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AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS

RUM JUNGLE ENVIRONMENTAL STUDIES

Edited by

D.R. DAVY

September 1975

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FOREWORD

The Rum Jungle (RJ) uranium mining project was planned in 1953, at a time when the environmental consequences of mining operations received less attention than they do now. The subsequent conduct of mining and milling operations at RJ did attract criticism on environmental grounds, and the realisation that our knowledge of the precise extent of environmental pollution in the RJ area and of the mechanisms underlying the spread of contaminants, was inadequate led to the initiation of the present study in October 1973.

Since uranium extraction on a large scale was then being planned for mines in the climatically similar Alligator Rivers area of the Northern Territory (NT), an important secondary objective of the study was to obtain background information which would help to assess the environmental consequences of the new developments and facilitate planning to minimise them.

The RJ study had the following local objectives:

- to identify the sources of pollution and their relative importance;
- to determine the extent of pollution and its seasonal variation;
- to obtain an understanding of the basic physical, chemical and biological mechanisms concerned in the continuing pollution;
- to determine the fate of radium and other heavy metals discharged during the operations of the mines; and
- to propose, assess and cost remedial measures.

From its inception the study has been a joint project of the Australian Atomic Energy Commission (AAEC) and the Department of Northern Australia*. The arrangements included revegetation trials which had been initiated in the previous year by the Animal Industry and Agriculture Branch DNA, an assessment of the recreational potential of the RJ

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* Until January 1975, called the Department of the Northern Territory (DNT).

area by the Forestry, Fisheries, Wildlife Environment and National Parks Branch DNA, and the preparation of cost estimates for some remedial proposals by the Department of Housing and Construction. Unfortunately, disruption of effort by Cyclone Tracy has hampered the last two of these projects, and the report is less detailed in these aspects than was originally planned.

The preparation of this report was influenced by the decision to hold a public inquiry into the environmental effects of the proposed development of the uranium deposits at Jabiru by Ranger Uranium Mines Pty Ltd. Since the subject matter of the RJ study is clearly relevant to that inquiry, the publication date of the report was advanced to make it available for the inquiry.

Two special acknowledgements are due: first to the chemists and their assistants, unnamed in the text, who have carried out the very large number of chemical analyses necessitated by a study of this type; second to the Scientific Editor and her staff. In conjunction with the Senior Draftsman, Drawing Office staff together with the Supervisor and staff of the Printing Section, and in spite of many unanticipated and frustrating set-backs, they were still able to meet deadlines. All authors wish to express their sincere appreciation of the unstinted assistance received from these groups.

D.R. DAVY
(Study Leader)

RUM JUNGLE ENVIRONMENTAL STUDIES

CHAPTER 1

MANAGERIAL HISTORY OF THE RUM JUNGLE PROJECT

by

G.M. WATSON

ABSTRACT

A brief managerial history of the Rum Jungle project is given and an assessment is made of the cost and benefits in order to remedy any environmental pollution.

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1. MANAGERIAL HISTORY OF THE RUM JUNGLE PROJECT

1.1 Introduction

Contemporary legislation, reinforced by the prevailing climate of public opinion, requires that a large scale mining development be allowed to proceed only after its probable environmental effects have been assessed and found to be acceptable. Assessment will usually require preparation of an environmental impact statement and the examination of this statement in private or public enquiry. Twenty-five years ago, when the Rum Jungle (RJ) uranium mining project was initiated, these requirements did not exist and no predictions of its environmental consequences were made for us to examine now with the benefit of hindsight. As it turned out, RJ mining operations did cause environmental degradation to an extent that is unacceptable if assessed by present day standards; and the immediate objective of the study reported here was to define the origin and extent of this degradation in sufficient detail to allow remedial measures to be identified, costed and, where feasible, executed. A further important objective was to obtain information which would help to assess the environmental effects of uranium mining and milling elsewhere, particularly in the monsoonal areas, and might facilitate their control.

Determination of the acceptability of environmental change demands that the costs attributable to this change are set against the value of the benefits flowing from the operation in question, however difficult it may be to find a common unit of currency for making the comparison. Environmental contamination at RJ is now a matter of history which has to be accepted, but the prescription of remedial measures for it requires a similar comparison of costs and benefits in order to answer the question: are the remedies worthwhile? To some extent the benefits are also a matter of history but need still to be borne in mind when the attempt is made to answer this question. There are intangibles on both sides of the ledger; for example, what positive money value might be thought to offset the present unattractiveness of the East Branch of the Finniss River for recreational purposes, or what credit should be allowed for having helped to meet the needs of allied countries for uranium in the decade to 1963? Nevertheless the costs, if not the effectiveness, of remedial measures can be estimated with some confidence, and the trading accounts of the operation are a matter of record. The possible remedial measures will be considered later; this section provides a summary of the overall national benefit, where possible in cash terms, that has resulted from the Rum Jungle mining operation.

1.2 Managerial History

In 1949-51, the existence of uranium deposits in the Rum Jungle area were reported and confirmed. In March 1952, representatives of the United States Atomic Energy Commission (USAEC) and of the United Kingdom Atomic Energy Authority (UKAEA) visited Australia to discuss development of the RJ and Radium Hill uranium fields. This led to the provision of funds for these projects by the Combined Development Agency (CDA, the joint Anglo-American uranium purchasing organisation), a formal agreement on Rum Jungle being executed in January 1953. In August 1952, the Commonwealth Government had made arrangements with Consolidated Zinc Pty Ltd for the management of the RJ project; Consolidated Zinc Pty Ltd (now Conzinc Riotinto of Australia Ltd) formed a wholly owned subsidiary, Territory Enterprises Pty Ltd (TEP) to manage the operation and this subsidiary took over the RJ development, as agent for the Commonwealth Government, on January 1 1953. The Australian Atomic Energy Commission (AAEC) was established in April 1953 and immediately assumed control of the Rum Jungle project, taking over from the Department of Supply. Production of uranium oxide commenced in 1954.

In January 1963, the sales contract with the CDA expired. At that time the decision was made to keep the plant in operation to treat ore from the Rum Jungle Creek South (RJCS) deposit, the mining of which was completed later in 1963. Treatment of the RJCS ore was completed in 1971, the treatment plant was then closed down and the assets at the site sold by auction. The uranium oxide produced from the RJCS, and a little remaining ore from Dyson's deposit, was not sold and has been held as a stockpile. This reserve has to be taken into account as a benefit from the operation.

1.3 Financial Aspects

The RJ project was the first large industrial enterprise undertaken in the Northern Territory (NT), the total operating and capital expenditure to January 1963 being £19.6 million, most of which was spent in NT. Standards for housing and community amenities were high and have no doubt influenced other mining ventures. The overall financial gain from the project can be estimated approximately from the AAEC's report on Rum Jungle issued at completion of the CDA contract in 1963 and from expenditure on exploration and advances to TEP after that date.

In January 1963, accounts running from 1954 showed a total net profit of £3 380 000 in round figures or, in terms of 1973 dollars*, \$11 270 000. Expenditure on exploration from January 1963 to the 1969-70 financial year, and on advances to TEP to 1971-72, when activities ceased, amounted to \$1 020 000 and \$22 133 000 respectively, also in 1973 dollars. Taking the quantity of uranium oxide as yellowcake produced from the ore stockpiled in 1963 as 2060 tonnes, the cost of production after that date was approximately \$5.10 lb^{-1} in 1973 dollars, and after making an appropriate allowance for interest charges, sales above this figure will contribute further profit. Allowance should also be made for the costs of storing yellowcake and for sums received from the auction of plant at RJ, but these are minor adjustments.

The national benefit from RJ has therefore been substantial. In addition to cash profits and a valuable stockpile of uranium, the operation has contributed significantly to NT development and has provided experience in mining in monsoonal conditions from which useful lessons can be learnt. The mining township of Batchelor was passed over by the AAEC to the Department of the Interior and was maintained as an open town; it has not become derelict. This summary of benefits has not taken into account the mining and extraction of copper from the Intermediate deposit by another subsidiary company of Consolidated Zinc Pty Ltd in 1964-70 although, as will be seen in a later section, this operation also made some contribution to the environmental contamination which can be detected in the Rum Jungle area.

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* Conversions to 1973 dollars were based on the 'Implicit Price Level Australia' [Costello & Levins, Reduction of capital costs in reprocessing power reactor fuels. A design study AAEC/E275, September 1973], updated from 1972 to 1973 by the Commonwealth CPI.

<u>Note</u> All costs quoted in the present report are in £A or \$A.

RUM JUNGLE ENVIRONMENTAL STUDIES

CHAPTER 2

THE GEOGRAPHY, GEOLOGY, AND MINING HISTORY OF RUM JUNGLE

by

R.T. LOWSON

ABSTRACT

The geology and geography of the Rum Jungle region are described. A description is given of the effect on the environment of mining operations such as ore processing, effluent disposal and the leaching of stockpiles and overburden heaps.

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In addition to these maps the following maps produced by the Department of Minerals and Energy, Division of National Mapping are referred to 1:50 000 series: Tumbling Waters 5072-II, Manton Dam 5172-III, Batchelor 5172-IV, Rum Jungle 5071-I, Sweets Lookout 5072-III, Fog Bay 4972-II.

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2. THE GEOGRAPHY, GEOLOGY, WEATHER AND MINING HISTORY OF RUM JUNGLE

2.1 Geography and Geology of Rum Jungle

Rum Jungle (RJ), which derives its name from a fight in the region between the drivers of two bullock teams over a cargo of rum, is 64 km south of Darwin and 80 km east of the Joseph Bonaparte Gulf, part of the Timor Sea (Map 2.1). It was originally surveyed by Goyder's team of surveyors on behalf of the South Australian Government in the second half of the 19th Century. The land was divided into 'hundreds' and the RJ area became known as the Hundred of Goyder. The RJ mine area forms the common corner of the Tumbling Waters 5072-II, Manton Dam 5172-III, Batchelor 5172-IV and RJ 5071-I maps of the 1:50,000, edition I-AAS, series R722 maps of Australia. The original track and Overland Telegraph between Darwin and Alice Springs passes through the area. The North Australian Railway was built at the turn of the century and a small settlement which lasted only a few years developed around the RJ siding.

A bitumen airstrip was built 4.8 km south of this siding during World War II and, following the discovery in 1949 of uranium 6.4 km to the north of the siding, a bitumen road was built between the uranium prospect and the Stuart Highway 11 km east of the area. The RJ Treatment Plant was developed at the uranium prospect and the township of Batchelor to serve the mine was developed alongside the airstrip in 1953.

The general area is a peneplain of gently undulating land interspaced by expansive plains. The small hills termed 'Mounts' are usually only 150 m above the level of the surrounding plains. With the exception of the mine, the sole use of the land is agricultural. The soil is generally poor except in the river valleys which can flood during the Wet. Large mangrove swamps develop towards the sea and the coastline is often difficult to define. The land is well populated by kangaroo, wallaby, buffalo, brumby horses, pigs and smaller wild life. The perennial sections of the rivers are generally well stocked with fish which provide a staple diet for freshwater crocodiles.

The area is drained by the Finniss catchment. Neighbouring catchments are the Darwin to the north, the Adelaide to the east and the Daly to the south. The Finniss River (FR) is one of the smaller rivers that drain the northwest of the Northern Territory (NT). It is approximately 140 km long entering the sea at Fog Bay via a wide mudflat mangrove swamp estuary. The upper reaches of the river are a series of tributaries, the most important being Florence Creek (FC), the South Branch and the East Branch (EB), along with FR itself. The RJ mine is located on EB which has no flow from approximately July to December, but FR has permanent flow from its junction with Banyan Creek, 26 km upstream from its junction with EB.

The RJ mine straddles the EB 8.5 km above the FR junction with about two thirds of the EB catchment remaining upstream of the mine. Since 1954, EB has been used to drain all runoff water from the mine area and all plant effluent. The river started to become polluted from this time. A gauging station was operated by the WRB from 1961 to 1965 at the roadbridge adjacent to the mine site. In 1965 this station was resited 6 km downstream and equipped with a weir and water level recorder. The average annual discharge across this weir for the past seven years of operation was $4.2 \times 10^7 m^3$. In addition to gauging the river flow, since 1962 the WRB has regularly sampled the EB at the North Australian Railway bridge crossing which is located 3.5 km upstream of the weir and 2.5 km downstream of the RJ mine.

Map 2.2 is a geological plan of the area while Table 2.1 is an explanatory chart of the sequence of geological events. In the Rum Jungle area, which is in the northwestern part of the Pine Creek Geosyncline, sedimentary rocks of the Lower Proterozoic age were deposited unconformably on the older Rum Jungle and Waterhouse granitic complexes. The oldest of these sedimentary rocks, the Beeston's Creek Dolomite, outcrops along the southern edge of the Rum Jungle Granite but is not known around the Waterhouse complex. The younger Crater Formation rims both granite complexes round most of their margin except where it is underlaid by the Beeston's Creek and Celia Creek sediments.

The Crater Formation is overlaid by the Coomalie Dolomite which forms the bed of the EB immediately below the treatment plant. Being a cavenous formation it has played an important part in determining the dispersion of polluted water emanating from the plant.

The uranium, copper, lead, nickel, zinc and cobalt mineralisation occurs in the subsequent Golden Dyke Formation near its contact with the

Coomalie Dolomite. The formation takes its name after the Golden Dyke goldmine which occurs in this formation and suggests that gold may be found in other parts of the formation. The Golden Dyke Formation is overlaid by the Acacia Gap Tongue in the treatment plant area, while at Mount Fitch some 8 km to the northwest it is replaced by the Burrell Creek Formation.

There is an unclassified rock unit, the Hematite Quartzite Breccia which consists of angular fragments of quartz up to ~ 1 dm in diameter contained in a pink sandy matrix. In places, the fragments are absent and the rock is pink quartzite. The formation invariably overlies the Coomalie Dolomite but its age and mode of formation are still the subject of speculation among geologists.

Following the deposition of the Acacia Gap Tongue, the structure folded and faulted. A major movement formed Giant's Reef Fault which strikes northeast to southeast through the RJ Granite and the overlying sediments. The north side is horizontally displaced 5.5 km east but the vertical displacement is unknown. This displacement created an embayment of sedimentary rocks into the RJ Granite within which the White's, Dyson's, Intermediate and Brown's orebodies occur. If the portion north of Giant's Reef Fault on Map 2.2 is shifted 5.5 km west along the fault line, the geological plan of the original RJ embayment before faulting occurred is revealed demonstrating that all the mines and prospects, including Rum Jungle Creek South (RJCS) mine, follow the line of the embayment along the Golden Dyke-Coomalie Dolomite interface. Quartz precipitated in the granite sections of the fault which highlights the fault line both on the ground and in aerial photographs.

Following formation of the Giant's Reef Fault, two further formations were laid down: the Buldiva Creek Sandstone which was used for construction work and a ferruginous laterite of Tertiary age which overlies the Coomalie Dolomite about 3 km west of the treatment plant. This formation conveniently straddles the railway line and was surveyed in 1969 for recovery of the iron ore. Several dolerite sills occur in the Golden Dyke Formation and there is one dolerite dyke in the Crater Formation.

The geology of the area is discussed in detail by Spratt [1965] and Berkman [1968]. It is currently being reviewed by the Bureau of Mineral Resources (BMR) and an updated version of the geological map is being prepared [Johnson 1974].

The genesis of the orebodies is still open to debate. All the orebodies occur in the Golden Dyke Formation and are associated with fault zones. There is evidence to suggest that the mineralisation was laid down with the host rock. However there is also evidence for hydrothermal reaction, possibly due to extensive heating of the host rock. A clearer understanding of the genesis may help in defining the sensitivity of the exposed ores to subsequent natural leaching.

EB rises in the RJ Granite and flows across the Giant's Reef Fault on to the Golden Dyke Formation immediately south of the Dyson's mine. Before the river was diverted, it used to traverse the Golden Dyke Formation and the underlying mineralisation of White's and Intermediate mines, before reaching the Coomalie Dolomite. It now traverses the Golden Dyke Formation immediately west of the Intermediate mine. There is some visual evidence that there is a preferential groundwater flow in the Coomalie Dolomite associated with EB at this point. After traversing the dolomite bed, EB strikes along the RJ Granite and runs parallel with the embayment for 8 km. A permanent spring from the dolomite zone feeds EB towards the end of this section. After crossing the embayment again between Mount Fitch and Mount Burton, EB crosses an alluvial plain and joins FR.

2.2 Mining Operations at Rum Jungle

The extensive mineralisation in RJ area was first noted by a surveyor named Wood in 1869 and the copper deposits were worked for a short time in the early 1900s. Specimens of malachite suitable for display may still be collected from the surface deposits close to the Batchelor road, east of Brown's shaft. The first report of uranium mineralisation was that of Mr. J.M. White, a local farmer and amateur prospector, who owned a farm on EB about 6 km downstream of the area. Subsequent drillings by the BMR established the presence of a high grade orebody and further investigations led to the discovery of Dyson's, White's Extended, Mount Burton and Mount Fitch uranium deposits, and Brown's lead and Intermediate copper deposits.

At the request of the Commonwealth Government, Consolidated Zinc Pty Ltd (later to amalgamate with Rio Tinto Pty Ltd as Conzinc Riotinto of Australia Ltd (CRA)) formed, in 1953, a wholly owned subsidiary company, Territory Enterprises Pty Ltd (TEP) to mine and treat the uranium orebodies on behalf of the government [Berkman 1968]. TEP also carried out an exploration program and discovered the RJCS orebody. Extensive copper mineralisation occurred with most of the uranium ores. This copper was also recovered by TEP through the treatment plant under a Commonwealth Government licence.

The Intermediate copper orebody was mined by Australian Mining and Smelting Co Ltd (AM&S), a subsidiary of the Zinc Corporation Ltd. The high grade ore passed through the treatment plant on a licence basis while the low grade ore was recovered from a leach pile. AM&S also carried out exploration of the associated orebody known as Brown's prospect. Although on paper a separate company, AM&S at that time was completely dependent on TEP for staff, administration and materials.

In 1971 mining and milling operations ceased and the treatment plant was closed down. With the demise of TEP, AM&S ceased operations at RJ as well. Currently no mining or treatment is being carried out. The AM&S interests in Intermediate, the Heap Leach, Intermediate Extended and Brown's prospect were then transferred to Dawk Ltd and subsequently to CRA Services Ltd, both wholly owned subsidiaries of CRA. CRA Services Ltd regularly renews the mining licences for these leases. The company now known as AM&S has no current direct link with RJ.

Table 2.2 presents the chronology of mining operations in the RJ area. Initially, it was intended to recover White's ore by underground mining and an exploratory shaft was sunk. However, because the orebody was of a very irregular nature and there was a shortage of experienced underground miners, it was decided to convert to opencut operation. Part of White's orebody was situated directly beneath the EB bed (Map 2.3). Accordingly, the river was dammed upstream of the orebody and a diversion channel cut to bypass the area of the proposed opencut. Also, to prevent surface water entering the opencut, an embankment, 6 m high, was built around the north and west sides of the area. The embankment crossed EB downstream of the opencut and so prevented flood waters from backing up and flooding the mine area.

The overburden was excavated by contractors and piled south of the diversion channel using a bridge that was subsequently dismantled. This mullock heap became known locally as Mount Wimpey. White's ore occurred in several distinct layers: uranium-copper, copper-cobalt,

cobalt-nickel and lead-nickel, all of which were mixed with pyrites. The composition of the various ores is listed in Table 2.3 A to E.

By 1969, all the ores had been treated with the exception of the lead ore. During excavation, groundwater entered the mine at a depth of 50-60 m and it was necessary to pump out 3.2 x $10^6 m^3$ of water while mining. After mining ceased in 1958, the opencut was allowed to fill up and the upstream and downstream dams across EB were breached allowing the river to resume its original course across the opencut. This provided a storage pond for the treatment plant.

All subsequent orebodies were also mined by opencut operation. The Dyson's mine was located on the slopes of the EB valley about 1.5 km upstream of White's. Apart from a protective wall on the high side of the cut to prevent entry of surface water, no other embankments or channels were constructed. The mullock was piled on the hillside immediately below the mine. All the uranium ore was treated before the mine closed down, but the Bogum stockpile is still in its original position at the head of the stockpile area. All the ore from White's Extended which was a small surface lode located between White's and Dyson's mine, has been treated.

The Mount Burton orebody was located close to FR about 3.2 km upstream of the EB junction. The orebody was at the base of a small hill and separated from Mount Burton by a small creek known as Mount Burton Spring Creek which has permanent flow. The ore was recovered by opencut mining and the overburden piled east of the opencut alongside the creek. Of the ores excavated, the uranium-copper ore was treated, while the copper and Bogum piles were reported as stockpiled in 1969. With the completion of mining, the opencut was allowed to flood.

The RJCS mine was located 6.5 km south of the treatment plant and 3.2 km west of Batchelor. The mine was located on level ground and, apart from some small embankments and channels to divert surface waters, no major earthworks were required. The overburden which contains a fair amount of pyrites was piled alongside the opencut. Both the uranium ore and Bogum were completely treated before the treatment plant was closed down. The opencut was allowed to fill when mining was completed.

The Intermediate orebody was located 500 m west of the White's ore and beneath the EB bed. Accordingly, embankments, 6 m high were built to encircle the mine completely and the river diversion channel was extended south and west of these embankments as far as the roadbridge The dam above White's opencut had been reconstructed previously with sluice gates to allow controlled flushing of White's opencut.

Three ores were excavated, a high grade mill ore, a sulphide ore and an oxide ore. The mill ore was treated by froth flotation in the treatment plant while the sulphide and oxide ores were piled between Whites's and Intermediate opencuts and treated by heap leaching. The overburden of copper pyritic shales was dumped south of the river diversion channel using a bridge which was dismantled after the treatment plant closed.

2.3 Ore Treatment

Ore treatment commenced in 1954 and continued until shutdown in 1971. Initially only White's ore was treated, but with the progressive stockpiling of ores, suitable blends were made of rich and lean ores to maintain an average uranium content of 3 kg U_3O_8 t^{-1} in a host rock of average chemical composition. The blended ore was first crushed to less than 1 cm and then added to a rod mill, together with 3 kg pyrolusite t^{-1} of ore as an oxidant, 0.6 kg lime t^{-1} of ore and mill water. The lime was added to neutralise the mill water. The resulting pulp was leached in rubber-lined tanks using sulphuric acid made on site. Acid consumption varied with the type of ore as listed below:

White's	118 kg t^{-1}
Dyson's	143 kg t^{-1}
RJCS	70 kg t^{-1}

After settling the slurry with 0.12 kg gum guar t^{-1} of ore as a flocculating agent, the pregnant liquor was drawn off. The solids or tailings were disposed of or treated for copper by froth flotation if warranted. The pregnant liquor contained about 1 g U_3O_8 ℓ^{-1} along with many other metals. Till 1962, the uranium was extracted by ion exchange followed by elution with 1.0 M NaCl, 0.18 M H_2SO_4 and precipitation with magnesia using 1.6 kg MgO kg^{-1} U_3O_8. After 1962, a solvent extraction process was used with an organic phase of 5% tertiary amine, 3% nonanol and 92% kerosene and a stripping solution of 60 g NaCl ℓ^{-1} at pH 5.8. Then sodium diuranate was precipitated from the strip solution with NaOH using 0.45 kg NaOH kg^{-1} U_3O_8. If warranted, the eluent from the ion exchange process and the raffinate from the solvent extraction process were processed for copper by cementation before being disposed of. An approximate chemical composition for the raffinate is given in Table 2.4.

A lay reader's description of the plant was given by Barlow [1962] and the Australian Atomic Energy Commission (AAEC) [1963]. A technical description of the plant was given by Allman, Harris & Bayly [1968].

Table 2.5 lists the plant records for 1954-69 for the total amount of ore treated, the amount of product and tailings produced and the amount of uranium and maximum amount of copper in the tailings. In addition to loss of uranium to tailings, it is estimated that in 1960-61 there was an annual loss of 3.84×10^3 kg U in the raffinate. Plant records do not give details of the unrecovered copper and the last column of Table 2.5 represents the difference between the amount of copper in the treated ore and the product. Exactly how much copper was lost to waste raffinate and how much to tailings are not known. Also, the plant records do not show how much copper was recovered from the copper launders.

The tailings were discharged as a 55 wt.% solids slurry to the tailings areas. The liquid effluent was discharged at a rate of $9.5 \times 10^2 m^3 d^{-1}$ at pH 1.5: this corresponded to 0.032 N H_2SO_4.

In 1966, AM&S started a heap leaching experiment on the low grade copper sulphide and oxide ores from Intermediate. The two orebodies were piled in separate heaps on a 'nonpermeable' pad located between White's and Intermediate opencuts. The pad was constructed by grading the ground into a very gentle slope and covering the surface with a layer of polythene, malthoid and/or bitumen-coated hessian. Culverts, also lined with nonpermeable material, were constructed around the periphery of the heaps to collect separately the sulphide and oxide pile liquors. In addition three ponds were constructed, an acid (or makeup) pond, a pregnant liquor pond and a barren dam pond. These were simply small paddies with low levees lined with malthoid or bitumen-coated hessian. A rise in water level of about 30 cm in these ponds would cause an overflow. The overflow discharged into the old EB bed; this had been diverted to form a small creek called Copper Creek which, after passing through the old embankments, turns north, passes under the Batchelor road and eventually discharges into EB about 360 m downstream of the Batchelor - RJ roadbridge. This creek may have been a small tributary of EB before the mine existed.

