform between all surveys to enable catches to be compared more easily.
3. If permission is to be granted by the ANPWS to aquarists to collect fish (under well-planned guidelines), ANPWS should consult with the Supervising Scientist, as such collections might interfere with fish monitoring studies in progress in the Region.

*These recommendations are of particular relevance to bodies other than the Supervising Scientist for the Alligator Rivers Region — ed.

7

Future predictive experimentation

Two major problems face research workers who undertake future toxicity experiments on freshwater fish in the present study area. These are the selection of fish species suitable for such experiments, and the selection of sites suitable for the location of an experimental mobile toxicity-testing laboratory.

7.1 Selection of fish species

After taking into account information from many other sources the following selection factors were agreed on at the December 1979 Workshop for the Office of the Supervising Scientist:

1. small size of fish (less than 1 g);
2. short life cycle;
3. abundance downstream of the Ranger Uranium Project Area (RUPA);
4. general abundance during all seasons;
5. sensitivity to extreme Dry season conditions;
6. importance in food chain of economically valuable (i.e. food and commercial) fish species;
7. importance as food fish;
8. commercial importance.

These factors were given a score (poor = 0, fair = 1, good = 2, and excellent = 3) for each species (Table 7). The scores were summed and the resulting total aggregate score indicated the suitability of the species for use in toxicity experiments. The higher the score, the more potentially useful the species.

Additional and very important selection factors are:

1. ability to withstand handling and transport;
2. ability to acclimatise to laboratory conditions;
3. relative sensitivity to toxicants;
4. availability of eggs and larvae.

These latter factors are currently being (or have been) elucidated by Midgley, Baker and Skidmore (pers. comm.) and should eventually be added to those listed in Table 7.

Each species was then given an overall rank relative to other fish species according to its 'usefulness' in these experiments (the most useful species start with rank number 1). Since the range of species selected should also be representative of various trophic niches exploited by the fish fauna of the Region, the overall ranked list of fish species was divided into four separate lists (Table 8) representing herbivores/detritivores, omnivores and carnivores (subdivided into invertebrate-feeders and piscivores).

Herbivores/detritivores all showed very low mean total scores, *Pingalla* sp. being the most useful species from this generally useless trophic group. Piscivores showed the next lowest mean total score with *Lates calcarifer* being the most useful species.

Table 7. Suitability of fish species from four trophic niches for future toxicity experiments

Selection factors: 1, small size; 2, short life cycle; 3, abundance downstream of RUPA as well as in 'control' downstream sites; 4, general abundance in all seasons; 5, sensitivity to extreme Dry season conditions; 6, importance in food chain to food and commercial fish species; 7, importance as food fish; 8, commercial importance

Scoring: 0 = poor; + = fair; + + = good; + + + = excellent

Trophic niche and fish species	*Selection factor*								*Total Score*
	1	2	3	4	5	6	7	8	
HERBIVORES/DETRITIVORES									
Liza diadema	0	0	+ +	0	+	0	0	0	3
Syncomistes butleri	0	0	+	+	+ + +	0	0	0	5
Pingalla sp.	+	+	0	+	+ + +	0	0	0	6
OMNIVORES									
Nematalosa erebi	+	+ +	+ +	+ +	+	+	0	0	9
Hexanematichthys leptaspis	0	+	+ +	+ +	0	0	+	0	6
H. australis	0	+	0	+	0	0	+	0	3
Melanotaenia nigrans	+ + +	+ + +	0	+ + +	+ + +	+	0	0	13
M. maculata	+ + +	+ + +	+ + +	+ + +	+ +	+ + +	0	0	17
Pseudomugil tenellus	+ + +	+ + +	+ +	+ +	+	+	0	0	12
Amniataba percoides	+	+ +	+ + +	+ +	+ +	+	0	0	11
Leiopotherapon unicolor	+	+ + +	+ + +	+ +	+ +	+ +	+	0	14
Hephaestus fuliginosus	0	0	0	+	+ + +	0	+ + +	0	7

Table 7. Suitability of fish species from four trophic niches for future toxicity experiments continued

Trophic niche and fish species	*Selection factor* 1	2	3	4	5	6	7	8	*Total Score*
CARNIVORES (INVERTEBRATE-FEEDING)									
Scleropages jardini	0	0	+	+	++	0	+	0	5
Anodontiglanis dahli	0	+	0	0	++	0	+	0	4
Tandanus ater	0	++	++	+	++	+	++	0	10
Neosilurus hyrtlii	+	++	++	+	+	++	0	0	9
Porochilus rendahli	+	+++	++	+++	0	+++	0	0	12
Craterocephalus marjoriae	+++	+++	+++	+++	++	++	0	0	16
C. stercusmuscarum	+++	+++	+++	+++	++	+++	0	0	17
Ambassis agrammus	+++	+++	+++	+++	+	+++	0	0	16
A. macleayi	+++	+++	++	++	+++	++	0	0	15
Denariusa bandata	+++	+++	++	++	++	++	0	0	14
Glossamia aprion	++	+	++	+++	+++	+	0	0	12
Toxotes chatareus	+	+	+++	++	++	+	++	0	12
Glossogobius giurus	+++	+++	++	+++	+	++	0	0	14
Hypseleotris compressus	+++	++	++	+	++	+	0	0	11
Mogurnda mogurnda	+++	+++	++	++	0	+	0	0	11
Oxyeleotris lineolatus	++	+	++	++	0	+	++	0	10
CARNIVORES (PISCIVOROUS)									
Megalops cyprinoides	0	+	+	+	+	0	+	0	5
Strongylura kreffti	+	+	++	++	++	0	++	0	10
Lates calcarifer	0[a]	0	+	+	+++	0	+++	+++	11

[a] Juveniles available from site CC.

Table 8. Species from four trophic niches ranked according to their usefulness in future toxicity experiments
For generic names see Table 7.

Herbivores/detritivores		*Omnivores*		*Carnivores* *Mainly invertebrate-feeding*		*Mainly piscivorous*	
Species	*Ranking*[a]	*Species*	*Ranking*[a]	*Species*	*Ranking*[a]	*Species*	*Ranking*[a]
Pingalla sp.	10	*M. maculata*	1	*C. stercusmuscarum*	1	*L. calcarifer*	7
S. butleri	11	*L. unicolor*	4	*A. agrammus*	2	*S. kreffti*	8
L. diadema	13	*M. nigrans*	5	*C. marjoriae*	2	*M. cyprinoides*	11
		P. tenellus	6	*A. macleayi*	3		
		A. percoides	7	*D. bandata*	4		
		N. erebi	9	*G. giurus*	4		
		H. leptaspis	10	*P. rendahli*	6		
		H. fuliginosus	12	*G. aprion*	6		
		H. australis	13	*T. chatareus*	6		
				H. compressus	7		
				M. mogurnda	7		
				T. ater	8		
				O. lineolatus	8		
				N. hyrtlii	9		
				S. jardini	11		
				A. dahli	12		
Mean total score	4.7		9.9		11.8		8.7

[a] The lower the number the more useful the species.