The heap was leached by spraying the top of the sulphide pile with pH 2 acid made by mixing appropriate quantities of plant raffinate, barren liquor and White's opencut water. As the acid percolated through the pile, the sulphide ore was converted by bacterial action to soluble copper and sulphuric acid. The liquor from the sulphide drain, nominally pH 1.5, was then pumped to the top of the oxide pile to make the copper oxide soluble under the highly acidic conditions. The liquors draining from the oxide heap were collected in a pregnant liquor pond before being pumped to launders for recovery of the copper by cementation. Typical operating parameters were

	pH	Cu $g\ \ell^{-1}$	Fe $g\ \ell^{-1}$
acid pumped to sulphide	2.2	0.15	3.6
liquor from sulphide heap	1.2	0.66	3.0
liquor from oxide heap	1.7	1.20	2.8
barren liquor from launders	2.1	0.16	4.6

The experiment was never particularly efficient, heavy losses occurring through seepage. At one stage, a trench was dug west of the pile, in between the two embankments to collect the seepage and pump it back to the collection ponds. All overflows and excess barren liquors were discharged first into Copper Creek and then into EB. The experiment was fully described by Anderson & Allman [1968].

2.4 Effluent Disposal

There is no continuous record of disposal of plant effluents and the following paragraphs are based on various reports, letters, site evidence and discussion between the author and plant operators in 1969.

At the start of operations in 1954, the tailings were discharged into a dispersal area north of the treatment plant now known as Old Tailings Dam. This was a fairly flat area with slopes rising north and east. A natural drainage pattern developed off these slopes to flow west across the dispersal area and form a small creek now known as Old Tailings Creek. This creek joined EB about 0.8 km downstream of the treatment plant. The top soil of the area was derived from a lens of Buldiva Creek Sandstone resting on a dolomite bed. The dolomite rises to the surface north, south and west of the area.

Site evidence suggests that initially the tailings slurry was simply discharged into the general area of the dam before any walls were built. The slurry settled out and the acidic supernatant liquors drained first into Old Tailings Creek and then into EB. Eventually the dam was covered to a depth of 1 m. However in addition to the supernatant, the tailings were also being washed down the creek. Accordingly, a perimeter wall was built around the area. Inspection of the downstream side of this wall between positions 010542 and 047570 on Map 2.4 shows that the wall was built on top of a bed of tailings. Also, it was built of tailings and then covered with a thin layer of orange Buldiva Creek sandstone. In some places, this covering has been washed away while in other areas a deft kick will reveal the underlying tailings. Hence the wall must have been built after the commencement of tailings discharge.

With continuing discharge of tailings, this perimeter wall was repeatedly breached between 026553 and 049560 until all that now remains is the occasional hillock and fence post. Accordingly, fresh walls were built towards the eastern end of the area to form a series of small dams. A relatively young wall runs along the 070 north-south grid line. This wall is 2 m high, again built of tailings with a sandstone covering, and runs straight across the drainage channels of the earlier deposited tailings. These dams were equipped with culverts and overflows allowing the supernatant to drain off. Consequently, acidic liquors and entrained tailings still entered Old Tailings Creek. The walls of the tailings dam were repeatedly breached by the wet season rains and excessive discharge of tailings. In 1961, the tailings were redirected to Dyson's opencut which was full by 1965 and, from then until shutdown in 1971, the tailings were discharged into White's opencut.

At the junction of Old Tailings Creek and EB, there are some partly destroyed major earthworks. From discussions with plant operators, it appears that these walls were built to form a dam backing up EB and acted as a plant water supply and swimming pool. Pumping equipment and tanks can be found in the vicinity of 940530. The walls extended round and across Old Tailings Creek. During the Wet, a lake of toxic effluent would have backed up Old Tailings Creek. This would account for the pollution line and tailings distribution being well above the present flood levels of the creek. Eventually the earthworks were breached and tailings are now washed downstream and into FR.

Until 1961, the ion exchange barren liquors were treated for copper, if warranted, in three cementation ponds adjacent to the Old Tailings Dam. Site evidence suggests that the barren liquors from the ponds and untreated effluent were discharged into a culvert on the southern edge of the dam. This culvert drains west into a holding lake which in turn overflows across Old Tailings Dam and into Old Tailings Creek. This policy continued after the plant converted to the solvent extraction process when the raffinate was similarly treated for copper.

In 1961 or 1962, a hole appeared in the ground near the copper cementation launders and all effluent for several weeks disappeared into the hole which apparently led to an underground cavern. The hole was eventually covered over and the Old Tailings copper cementation launders abandoned. It may be concluded that, until 1961-62, all liquid effluent treated or untreated for copper was ultimately discharged into EB.

Following abandonment of the Old Tailings copper cementation launders, new launders were constructed alongside Dyson's opencut; at the same time, a system of controlled discharge was introduced. EB was dammed at the centre of the area now known as Acid Dam. Also the dam wall on the eastern side of White's opencut was rebuilt and extended across the river diversion channel, then around and across Fitch Creek. The walls alongside White's opencut and the river diversion channel were equipped with sluice gates. During the Dry, plant effluent that did not warrant treatment for copper was discharged into the downstream dam called Lower Acid Dam. Otherwise, the effluent was directed to Dyson's copper cementation launders. The barren liquor from these launders was discharged into the Upper Acid Dam. Waters backing up behind the wall across Fitch Creek were known as Sweet Water Dam. During the Wet, the EB upper reaches would flood Upper Acid Dam and Sweet Water Dam and overflow into Lower Acid Dam. At this stage, the sluice gates into White's opencut and the river diversion were opened and it was considered that the flood waters would sufficiently dilute the plant effluent stored in the Lower Acid Dam to permit safe discharge. Subsequent calculations show this could not have been the case. If it is assumed that the Acid Dam was used as an effluent storage pond for half the year, then, with a daily discharge of $9.5 \times 10^2 m^3$, the total volume of 0.032 N H_2SO_4 would have been $1.7 \times 10^5 m^3$. However, the annual discharge of the river was only $4.2 \times 10^7 m^3$ resulting in an overall average dilution to 0.000 13 N H_2SO_4 or pH 3.9. Hence, this policy of safe discharge through dilution could never have worked.

Between 1966 and 1968, this policy was in turn abandoned. The wall between Upper and Lower Acid Dam, and the one across the river diversion channel, were breached. Plant raffinate was now directed to the Heap Leach experiment and the excess discharged into White's opencut; also a partial recirculation of raffinate was commenced in the treatment plant. White's opencut was flushed out with fresh water from EB until 1969 when, for the first time, all treatment plant effluent was retained. Surface water was prevented from entering the opencut and embankments were built around the opencut to prevent overflow. This practice continued until shutdown in 1971.

2.5 Development of Natural Leaching of Stockpiles Overburden Heaps

While there can be no doubt that, during the major part of the operating history of the treatment plant, the discharge of effluent caused severe pollution in EB, it became apparent in later years that there were two other interrelated sources of contamination that could cause severe pollution irrespective of the discharge of plant effluent. These sources were the leaching of the stockpiles and overburden heaps by rainwater. The leaching was particularly severe if the heap contained a high level of pyrites permitting bacterial catalysis, as in the case of the Heap Leach experiment.

The stockpile area which was located northeast of the treatment plant, underwent continuous change as different ores were mined, piled and treated; very little is known about its history. At shutdown the entire surface of the stockpile area was scraped and put through the treatment plant. This left the White's lead ore pile, number 8, and Dyson's Bogum, number 20, untreated.

The area rests on a gentle slope rising to the east. A ridge running east-west divides the area in half. The two remaining piles are located towards the top of the slope on either side of the ridge. Runoff from the White's lead ore pile flows into a deep channel which drains the northern half of the area. This channel crosses the Mount Fitch road and enters the Old Tailings area. Similarly, runoff from the

Dyson's Bogum develops into a deep channel which drains the southern half of the area. This channel runs into Lower Acid Dam and used to be the plant effluent culvert when the Lower Acid Dam was used as a storage pond.

The natural leaching of the overburden dumps was first noticed in the mid-1960s when it was found that very acidic liquors loaded with heavy metals were running off the dumps, and springs with outlet temperatures as high as 36.5°C (compared to the river temperature of 28°C) developed at the base of the heaps midway through the Wet. The excessive leaching is due to bacterially catalysed oxidation of pyrites to sulphuric acid and ferric iron; the resulting acid-oxidising solution then leached out the heavy metals in the dump. The current state and contribution of these areas to the pollution load will be discussed in Chapter 6; a description of the overburden heaps is given below.

2.5.1 White's Overburden Heap

The White's orebody was located under EB; recovery of the ore was described in Section 2.3. The area was a geological complex zone of folds, faults and shears. The geological plan is shown in Figure 2.1. The orebody occurred in a layered series of near vertical zones with the north-south sequence uranium-copper, copper-cobalt-nickel and lead-cobalt. The layers occasionally overlapped but were sometimes separated by barren material. The orebody extended to 160 m below the surface and was truncated at its base by an intense shear zone. The first 120 m was recovered.

Table 2.3A lists the total rock analyses for the ore zones. The uranium-copper zone had a thin oxidised capping containing various yellow and green uranium ochres and secondary copper minerals. The remainder of the orebody consisted of the phosphate minerals torbernite [$Cu(UO_2)_2(PO_4)_2 8\text{-}12H_2O$], autunite [$Ca(UO_2)_2(PO_4)_2 10\text{-}13H_2O$], phosphuranylite [$Ca_3(UO_2)_5(PO_4)_4(OH)_4H_2O$] and saleeite [$Mg(UO_2)_2(PO_4)_2 10H_2O$] together with the oxide gummite [$UO_3.nH_2O$]. The sulphate minerals johannite

$[Cu(UO_2)_2(SO_4)_2(OH)_2 6H_2O]$ and zippeite $[(UO_2)_2(SO_4)OH.H_2O]$ and the oxide scheopite $[UO_3.2H_2O]$ have also been reported. Pitchblende started to occur at ~ 9 m depth.

The copper-cobalt-nickel zone was subdivided into a copper-cobalt zone containing the sulphides chalcopyrite $[CuFeS_2]$,chalcocite $[Cu_2S]$, digenite $[Cu_2.nS]$, bornite $[Cu_5FeS_4]$ and covellite [CuS]; and a cobalt-nickel zone containing linnaeite $[Co_3S_4]$, carrollite $[Co_2CuS_4]$ and gersdorffite [(Ni,Fe,Co)AsS]. The lead-cobalt zone contained galena [PbS] and linnaeite. Pyrite $[FeS_2]$ was common to all zones [Roberts 1960].

The orebody was sandwiched between a black slate sequence of the Golden Dyke Formation to the north. Below 30 m the mudstone sequence gave way to the dolomite bed; the slates were pyritic. An intense shear zone passed through the black slate bed touching the western edge and base of the orebody. Pods of high grade uranium ore were mined from this shear zone and minor mineralisation of uranium, copper and lead was indicated at depth on the south side of the shear zone immediately above the dolomite.

The orebodies were recovered by opencut operation. The overburden heap was built on a level, well drained portion of land to the south of the mine. The bedrock was hematite-quartzite breccia and the Giant's Reef Fault passed directly underneath the area. An initial ramp of hematite-quartzite breccia was built to form the central core of the heap, and then the slates and shales which formed the major portion of the overburden were back-dumped off this ramp. As excavation continued the ramp was extended using the slates and shales, and branch ramps to the northeast and northwest corners were developed, again using the slates and shales. The excavated dolomite which occurred towards the bottom of the opencut, formed the top surface of the northwest corner. Inspection of the geological plan shows that the heap is principally composed of slates and shales together with a small portion (10-15%) of dolomite. An auger-drill survey was carried out on the heap in 1969 and the sectional analysis showed no variation in the copper and uranium values around the heap [Cayzer 1969].

Chemical analysis of the crushed and bulked samples from this drilling program is listed in Table 2.3A which shows that the heap contains approximately the equivalent of 3% sulphur. It may be assumed that most of the sulphur is in the form of heavy metal sulphides, principally pyrites.

The heap is classically heartshaped with a concave inner surface downhill northwards forming the ramp approaches; The southern end rises 27 m above the surrounding land. It has very steep walls which wrap round into the ramp approaches. The method of construction has delineated the following catchment areas; the inner approaches, the northeast area, the southern area, the southwest central area, the west area and the northwest area.

The eastern half of the inner approaches is a well graded road of hematite-quartzite breccia. The road separates the other half by a channel, 1 m deep, which drains the majority of the top surface of the heap. The remaining half of the inner approaches is composed of levelled shales and slates.

The top surface of the northeast area is composed of black shales and slates. The centre has been crushed by construction traffic to a smooth surface while the boundaries are ringed by walls and piles of weathering friable pyritic shales and slates. Pyrite abounds in the area and there is very little vegetation.

The top of the southern area is also composed of shales and slates. The entire surface has been crushed smooth, but the subsurface is composed of hand sized friable rock. The area was devoid of vegetation except for some experimental vegetation plots near the southern edge.

The southwest central area is entirely composed of loose piles of weathering rock of all types excavated. There was no vegetation in this area.

The surface of the west area has been crushed smooth except where the last loads of material were dumped on the inner boundary. The surface is considerably weathered, the soluble, toxic salts having been leached out leaving behind quartz, dolomite, hydrated dolomites and soapstone. Frequently the rocks have a bright red iron coloration and the area is probably rich in phosphates. Parts of this area are supporting grasses and there are some sturdy trees.

The northwest area has a wide smooth ramp leading from the central ramp up to the trig. point known as the Mt Wimpey trig. This trig. point is due magnetic south of the treatment plant trig. point. The area is bounded by loose piles and rubble walls. The surface is principally composed of quartz-dolomite-magnesite and iron minerals. It supports some flourishing grasses and shrubs. A large number of old, massive tyres used on excavators have been liberally scattered over the track leading up to the trig. point, earning the area the name Tyre Valley.

Figure 2.2 is a sketch of the plan areas of the catchment areas of the heap and Table 2.3A lists the distribution of these areas. The inner top surface accounts for 75% of total area and the walls 25%. Like Dyson's heap, the walls tend to absorb the rain rather than allowing it to run off. The northeast, southern, southwest, northwest and central areas drain into a principal runoff which flows on the west side of the ramp, crosses the RJCS ore road and discharges into the river diversion channel. Two minor runoffs drain a small part of the northeast area but the remaining runoff travels down the ramp of the area to join the principal runoff. The actual stream pattern varies with storm intensity. The southern area forms the root of the principal runoff. The drainage pattern is indistinct. During intense storms the area is awash with water. As the storms abate a stream develops on the eastern portion, disappearing into the walls bounding the north edge. This stream re-appears some 150 m further north and continues to flow for a further 2-3 days after a storm.

Rainfall in the southwest area tends to accumulate in between the rubble piles, and in one part there is a permanent pool for the Wet. At the height of a storm, flow finally develops to form individual streams which drain into the principal runoff. The entire western area which is 15.6% of the top area, is drained by a major runoff on the west wall. The drainage pattern is well defined. The northwest area is drained by a number of small streams which coalesce into the principal runoff.

By the middle of the Wet, springs develop along the complete length of the eastern wall, all of which discharge into Fitch Creek;

flow is sustained into the early part of the Dry. Some springs also develop around the base of the northwest area; flow ceases from these springs 5-7 days after an intense storm.

2.5.2 Dyson's Overburden Heap

The Dyson's orebody was located on the southern slopes of a small hill rising to the north of the East Branch of the Finniss River valley. It occurred as a vertical lens extending to 100 m below the surface. The geological features are shown in Figure 2.3. Only the first 50 m were mined; the oxidised ore was almost entirely saleeite. [$Mg(UO_2)_2(PO_4)_2.10H_2O$] which was sometimes pseudomorphously replaced by limonite [$FeO(OH)_2$]. The saleeite was occasionally accompanied by a pale green platy mineral with a strong greenish yellow fluorescence, possibly autunite [$Ca(UO_2)_2(PO_4)_2.10\text{-}12H_2O$]. The near-surface zone contained nodules of sklodowskite [$Mg(UO_2)_2(SiO_3)_2(OH)_2.6H_2O$] together with traces of an orange mineral, possibly uranosphaerite [$Bi_2O_3 2UO_3.3H_2O$]. The orebody was sandwiched between a bed of black graphitic slate and a dome of dolomite, capped by a hematite-quartzite breccia and mudstone bed. Saleeite mineralisation extended into the fracture planes of the hematite-quartzite breccia and the black graphitic slates. Below 27 m the black graphitic slates became strongly pyritic and contained pitchblende [UO_2]. A main fault to the east of the orebody separated the black graphitic slates from a bed of grey hematitic sericitic phyllites (slates). Except for the uranium values listed in Table 2.3B, no other chemical assay data are available. Copper, lead, cobalt and nickel were reported to be absent, Berkman [1968], Spratt [1965].

The ore was mined by opencut operation, the overburden being dumped on the hillside immediately to the east of the mine. Initially a ramp was built, either from a natural spur or from the hematite-quartzite breccia of the opencut. A compact heap was then formed by back-dumping off this ramp. The result is an approximately round heap resting on the broad slopes of the southeast corner of the hill from which the ore was mined. The southern wall extends into the EB valley. The heap has steep walls on all sides with the exception of the northwest corner where it runs into the hillside and forms the ramp approaches. The top surface is slightly concave with a downhill tilt towards the northwest corner.

Inspection of the geological plan of the opencut shows that the heap is made up of 30% hematite-quartzite breccia, mudstone and dolomite, 30% black graphitic slates and 30% grey hematitic sericitic slates. Much of the hematite-quartzite breccia has been used to build the ramp. The rest is in the bottom central portion of the heap. With the exception of the ramp this central core was then covered with the slates. These slates were not mined in any particular order and were simply back-dumped at the top of the ramp before being bulldozed over the expanding edge of the heap. The result is that the walls are a series of clearly defined 5 m wide zones of red-brown and blue-black slates. The red-brown zones support a limited number of grasses while the blue-black zones support no vegetation at all. The ramp is now completely overgrown with large shrubs and grasses.

The top surface south and west of the ramp has been crushed by construction traffic to a fine slate dust which contains a yellow metallic pyritic glitter. This area supports no vegetation. The entire top surface to the north of the ramp is covered with disintegrating rubble piles loaded with pyritic nodules of up to 1 cm cross section. During a storm these piles trap water between them to form shallow pools which subsequently seep into the heap. On the northeast corner there is a 2 m bench on the top edge. The rock composition is different for the piles on this bench and the soil supports medium sized trees and shrubs. The pools in this area support lush, green undergrowth. In general no vegetation exists where there is pyrite.

The amount of pyrite present in the overburden was believed to be 10-15%, however this figure only applies to the black graphitic slates that were mined towards the bottom of the opencut. At most this would be 20% of the overburden which would give a pyrite concentration of 2-3% of the total overburden, i.e. 1.5-2.0 x 10^8 kg pyrite. This figure is in agreement with the figures for the White's and Intermediate overburden heaps. Although Berkman [1968] reported that heavy metals were absent, at least a low concentration of copper, cobalt, nickel and zinc is to be expected in the pyritic slates along with some uranium.

The overburden heap has a relatively simple drainage pattern as shown in Figure 2.4. The tilt and concavity of the top surface has formed a number of drainage channels across the heap which combine at the northwest corner to form the principal runoff. This runoff turns south, passes through a narrow defile and then combines with the overflow and seepage from the opencut. The combined stream flows south along the base of the west wall, collecting the only other runoff from the top surface, named the west runoff. The total stream then discharges into EB. Table 2.3B lists the distribution of plan areas for the overburden heap. The top surface accounts for 70% of the total area, while the steep sides account for 30%. The sides are composed of boulders and massive rock. Rainfall tends to be absorbed into the sides owing to their open structure rather than running off. The principal runoff accounts for 83% of the top surface while the west runoff 17%. However, the west runoff drains a compacted surface, hence the runoff/absorption ratio is expected to be higher for the west runoff than for the principal runoff which drains an area almost entirely composed of loose rubble piles. Consequently, the west runoff may contribute a slightly higher percentage flow than is indicated from the plan areas.

2.5.3 Intermediate Overburden Heap

The Intermediate orebody which lay 700 m west of the White's orebody in the Golden Dyke Formation, was partially located under the EB bed. An associated orebody lies a further 400 m west of the Intermediate mine but has not been recovered. There is no geological plan available for the mine. The orebody was reported to be sulphide mineralisation, predominantly chalcopyrite [$CuFeS_2$] with minor quantities of chalcocite [Cu_2S] and bornite [Cu_5FeS_4] in a graphitic schist. It was covered by an extensive capping of oxidised ore containing malachite [$Cu_2(OH)_2(CO_3)$] with minor quantities of cuprite [Cu_2O], azurite [$Cu_3(OH)_2(CO_3)_2$] and native copper also in schist [Andersen, Herwig & Hoffitt 1966]. The orebody was sharply delineated. From an examination of the overburden heap the host rock was principally pyritic graphitic shale. Part of a hematite-quartzite breccia bed was also mined although the original location of the bed is unknown.

The ore was recovered by opencut operation. The high grade sulphide ore was treated by froth flotation while the subgrade ore containing 0.7-2.0% copper along with the oxidised capping containing 2.0% copper, was treated by heap leaching. The overburden was dumped on a level portion of ground immediately south of the mine and on the south side of the river diversion channel. The heap was built on top of a bed of hematite-quartzite breccia by constructing a ramp of shales. The remaining shales were then back-dumped east and southwest of the ramp while hematite-quartzite breccia was separately dumped northwest of the ramp.

The resulting heap is approximately square and the construction has delineated three areas, an eastern zone, a southwest square and a northwest square. The eastern zone lies east of the ramp and has a concave top surface criss-crossed by tracks which were pushed through areas of rubble piles. The southwest square is in the form of a spiral which leads off the ramp. The centre part of the spiral has been crushed smooth by construction traffic while its edges are bounded by rubble piles. The northwest square has a flat surface tilted downhill towards the ramp. The western part is covered with massive piles and rocks of hematite-quartzite breccia and silicified dolomite; there is also the occasional pile of massive or staining gersdorffite [(Ni,Fe, Co,)AsS]. Pyrite is visible all over the heap and there is very little vegetation.

Figure 2.5 is a sketch of the catchment areas and drainage pattern of the heap. The drainage pattern is complex: the walls which represent 30% of the total area, because of their open nature probably absorb a lot of the rain falling directly on to them; the eastern zone is broken up into four areas which drain according to the convexity of the surface; the southwest and northwest squares drain onto a central runoff which runs down the ramp and discharges into the river diversion channel. The separate areas have been numbered; Table 2.3E lists their estimated values and their percentage contributions to the various runoffs.

Some small springs have been observed around the base of the heap in the approximate positions indicated in the sketch, but they were observed to flow only immediately after a storm. Between January and April, water draining from the slopes to the south of the heap converges on the base of the south and west walls and forms a stream known as Wandering Creek which flows west for 250 m before joining EB. The result is that the base of the heap is saturated and drained by the stream.

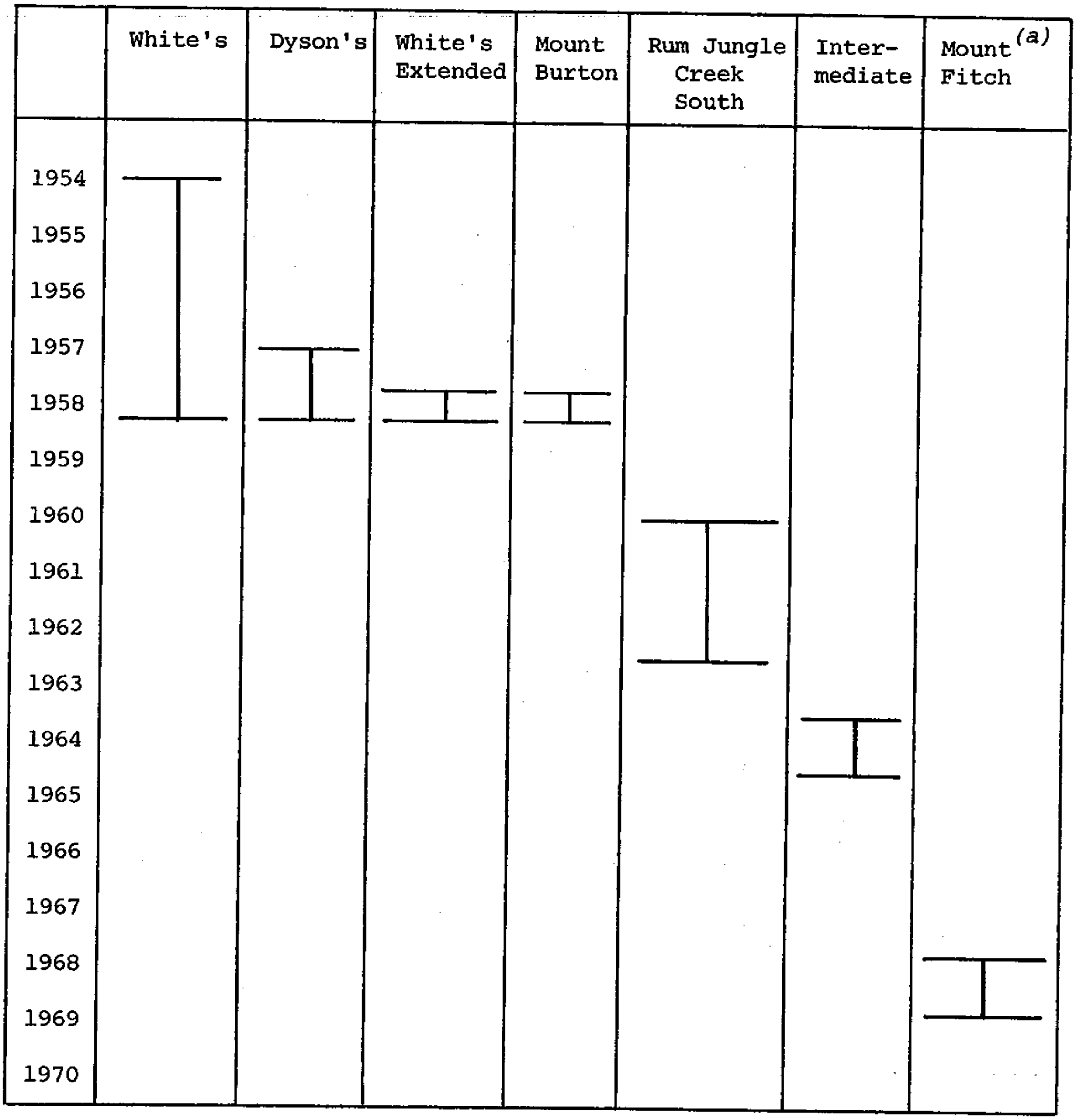
TABLE 2.1

GEOLOGICAL SEQUENCE AT RUM JUNGLE

Type	Age 10^6y	Maximum Depth m	Group	Name	Nature
Tertiary	10-70			Ferruginous Laterite	Iron oxides.
				Buldiva Creek Formation	Sandstone.
Pre-Cambrian: Upper Proterozoic	1000+			Giant's Reef Fault	Quartz vein in granite sections.
Middle Proterozoic		200		Hematite-Quartzite Breccia	Quartz in a pink sandy matrix.
Lower Proterozoic		2000	Goodparla	Burrell Creek Formation	Grey pyritic quartzite.
			Goodparla	Acacia Gap Tongue Golden Dyke Formation	Graphitic, sericitic and chloritic slates and siltstones with dolomite lenses and quartz and calcite veining.
		700	Batchelor	Coomalie Dolomite	Dolomite, dolomitic marl and siltstone.
		800	Batchelor	Crater Formation	Greywacke, sandstone, quartzite and hematite boulder conglomerate.
		300	Batchelor	Celia Creek Formation	Silicified dolomite, dolomite and dolomitic breccia.
		300	Batchelor	Beestons Creek Formation	Arkose with minor quartzite, slate, grit and conglomerate.
Archaean	2000?			Rum Jungle and Waterhouse Granite	Granite gneiss, diorite, granite, pegmatite with quartz-tourmaline veins and dolerite dykes

TABLE 2.2

MINING OPERATIONS AT RUM JUNGLE



(a) *The orebody was exposed by opencut excavation for process evaluation, but the ore was not recovered and remains in the opencut.*

TABLE 2.3A

WHITE'S MINE

ORE

Type of Ore	Amount x 10^6kg[c]	Constituents mg g^{-1}							
		U	S	Co	Cu	Mn	Ni	Pb	Zn
Uranium-copper	402	2.2			27				
White's Extended	0.102	1.51							
Copper	295			3	28				
Lead[a]	86			3	8			51	
Mullock[b]	7100	0.0335	32.7	0.13	0.86	0.99	0.26	0.48	0.11

(a) Stockpile number 8.

(b) AAEC analysis of bulked crushed, auger-drill samples collected 1969 Dry.

(c) $10^6 g = 10^3 kg = 1$ Mg = 1 tonne(t)

TABLE 2.3A (continued)

TOTAL ROCK ANALYSIS OF WHITE'S OREBODIES

[Berkman 1968]

	Uranium-Copper	Copper zone	Lead zone
SiO_2	49.3	50.2	55.7
Al_2O_3	13.24	8.89	6.24
Fe (total)	5.5	4.7	3.2
MgO	2.72	2.47	1.04
CaO	0.02	0.02	trace
Na_2O	0.03	0.02	0.02
K_2O	1.89	1.12	1.16
H_2O-	1.80	0.86	0.50
H_2O	1.83	1.00	0.58
CO_2	8.5	9.9	9.3
P_2O_5	0.26	0.27	0.06
S	2.45	1.84	1.61
MnO	0.02	0.02	0.01
C	3.98	4.84	4.90
U_3O_8	0.32	0.01	trace
Cu	3.32	2.11	0.33
Co	0.04	0.04	0.16
Ni	0.13	0.40	0.15
Pb	0.04	0.20	5.90
As	0.01	nf	trace
Sb	0.01	0.01	trace
Bi	0.07	trace	trace
Ag	trace	trace	trace
Zn	trace	0.20	0.41
Balance	4.9	11.6	8.9

nf - not found.

TABLE 2.3A (continued)

OPENCUT

Excavated volume (as per contractor's bill)	$3.53 \times 10^6 m^3$
Original depth [Berkman 1968]	111 m
Original depth [AAEC 1963] †	105 m
Present depth (by lead line, March 1974)	58 m
Diameter (by aerial survey)	370 m
Rock density [Berkman 1968]	$2.65\ g\ cm^3$

† *Difference due to printing error between 365 and 345 ft.*

MULLOCK HEAP

Volume* (by aerial survey)	$3.95 \times 10^6 \pm$ 11-20% m^3

* *Volume expansion from rock to loose pile quoted by a Sydney excavator is normally 70%.*

CATCHMENT AREAS ON WHITE'S OVERBURDEN HEAP

	Area $\times 10^4 m^2$	Percentage of total area	Percentage of top area	Percentage of principal runoff
Total area	26.37			
Top area	19.58	74.6		
Wall area	6.79	25.0	34.7	
Principal runoff	15.92	60.4	81.3	
Central	2.30	8.7	11.7	14.4
Northeast	2.87	10.9	14.7	18.0
Southern	4.83	18.3	24.7	30.3
Southwest	2.72	10.3	13.9	17.1
Northwest	3.05	11.5	15.6	19.1
West runoff	3.06	11.6	15.6	
Small north runoff	0.25	0.9	1.3	
Small east runoff	0.29	1.1	1.5	

TABLE 2.3B

DYSON'S MINE

ORE

Type of Ore	Amount x 10^6 kg	Uranium mg g^{-1}
Uranium	156	2.89
Bogum (a)	47.8	0.65
Mullock (b)	2032	

(a) *Stockpile number 20.*

(b) *10-15% pyrites. (This is a quoted figure and believed to be in error, see discussion in text, Section 2.5.2)*

OPENCUT

Original volume	0.917×10^6 m^3
Present volume of water calculated as base x depth	7×10^4 m^3 (dry season) 15×10^4 m^3 (wet season)
Original depth	45.7 m
Present depth of water	3 m (dry season) 6 m (wet season)
Water pumped out during mining	4.56×10^4 m^3
Estimated amount of tailings	3.8×10^8 kg of solids discharged as 55 wt% solids slurry

MULLOCK

Volume (by aerial survey)	1.15×10^6 m^3 ± 11-20%

CATCHMENT AREAS ON DYSON'S OVERBURDEN HEAP

	Area x 10^4 m^2	Percentage of total area	Percentage of top area
Total area	8.43		
Top area	5.86	70	
Wall area	2.57	30	
Principal runoff	4.84	58	83
West runoff	1.01	12	17

TABLE 2.3C

MOUNT BURTON MINE

Type of Ore	Amount $\times 10^6$ kg	U $mg.g^{-1}$	Cu $mg.g^{-1}$
Uranium-copper	6.1	1.78	10.4
Copper	1.4		26.6
Bogum	3.5	0.61	6.9
Mullock	254.0		

OPENCUT

Original volume	0.101×10^6 m^3
Present volume of water	900 m^3
Original depth	30 m
Present depth of water	6.3 m
Water pumped out during mining	9.09×10^3 m^3

MULLOCK

Volume	1.0×10^5 m^3
Calculated density	2.5 g cm^{-3}
Top plan area	2.23×10^4 m^2
Bottom plan area	3.28×10^4 m^2
Catchment area of principal runoff	2.23×10^4 m^2

TABLE 2.3D

RUM JUNGLE CREEK SOUTH MINE

ORE

Type of Ore	Amount x 10^6 kg	Constituents $mg.g^{-1}$							
		U	S	Co	Cu	Mn	Ni	Pb	Zn
Uranium	660	3.65							
Bogum	116	0.556							
Mullock	4877	0.151	2.9	0.06	0.13	0.53	0.19	0.31	0.11

OPENCUT

Original volume	2.22×10^6 m^3
Present volume of water	2.0×10^6 m^3
Original depth	68.5 m
Present depth of water	62.5 m
Diameter major axis	400 m
Diameter minor axis	300 m
Water pumped out during mining	0.936×10^6 m^3

MULLOCK

Volume	1.95×10^6 m^3
Calculated density	2.5 $g.cm^{-3}$
Top plan area	0.141×10^6 m^2
Bottom plan area	0.219×10^6 m^2
Catchment area of principal runoff	0.070×10^6 m^2

TABLE 2.3D (continued)

TOTAL ROCK ANALYSIS OF RUM JUNGLE CREEK SOUTH MINE

	Black Slate	Chlorite Schist	Chloritic Slate
SiO_2	59.3	48.2	47.3
Al_2O_3	10.2	14.9	15.8
Fe_2O_3	3.05	4.00	3.70
FeO	1.19	6.45	6.30
MgO	7.35	11.4	11.7
CaO	2.70	0.69	0.76
Na_2O	0.03	0.04	0.07
K_2O	2.20	2.25	2.50
H_2O-	3.85	7.05	7.25
H_2O	0.66	0.95	0.87
CO_2	3.65	0.12	0.08
P_2O_5	0.13	0.32	0.24
S	0.71	1.19	1.15
MnO	0.01	0.03	0.03
C	4.45	0.39	0.35
TiO_2	0.49	1.89	1.92
ThO_2	trace	0.03	trace
U_3O_8	trace	0.14	0.04
	100.0%	99.9%	100.0%

TABLE 2.3E

INTERMEDIATE MINE

ORE

Ore	Amount x 10^6 kg	Constituents mg g^{-1}							
		U	S	Co	Cu	Mn	Ni	Pb	Zn
Mill ore *(a)*	358				27				
Sulphide ore *(b)*	305				17				
Oxide ore *(b)*	244				20				
Mullock *(a)(c)*	1727	0.046	30.6	0.3	2.0	0.27	2.0	5.0	0.25

(a) *Internal report*

(b) *Anderson & Allman (1968)*

(c) *AAEC analysis of crushed, bulked auger-drill samples collected in 1969*

OPENCUT

Original volume	0.971×10^6 m^3
Present volume of water	1.5×10^6 m^3 (as half-ellipsoid)
Original depth	70 m
Present depth of water	67 m
Diameter major axis	270 m
Diameter minor axis	160 m

MULLOCK

Volume (by aerial survey) 0.645×10^6 m^3

TABLE 2.3E (continued)

CATCHMENT AREAS ON INTERMEDIATE

OVERBURDEN HEAP

Area	Reference number	Area x $10^2 m^2$	Percentage of total area	Percentage of top area	Percentage of principal runoff
Total area		685			
Top area		482	70		
Wall area		203	30		
West zone (1,2,3,4)		261	38	54	
Southeast spur	1	29	4	6	
East catchment	2	56	8	12	
North catchment	3	110	16	23	
West catchment	4	66	10	14	23
Southwest square (5,6)		103	15	21	35
Top portion	5	70	10	15	24
Side portion	6	33	5	7	11
Northwest square	7	54	8	11	19
Principal runoff (4 to 8)		287	42	60	
Inner approaches	8	64	9	13	22

TABLE 2.4

APPROXIMATE CHEMICAL COMPOSITION OF RAFFINATE FROM THE RUM JUNGLE MILL (1969)

Component	Concentration (g ℓ^{-1})
Fe (III)	2.0
Mg	1.3
Mn (II)	0.4
Ni	0.018
Pb	0.02
Mo (VI)	0.001
Cu (II)	0.13
V (V)	0.015
SiO_2	0.42
Ca	0.23
U (VI)	0.001
Na	6.5
Cl	0.0002
SO_4 *	23.4

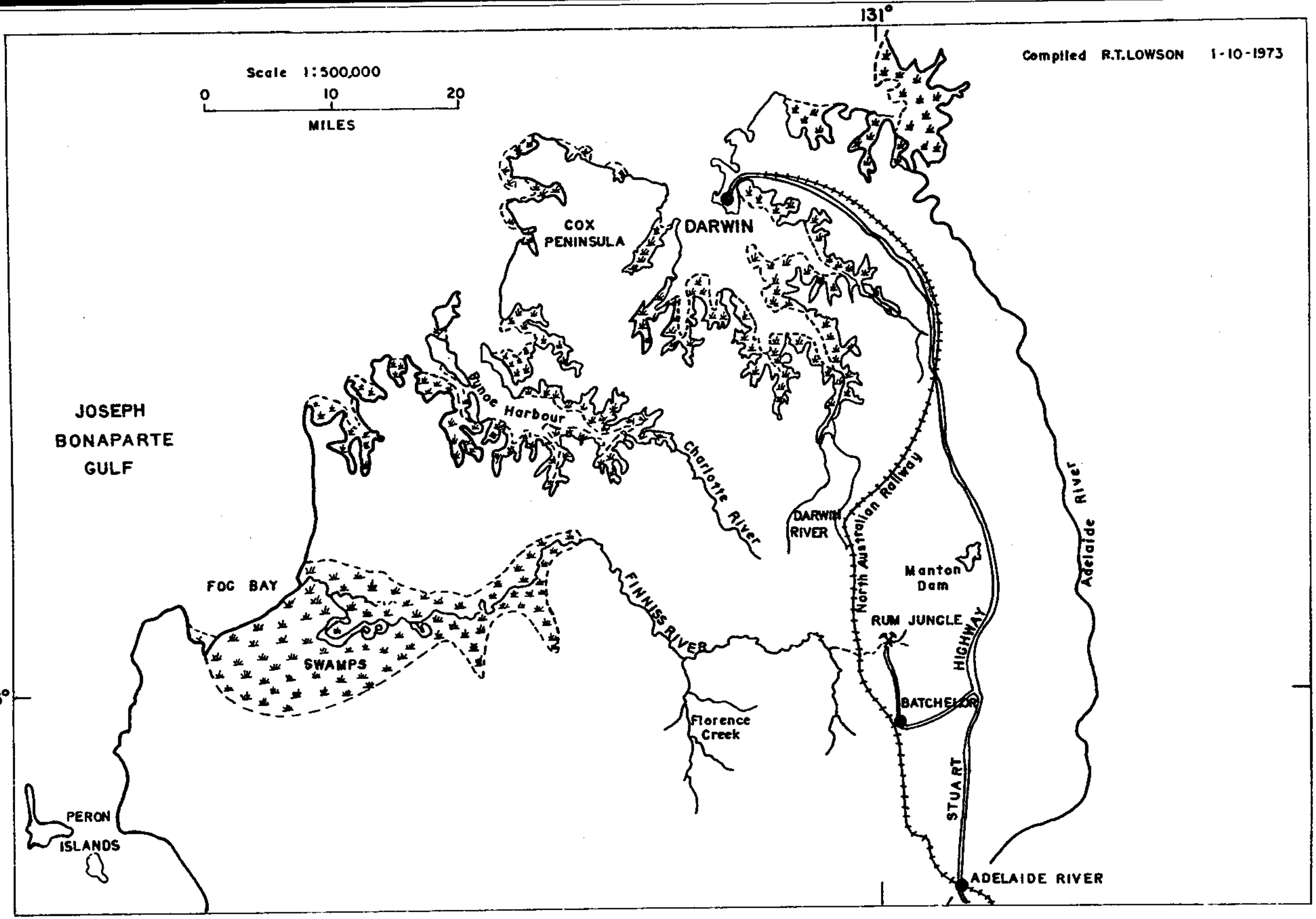
* *free sulphuric acid : 0.07 M*

TABLE 2.5

RUM JUNGLE PRODUCTION FIGURES

Year	Ore Treated		Product[(a)]		Tailings		
	U x 10^6kg	Cu x 10^6kg	U x 10^3kg	Cu x 10^6kg	Amount x 10^6kg	U x 10^4kg	Max Cu x 10^6kg
54-55	23	0.44	24	0.089	23	1.9	0.48
55-56	53	2.9	128	0.67	55	3.9	0.79
56-57	75		208	1.4	74	5.1	0.40
57-58	76		171	1.41	75	2.6	0.49
58-59	76	26	129	1.8	100	1.8	0.49
59-60	77	67	126	2.7	141	1.8	0.38
60-61	75	97	151	3.1	168	2.7	0.99
61-62	80	92	212	1.6	170	3.7	0.47
62-63	73	10	215	0.53	83	2.2	0.17
63-64	74		222		73	0.85	
64-65	74	121	220	2.2	196	0.81	0.80
65-66	79	144	233	2.6	220	1.00	0.82
66-67	79	103	212	1.8	180	0.88	0.75
67-68	91		218		91	0.92	
68-69	109		209		108	1.00	

(a) *Product as U_3O_8 and Cu concentrate, approximate purity 90%*

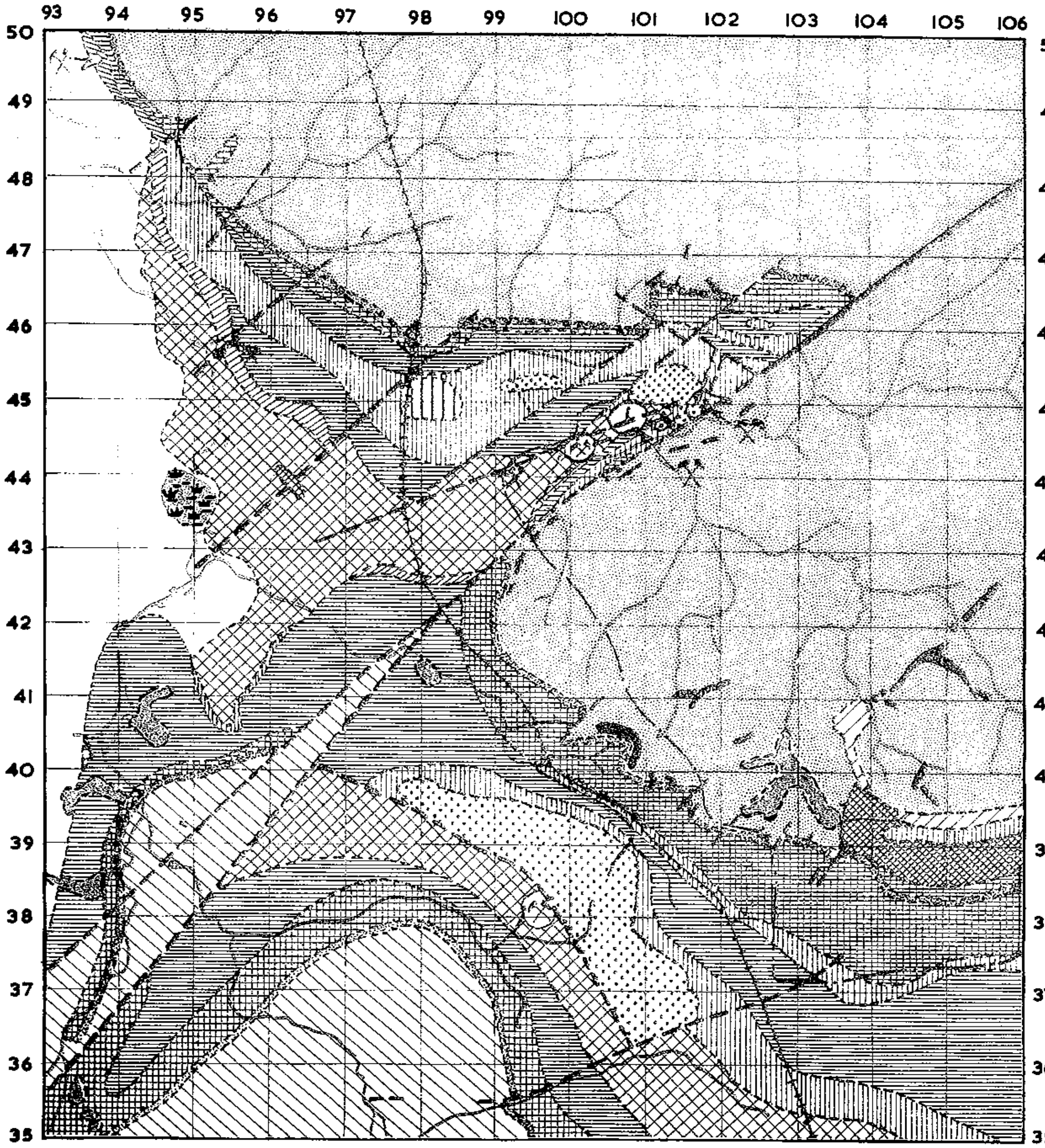


THE DARWIN AREA

MAP 2.1

1:50 000

DRAWN BY R.T. LOWSON
OCTOBER 1974



Black numbered lines indicate the 1000 yard transverse Mercator Grid, zone 4 (Australia Series), CLARK 1858 spheroid