The invertebrate-feeding and omnivorous trophic groups provided a wide selection of fish species. These gave respectively the highest and second highest mean total scores of all species. The two most useful omnivorous species were *Melanotaenia maculata* and *Leiopotherapon unicolor*; however, Jeffree and Williams (1975) found that the former species was relatively insensitive to heavy metal pollution in the Finniss River, and the present authors found the latter species difficult to keep in aquaria with other species because they readily consumed live fish. *Craterocephalus stercusmuscarum*, *Ambassis agrammus*, *Craterocephalus marjoriae*, *Ambassis macleayi*, *Denariusa bandata* and *Glossogobius giurus* appear to be the most useful carnivorous species for toxicity experiments.

Table 9. Suitability of sites as location for mobile toxicity-testing laboratory

A = access by air only
B = access by boat or air only

0 = poor
\+ = fair
++ = good
+++ = excellent

E = potentially exposed
C = control

Type of habitat, site name and site code	*Access*			*Site construction suitability*	*Security*	*Year-round supply*		*Exposure to possible contaminants*	*Total score*
	Late-dry	*Mid-wet*	*Early-dry*			*Water*	*Fish*		
Escarpment main-channel waterbody									
Bowerbird (BD)	A	A	A	++	+++	+++	+++	C	11
Escarpment perennial stream									
Radon Springs (RS)	++	A	+	+++	+++	+	+	C	11
Lowland sandy creek bed habitats									
Magela bed (MD)	+++	+	++	++	++	+	+	E	12
Gulungul bed (GD)	+++	A	+	+	++	+	+	E	9
Nourlangie crossing (NC)[a]	+++	A	+++	++	0	+	+	C[b]	10
Lowland shallow backflow billabongs									
Fishless (FS)	+	A	A	+	+++	+	+	C	7
Djalkmara (DA)	+++	+	++	++	++	++	++	E	14
Coonjimba (CA)	+++	+++	+++	+++	+++	+++	+++	E	21
Gulungul (GL)	+++	+	++	++	+	+	+++	E[c]	13
Corndorl (CL)	++	+	++	+	+	++	+	E[c]	10
Nourlangie Rock (NR)[a]	++	A	+	++	+	++	++	C[b]	10
Lowland channel backflow billabongs									
Georgetown (GN)	+++	+	++	+++	+++	+++	+++	E	18
Indium (IM)	+++	+	++	++	++	+++	++	E	15
Baroalba crossing (BX)[a]	+++	+++	+++	+++	0	+++	+++	C	18
Deaf Adder (DR)	+	A	A	++	+++	+++	+++	C[b]	12
Goanna (GA)	+++	+	+++	++	+	+++	++	C[c]	15
Corridor waterbodies									
Mudginberri (MI)	+++	+++	+++	+++	+++	+++	+++	E	21
Buffalo (BO)	+++	+	+++	++	+	+++	+++	E	16
Island (ID)	+++	B	++	+++	+	+++	+++	E	15
Magela Crossing (MX)	+++	+++	+++	+++	+	++	++	E	17
Flying Fox (FX)[a]	++	B	+	+	++	+++	+++	C	12
Skull Rock (SR)[a]	++	B	+	+++	+	+++	+++	C	13
Muriella Park (MA)[a]	+	B	+	+	+	+++	+++	C[b]	10
Nourlangie 2 (N2)[a]	++	B	++	++	+++	+++	+++	C[b]	15
Floodplain billabongs									
Ja Ja (JJ)	+++	B	++	+++	+++	+++	+++	E	17
Leichhardt (LT)	+	B	+	+	++	+++	++	E	10
Jabiluka (JA)	++	B	+	++	+	+++	+++	E	12
Nankeen (NN)	+	B	+	0	++	+++	+	E	8

[a] Nourlangie Creek system; [b] Effluents may come from Noranda Mines. [c] Effluents may come from Jabiru township.

7.2 Selection of mobile toxicity-testing sites

The following factors must be considered in evaluating a potential site:

1. access during the Late-dry, Mid-wet and Late-wet–Early-dry seasons
2. site suitability for construction
3. security from public interference
4. year-round supply of water
5. year-round supply of fish.

These factors were given a score (in a similar manner to the fish species) for each site (Table 9). The scores were summed for each site and the resulting total indicated the overall suitability of a site for use in toxicity experiments. Each site was then given an overall rank according to its usefulness as a location for the mobile toxicity-testing laboratory.

The range of selected sites should also include both control areas and areas that might be exposed to effluents. Therefore, the overall list of ranked sites was divided into two separate lists (Table 10) based on this criterion.

The four most useful potentially effluent-exposed sites were Mudginberri, Coonjimba, Georgetown and Magela crossing. The four most useful control sites were Baroalba crossing, Goanna, Nourlangie 2 and Skull Rock.

Table 10. Ranked list of sites suitable for mobile toxicity-testing laboratory
The lower the number the more suitable the site.

Potentially effluent-exposed sites	*Overall ranking*	*Control sites*	*Overall ranking*
Mudginberri (MI)	1	Baroalba crossing (BX)	2
Coonjimba (CA)	1	Goanna (GA)	5
Georgetown (GN)	2	Nourlangie 2 (N2)	5
Magela Crossing (MX)	3	Skull Rock (SR)	6
Ja Ja (JJ)	3	Deaf Adder (DR)	7
Gulungul (GL)	4	Flying Fox (FX)	7
Buffalo (BO)	4	Bowerbird (BD)	8
Indium (IM)	5	Radon Springs (RS)	8
Island (ID)	5	Nourlangie crossing (NC)	9
Magela bed (MD)	7	Nourlangie Rock (NR)	9
Djalkmara (DA)	7	Muriella Park (MA)	9
Jabiluka (JA)	7	Fishless (FS)	12
Leichhardt (LT)	8		
Corndorl (CL)	9		
Gulungul bed (GL)	10		
Nankeen (NN)	11		

APPENDIX 1

Environmental card (type A)

The following variables are used in describing the fishing environment. Columns on data card (80 columns wide) are shown in parentheses.

Sample reference code (1–17)

Date (6 columns: year, month, day), time (4), sampling site (2), sampling method (2) and mesh size (3) See Table 4 for site codes and section 3.2 for details.