1000 500 0 1000 2000 3000 4000 METRES

Soils & Alluvium

Swamp

Ferruginous Laterite

Hematite Quartzite Breccia

GOODPARLA GROUP

Acacia Gap Tongue

Burrell Creek Formation

Golden Dyke Formation

Chloritic & Hematitic mudstones

BATCHELOR GROUP

Coomalie Dolomite

Crater Formation

Hematite Boulder Conglomerate

Celia Creek Dolomite

Beeston's Creek Formation

Mine or Prospect

IGNEOUS

Rum Jungle Granite

Waterhouse Granite

Dolerite

Fault

Reef Quartz

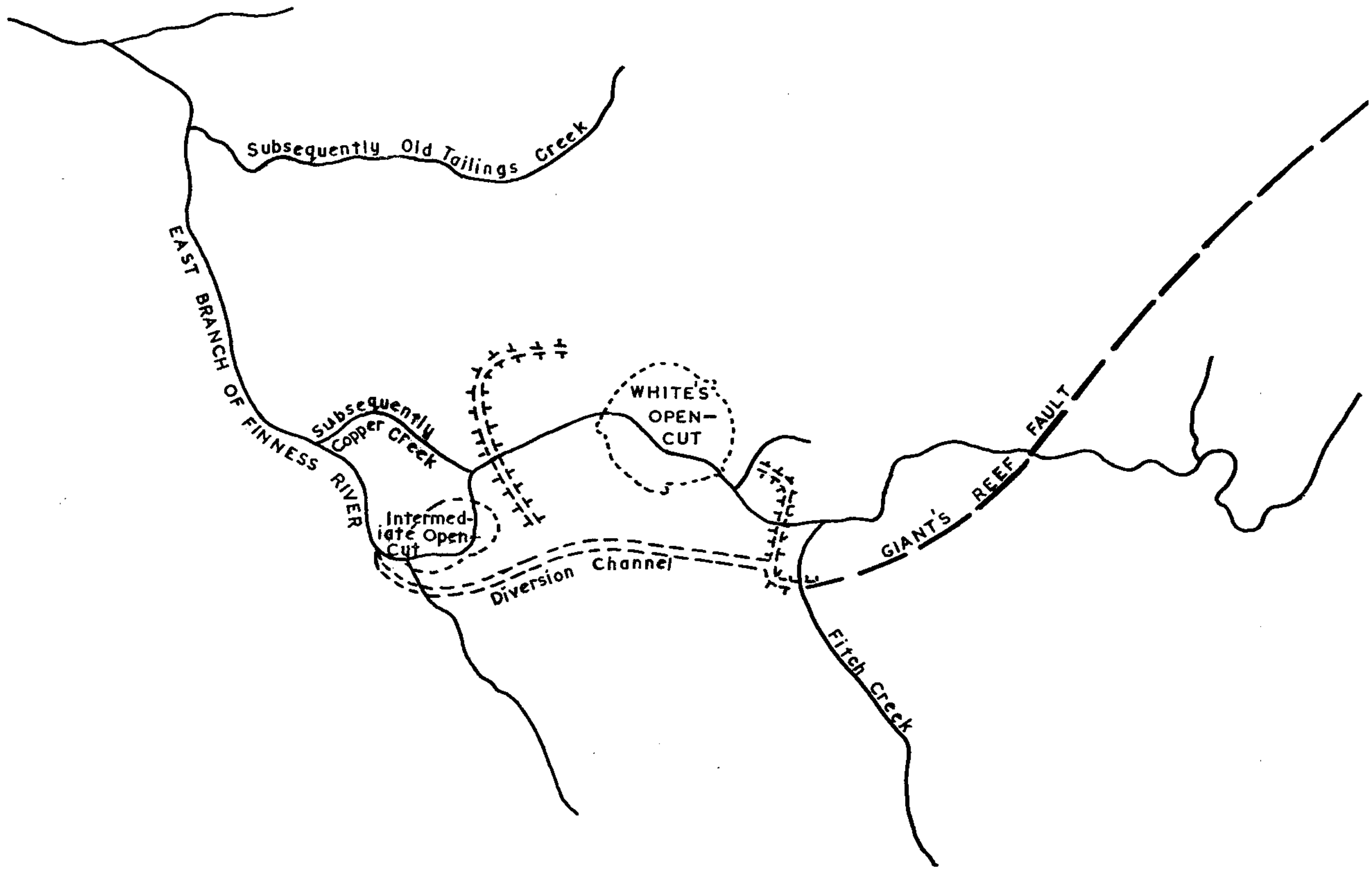
Railway

Road

River

GEOLOGICAL MAP OF RUM JUNGLE

MAP 2.2



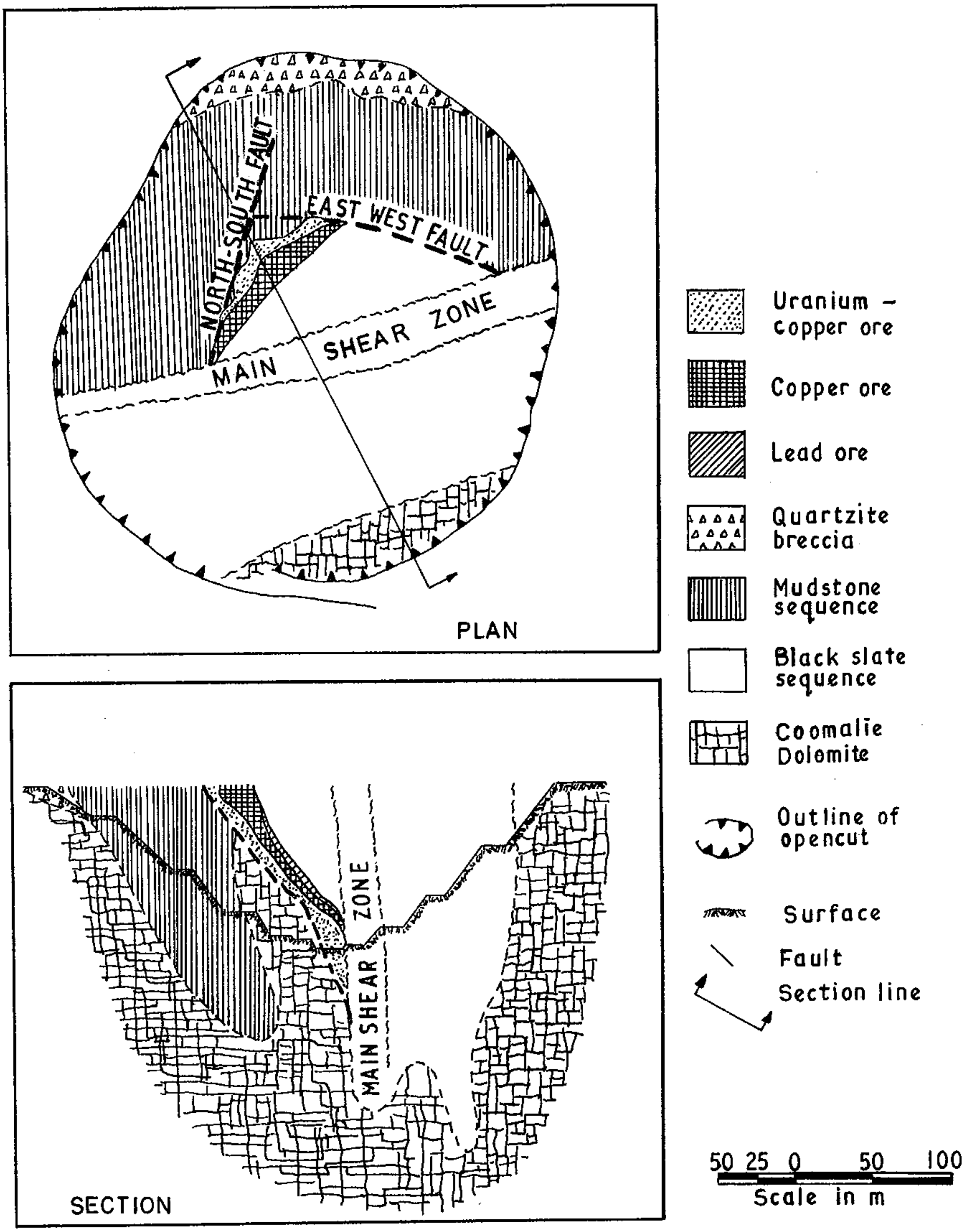
THE EAST BRANCH OF THE FINNISS RIVER PRIOR TO MINING OPERATIONS IN 1954

MAP 2.3

MAP 2.4

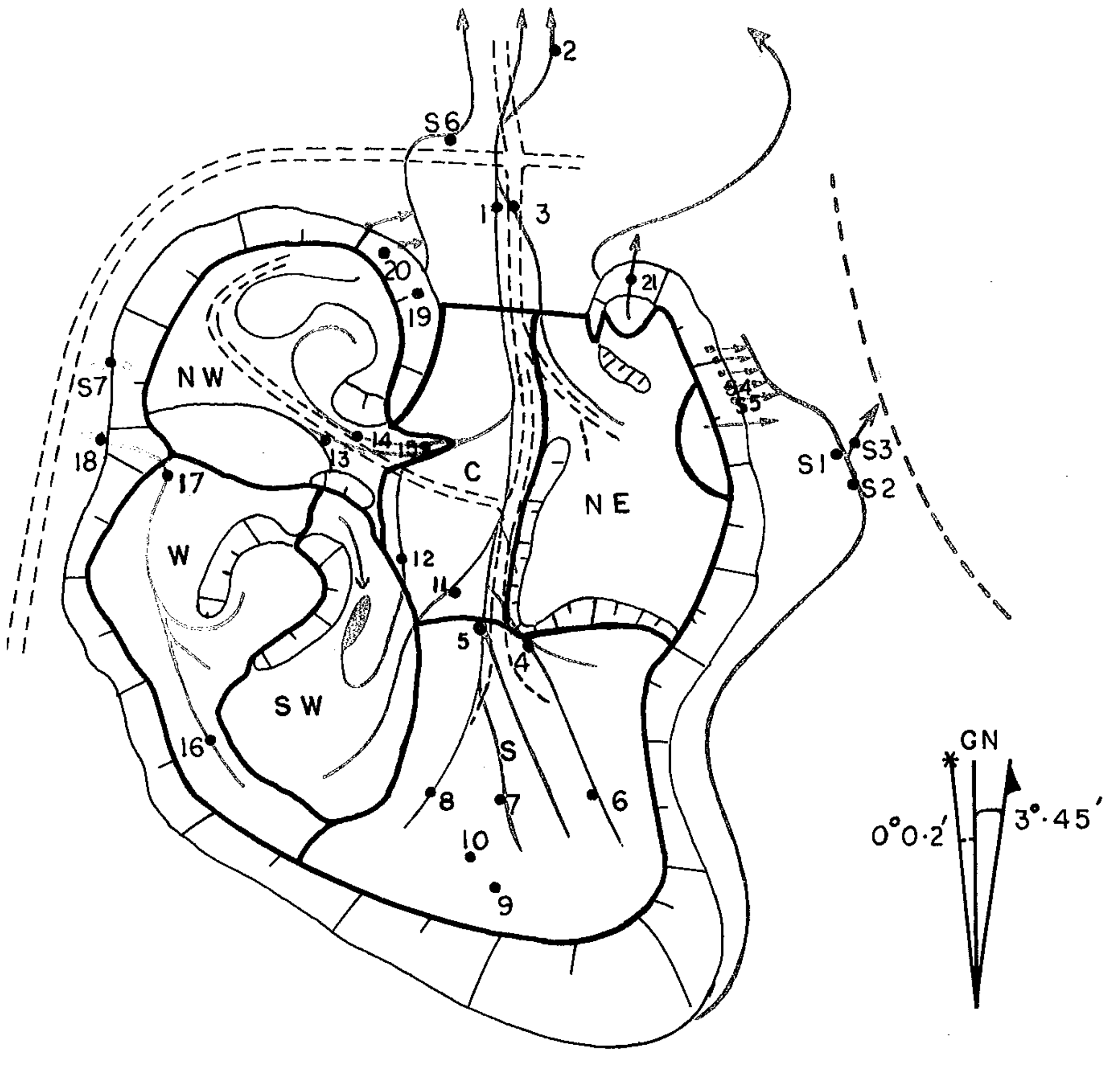
THE RUM JUNGLE MINE

Map 2.4 is contained in the envelope inside the back cover of this report.



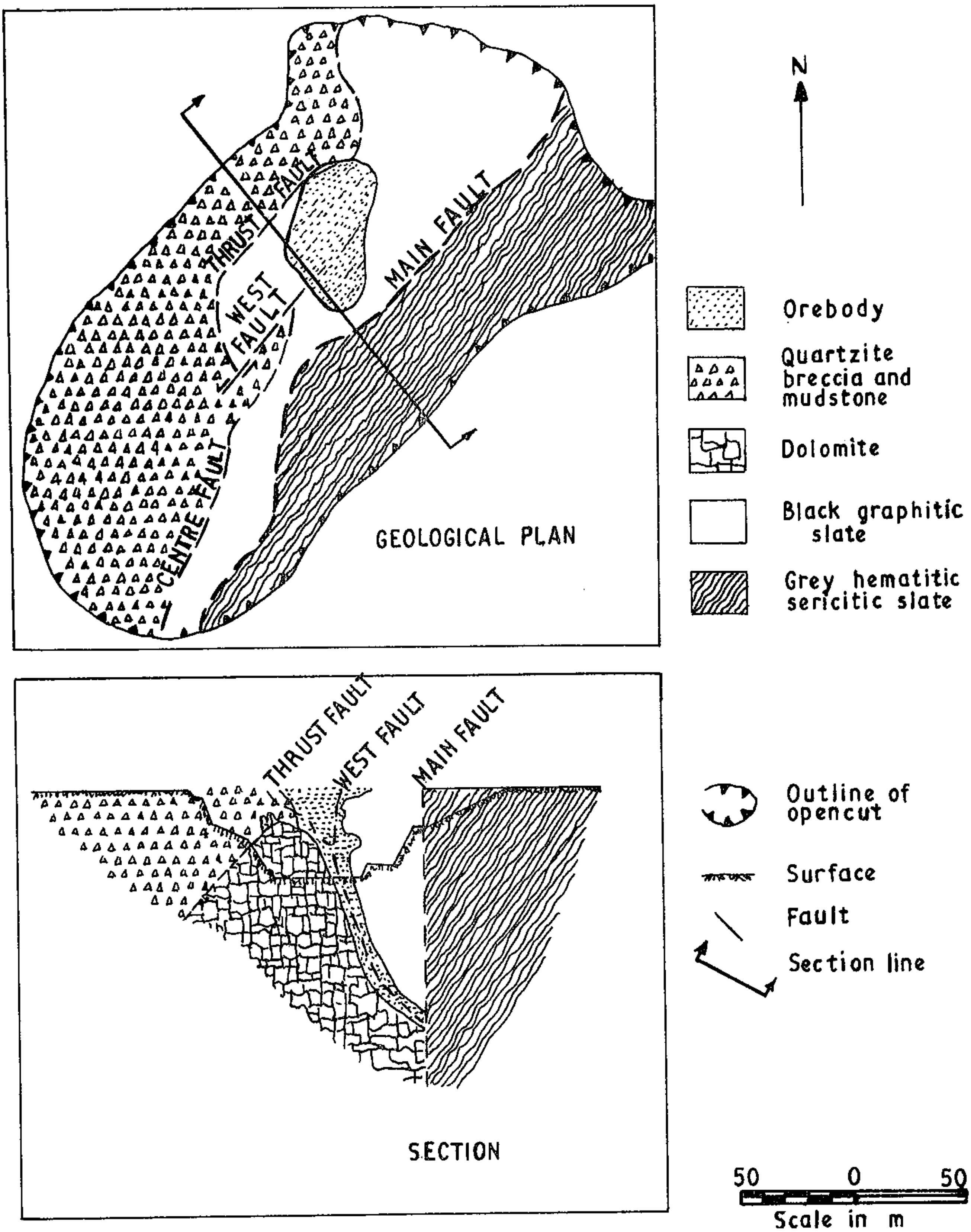
GEOLOGY OF WHITE'S MINE

FIGURE 2.1



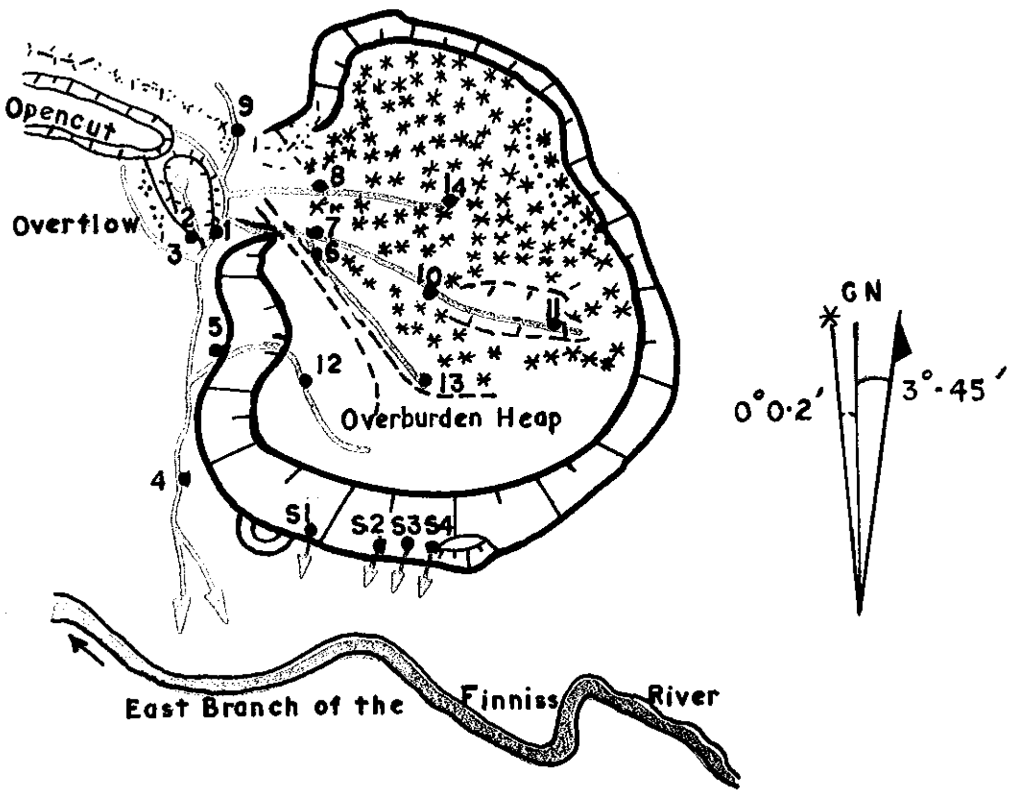
DRAINAGE PATTERN ON WHITE'S OVERBURDEN HEAP

FIGURE 2.2



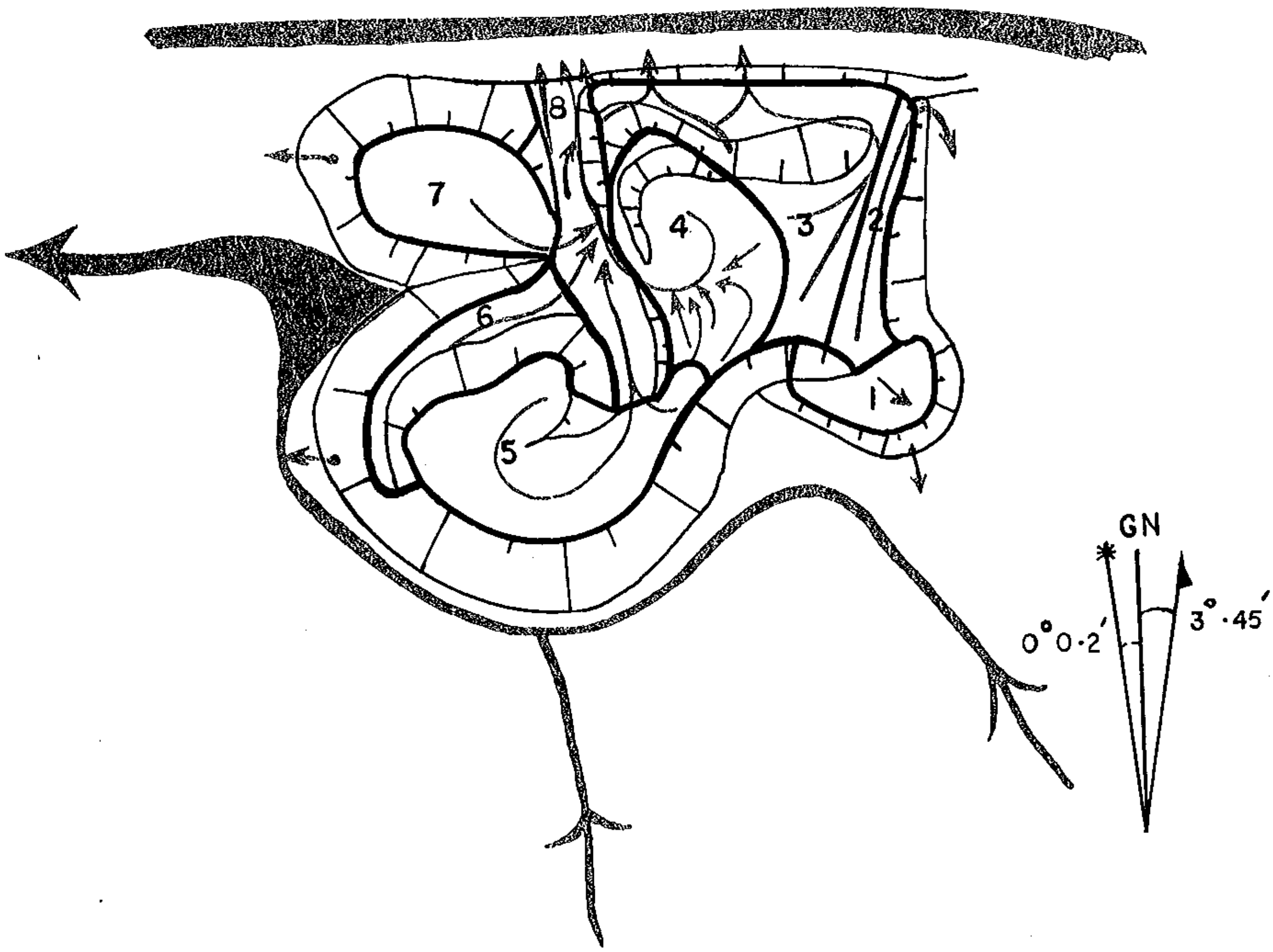
GEOLOGY OF DYSON'S MINE

FIGURE 2.3



DRAINAGE PATTERN ON DYSON'S OVERBURDEN HEAP

FIGURE 2.4



DRAINAGE PATTERN ON INTERMEDIATE OVERBURDEN HEAP

FIGURE 2.5

RUM JUNGLE ENVIRONMENTAL STUDIES

CHAPTER 3

THE POLLUTION CYCLE AT RUM JUNGLE - CONTROLLING FACTORS, BASIC MECHANISMS AND DEGREE

by

N.F. CONWAY

D.R. DAVY

ABSTRACT

A description is given of the climatology of the Rum Jungle region including such factors as the rainfall, evaporation and runoff coefficients. The river system and seasonal factors which affect the pollution cycle are also discussed.

CONTENTS

3. THE POLLUTION CYCLE AT RUM JUNGLE - CONTROLLING FACTORS, BASIC MECHANISMS AND DEGREE

3.1 Introduction

The degree of the continuing heavy metal pollution in the Rum Jungle (RJ) area is the result of the interdependence of past mining practices, geology, climatology and the basic physical, biological and chemical processes that make the heavy metals soluble. The first two of these factors are described in the previous chapter; the remainder combine to form a seasonal pollution cycle which is the subject of this chapter.

3.2 Climatology

3.2.1 Rainfall

Two distinct seasons occur in the area, an almost rainless Dry from May to September and a Wet from November to March. Southern [1966] in discussing rainfall types differentiates between organised rainfall, typified by monsoonal, cyclonic and widespread convection influences and nonorganised rainfall typified by mesoscale convection. He distinguishes five categories of rain producing systems, the interplay of which produces the seasonality and character of the rainfall in the area (Figure 3.1).

The rainfall regime of the area has three major characteristics; it is highly seasonal, it is highly reliable (on both an annual and monthly basis), and does not on average vary greatly in seasonality or amount from place to place (Figure 3.2).

It is said that thunderstorm activity is higher in some local areas than it is in others and that RJ is in a thunderstorm corridor. The Bureau of Meteorology is analysing available data for any such patterns but results are not yet available. It is important in that early induced flow in the nonperennial East Branch (EB) causes fishkills in the perennial Finniss River (FR). The number of fishkills per year depends on the relative occurrence of storms in the respective catchments.

The cyclones move predominantly from east or northeast to southeast or south. They are generally not strong depressions until they reach the northwest shelf area from where they generally move south-southeast. In some years these intensified depressions move almost due east leading to heavy rainfall in the top end of the Northern Territory (NT). It was such a chain of events that caused the exceptionally high rainfall of March 1974. The mean annual rainfall in the RJ area is about 1500 mm. The annual rainfall frequency curve is expected to be similar to that for Darwin which is shown in Figure 3.3.

The only detailed pollution studies in the RJ area were carried out during the 1969-70 and 1973-74 Wets which had rainfalls of 900 and 2000 mm respectively. The probability that for any year such a rainfall would be equalled or exceeded is 0.98 or 0.02 respectively, indicating that both were exceptional rainfall years.

No temporal patterns for NT rainfall are available. The data reduction on Darwin records suggests that temporal patterns are similar to those for Sydney. Sydney temporal patterns have been used for deriving total runoff (see Section 3.2.2). Figure 3.4 shows a typical storm intensity pattern for Sydney; Figure 3.5 shows temporal storm patterns derived from Sydney data by the Water Resources Branch (WRB), Department of NT (DNT). That branch has also compiled frequency curves for Oenpelli (NT) for point rainfall intensity-duration which are reproduced in Figure 3.6 [DNT 1974].

3.2.2 Evaporation

A pan evaporation instrument is not operated at Batchelor, the nearest station with long term records being at Darwin. Figure 3.7a indicates the annual distribution of evaporation for that station. Limited data are available from stations at Humpty Doo and Jabiru. None of these stations provides a good approximation for Batchelor in a topographic sense, but the lack of clearcut spatial effects indicates that the Darwin data are probably a reasonable approximation for the RJ area. They have been used as such in this report.

The relationship between the results from an evaporation pan and the evaporation from a free water body is uncertain. Table 3.1 indicates the range of values reported in the literature [AWRC 1970]. For this study a value of 0.65 has been used to relate evaporation from the opencuts to that from a class A pan, and a value of 0.8 to represent the relationship between the Australian pan (as used in Darwin) and the class A pan.

Evaporation from soil is a complex function of hours of sunshine, local meteorology, rainfall history, soil type and vegetation cover. The annual variation in hours of sunshine for Darwin is given in Figure 3.7b and an approximate soil moisture storage for the top end of NT is given in Figure 3.8 [McAlpine 1974].

These data were used for estimating the annual evaporative loss from the overburden heap by the same simple expedient as used by agronomists, i.e. real evaporation (et) is related to evaporation from an Australian pan evaporimeter (e) by the relationship et = 0.8e for those weeks when storage plus rainfall exceeds 65 mm, and by et = 0.4e when it is below this. With these approximations et was 850 mm for the 74-75 water year. Apparently this approach gives good agreement with results from a more detailed study on the Katherine (NT) area [Dyer 1967].

The growing period for vegetation is related to soil moisture storage. Table 3.2 presents estimates [Story et al. 1969] for Darwin, Adelaide River and Oenpelli. This characteristic is important with respect to runoff coefficients in the early part of the Wet and to the effectiveness of revegetation of waste material at mining/milling sites.

3.2.3 Runoff coefficients

Runoff is a residual, not a fraction of rainfall. For a runoff-producing storm, the rate of loss due to storage and infiltration is practically independent of rainfall intensity. Therefore the value of the runoff coefficient varies with rainfall intensity. Because of raindrop compaction, infiltration capacity decreases with time from the start of a storm but approaches a constant value within about an hour.

Infiltration rates for the waste rock dumps have not been measured and it is difficult to estimate a reliable value because of contradictory characteristics. For example the surface shale is very friable and is underlain with a sandy loam. However areas of local run-on exhibit surface cracking when dry and form clods when tilled. The value chosen (see Figure 3.9) stemmed from the observation that sharp storms delivering ~ 20 mm of rain during September 1974 produced runoff.

One of the runoff curves recommended in 'Australian Rainfall and Runoff' [Aust. Inst. Eng. 1958] is given in Figure 3.10. It applies to pre-wet soil conditions or where rainfall has continued for some hours. The only rainfall data available for all of the 73-74 Wet are daily records for Batchelor. Since data on the distribution of rainfall intensity in Sydney give an acceptable approximation to such distributions at locations in the NT, we have used rate-of-rainfall data for Lucas Heights to estimate runoff coefficients in the RJ area.

This was estimated in two ways. First, all rainfalls for Lucas Heights during 1973 and 1974 were analysed. The average runoff coefficient applicable to that two years' rain was 0.14. Second, only data from the first six months of 1974 were analysed. This period included daily rainfall values higher than any recorded at Batchelor during the same period. The average runoff coefficient for this period was 0.19.

An upper limit for average runoff coefficient ($\bar{c}$) can be obtained by assuming that each day's rain recorded at Batchelor resulted from a single storm. Under these conditions experimental values for the Badlands of Western Colorado [Schumm & Lusby 1963] become appropriate. These together with our experimental values for specific storms (see Chapter 7 for details) for the heaps at RJ, are plotted in Figure 3.11. The average runoff coefficient for the 73-74 Wet becomes, under these assumptions, about 0.4.

The value finally taken for $\bar{c}$ average over the 73-74 Wet was $0.2 \begin{smallmatrix} +\,0.2 \\ -\,0.1 \end{smallmatrix}$.

3.3 <u>The Finniss River System</u>

With respect to this study, the FR system can be thought of as having six components:

- the East Branch (EB) that drains the RJ area;
- the perennial Finniss upstream of the EB junction;
- the South Branch, a major tributary that joins the Finniss 12 km upstream from EB;
- Florence Creek (FC), a major tributary that enters the FR 30 km downstream from EB; and
- the flood plains.

EB is a nonperennial stream with a catchment of about 6500 ha. The WRB established a gauging station near the Batchelor/RJ road bridge but subsequently moved it 4 km further downstream and converted it to a recording station. Figure 3.12 shows the original rating curve for the roadbridge site together with ten spot ratings taken during 1974. It can be seen that changes have occurred in the cease-to-flow (CTF) value and in the shape of the calibration curve. No doubt these changes are due to sedimentation and bank instability respectively and are attributable to mining operations. Several gauge boards were installed at this site during the 1973-74 Wet and datum corrections for each are given on Figure 3.12.

The quantity of flow in EB per unit of rainfall over its catchment varies substantially during the Wet. For example monthly average values for daily equivalent runoff mm d^{-1} (river flow/catchment area) during the 1971-72 Wet were:

Oct	Nov	Dec	Jan	Feb	March	April	May	June	July	Aug
0	0.01	0.36	0.54	1.62	13.2	2.11	0.21	0.06	0.02	0

The reason for the rapid build-up in March is that much of the prior rainfall infiltrates and raises the water table which reaches the surface by about March. With falling river heights after the end of the Wet, the groundwater acts as a reservoir that leads to continuing river flow into June or July. Figure 3.13, a plot of water table height for a bore 300 m south of Old Tailings Creek, illustrates this seasonal variation.

Because of recorder malfunction, years with complete flow records are few. For 1969-70 (900 mm of rain), the total runoff down EB was 11% of incident rain; for 1971-72 (1550 mm of rain) it was 30%.

Though EB is nonperennial there is a series of permanent pools along its bed that are maintained by seeps from the dolomite zone. Only one of the seeps is substantial enough to be called a spring and it is located downstream of the gauging weir. These seeps have nourished some thickets of vegetation along the EB banks but their influence is localised to where they enter.

The perennial flow of FR is maintained by the spring fed creeks - Mount Burton, Rum Jungle, Meneling and Banyan. All these springs are from the dolomite zone.

The South Branch is nonperennial and is subject to rapid changes in water height. Fluvial erosion appears to be greater in this branch than anywhere else and the water quality (in terms of suspended solids, organic debris, pH and hardness) in the FR at the EB junction during the early part of the Wet depends markedly on the thunderstorm activity within the catchment of the South Branch. Table 3.3 summarises the range of water quality for different sections of the river system; no gauging stations are maintained in these upper reaches. A site on FR almost due west of Batchelor is one of the many possible dam sites being considered for future water supply to Darwin.

Florence Creek which is perennial enters FR about 30 km downstream from EB: a gauging station is maintained a little further downstream. The ratio of monthly flow past this station to that down EB (i.e. the dilution factor for pollutants from the RJ area before discharge onto the flood plains) varies erratically from month to month and year to year. Table 3.4 summarises the available information. FR is not continuous over the flood plains. Map 3.1 is a simplified diagram showing the areas where the floodwaters discharge onto the plains, the order in which this is expected to occur and the sites at which evidence still exists for earlier loss of vegetation (paperbarks) as a result of waste management procedures.

3.4 Basic Pollution Producing Mechanisms

3.4.1 Erosion

The erosion process in monsoonal climates has recently been reviewed by Williams [Story et al. 1974]. In our study, calculations have been limited to estimates of annual loss of surface material from the overburden heaps and tails dump, together with spot measurements of suspended material (and heavy metal content) in the runoff water. A reasonable fit to Williams' data on soil loss (sl) from granite slopes near Brocks Creek (NT) has the form

$$sl = 4 \times 10^{-4} r^{1.5} \text{ mm}$$

for storms during November and

$$sl = 3.2 \times 10^{-7} r^{1.5} \text{ mm}$$

for rainfall during February after a vegetation cover has been established; r (rainfall) is in mm.

Both the waste rock heaps and tails dump are bare of vegetation. For the tails dump, observations of erosion pedestals are consistent with the prediction that about 1 cm of tails material is eroded away during an average Wet. All this material (400 t y^{-1}) does not enter the creek system, much being deposited in the immediate area which leads to a continuing expansion of the tails dump. Significant quantities do however enter the creek system and deposited tails material is evident in aerial photographs of EB from the mine site to its junction.

A section of Old Tailings Creek that flooded for the first time during the 1973-74 Wet, accumulated about 1 cm of tailings crust. The characteristics of this deposited material are described in Chapter 6.

Spot measurements of the erosion from the embankment ponds were taken during light rain (~ 2 mm h^{-1}). Just downstream from an embankment breach the suspended sediment load was 7.5 g ℓ^{-1} corresponding to an erosion rate of 14 g m^{-2} h^{-1}. However this rate obviously includes a component of gully erosion at the breach and is not applicable to the tails area as a whole.

Field measurements of sheet erosion on the overburden heaps proved difficult with the sampling procedure adding, at least temporarily, to the suspended solids. The value finally adopted, 0.3 cm y^{-1} was arrived at by measuring the depth of sludge accumulated in the sulphide and oxide dams that formed part of the heap leach experiment.

Many samples were collected from the various runoff streams on the overburden heaps. The percentage of pollutant load carried as suspended solids was very variable (4-80%) and the results are suspect because of the sampling method used.

Results for the central runoff near where it enters EB show a more consistent trend. For example, the early, low volume runoff from White's overburden heap at the beginning of a storm carried almost all the copper load (~ 25 mg ℓ^{-1}) as dissolved material. By the peak of the storm the copper load (1-2 mg ℓ^{-1}) was about equally split between the dissolved and suspended states.

3.4.2 Bacterial oxidation

The solid waste dumps at RJ contain pyritic shales and other sulphide ores. The oxidation of these materials is linked to the activity of thionic bacteria that occur naturally in such deposits. *Thiobacillus ferroxidans* is capable of chemoautotrophic growth during the oxidation process. Many descriptions of the process are available (see for example Dugan 1972); it can be summarised thus:

in deposits containing pyrite (FeS_2), $FeSO_4$ is continually formed i.e.

$$2FeS_2 + 2H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4 \;;$$

the ferrous sulphate becomes oxidised through the action of *T. ferroxidans* i.e.

$$12FeSO_4 + 3O_2 + 6H_2O \rightarrow 4Fe_2(SO_4)_3 + 4Fe(OH)_3 \;;$$

ferric sulphate is an aggressive solvent of sulphides and these reactions liberate more heavy metals e.g.

$$2CuS + 2Fe_2(SO_4)_3 + 2H_2O + 3O_2$$
$$\rightarrow 2CuSO_4 + 4FeSO_4 + 2H_2SO_4 \quad .$$

This series of reactions, which only require the presence of water and atmospheric oxygen, releases heavy metals from the solid wastes. The growth of *T. ferroxidans* is optimum at pH 2.5 to 3.0; soil acidity and the pH of seepage through the waste approach this limit.

Bacterial oxidation leads to pollution of the Finniss system as a result of runoff and seepage from the overburden heaps and tails dump, and from the sulphide bearing sediments deposited in the creek beds.

3.4.3 Secondary interactions

There is some evidence of the release of manganese from the rock matrix in the Dyson's area. The origin of the manganese may have been natural (e.g. ankasite - a dolomite in which some calcium has been replaced by manganese which is not uncommon in deposits of marine origin) or may have resulted from interactions between raffinate (containing 400 mg ℓ^{-1} of manganese) and dolomite at the site of the Old Acid Dam.

It is imagined that the present day substitution is one of ferrous iron for manganese, the ferrous iron coming from the oxidation of pyrite.

3.5 The Seasonal Pollution Cycle

For convenience this description starts with early April at the end of the Wet. At this time river flow results from the groundwater storage and the pollution inputs are seepage losses from the overburden heaps and opencuts. The EB flow is typically 3 m^3s^{-1} dropping to 0.3 m^3s^{-1} by early May and 0.03 m^3s^{-1} by early June. Seepage from the opencuts and overburden heaps contains levels of acidity, copper, manganese and zinc as indicated

		Concentration mg ℓ^{-1}			
Source	pH	SO_4	Cu	Mn	Zn
White's opencut	2.7	8600	50	220	6
Intermediate opencut	3.2	3200	53	58	7
White's overburden	3.6	20 000	63	39	37
Intermediate overburden	3.0	34 000	760	150	~150

With decreasing river flow and an almost steady pollution input, the water quality at the RJ roadbridge rapidly deteriorates e.g.

	Concentration mg ℓ^{-1}				
Date 1974	pH	SO_4	Cu	Mn	Zn
9/4	4.8	160	0.9	0.7	0.5
16/4	4.8	140	0.9	0.9	0.5
23/4	4.7	190	1.3	1.1	0.5
30/4	4.5	280	1.5	1.7	0.7
7/5	4.9	400	2.0	2.1	0.9
14/5	4.6	800	5.0	5.0	1.7
21/5	4.1	1400	8.8	9.6	2.4
28/5	4.2	1900	21.0	22.0	4.0
4/6	4.3	3000	30.0	29.0	8.3

During this period seeps entering EB from dolomite beds lead to the precipitation of much of the heavy metal load so that the water quality improves downstream from the mine area. For example the ratios of concentration of Cu, Mn and Zn at the railway crossing to that at the road crossing are:

Date 1974	SO_4	Cu	Mn	Zn
9/4*	1.3	1.9	2.4	0.8
16/4*	1.8	2.7	2.7	1.0
23/4*	1.8	2.3	3.0	1.0
30/4*	1.7	3.3	2.6	1.1
7/5	1.2	1.8	2.4	0.9
14/5	1.0	1.4	1.8	0.6
21/5	0.7	1.0	1.0	0.5
28/5	0.6	0.5	0.5	0.3
4/6	0.4	0.3	0.5	0.2

**Copper Creek and Old Tailings Creek were flowing and contributing pollutants, during this period.*

The precipitated material - Ca, Mg, Al, Cu, Zn, Mn, SO_4 etc. settles out as a flocculent on the river bed. Much of it is redissolved in the early part of the next Wet and contributes to the heavy metal load of the first flush.

From July to August, a trickle of water continues to flow in EB past the mine area. By this time concentrations of contaminants are so high that gross reactions are evident. For example within less than a metre from a point where seepage from the Intermediate overburden heap is believed to enter the diversion channel, marked changes in colour and pH occur and a green floating floc develops. The ash of this floc assays at about 30% copper. This floc is also available for redissolution during the first flush.

From September to November there is essentially no flow in EB but the occasional thunderstorm redistributes precipitated contaminants. Incrustations of sulphate and heavy metals develop on the creek beds as a result of evaporation. For example the incrustation on the Old Tailings Creek bed yielded the following analyses for soluble material in mg kg^{-1}.

Cu : 12 700; SO_4 : 41 000; Al : 1300; Mg : 1500;
Mn : 450; Zn : 64; Ni : 480; Co : 720; Ca : 110 .

By the end of the Dry only three pools of any size remain in the EB bed. Along the length of these pools there can be a wide range of pollutant levels resulting from the combination of evaporation, seepage input and chemical reactions. The changes that can occur are indicated by the results of analyses on water from the seepage trench located between the Heap Leach pile and the Intermediate opencut:

	Concentration mg ℓ^{-1}							
Date 1973	SO_4	Fe	Mg	Ca	Al	Cu	Mn	Zn
1/8	18 000	880	880	250	1500	125	700	56
1/11	46 000	30	150	60	2100	2600	1600	160

For the waterhole upstream of the weir there was in November 1973 a 10-fold change in concentration of important contaminants with copper reaching a level of 500 mg ℓ^{-1}. This dissolved material is a significant component of the pollution load carried by the first flush.

The extent, frequency and degree of the fishkills resulting from the EB's early flushes depend on the intensity and location of thunderstorms within each subcatchment. The fishkill observed in November 1973 and described in Chapter 7, resulted from thunderstorms over Old Tailings Creek, FR and South Branch respectively. The chain of events observed (substantial precipitation of pollutants, a two-phase rise in river height with an increase in sediment load during the second phase, and backflow up EB and its delta structure) is characteristic of that thunderstorm sequence.

The existence of this delta structure function of EB with the FR, and the backflow up these channels during the early part of the Wet, effectively damming the EB, explains the extensive area of damaged vegetation that exists there.

Flow in EB is erratic in November-December, sustained flow generally not occurring until January. During this period the source of pollution gradually changes from that left over from the previous Wet together with that produced during the Dry (bacterial oxidation of sediment in the creek beds), to new inputs resulting from runoff from the solid waste dumps, i.e. overburden heaps, tails dump and stockpile heaps.

By January the local water table has risen and is contributing to the creeks. This early contribution can be thought of as a displacement of contaminated groundwater (resulting from seepage through the solid waste dumps and seepage from the opencuts). For example for groundwater from the tails dump area:

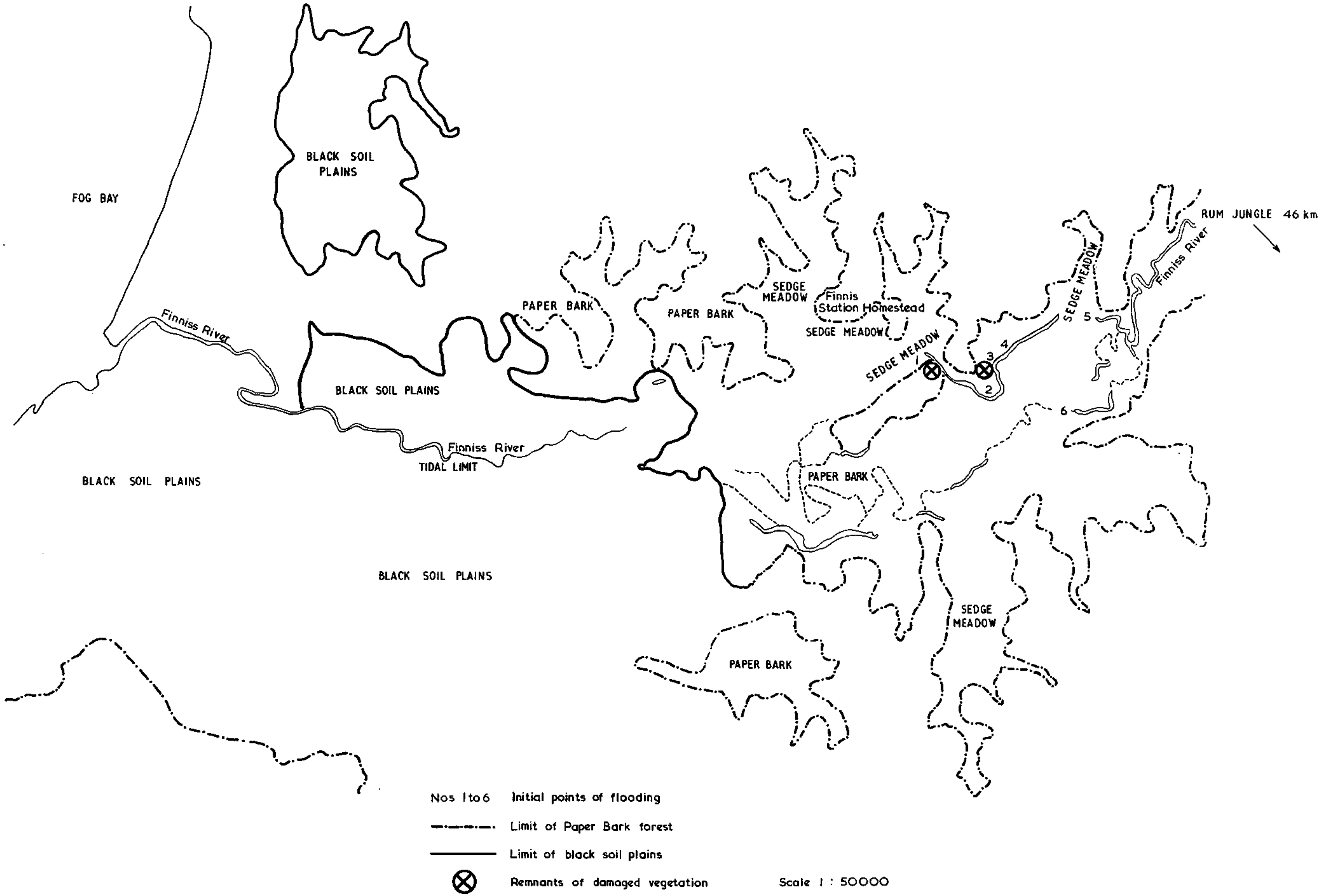
Date		Concentration mg ℓ^{-1}			
1973-4	pH	SO_4	Cu	Mn	Zn
26/10	4.3	920	22	18	1
18/12	4.3	1500	47	33	1
19/3	6.1	900	0.3	0.4	0.17
30/4	7.5	1000	< 0.1	< 0.1	< 0.1

With increasing river flow the number of tonnes of pollutant per day carried by EB increases but with decreased concentrations. For example, for spot samples from the railway bridge site:

Date	Pollutant					
	Cu		Mn		Zn	
1973-4	$t\ d^{-1}$	$mg\ \ell^{-1}$	$t\ d^{-1}$	$mg\ \ell^{-1}$	$t\ d^{-1}$	$mg\ \ell^{-1}$
12/11	0.13	32	0.3	74	0.008	2.0
19/11	0.005	78	0	13	0	0.9
26/11	0.11	22	0.05	11	0.02	4.0
3/12	0	25	0	13	0	4.4
10/12	0	87	0	19	0	3.3
18/12	0.02	23	0.01	14	0.002	2.5
8/1	0.4	2.8	0.3	2.2	0.16	1.1
15/1	8.4	1.7	4.0	0.8	2.0	0.4

This table illustrates another important factor. Even though days with more intense rainfall will follow and river flows will be even greater, it is this first intense rain session, generally in January, that transports the greatest slug of pollutants. Nothing is known about the effect of this slug on aquatic life. Presumably where it enters the flood plains, a location that would vary from year to year depending on rainfall history, is where vegetation shows increased concentrations of heavy metals (see Chapter 8).

The source of the pollutants in this slug is also not known with any precision; the timing is too early for the opencuts to be significant sources and the slug is too concurrent with the rainfall for the waste rock heaps to be contributing other than by runoff. In some way it must represent the release, presumably from the waste rock heaps of much of the material that has been made soluble during the previous Dry.



THE LOWER REACHES OF THE FINNISS RIVER. PROBABLE SITES OF CRITICAL FLOODING AND REMNANT DEAD VEGETATION

MAP 3.1

TABLE 3.1

ANNUAL COEFFICIENTS FOR LAKE RELATIVE TO CLASS A PAN $\frac{e_1}{e_p}$

Location	Surface area in square miles	Average depth in feet	Pan coefficient	Obser-vation period	Control method
Lake Elsinore, California	8.6	10	0.77	1939-41	Water budget
Red Bluff Reservoir, Texas			0.68	1939-47	Water budget
Lake Okeechobee, Florida	700	10	0.81	1940-46	Water budget
Lake Hefner, Oklahoma	3.4	26	0.68	1950-51	Water budget
Felt Lake, California	0.1	21	0.77	1955	Water budget
Lake Colorado City, Texas	3.2	16	0.72	1954-55	Energy budget
Lake Mead, Arizona	198	176	0.60	1952-53	Energy budget
Lake Mead, Arizona	198	176	0.74	1952-53	Bulk aerodynamic
Lake Mendota, Wisconsin	15.1	40	0.82	27 years	Heat budget
Salton Sea, California	300	24	0.52	1961-62	
Silver Lake, California	20	3	0.61	1938-39	Water budget
Fort McIntosh, Texas			0.79	1950-51	
Kempton Park, London	0.04	23	0.70	1956-62	Water budget
Lake Nyasa, Malawi	11 430		0.86	1958-62	Penman
Lake Eucumbene, New South Wales	37.9	78	0.86	1962-64	Bulk

TABLE 3.2

CHARACTERISTICS OF THE PERIOD OF PASTURE GROWTH

	Darwin	Adelaide River	Oenpelli
Commencement of estimated useful pasture growth			
Median date	2/11	9/11	11/11
Lower quartile	19/10	31/10	2/11
Upper quartile	17/11	16/11	26/11
Cessation of estimated useful pasture growth			
Median date	16/5	4/5	10/5
Lower quartile	8/5	28/4	3/5
Upper quartile	25/5	14/5	16/5
Total duration of estimated useful pasture growth (i.e. average annual number of weeks with available water)	28	25	25
Total duration of estimated active pasture growth (i.e. average annual number of weeks with available water exceeding 65 mm)	20	19	19

TABLE 3.3

PRINCIPAL STREAMS OF THE FINNISS RIVER SYSTEM

Stream, or Section of stream	Approximate length km	Seasonality	Catchment area relative to that of the East Branch	Chemical Characteristics mg ℓ^{-1}									
				pH	SO_4	HCO_3	Ca	Mg	Cu	Mn	Zn	Pb	U
Upper FR to junction with South Branch	40	Perennial for downstream 15 km	2.2	7.4-7.7	< 0.4-14	177-226	13-22	1.5-33	< 0.005-0.03	< 0.025-0.05	< 0.025-0.033	< 0.003-<0.2	0.001-0.013
South Branch	42	Ceases flowing August	2.5	6.6	< 1.0-6.5	65	3.0-4.0	0.8-10	<0.005-<0.03	< 0.025-0.01	< 0.005-<0.025	<0.005-<0.006	0.002
FR between junctions with SB and EB	12	Perennial	5.3	4.5-8.5	5-170	45-126	6-24	2-48	0.01-18	0.01-33	< 0.005-<0.03	0.003-0.07	0.05-0.86
EB	21	Ceases flowing June	1										
1 Upstream of mined area				6.0-7.6	< 2-85		<10-95	0.014-12.5	<0.001-1.5	< 0.001-1.25	< 0.1-0.1	< 0.002-0.019	<0.0001-0.7
2 Downstream of mined area				2.0-8.2	1.2-4050	2-138	2-224	2-560	<0.02-155		< 0.002-8.1	< 0.003-0.1	0.02-6.7
FR between junctions of EB and FC	28	Perennial	7.9	3.1-8.2	2-868	7-271	16-78	5-164	0.02-25	0.02-8	< 0.005-0.84	0.003-0.06	0.006-0.23

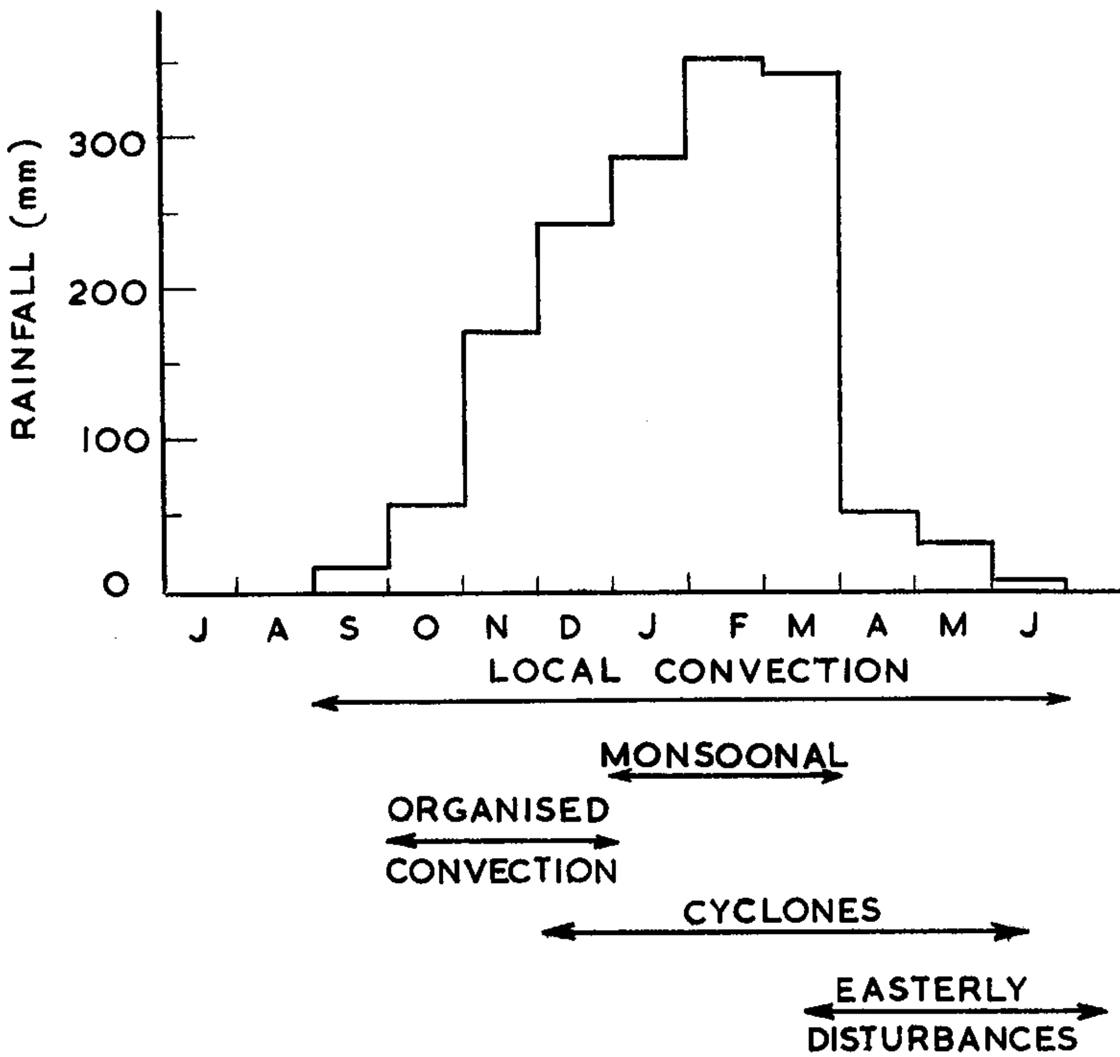
TABLE 3.4

MONTHLY STREAM FLOWS IN $m^3 \times 10^{-6}$*

((a) indicates insufficient records)