Period (18)

D = day	1 hour after sunrise to 1 hour before sunset
N = night	1 h after sunset to 1 h before sunrise
K = dusk	1 h before and after sunset
W = dawn	1 h before and after sunrise

Finishing time (19–22)

Time (to the nearest minute) of removal of sampling gear from the water.

Zone (23)

P = plateau (above falls, rapids, etc.); E = escarpment (valleys and gorges); R = lowlands; C = corridor; U = upper flood plains; L = lower (riverine) flood plains; T = estuarine upper reaches; S = estuarine middle and lower reaches.

Habitat category (24)

C = continuous channel; P = isolated pools; S = springs; R = riffles; B = backwaters; D = artificial dams; K = costeans; W = buffalo wallow; T = tidal creek.

Habitat subtype (25)

I = inshore; O = offshore; C = cross-section (of both the above); B = backwater; R = riffle; T = total sample; S = submerged bank; Y = tributary.

Method notes (27)

Seine net: S = semicircle; P = parallel to bank; T = around a point; C = at right angles to bank.

Gillnets and longlines: M = set to middle of waterbody; X = set from bank to bank; L = set longitudinally from bank; D = dragged through centre of waterbody.

Other methods: I = inshore; O = offshore.

Dimension A (28–30) and Dimension B (31–34)

Dimensions needed to calculate area netted (generalised according to shape of waterbody). Usually recorded only when seine netting. Measured in metres, or estimated to nearest 5 m.

Maximum depth (35–36) and minimum depth (37–38)

Measured to nearest 0.1 m at fishing site.

Gauge height (39–40)

Height read to the nearest 0.1 m, from which water depth was calculated. N in column 39 indicates level is below indicated zero.

Bank incline (submerged) (41–42)

Column 41 is the most dominant incline.
U = undercut; V = near vertical; A = acute; S = shallow (less than 10° to horizontal).

Vegetation type (43–46)

Column	*Vegetation Type*	*Rank*
43	emergent	0 = absent
44	submergent	1 = trace
45	floating attached	2 = quarter
46	floating unattached	3 = half
		4 = three-quarters
		5 = total
		6 = vegetation adjacent
		7 = submerged terrestrial vegetation.

Substrate (47–48)

Column 47 is the most dominant incline.

Classification	*Particle diameter*
B = boulders and bedrocks	> 1 m
R = rocks	0.05–1.0 m
G = gravel	2–50 mm
S = sand	0.1–2 mm
M = mud (soft)	< 0.1 mm
C = clay (firm)	< 0.1 mm
L = leaf litter	

Bank cover (49–51)

Column 49: most dominant bank cover species; 50: second; 51: third.

Thick	*Medium*	*Sparse*	
L	A	C	= logs
P	D	E	= *Pandanus* sp.
M	F	H	= *Melaleuca* sp.
R	I	J	= rainforest
G	K	Q	= grass/sedge
B	S	T	= boulders
U	V	W	= *Eucalyptus* sp.
X	Y	Z	= *Barringtonia* sp.
N	N	N	= no cover

pH: surface (53–54), bottom (68–69)

Measured to 0.1 pH unit at the fishing site.

Dissolved oxygen: surface (55–57), bottom (70–72)

Measured to the nearest 0.1 mg/L.

Water temperature: surface (58–59), bottom (60–61)

Measured to the nearest 1°C at the fishing site.

Turbidity (62–65)

Secchi depth measured to the nearest 1 cm where < 10 cm and to the nearest 10 cm where > 10 cm.

M is entered in column 62 when Secchi depth > maximum depth at sampling site.

Flow (66–67)

FA = fast	> 1.0 m/s
ME = medium	0.5–1.0 m/s
ST = slow	0.1–0.5 m/s
SL = slight	< 0.1 m/s
LE = lentic	0 m/s

Conductivity: surface (73–75), bottom (76–78)

The natural logarithm of the meter read-out (±2 μS/cm) was recorded to two decimal places.

Species cards (79)

Number of fish species recorded at each sampling station.

Card type (80)

Environmental data card coded as A.

APPENDIX 2

General habitat card (type E)

The following variables are used in describing the general character of waterbodies inhabited by fish. Columns on data card (80 columns wide) are shown in parentheses.

Sample reference code (1–17)

Date, time, sampling site, sampling method and mesh size (if applicable); see Appendix 1.

Zone (18)

See Appendix 1.

Habitat category (19)

See Appendix 1.

Habitat width (20–22)

Measured to the nearest 1 m or average width estimated to the nearest 10 m. If F (floodplain) is in column 20 then the smallest unit is 100 m rather than 1 m.

Habitat length (23–26)

Measured to the nearest 1 m or average length estimated to the nearest 10 m.

Maximum depth (27–28)

Measured to the nearest 0.1 m at the deepest part of the waterbody.

Bank inclination (29–30)

See Appendix 1.

The average inclination of the submerged bank of the total waterbody is assessed rather than that of the particular fishing site.

Aquatic vegetation (31–42)

Columns 31–32 record the aquatic plant species covering the greatest area, 34–35 that covering the second greatest area, 37–38 that covering the third greatest area and 40–41 that covering the fourth greatest area (see list of vegetation species below for code numbers).

Columns 33, 36, 39 and 42 indicate the reproductive state of each species at the timing of sampling:

0 = sterile; 1 = buds only; 2 = open flowers present; 3 = fruits and/or seeds only; 4 = flowers, fruits and/or seeds present; 5 = asexual propagules present only; 6 = asexual propagules with flowers, fruits and/or seeds; 7 = not examined.

Bank vegetation (43–48)

Columns 43–44 record bank plant species covering the greatest area, 46–47 that covering the second greatest area (see list of vegetation species below for code numbers).

Columns 45 and 48 indicate the reproductive state of each species (see 'Aquatic vegetation').