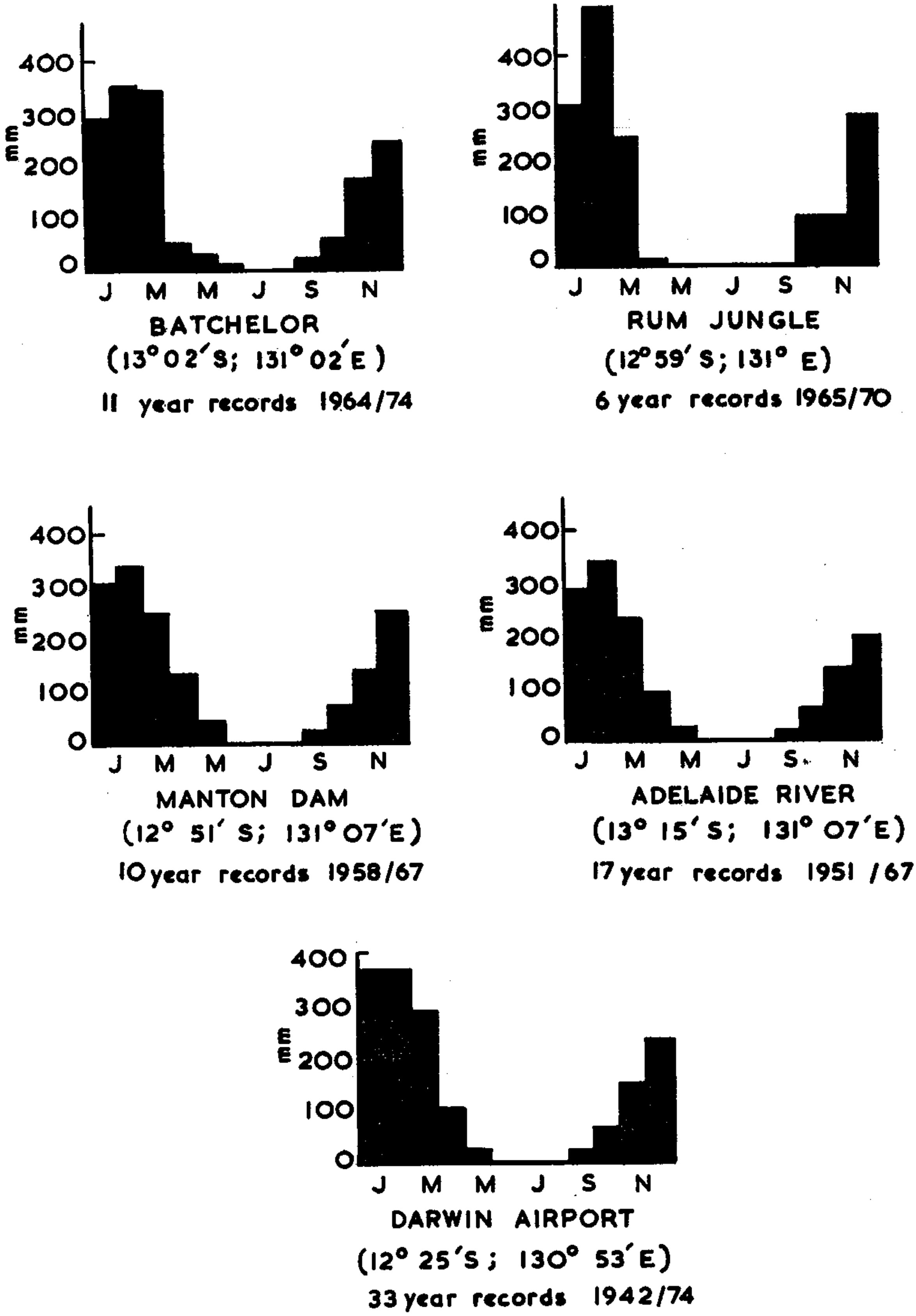
Month	East Branch			Finniss River					
	Period of records			Period of records					
	69-70	68-69	62-70	69-70	68-69	62-70	71-72	70-71	60-72
Sept	0	0	0	0.91	1.3	0.52	0.43	0.49	0.58
Oct	0	0.4	0.01	1.76	0.98	0.55	0.44	0.58	0.55
Nov	0	(a)	0	2.39	0.86	1.23	1.70	1.43	1.29
Dec	0.21	(a)	0.89	3.89	3.41	6.36	56.3	11.6	11.0
Jan	0.17	(a)	3.13	5.17	13.7	27.8	33.1	9.13	26.7
Feb	4.48	23.5	29.9	48.3	(a)	106	40.7	47.0	92.4
March	1.88	29.6	14.1	17.7	(a)	85.5	237	129	107
April	0.14	0.87	1.57	3.14	(a)	16.5	27.1	32.0	19.1
May	0.05	0.1	1.07	1.23	5.1	7.2	5.72	7.56	7.11
June	0	0.02	0.2	0.58	2.63	2.24	2.41	1.86	2.23
July	0	0	0.03	0.36	1.76	1.11	1.50	0.91	1.13
Aug	0	0	0.01	0.27	1.37	0.70	1.10	0.64	0.74

* *From 'Monthly and Annual Stream Flow Statistics for the Northern Territory'*



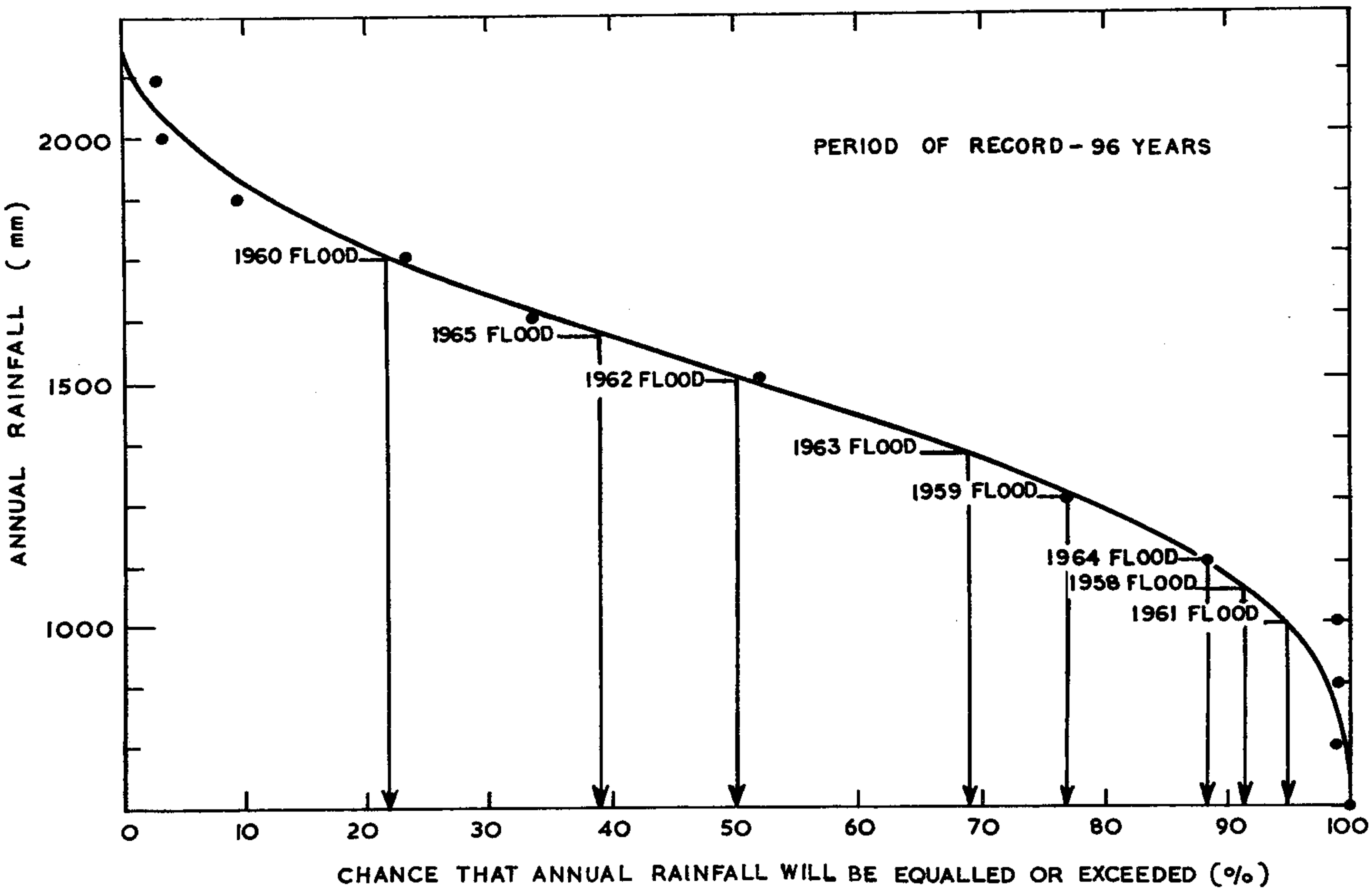
ANNUAL RAINFALL REGIME AT BATCHELOR BASED ON 11-YEAR RECORDS (1964-74)

FIGURE 3.1



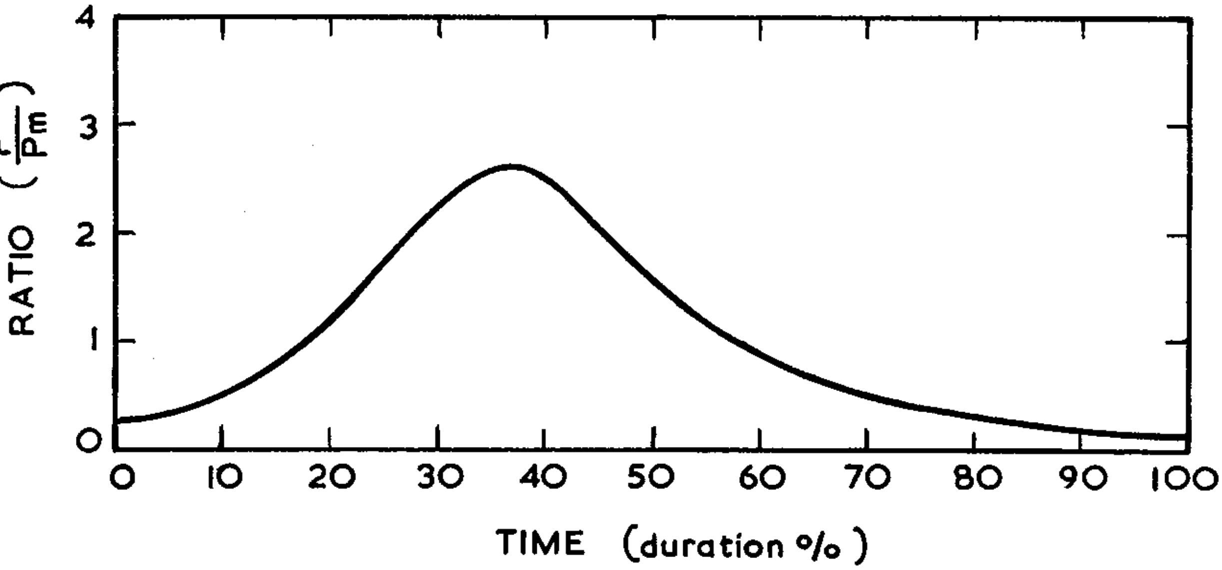
ANNUAL AND SPATIAL DISTRIBUTION OF RAINFALL

FIGURE 3.2



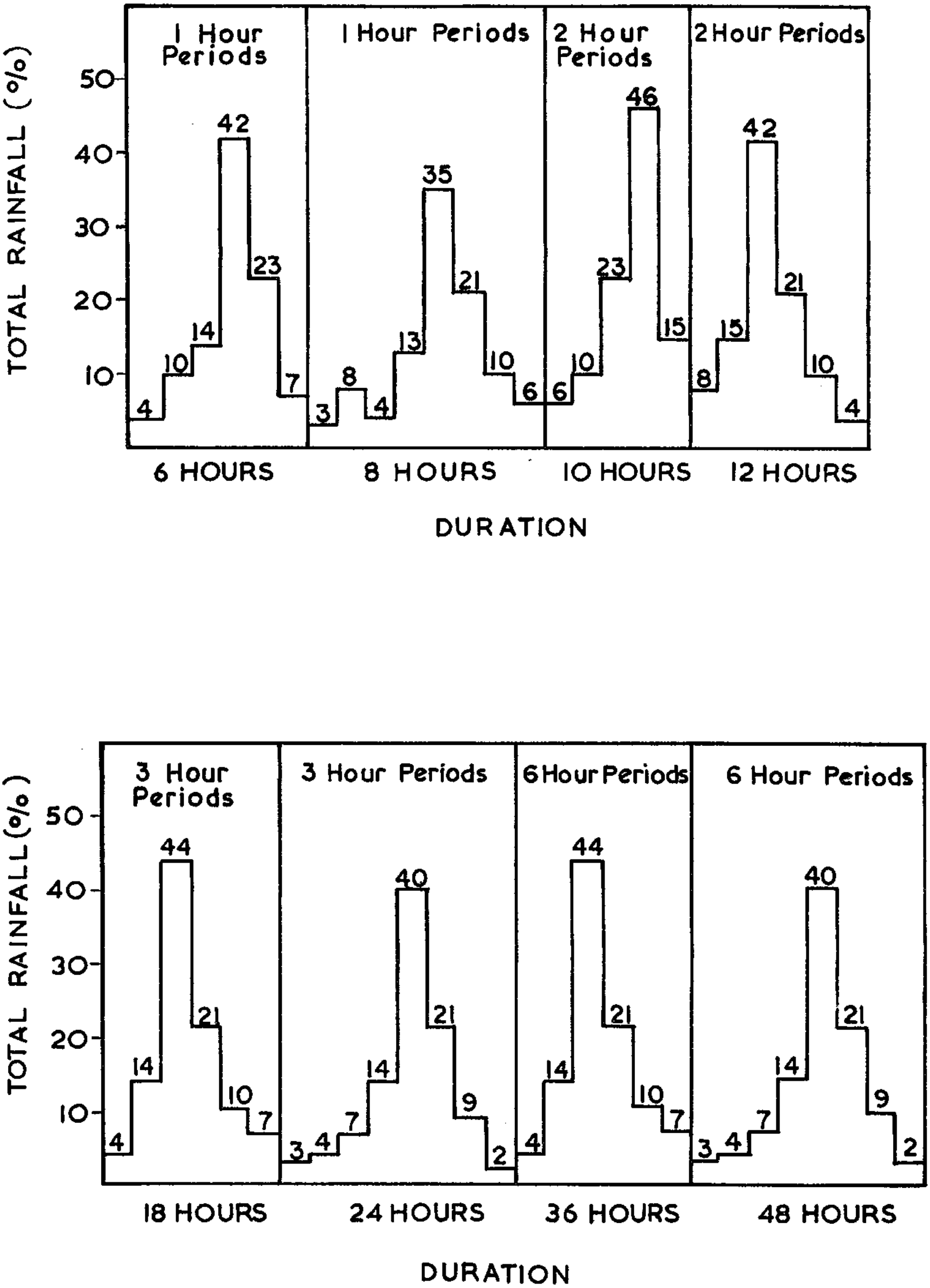
RAINFALL FREQUENCY FOR DARWIN

FIGURE 3.3



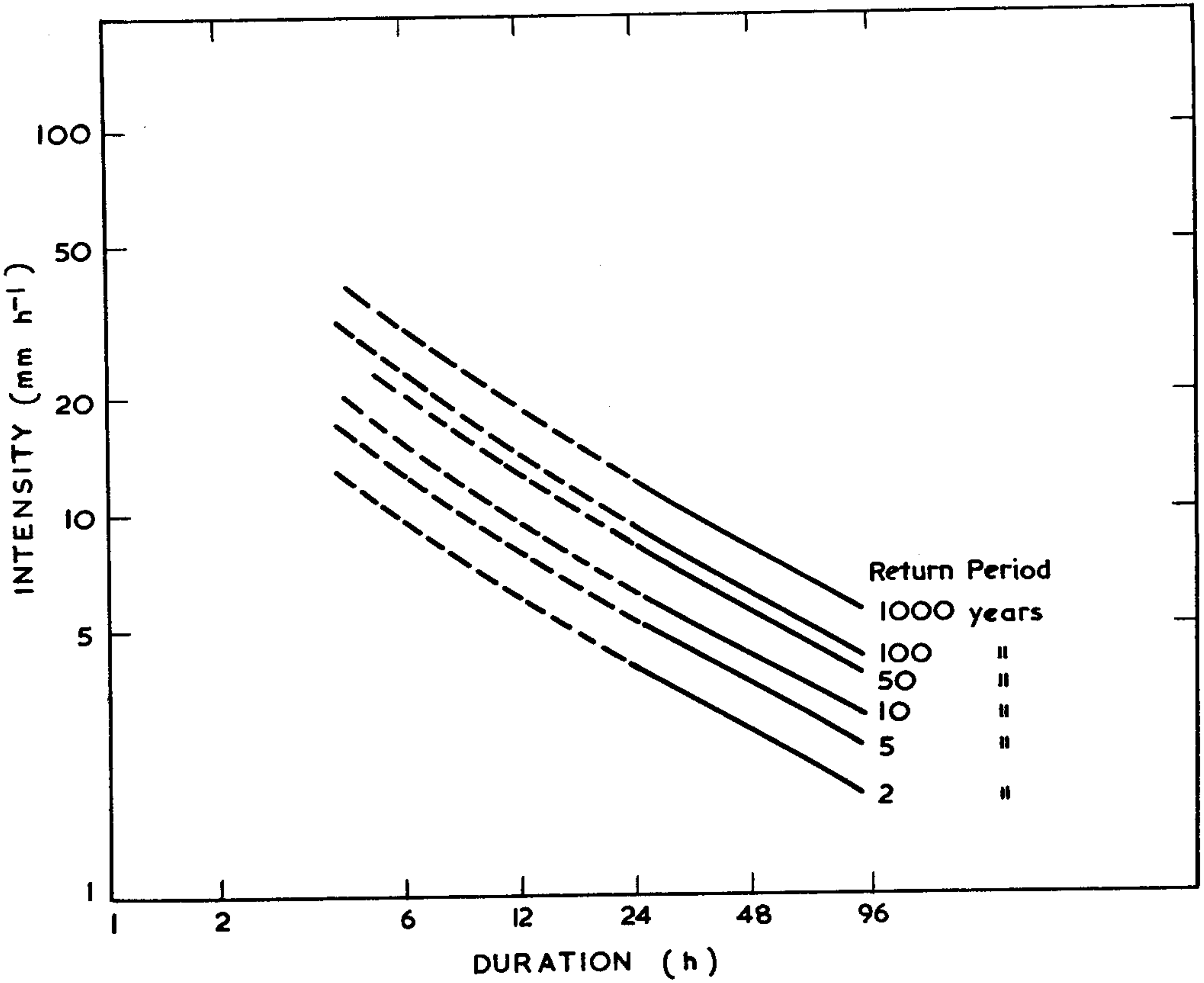
TYPICAL STORM INTENSITY PATTERN FOR SYDNEY

FIGURE 3.4



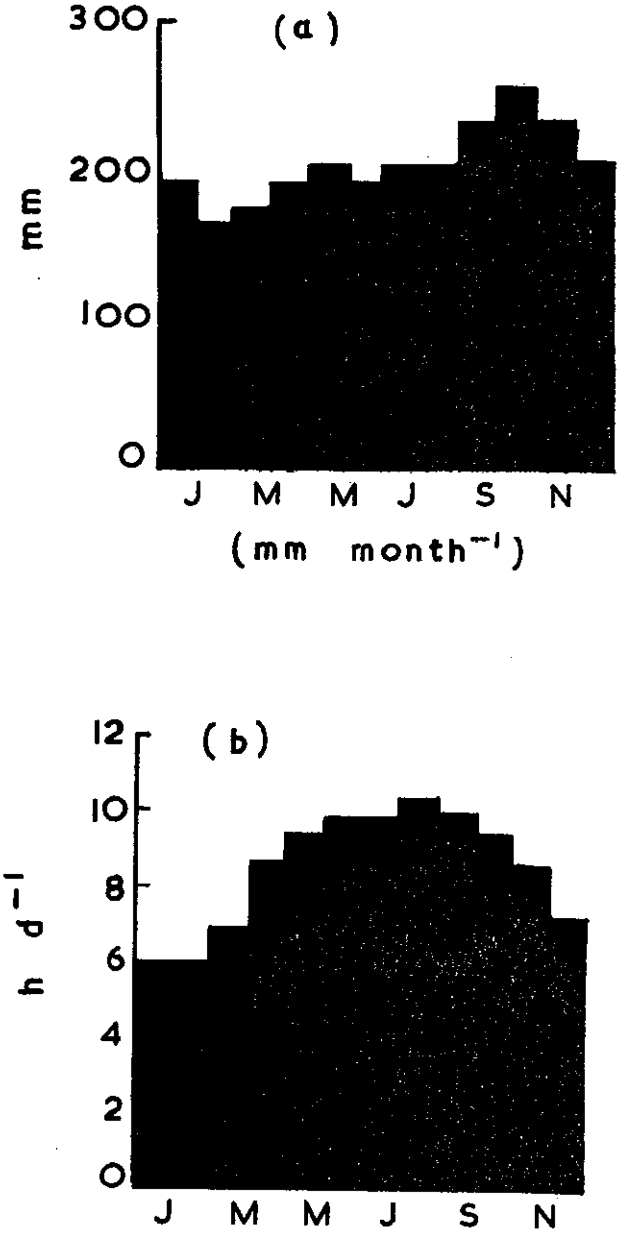
DESIGN TEMPORAL STORM PATTERNS

FIGURE 3.5



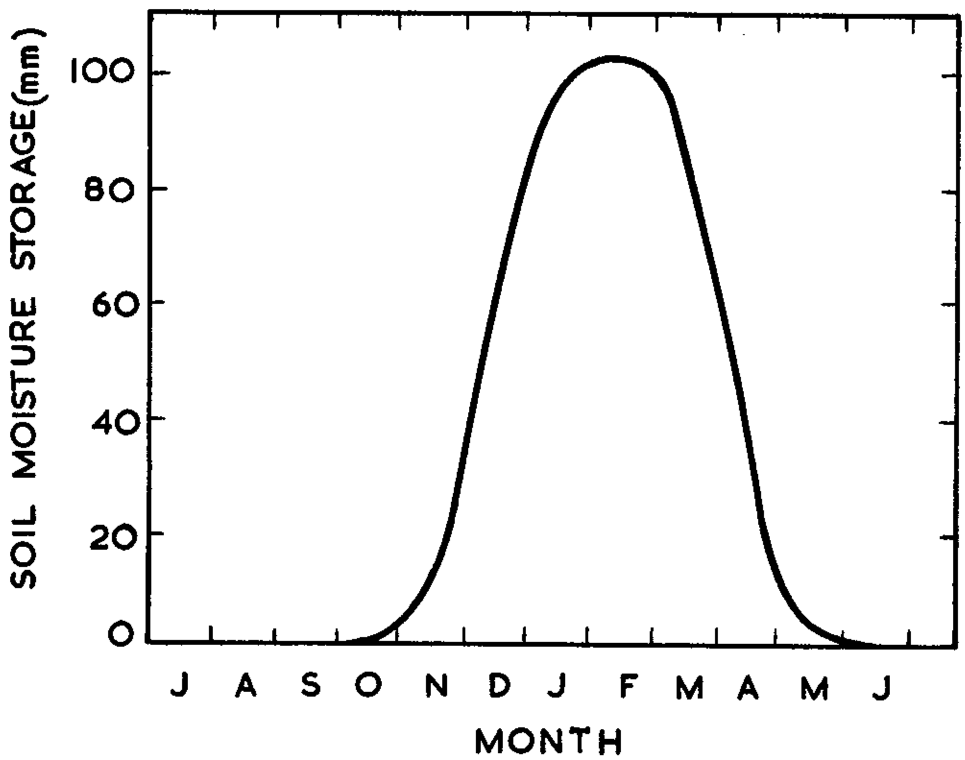
FREQUENCY CURVES OF POINT RAINFALL INTENSITY - DURATION

FIGURE 3.6



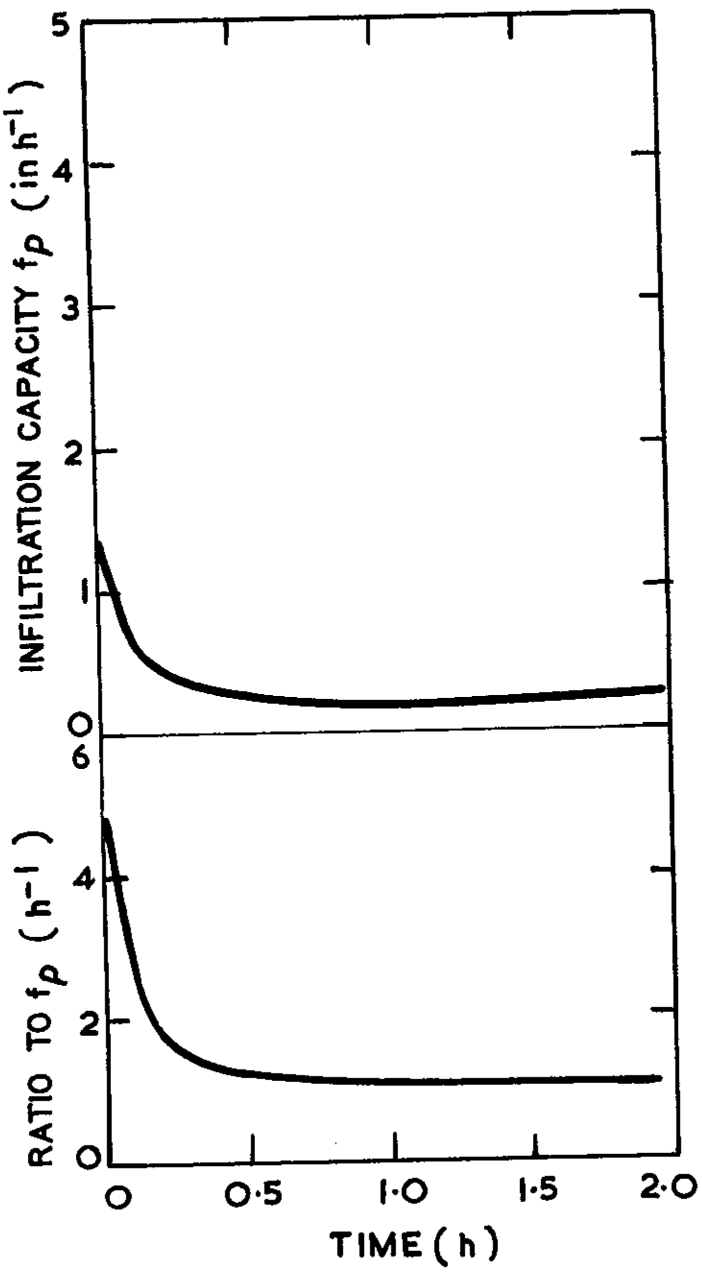
ANNUAL DISTRIBUTION OF EVAPORATION (a) AND DAILY HOURS OF SUNSHINE (b) FOR DARWIN