Codes for aquatic and bank vegetation species:

01 Filamentous Alga sp. 1
02 *Elatine* sp. 1
03 Alga sp. 1 (*Spirogyra*?)
04 *Pseudoraphis spinescens*
05 *Nymphoides minima*
06 *Nymphaea gigantea*
07 *Ipomoea aquatica*
08 *Barringtonia acutangula*
09 *Pandanus aquaticus*
10 Terrestrial grasses
11 *Ceratophyllum demersum*
12 *Hydrilla verticillata*
13 *Nelumbo nucifera*
14 *Azolla pinnata*
15 *Fimbristylis minima*
16 Rainforest trees
17 *Melaleuca* spp.
18 *Marsilea* sp.
19 *Najas tenuifolia*
20 *Hymenachne acutigluma*
21 *Eriocaulon setaceum*
22 *Cyperus* sp. 1
23 *Brachiaria mutica*
24 *Polygonum* sp. 1
25 *Utricularia* sp. 1
26 *Cyperus javanicus*
27 *Utricularia* sp. 2
28 Aquatic grass (sp. indet.)
29 *Eriocaulon setaceum* (?)
30 Alga sp. 2 (*Mougeotia*?)
31 *Ludwigia adscendens*
32 Reed (sp. indet.)
33 Forb (sp. indet.)
34 *Vallisneria* sp.
35 *Aponogeton elongatus*
36 *Lepilaena* sp. 1
37 *Myriophyllum* sp. 1
38 *Myriophyllum* sp. 2
39 *Ceratophyllum* sp. 1
40 *Eucalyptus/Syzygium* trees
41 *Eleocharis dulcis*
42 *Nymphoides furculifolia*
43 *Nymphoides* sp. 1
44 *Limnophila* sp. 1
45 Hydrocharitaceae sp. 1
46 *Eleocharis* sp. 1
47 *Caldesia oligococca*
48 Filamentous Alga sp. 2
49 *Utricularia stellaris*
50 *Nymphoides indica*

Zonation (49)

0 = absent; 1 = present but not well marked; 2 = two distinct zones in at least one section of the waterbody; 3 = three distinct zones in at least one

section of the waterbody; 4 = four distinct zones in at least one section of the waterbody.

Total vegetation cover above water (50)

0 = absent; 1 = slight (less than 1/3); 2 = moderate (1/3–2/3); 3 = extensive (more than 2/3 but less than complete); 4 = complete cover of specific habitat; 5 = complete cover of waterbody.

Total vegetation cover below water (51)

Submerged cover as a proportion of total surface area of waterbody (see key in 'Total vegetation cover above water')

Density of bank vegetation (52)

0 = absent; 1 = rare; 2 = occasional; 3 = common; 4 = frequent; 5 = locally contiguous canopies; 6 = contiguous canopies.

Feeding damage on aquatic plants (53)

0 = no damage; 1 = fewer than 1/3 of the plants slightly damaged; 2 = fewer than 1/3 of the plants heavily damaged; 3 = 1/3 to 2/3 slightly damaged; 4 = 1/3 to 2/3 heavily damaged; 5 = 2/3 to nearly all slightly damaged; 6 = 2/3 to nearly all heavily damaged; 7 = all plants slightly damaged; 8 = all plants heavily damaged; 9 = not examined.

Condition of aquatic vegetation (54)

Aquatic plant condition was keyed as follows: 1 = no evidence of disease or nutrient deficiency (as indicated by yellowing of leaves and/or loss of turgidity); 2 = incipient signs in fewer than 1/4 of the plants; 3 = serious signs in a few plants, or slight signs in 1/4 to 1/2; 4 = fewer than 1/2 the plants badly affected or all affected slightly; 5 = all plants show marked evidence of disease and/or nutrient deficiency.

Algae: epiphytic (55) and benthic (56)

0 = absent; 1 = rare; 2 = occasional; 3 = common; 4 = frequent; 5 = locally common; 6 = abundant; 7 = not examined.

Phytoplankton (57)

0 = water crystal clear with no apparent green colour; 1 = water slightly green; 2 = water green, but clear; 3 = water green/blue, phytoplankton organisms visible; 4 = water very green/blue, phytoplankton organisms visible; 5 = water turbid or coloured (e.g. by tannin).

Surface algae (58–59)

Column 58 gives colour of algae: R = red; G = green; N = no algae. Column 59 gives cover as a proportion of the surface area of the waterbody (see 'Total cover above water').

Stream order (60–64)

The stream order of the main drainage for the catchment was entered into column 60, and the stream orders of sampled ensuing tributaries were entered thereafter.

Latitude (65–68) and Longitude (69–73)

Columns 65–66: degrees of latitude; columns 67–68: minutes of latitude; columns 69–71: degrees of longitude; columns 72–73: minutes of longitude.

Altitude (74–75)

10 metre units above mean sea level, Van Diemen Gulf.

Distance to estuary (76–78)

Distance to estuarine reaches, measured in km.

Card type (80)

General habitat data card coded as E.

APPENDIX 3

Genus species card (type B)

The following variables are recorded on the genus species card. Columns on data card (80 columns wide) are shown in parentheses.

Sample reference code (1–17)

Date, time, sampling site, sampling method and mesh size (if applicable).

Genus and species (18–54)

Generic and specific names follow the usage of the Australian Museum, 1979.

Total number (55–58)

Total number of fish.

Total weight (59–64)

Total weight (in g $\times$ 10^{-1}) of fish.

Length: minimum (65–68), maximum (69–72)

Minimum and maximum length (mm, TL or LCF) of fish.

Species code (73–77)

Australian Museum fish family codes are used for fish captured during the study or recorded from 'freshwater' habitats. These codes are:

Code	*Family*	*Genus and species*	*Common name*
00801	Carcharhinidae	*Carcharhinus leucas*	River whaler shark
02301	Pristidae	*Pristis leichhardtii*	River sawfish
03501	Dasyatidae	*Dasyatis fluviorum*	Brown river stingray
05402	Megalopidae	*Megalops cyprinoides*	Tarpon or ox-eye herring
08501	Clupeidae	*Nematalosa erebi*	Bony bream
08502	Clupeidae	*Nematalosa come*	Bony bream
08503	Clupeidae	*Hilsa kelee*	Black spotted bream
08801	Osteoglossidae	*Scleropages jardini*	Saratoga
18801	Ariidae	*Hexanematichthys leptaspis*	Lesser salmon catfish
18803	Ariidae	*Hexanematichthys* sp. A (= *leptaspis*)	Forktailed catfish
18804	Ariidae	*Hexanematichthys* sp. B (= *proximus*)	Forktailed catfish
18805	Ariidae	*Hexanematichthys* sp. C (= *australis*)	Forktailed catfish
19201	Plotosidae	*Anodontiglanis dahli*	Toothless catfish
19202	Plotosidae	*Neosilurus* sp. A	Eel-tailed catfish
19203	Plotosidae	*Neosilurus* sp. B	Eel-tailed catfish
19204	Plotosidae	*Porochilus obbesi*	Obbes catfish
19205	Plotosidae	*Neosilurus* sp. C	Eel-tailed catfish
19211–3	Plotosidae	*Tandanus ater* (3 colour types)	Narrow-fronted tandan
19214–6	Plotosidae	*Neosilurus hyrtlii* (3 colour types)	Hyrtl's tandan
19217–9	Plotosidae	*Porochilus rendahli* (3 colour types)	Rendahl's tandan
23401	Hemirhamphidae	*Zenarchopterus caudovittatus*	Garfish
24501	Melanotaeniidae	*Melanotaenia nigrans*	Black-banded rainbow-fish
24502	Melanotaeniidae	*Melanotaenia maculata*	Chequered rainbow-fish
24503	Melanotaeniidae	*Melanotaenia australis*	Red-tailed rainbow-fish

Code	*Family*	*Genus and species*	*Common name*
24600	Atherinidae	*Craterocephalus* sp.	Hardyhead
24601	Atherinidae	*Craterocephalus marjoriae*	Marjorie's hardyhead
24602	Atherinidae	*Craterocephalus stercusmuscarum*	Fly-specked hardyhead
24603	Atherinidae	*Pseudomugil tenellus*	Dainty blue eye
28501	Synbranchidae	*Ophisternon gutturale*	One-gilled eel
31001	Centropomidae	*Ambassis agrammus*	Sail-fin perchlet
31002	Centropomidae	*Ambassis macleayi*	Reticulated perchlet
31003	Centropomidae	*Denariusa bandata*	Penny fish
31004	Centropomidae	*Lates calcarifer*	Silver barramundi
31005	Centropomidae	*Ambassis elongatus*	Yellow-fin perchlet
31006	Centropomidae	*Ambassis* sp.	Perchlet
32101	Teraponidae	*Amniataba percoides*	Black-striped grunter
32102	Teraponidae	*Hephaestus fuliginosus*	Black grunter or bream
32103	Teraponidae	*Leiopotherapon unicolor*	Spangled grunter
32104	Teraponidae	*Syncomistes butleri*	Sharp-nosed grunter
32105	Teraponidae	*Pingalla* sp.	Black-blotched anal-fin grunter
32701	Apogonidae	*Glossamia aprion*	Mouth almighty
35901	Toxotidae	*Toxotes lorentzi*	Primitive archer fish
35902	Toxotidae	*Toxotes chatareus*	Common archer fish
35903	Toxotidae	*Toxotes jaculator*	Archer fish
36301	Scatophagidae	*Scatophagus* sp.	Butter fish
38101	Mugilidae	*Liza diadema*	Ord River mullet
38102	Mugilidae	*Liza dussumieri*	Green-backed mullet
38103	Mugilidae	*Squalomugil nasutus*	Mud mullet
38104	Mugilidae	*Liza macrolepis*	Mullet
42801	Gobiidae	*Glossogobius giurus*	Flat-headed goby
42802	Gobiidae	*Glossogobius aureus*	Goby
42901	Eleotridae	*Hypseleotris compressus*	Northern carp gudgeon
42902	Eleotridae	*Mogurnda mogurnda*	Purple-spotted gudgeon
42903	Eleotridae	*Oxyeleotris lineolatus*	Sleepy cod
42904	Eleotridae	*Prionobutis microps*	Small-eyed sleeper
42905	Eleotridae	*Oxyeleotris* sp.	Black-banded gauvina
45101	Belonidae	*Strongylura kreffti*	Long tom
46201	Soleidae	*Aseraggodes klunzingeri*	Tailed sole
46202	Soleidae	*Brachirus salinarum*	Salt-pan sole
46301	Cynoglossidae	*Cynoglossus heterolepis*	Tongue sole

Card type (80)

Genus species card coded as B.

APPENDIX 4

Biology card (type C)

The following variables are recorded on the biology card. Columns on data card (80 columns wide) are shown in parentheses.

Sample reference code (1–17)

Date, time, sampling site, sampling method and mesh size.

Species code (18–22)

See Appendix 3.

Fish numbers (23–25)

In each sample, for each species, fish were numbered individually up to 100; these columns record the individual's number. For samples with more than 100 fish per species, 100 fish were randomly sub-sampled for measurement.

Genus and species (26–58)

See Appendix 3.

Fish length (59–62)

Length of each fish (LCF or TL in mm)

Fish weight (63–68)

Weight of each fish, in g × 10^{-1}

Sex (69)

M = male; J = juvenile or indeterminate; F = female; H = hermaphrodite.

Gonad weight (70–75)

Gonad weight recorded (in g) to two decimal places for larger species and to three decimal places for small species.

Gonad stage (76)

Stages I–VII (see Section 3.4) recorded as 1–7.

Fullness (77)

Coded as follows (adapted from Ball, 1961):
0 = empty; 1 = 1/4 full; 2 = 1/2 full; 3 = 3/4 full; 4 = full; 5 = distended and full; 6 = distended, remnants only.

Number of stomach cards (78–79)

Number of stomach contents cards (type D) used per specimen examined in biological card.

Card type (80)

Biology data card coded as C.

APPENDIX 5

Stomach contents card (type D)

The following variables are recorded in the stomach contents card. Columns on data card (80 columns wide) are shown in parentheses.

Sample reference code (1–17)

Date, time, sampling site, sampling methods and mesh size (if applicable).

Species code (18–22)

See Appendix 4.

Fish number (23–24)

See Appendix 4.

Item (25–48, 52–76)

Stomach contents food items. Taxonomic item prefixes (25–27, 52–54) as follows:

Item prefix	*Taxon*
KIN	Kingdom
SPP	Superphylum
PHY	Phylum
SBP	Subphylum
SPC	Superclass
CLA	Class
SBC	Subclass
DIV	Division
SPO	Superorder
ORD	Order
SBO	Suborder
SEC	Section
SPF	Superfamily
FAM	Family
SBF	Subfamily
TRI	Tribe
GEN	Genus
SPG	Supergenus
SBG	Subgenus
SPS	Superspecies
SPE	Species
SBS	Subspecies
Miscellaneous:	
EMP	empty
DEC	decomposed
DAM	damaged
LIQ	liquid
MAT	material

Percentage (49–51, 77–79)

Percentage volume of each food type in stomach contents recorded to nearest 5%.

Card type (80)

Stomach contents data card coded as D.

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(*a*)

(*b*)

Plate 1. Escarpment area habitats. (*a*) terminal waterbody (site KD); (*b*) main-channel waterbody; (*c*) perennial stream (site RS); (*d*) just downstream of terminal waterbody (site KD).