FIGURE 3.7



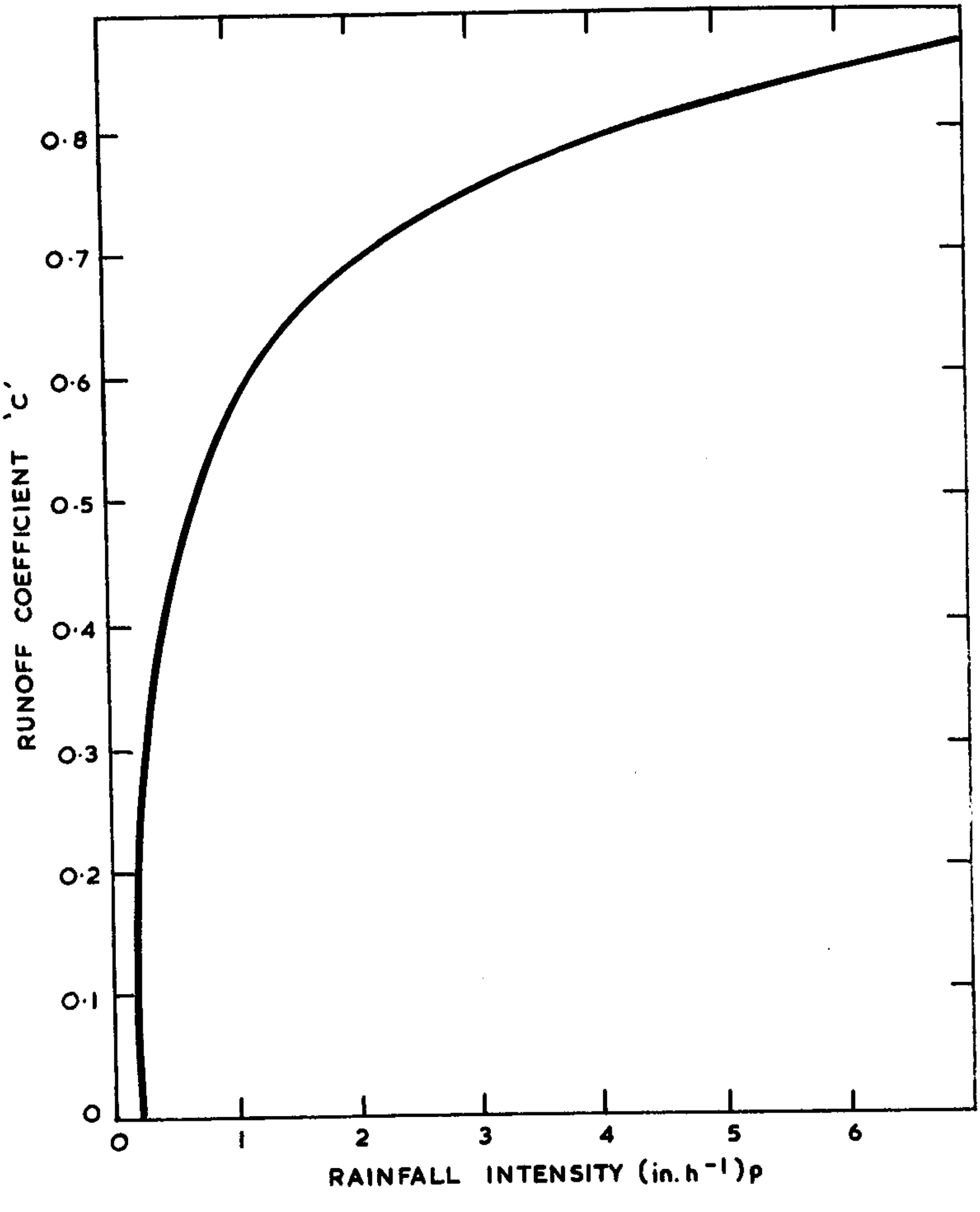
MEAN WEEKLY SOIL MOISTURE STORAGE AT OENPELLI

FIGURE 3.8



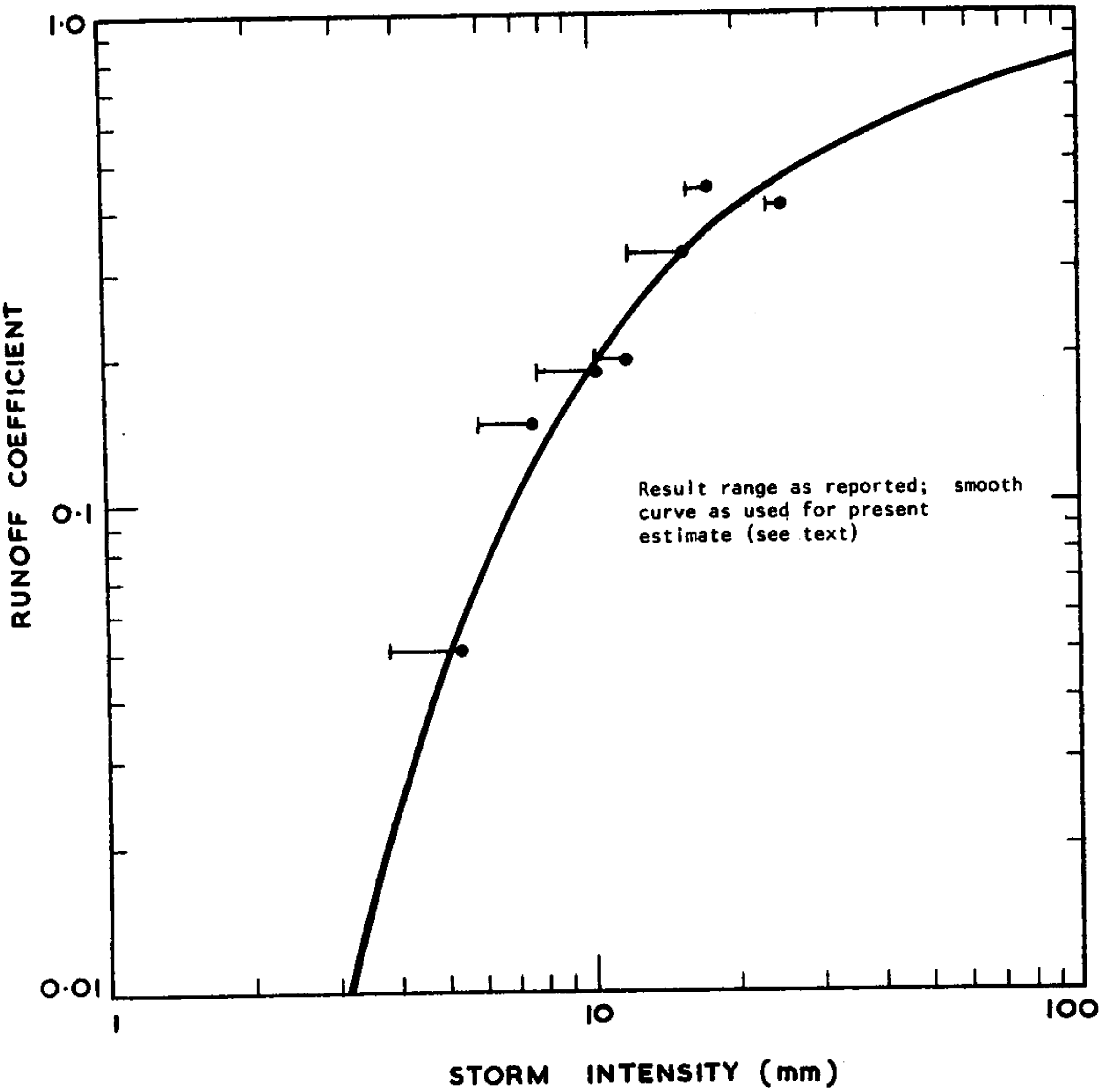
TYPICAL INFILTRATION CAPACITY CURVES
(After Aust. Inst. Eng. 1958)

FIGURE 3.9



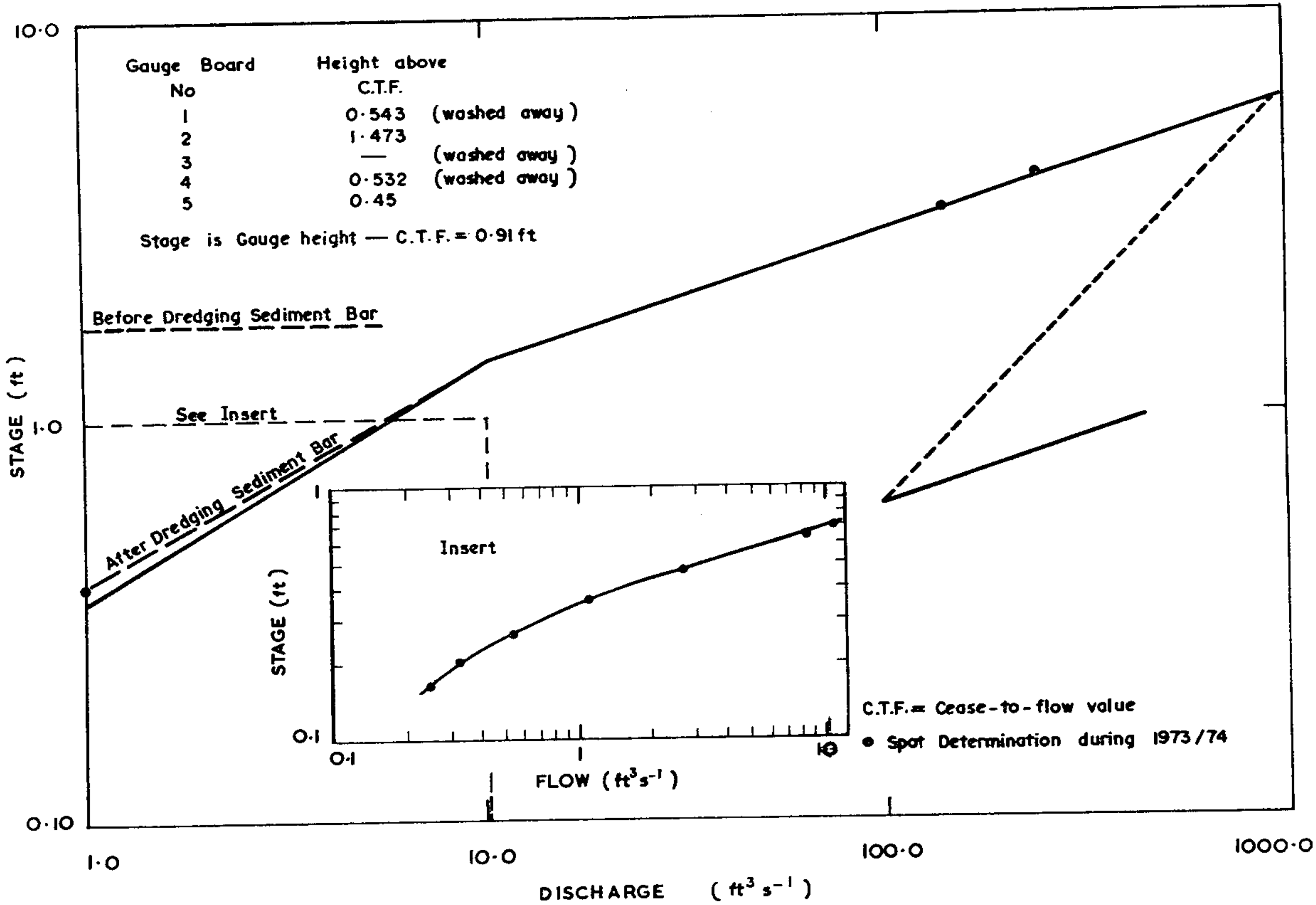
RUNOFF COEFFICIENT

FIGURE 3.10



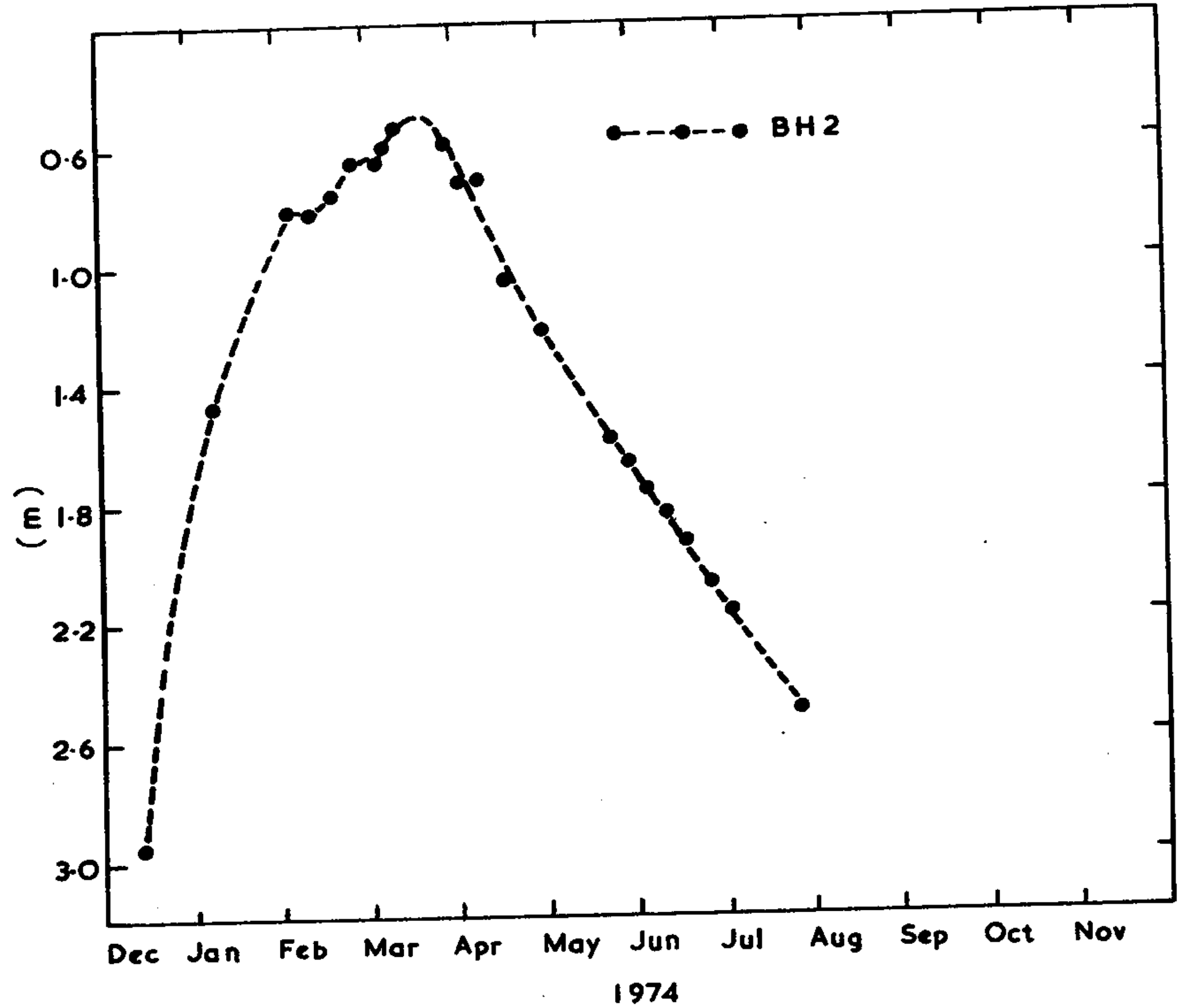
RUNOFF COEFFICIENT FOR THE BADLANDS OF WESTERN COLORADO (After Schumm and Lusby (1963)

FIGURE 3.11



RATING CURVE FOR THE ROADBRIDGE GAUGING STATION

FIGURE 3.12



CHANGES OF WATER HEIGHT IN A BORE LOCATED AT THE TAILINGS DUMP AREA

FIGURE 3.13

RUM JUNGLE ENVIRONMENTAL STUDIES

CHAPTER 4

ANNUAL INPUTS OF POLLUTANTS TO THE FINNISS SYSTEM

by

D.R. DAVY

J. JONES *

ABSTRACT

The pollution load carried by the East Branch downstream of the mine area was estimated in order to determine the annual input of pollutants to the Finniss River system. Results for the 1969-74 Wets are tabulated.

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* Water Resources Branch, DNT.

CONTENTS

4. ANNUAL INPUT OF POLLUTANTS TO THE FINNISS SYSTEM

4.1 Introduction

Three independent methods were used to assess the annual input of pollutants to the Finniss River system. First, the pollution load carried by the East Branch (EB) downstream of the mine area was calculated; this is described in the present chapter. Second, the diversion channel, Old Tailings Creek and Copper Creek subcatchments of EB in the vicinity of the mine area were separately assessed; these assessments are given in Chapter 5. Third, the opencut, waste rock, Bogum heap and tailings disposal area individual sources were separately assessed; these, together with a comparison of the results from the three methods, are given in Chapter 6.

The Water Resources Branch (WRB) has maintained a recording gauging station on EB downstream from the Rum Jungle (RJ) area (GS 815097) since 1965. Over the same period this branch has collected weekly water samples from the railway bridge site about 3 km upstream from the gauging station. Over the years varying estimates have been made of the pollution load carried by EB. This chapter brings together those estimates.

4.2 Accuracy

The method used is simple numerical integration of the plot of flow concentration versus time. The usual output from the gauging station records is the average daily stream discharge and it is this value that was used (except for 1973-74) to determine the flow concentration value for that day. In other words, the approach generally used implicitly assumes that the spot value of concentration for a particular day is the same as the average concentration over that day. The data reduction for the 1973-74 Wet used the concentration values determined from the spot sample together with the EB flow at that particular time.

The concentration data are on a weekly basis the flow data, daily. Daily flow values were used to interpolate the quantity versus time curve between weekly values. Differences of up to 80% result if this approach is compared with a histogram approach (i.e. quantity versus time assumed constant between weekly samples). The flow data interpolation implicitly assumes that, over a period of a week, concentration is inversely proportional to flow. This assumption cannot be true in detail because the pollution source terms, involving runoff, change nonlinearly with rainfall and source terms involving seepage are independent of rainfall within a week. The uncertainty resulting from this assumption is indicated by estimates for 1969-70. During that Wet both WRB and the AAEC were routinely sampling from the railway bridge site. For the combined data the sampling period was much shorter than one week. Quantity estimates based on WRB data above and based on the combined data, differed by less than 10%.

During some years, recorder malfunction led to no flow data being available for days on end. For these cases, daily flows were estimated by normalising on the previous 24-hour daily rainfall data from Batchelor.

Most samplers collect the spot samples from the edge of the stream at the railway crossing site. The quantity estimates assume that the concentration of pollutants in that spot sample correctly represent the velocity weighted average value of concentrations across the stream. No data are available for an estimation of the error involved in this assumption.

The results of chemical analyses on the spot samples include an absolute error of ± 0.1-0.2 mg ℓ^{-1}. The average concentration of pollutant during the Wet is commonly in the range 0.6 (for zinc) to about 2.0 (copper and manganese). These errors are not necessarily self cancelling over the Wet (days with the highest pollution load involved the lower values of contaminant concentrations).

The river flows fluctuate widely from day to day and the data for most years contain instances where the flow for a particular day is 10 to 50 times that of the previous day. Not infrequently the pollution load carried by the river on those particular days is a substantial part of the total load for the Wet; 1973-74 was such a year (see Figure 4.1). Thus the absolute error in the chemical analyses for those particular days is important. Note also that for high flow days, the concentration of pollutant will be lowest, so that a fixed absolute error represents the highest percentage error.

4.3 Results

Results for the 1969-74 Wets are presented in Table 4.1. In view of the factors discussed above no absolute accuracy is quoted. The mill at RJ was operated during the 1969-70 and 1970-71 Wets and part of the pollution load during those years must be attributed to waste streams originating from the mill. The results for the three subsequent years are for the decommissioned and abandoned site. During 1970-71 a general site cleanup was undertaken and the debris was dumped into White's opencut. This would have led to an increased loss (as seepage) of contaminated water.

If the results for 1971-72 are taken as indicating the pollution load originating from the mine environment as a result of about 1600 mm of rain, then the difference between these and the actual values for 1970-71 (i.e. 26 t of copper and 46 t of manganese) has a Mn/Cu ratio of 1.8, reasonably close to the 1970 value for water from White's opencut (2.2) but dissimilar to that for raffinate (3) or seepage from the heap leach experiment (0.13). Further if the difference in the depth of White's opencut as measured in 1970 and 1974 is attributed to tails and debris deposited there during 1970-71, the amounts of copper and manganese in the water displaced are consistent with the 'excess' pollution load (26 t of Cu; 46 t of Mn) for that year.

It seems reasonable to assert then that the existing mine environment contributes a pollution load of about 50 t of copper, 50 t of manganese and 20 t of zinc to the FR system during years of near normal rainfall and that there has been essentially no change over the 1970-74 period. As this quantity of heavy metal is but a small part of that existing in the solid waste dumps and contained in the opencuts, a pollution problem of this magnitude should continue for many years.

The results for the 1973-74 Wet suggest a disproportionate increase of pollution load with respect to rainfall and perhaps a disproportionate increase of copper with respect of manganese and zinc. No explanation is offered except to note that, if the rainfall effect was due to an average runoff coefficient for 1973-74 different from that for other years, both copper and zinc levels should have moved in a similar manner with respect to that for manganese. If the rainfall effect had resulted from a disproportionate increase in seepage from the opencuts then the manganese load would have increased with respect to that for copper and zinc.

4.4 Other Characteristics

Some general characteristics of the pollution load passing the railway crossing site on EB are evident from an examination of the way in which the ratios of specific pollutants change during the Wet. Curves for Cu/Mn for the Wets 1969-70 to 1973-74 and for Cu/Zn for the Wets 1970-71 to 1973-74 are shown in Figures 4.2 and 4.3 respectively. There are significant variations in the ratios on a week-to-week basis and so the curves shown in the figures have been smoothed; they have been interpreted to yield the following conclusions:

(i) The pollution load at the beginning of the Wet is relatively rich in copper. This could result from the heap leach pile (a source of copper pollution only) as a seepage source being delayed in time with respect to the other heaps, or from bacterial oxidation of tails material in the EB bed during the Dry, or some combination of these two factors.

(ii) Sources that contribute mainly copper (the tails dump and the heap leach) and those that contribute mainly copper and zinc (Intermediate and White's heaps) maintain their relative strengths during most of the Wet.

(iii) At the beginning of the Dry when EB is still flowing, zinc is preferentially precipitated (see also tables in Chapter 3, Section 5).

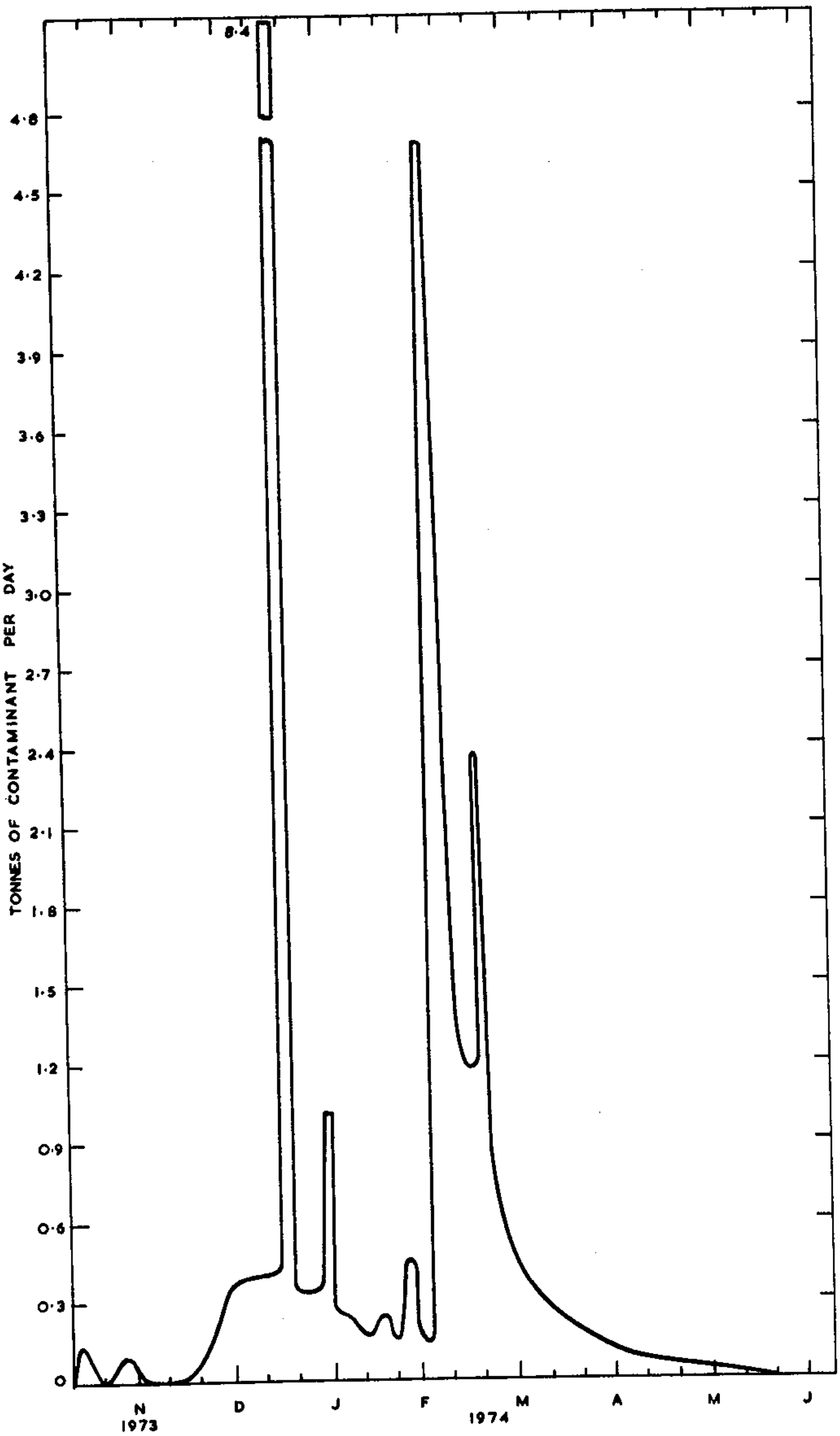
(iv) Sources that contribute mainly manganese (White's opencut and Dyson's area) increase in importance as the Wet develops. Presumably this results, on the one hand, from seepage from White's opencut not being an important source until incident rain has significantly raised the water level, and on the other, from the time needed for the chemical substitution of ferrous iron for manganese in the Dyson's area.