(*c*)

(*d*)

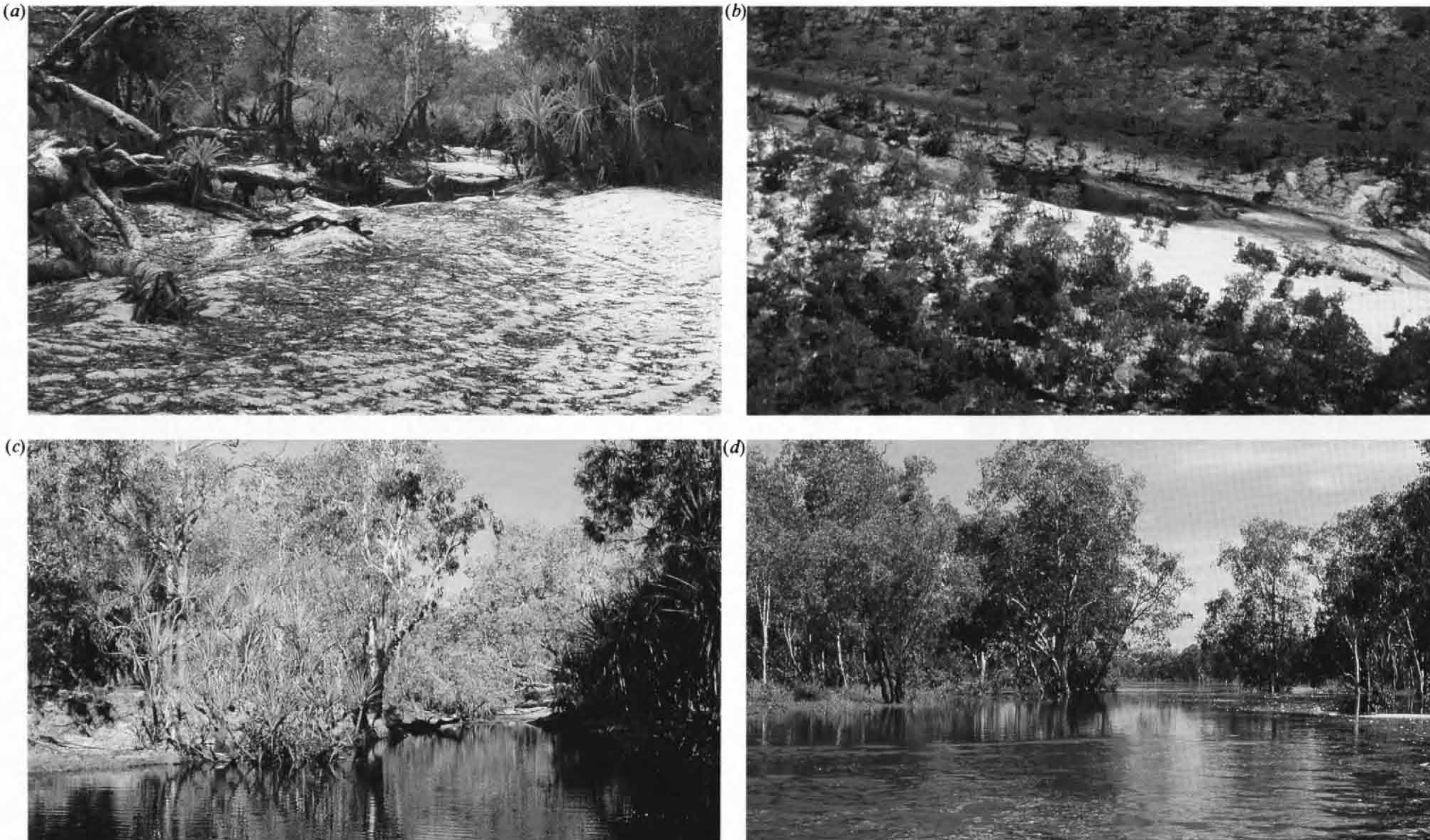
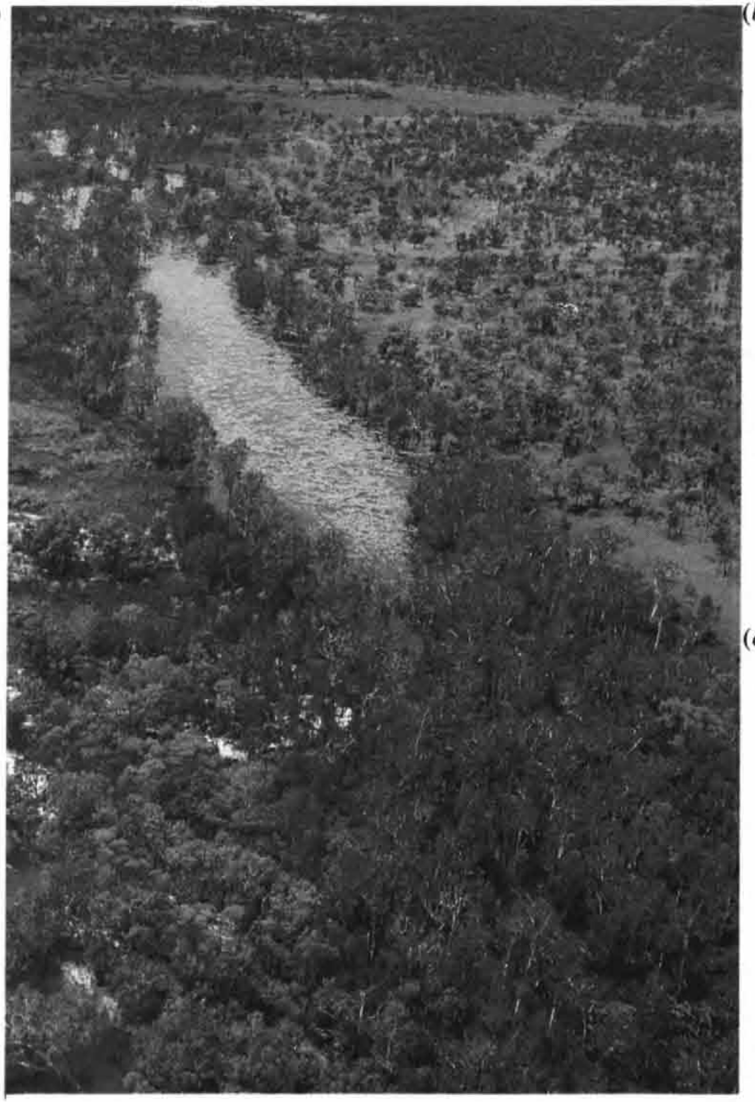


Plate 2. Sandy creek bed habitat, Magela Creek. (*a*) Late-dry season (site MD) (2.xi.79); (*b*) aerial view of upper Magela Creek, Late-wet–Early-dry season; (*c*) Mid-dry season (site MD) (.viii.78); (*d*) Early-wet season (site MD) (5.xii.78).

(a)



(b)

(c)

Plate 3. Lowland shallow backflow billabong habitats (site DA). (*a*) aerial view, 1978–79 Mid-wet season; (*b*) Late-dry season (2.xi.79); (*c*) Mid-wet season (28.ii.79).

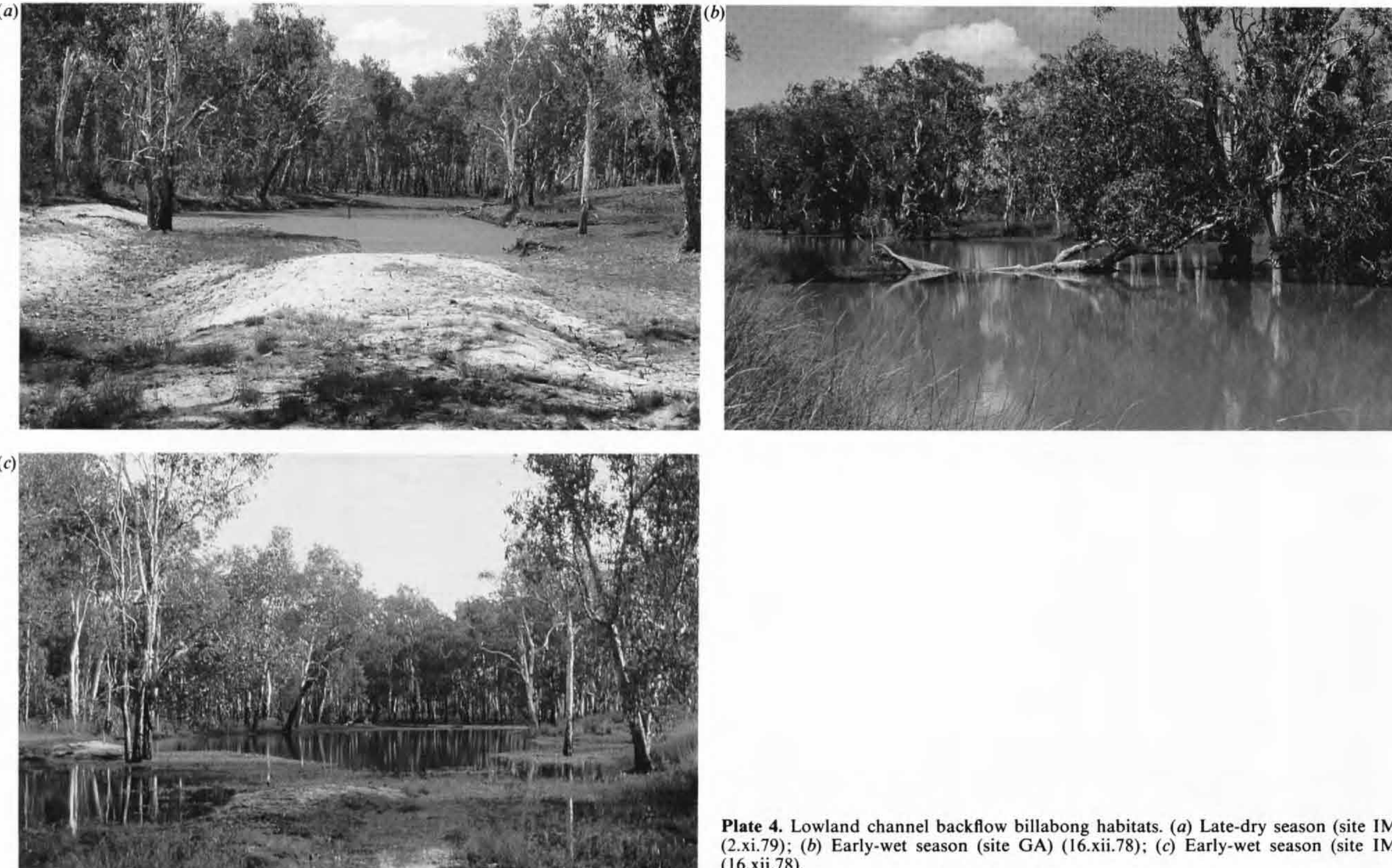


Plate 4. Lowland channel backflow billabong habitats. (*a*) Late-dry season (site IM) (2.xi.79); (*b*) Early-wet season (site GA) (16.xii.78); (*c*) Early-wet season (site IM) (16.xii.78).

(*a*)

(*b*)

(*c*)

Plate 5. (*a*) Corridor waterbody habitat (site MI), Early-wet season (.xii.79); (*b*) upper Magela flood plain, showing luxuriant aquatic plant growth in the Mid-wet season (.iii.79); (*c*) upper flood plain habitat (site NN), Early-wet season (14.xii.78).

Plate 6. Lower (riverine) flood plain and estuarine habitats (East Alligator River). (*a*) at the limit of tidal influence (site RH); (*b*) floodplain billabong (site WL); (*c*) upper reaches of estuary at Cahill's Crossing (site CC); (*d*) aerial view of meandering lower reaches of estuary, Mid-dry season (.viii.78).

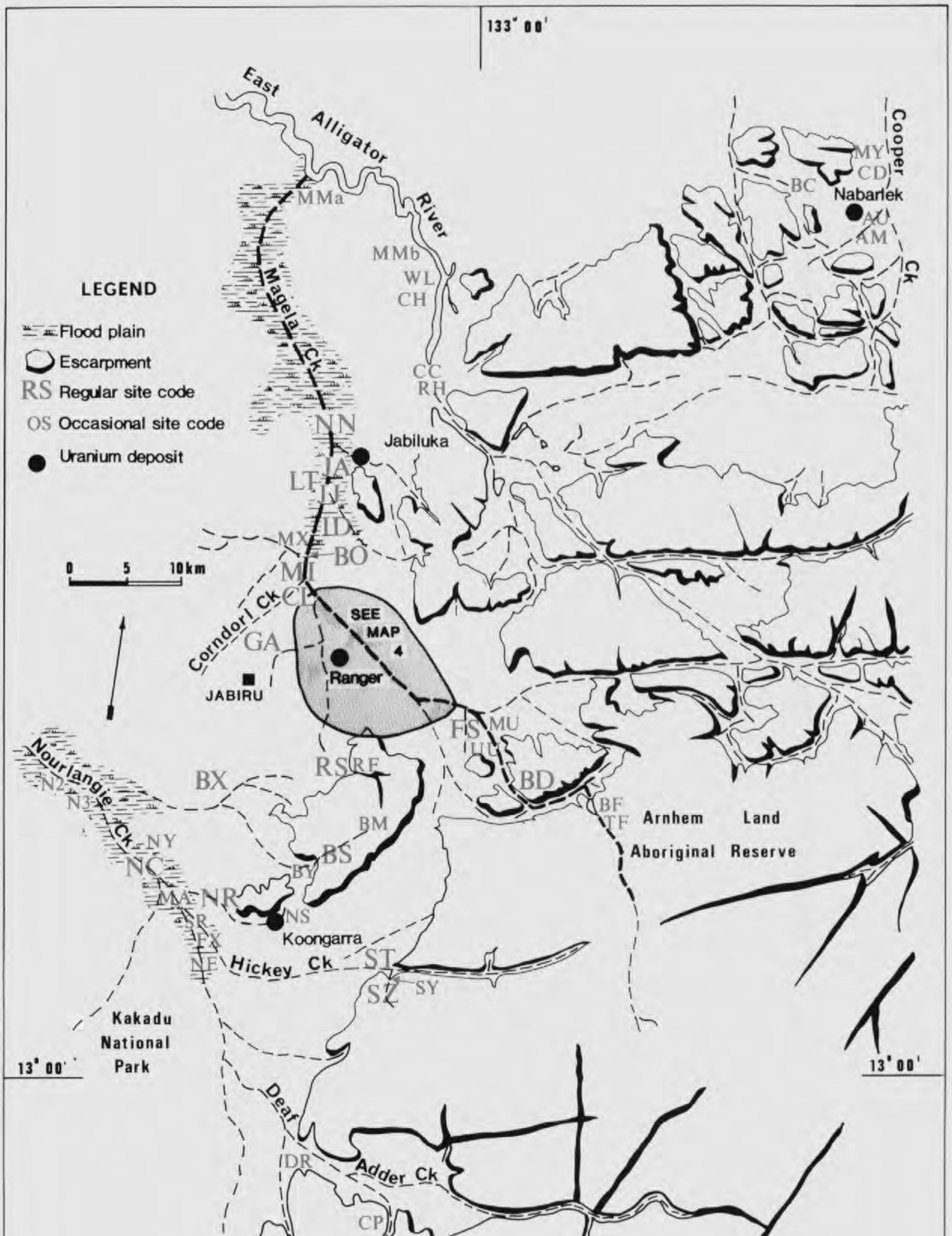
SUPERVISING SCIENTIST FOR THE ALLIGATOR RIVERS REGION RESEARCH PUBLICATIONS

Alligator Rivers Region Research Institute Research Report 1983-84
Alligator Rivers Region Research Institute Annual Research Summary 1984-85

Research Reports (RR) and Technical Memoranda (TM)

RR1	The macroinvertebrates of Magela Creek, Northern Territory. April 1982 (pb, mf – 46 pp)	Marchant, R.
RR2	Water quality characteristics of eight billabongs in the Magela Creek catchment. December 1982 (pb, mf – 60 pp)	Hart, B.T. & McGregor, R.J.
RR3	A limnological survey of the Alligator Rivers Region. Part I. Diatoms (Bacillariophyceae) of the Region. August 1983 (pb, mf – 160 pp)	Thomas, D.P.
	A limnological survey of the Alligator Rivers Region. Part II. Freshwater algae, exclusive of diatoms. 1986 (pb – 178 pp)	Ling, H.U. & Tyler, P.A.
TM1	Transport of trace metals in the Magela Creek system, Northern Territory. I. Concentrations and loads of iron, manganese, cadmium, copper, lead and zinc during flood periods in the 1978-1979 Wet season. December 1981 (pb – 27 pp)	Hart, B.T., Davies, S.H.R. & Thomas, P.A.
TM2	Transport of trace metals in the Magela Creek system, Northern Territory. II. Trace metals in the Magela Creek billabongs at the end of the 1978 Dry season. December 1981 (pb – 23 pp)	Davies, S.H.R. & Hart, B.T.
TM3	Transport of trace metals in the Magela Creek system, Northern Territory. III. Billabong sediments. December 1981 (pb – 24 pp)	Thomas, P.A., Davies, S.H.R. & Hart, B.T.
TM4	The foraging behaviour of herons and egrets on the Magela Creek flood plain, Northern Territory. March 1982 (pb, mf – 20 pp)	Recher, H.F. & Holmes, R.T.
TM5	Flocculation of retention pond water. May 1982 (pb, mf – 8 pp)	Hart, B.T. & McGregor, R.J.
TM6	Dietary pathways through lizards of the Alligator Rivers Region, Northern Territory. July 1984 (pb, mf – 15 pp)	James, C.D., Morton, S.R., Braithwaite, R.W. & Wombey, J.C.
TM7	Capacity of waters in the Magela Creek system, Northern Territory, to complex copper and cadmium. August 1984 (pb, mf – 42 pp)	Hart, B.T. & Davies, S.H.R.
TM8	Acute toxicity of copper and zinc to three fish species from the Alligator Rivers Region. August 1984 (pb, mf – 31 pp)	Baker, L. & Walden, D.
TM9	Textural characteristics and heavy metal concentrations in billabong sediments from the Magela Creek system, northern Australia. October 1984 (pb, mf – 39 pp)	Thomas, P.A. & Hart, B.T.
TM10	Oxidation of manganese(II) in Island Billabong water. October 1984 (pb, mf – 11 pp)	Hart, B.T. & Jones, M.J.
TM11	*In situ* experiments to determine the uptake of copper by the aquatic macrophyte *Najas tenuifolia* R.Br. December 1984 (pb, mf – 13 pp)	Hart, B.T., Jones, M.J. & Breen, P.
TM12	Use of plastic enclosures in determining the effects of heavy metals added to Gulungul Billabong. January 1985 (pb, mf – 25 pp)	Hart, B.T., Jones, M.J. & Bek, P.
TM13	Fate of heavy metals in the Magela Creek system, northern Australia. I. Experiments with plastic enclosures placed in Island Billabong during the 1980 Dry Season: heavy metals. May 1985 (pb, mf – 46 pp)	Hart, B.T., Jones, M.J. & Bek, P.
TM14	Fate of heavy metals in the Magela Creek system, northern Australia. II. Experiments with plastic enclosures placed in Island Billabong during the 1980 Dry Season: limnology and phytoplankton. May 1985 (pb – 32 pp)	Hart, B.T., Jones, M.J., Bek, P. & Kessell, J.
TM15	Use of fluorometric dye tracing to simulate dispersion of discharge from a mine site. A study of the Magela Creek system, March 1978. January 1986 (pb, mf – 51 pp)	Smith, D.I., Young, P.C. & Goldberg, R.J.

pb = available as paperback; mf = available as microfiche



Map 2. Location of regular and occasional sampling sites. Sites JD and TW are further south than the coverage of this map. Sites CA, C1, C2, C3, C4, DA, GD, GL, GN, GU, IF, II, IM, LC, MD, MG, MJ, RO, RT, TD and ZZ are shown on Map 4.