(v) The shape of the ratio curves somewhat depends on both the total rainfall (e.g. 1973-74) and the monthly distribution of this rainfall (e.g. 1972-73).

TABLE 4.1

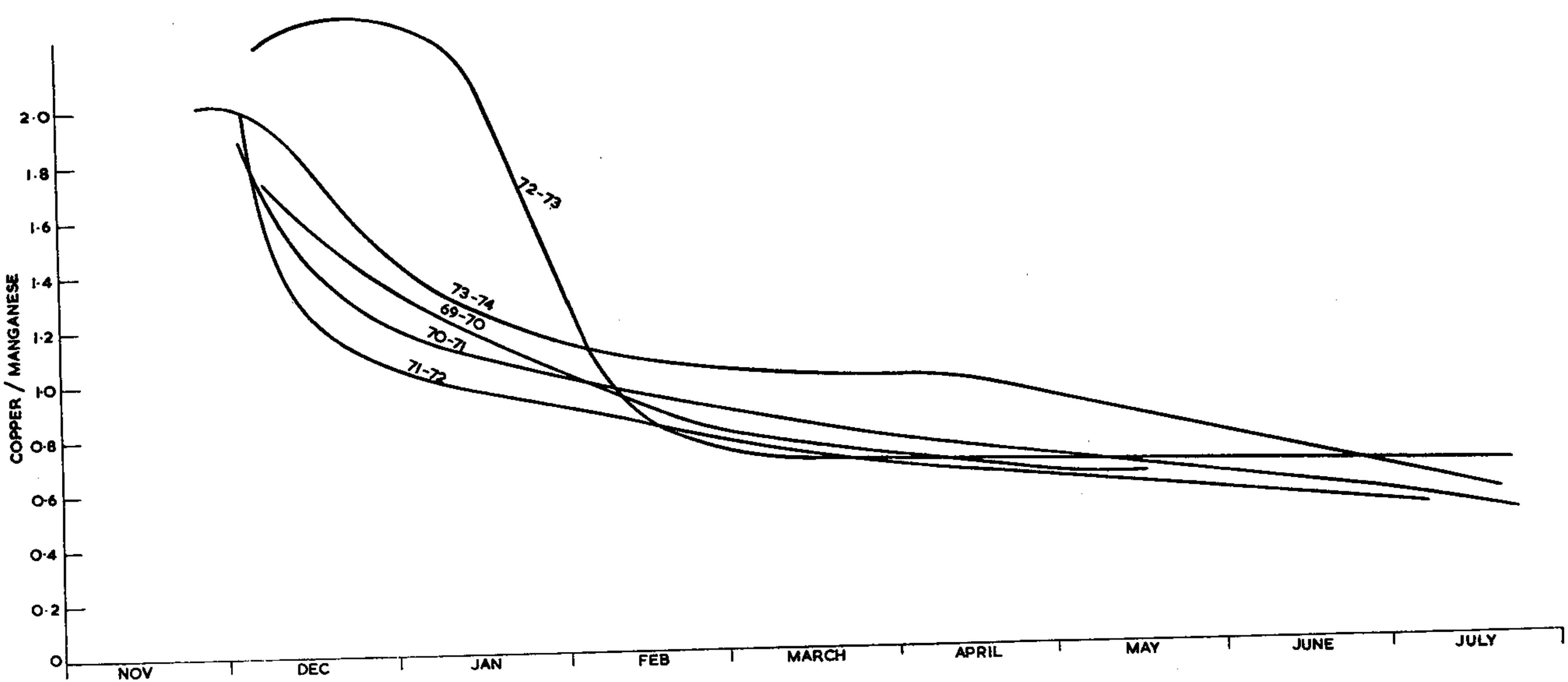
POLLUTION LOAD CARRIED BY THE EAST BRANCH

Season	1969-70	1970-71	1971-72	1972-73	1973-74
Rainfall (mm)	896	1611	1542	1545	2000
Period of flow in EB	Dec – May	Nov – Aug	Nov – July	Dec – July	Nov – Sept
Flow ($m^3 \times 10^{-6}$)	7.0	33.2	30.9	26	n.a.
Pollution load (tonne)					
Cu :	44	77	51	45	130
Mn :	46	110	64	49	100
Zn :	n.a.	24	19	16	40
SO_4 :	3300	12 000	6600	5500	13 000



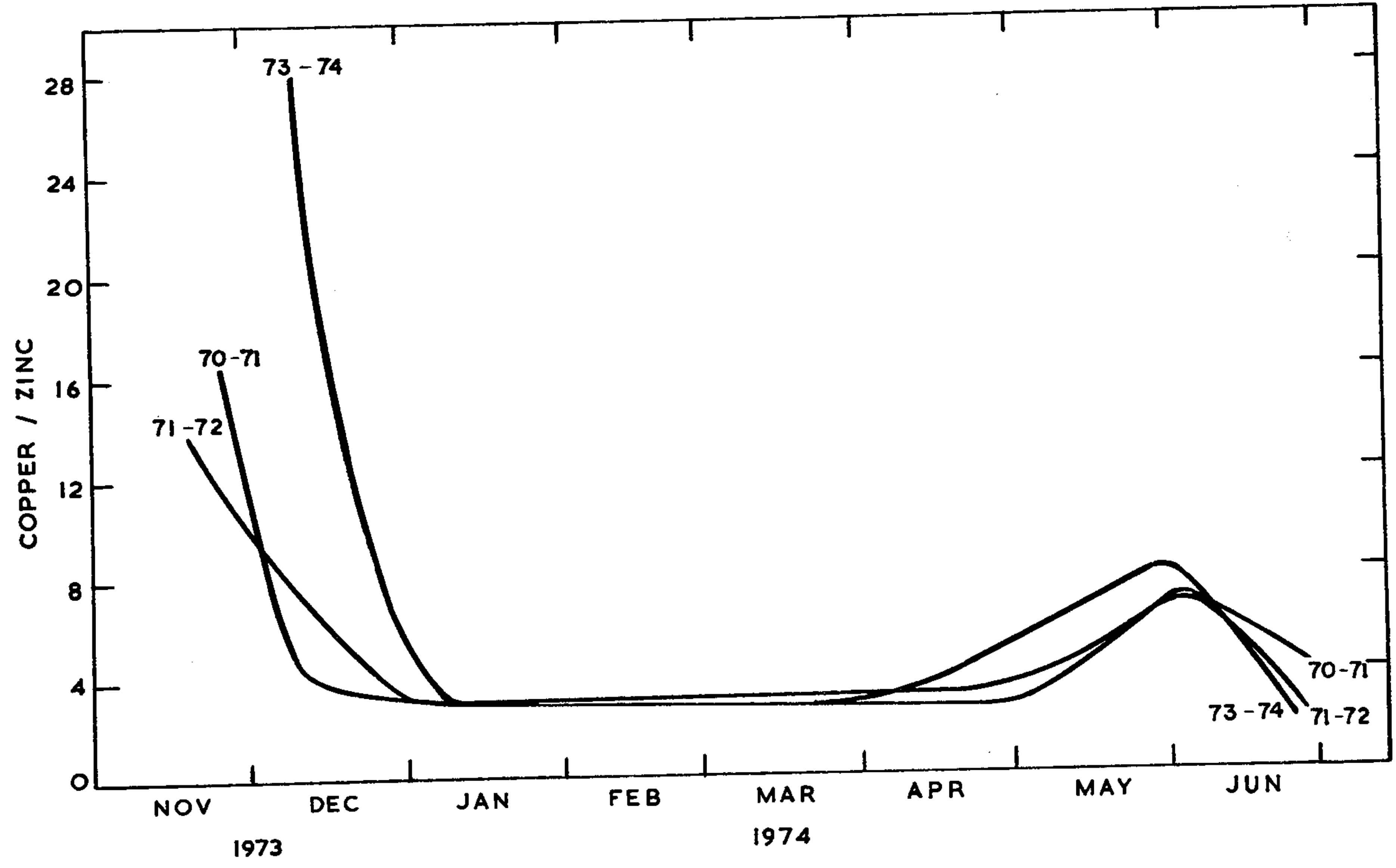
THE SEASONAL VARIATION IN THE COPPER LOAD CARRIED BY THE EAST BRANCH 1973-74

FIGURE 4.1



THE SEASONAL VARIATION IN THE Cu/Mn RATIO FOR POLLUTION OF THE EAST BRANCH

FIGURE 4.2



THE SEASONAL VARIATION IN THE Cu/Zn RATIO FOR POLLUTION OF THE EAST BRANCH

FIGURE 4.3

RUM JUNGLE ENVIRONMENTAL STUDIES

CHAPTER 5

WATER QUALITY IN THE RUM JUNGLE AREA

by

D.R. DAVY

J. JONES*

R.T. LOWSON

ABSTRACT

Percentages of contaminants entering the East Branch of the Finniss River from its polluted tributaries were determined. An assessment was made of the pollution arising from each East Branch subcatchment.

* Water Resources Branch, DNT.

CONTENTS

5. WATER QUALITY IN THE RUM JUNGLE AREA

5.1 The Plant Area

5.1.1 Introduction

The attempted determination of the quantity of pollutants entering the East Branch (EB) from each of the sources in the plant area had three components:

- An assessment of the total quantity of pollutants carried by EB during the Wet. Results are reported in Chapter 4.
- An assessment of the pollution arising from each EB subcatchment during the year; this is the subject of the present chapter.
- An assessment, in terms of basic mechanisms, of the pollution contributed by each source; this is the subject of Chapter 6.

The estimates for the source terms are deemed adequate if:

(i) within experimental error, the sum of the quantities of pollution arising from each source within each subcatchment agrees with the pollution load carried by that subcatchment; and

(ii) the sum of the pollution loads carried by each subcatchment is in reasonable agreement with the total pollution load carried by EB.

5.1.2 Sampling program

Estimates for the subcatchments are based on the analyses of samples from sites W1, W2, W3, W5, W6, W7, W17, A1, A2, A3, A4, A5 and A6 (see Map 2.4. Collection and analysis for the W series was done weekly by WRB (DNT), those in the A series irregularly by AAEC.

5.1.3 Data reduction

Mass balance for the major tributaries

The EB upstream of the railway crossing site (W17) can be thought of as consisting of three tributaries - river diversion channel, Copper Creek and Old Tailings Creek. Sampling sites W1, W2 and W3 are respectively situated at the mouth of the three tributaries; samples from these sites were routinely analysed for, amongst other things, Cu, Mn, Zn and SO_4 concentration.

If C_{ij} is the concentration of the i-th ion in the j-th stream with a volume flow V_j, and if C_{iT} is the concentration of the i-th ion at W17 where the flow is V_T then the series of simultaneous equations of the form

$$\sum_{j=1}^{n} C_{ij} V_j = C_{iT} V_T$$

can be solved to provide values of V_j/V_T, the fractional flow in each tributary, and $C_{ij} V_j/C_{iT} V_T$, the fractional pollution load carried by each tributary for each of the monitored contaminants.

This approach makes several implicit assumptions:

(i) No further pollution enters EB after the confluence of Old Tailings Creek. This assumption is obviously not true in the early part of the Wet when incrustations, bacterial oxidation of river sediments and isolated pools of polluted water are all contributing to the concentration of contaminants at site W17.

(ii) No precipitation of contaminants occurs in EB between sites W1 and W17. Information presented in Figure 4.3 and Section 3.7 indicates that this assumption does not hold after the beginning of the Dry.

(iii) No adsorption of contaminants onto suspended particulates or bottom sediments occurs. The error resulting from this assumption is not known but, on the basis of analysis of filtrates and suspended material, is believed to be small.

(iv) The streams are in a steady state.

To a large extent these errors are assessed by the data reduction process. Not infrequently the solutions were physically unreliable and were rejected e.g. individual V_js are large and negative, or $\Sigma V_j/V_T \gg$ or $\ll 1$. In fact very few cases yielded acceptable (± 10%) solutions but many more were of an intermediate nature and these are asterisked in Table 5.1 which summarises this approach.

Mass balance for particular tributaries

A series of sampling sites provide samples that are upstream of, downstream of, and in the EB tributaries Wandering Creek, Copper Creek and Old Tailings Creek. If V_1 is the volume flow of EB upstream of the tributary and C_{1i} the concentration of the i-th ion at that point, and if V_2 and C_{2i} are corresponding quantities for the tributary and if C_{3i} is the downstream concentration, then

$$\frac{V_1}{V_2} = \frac{C_{2i} - C_{3i}}{C_{3i} - C_{1i}} ;$$

and the fractional pollution load carried by the tributary is

$$C_{2i}/\left(C_{1i}\left(\frac{C_{2i} - C_{3i}}{C_{3i} - C_{1i}}\right) + C_{2i}\right) .$$

With this approach it frequently happened that the solutions for V_1/V_2 obtained from the set of ionic values contained one solution that was well removed from the average and from physical reality (e.g. ratio of the catchment areas). For these cases the average of the remaining solutions was used to calculate the fractional pollution load coming from the tributary. No doubt this means that the contributing error is still propagated but it should ensure that the error bounds are similar to the error bounds in the chemical analyses. Table 5.2 summarises the results of this approach.

Change of water quality down the river diversion channel

The quality of unpolluted water entering the river diversion channel is obtained from sampling site W7. The catchment of the Dyson's area is trivial compared to the EB catchment upstream of it so that the deterioration in water quality between W8 and W7 leads to an immediate estimate of the pollution input from the Dyson's area.

Fitch Creek has a catchment area about equal to that part of EB upstream of it. Thus to a first approximation the water flow from Fitch Creek would halve the concentration of pollutants present at W7 when measured at W5. The difference between those values and the values measured at W5 is due to pollutants carried by Fitch Creek.

The central runoff from White's overburden heap and any seepage from the cavern system joining the bed of the diversion channel to White's opencut, enter the diversion channel between W5 and W6. The deterioration of water quality between these sites is attributable to White's opencut and overburden heap.

Wandering Creek enters the diversion channel between W6 and W1; its catchment area is about 7% of that of EB upstream of it. With the assumption that the relative flows are the same as the relative catchment areas, the relative contribution of pollutants arising from the Intermediate opencut (overtopping) and the Intermediate overburden heap (runoff and seepage) can be calculated.

Table 5.3 lists the various subcatchment areas within EB system. Table 5.4 summarises the measured concentrations of pollutants down the diversion channel. The horizontally aligned figures in brackets represent the concentration of contaminants at each of the sampling sites that results, after the appropriate dilution, from the contaminants detected at upstream sampling sites. Table 5.5 is related to the column W1 of Table 5.4 and represents the percentage of each of the major pollutants that has entered the system in the diversion channel between adjacent sampling sites.

5.1.4 Results

Tables 5.1, 5.2, 5.4 and 5.5 express the amount of pollution coming from particular subcatchments as a percentage of the total pollution load. To convert these values to absolute, the flow for at least one of the sampling sites must be known.

Gauge boards were installed at W1, W2 and W3. The general shape of the rating curve for W1 was known from earlier work by WRB and was checked out with a series of 10 spot ratings during the year. The resultant curve is shown as Figure 3.12. The gauge boards at W2 and W3 were each rated twice during periods of strong flow.

The pollution load coming from each subcatchment was split into three components that arose during

- the Wet excluding days of intense rainfall,
- days of intense rainfall, and
- the Dry.

Contributions during the Wet

In 73-74 EB continued to flow strongly during April 1974 and the integrations for pollution loads were carried through to 30th April. The method of integration was similar to that described in Chapter 3 and the uncertainties in the integrations are expected to be the same as those listed there.

To obtain the contributions from the subcatchments of the diversion channel, the quantity of pollutant passing W1 was distributed amongst the subcatchment on the basis of Table 5.5.

For Copper Creek and Old Tailings Creek, three methods were used. First, the results presented in Tables 5.1 and 5.2 were applied to the pollutant load passing W1 to yield one set of estimates. For the second approach it is argued that over the Wet, each of the volume flows down Copper Creek and Old Tailings Creek relative to the volume flow down the river diversion channel will be in the ratio of the catchment areas (0.016 and 0.075 respectively). Copper Creek was rated during a period of steady rainfall and found to be flowing at 0.016 times the measured flow rate in the diversion channel at W1. For Old Tailings Creek, the agreement was much poorer, the ratio of the spot ratings (0.04) being about half the ratio of catchments (see Table 5.3). These two approaches yielded estimates varying by less than 20%, with the second approach always giving higher values.

For the third approach concurrent measurements of flow and concentrations at W1 or concurrent measurements of concentrations at locations up and downstream of the confluences of Copper Creek and Old Tailings Creek were not always available when sampling was carried out on these creeks. For those cases and for the cases where the mass balance of Section 5.1.3 gave meaningless results, an estimate of the input of pollutants was obtained from the spot rating results. The 'rating curve' was assumed to be linear on a log-log plot; the errors involved in this procedure are of course unknown. The estimates obtained were consistent with the results from the alternative methods for those cases with a complete data set; Table 5.6 summarises the results for copper inputs; Table 5.8 summarises the pollution load from each subcatchment area.

Days of intense rainfall

During the 1973-74 Wet the roadbridge had collapsed and it was not possible to drive to the site during periods of intense rain. Results for such days are therefore meagre.

As is normal practice, daily rainfall values are read at 0900 standard time and relate to the previous 24 hours. The W series of sites were never sampled before 0900 and in what follows the rainfall data is credited to the date preceding the reading date.

The one-only detailed study of a storm in the river system was on 3.3.74, when sampling and rating were carried out before, during and after an isolated storm. The observations were carried out by Lowson and Conway and the final sample was collected by WRB. The first sample was collected at 3.15 p.m. when the river was quiescent. Around 4 p.m. an intense storm developed over the mine site and detailed sampling was carried out on the White's overburden dump. A second sample was taken at 5.25 p.m. at the roadbridge after completion of the overburden dump sampling and cessation of the storm; 40 mm of rain had fallen. The river had risen 0.5 m. A further sample was collected at 7.20 p.m; 8 mm of drizzle had fallen during the intervening 2 hours. The river had now risen 2.5 m above its quiescent state, it was lapping the girders of the roadbridge and had flooded the approaches to a depth of 0.5 m. The sample was collected from midstream under the bridge. An examination of debris and vegetation the following day showed that this sample had been collected possibly at the flood peak. By 9.00 a.m. the following day the river had dropped to near normal level but no sample was collected. The final sample was collected by WRB at 10.30 a.m. on the 5th March when the river had returned to its quiescent state and only a further 1.1 mm of rain had fallen.

The results are illustrated in Figure 5.2 Maximum copper discharge occurred at 5.25 p.m., that is, after the storm but before the flood peak. Graphical integration of Figure 5.2 indicates that about 0.55 tonnes of copper was carried down the river diversion channel by this flash flood. If the quantity of copper had been assessed in terms of only the 10.15 a.m. readings, the estimate would have been about half of this.

From the rainfall data it was concluded that similar storm activity occurred on 28/1, 24/2, 8/3 and 18/3. It was assumed that for these days as well, the pollution load carried by the flash flood was twice that calculated on the basis of measurements taken on the morning following the storm. Table 5.7 lists the estimated pollution load carried by the tributaries during periods of intense rainfall.

Over and above the extrapolations to cover flash floods, Table 5.7 includes the following simplifying assumptions:

(i) 28.1.74 The pollution trend lines for late January have about the same value as those for late February. The pollution load for 28/1 was therefore set equal to that for 24/2 which had been measured.

(ii) 3-10.3.74 Three sets of results are available for this 7-day period and the pollution loads were determined by integrating the smooth curves drawn through these data points.

(iii) 18.3.74 Sampling was done on the 19th. To arrive at values for the 18/3 it was assumed that the ratios of the results for the 26/2 to the 24/2 held also for 19/3 to the 18/3.

Table 5.7 lists the estimates for each of the above periods and the subtotals are presented in Table 5.8.

Contributions during the Dry

At the end of April, flow down the river diversion channel was 0.4 $m^3 s^{-1}$ and contained 1.5, 1.7 and 0.7 mg ℓ^{-1} of copper, manganese and zinc respectively. This pollution load (0.05, 0.06. 0.02 t d^{-1}) gradually builds up to 0.24, 0.25 and 0.07 t d^{-1}, and these values were maintained through June, July and the early part of August when the channel ceased to flow. It is impossible to divide this pollution load between the various subcatchment areas of the diversion channel since the contaminated water enters the system as general seepage.

During the same period, the copper, manganese and zinc concentrations in water from Copper Creek ranged respectively from 80-25, 70-50 and 3.5-2.2 mg ℓ^{-1}. The flow weighted average concentrations were, respectively 55, 62 and 3 mg ℓ^{-1} at an average flow of 0.0014 m s^{-1}. Old Tailings Creek ceased to flow early in May. Table 5.8 summarises the pollution arising during this period.

The estimates of total contaminant losses derived in the above sections are in reasonable agreement with the estimates arrived at in Chapter 4.

5.2 Sundry Sites

5.2.1 Rum Jungle Creek South

The Rum Jungle Creek South (RJCS) orebody was located 6.5 km south of the treatment plant and 3.2 km west of Batchelor. It lay at the base of Castlemaine Hill and under part of the headwaters of Meneling Creek. Map 5.1 shows the mine site in detail and Figure 5.1 is the geological plan. The orebody occurred towards the southern end of a radiometric anomalous zone 1.2 km long which ran northwest along the base of Castlemaine Hill. The northern end of this zone was known as the Rum Jungle

Creek Prospect. The orebody was contained within a flat tabular zone, 230 m long by 46 m wide by 40 m thick. Its top surface was 30 m below ground level and coincided with the base of oxidation of the surrounding chloritic schist. The orebody was encapsulated in a highly sheared zone of chloritic schist, chloritic slate and black slates of the Golden Dyke Formation. Unlike the White's and Dyson's orebodies the RJCS orebody was not localised at a dolomite contact although dolomite was located within 60 m of the mine. Mineralisation consisted of sooty pitchblende in shears, and joints of the greyish-green pyrite chlorite schist.

The ore was recovered by opencut operation, the pit extending to a depth of 66 m below ground level. After mining the pit was allowed to fill with water to a natural depth of 62.5 m. The first 36 m of ore was recovered leaving 4 m of ore at the base of the pit. The overburden of chloritic schist, slates and black slates was dumped immediately west of the opencut. Table 2.3D lists the chemical composition of these rocks, as well as the chemical analysis of crushed and bulked samples from an auger-drill survey carried out on the overburden heap in 1968. The heavy metal content is similar to White's overburden heap with 0.013% Cu (63 t) and 0.015% U (73 t). However the sulphur concentration is low, 0.2% and bacterial leaching would not be expected to occur. Pilot plant experiments have shown that the uranium could be recovered by acid leach methods at a cost of less than \$14 kg^{-1} U_3O_8 [AAEC 1971].

The overburden heap is approximately rectangular rising to 24 m on its western wall. There is a spur on the northwest corner which used to allow vehicular access to the top of the heap. The alternative vehicular access is via a steep track from the opencut up through the centre of the heap. The top surface is concave and tilts towards the opencut forming a major runoff which drains the inner surfaces of the heap and empties into the opencut. The other surfaces drain down the outer walls to form small streams at the base of the heap and flow west to discharge ultimately into Meneling Creek.

No major streams pass through the immediate vicinity of the mine. However, the western slopes of Castlemaine Hill drain into the opencut as evidenced by a deep erosion gully on the eastern wall of the opencut. For Wets with a high rainfall as in 1973-74, the combination of runoff waters from Castlemaine Hill and the overburden heap causes the opencut to overflow at its southwest corner. The resulting stream skirts the wall of the overburden heap and discharges into Meneling Creek.

The high grade ore was transported to the treatment plant while the Bogum was stockpiled north of the opencut. During the Wets this stockpile area became awash with water flowing south to form a small stream which emptied into Meneling Creek upstream of the X20 marker. The Bogum was eventually treated between 1969 and 1971.

Meneling Creek, a permanently flowing creek about 300 m west of the overburden, receives all the surface water from RJCS area. It joins FR approximately 3 km downstream from RJCS.

A number of water sampling sites have been located in the RJCS area from time to time, although the last detailed survey was carried out in the 1969-70 Wet. This survey showed that the only serious contamination came from the stockpile area. By the end of 1971 this area had been scraped clean of ore and heavy metal contamination can be considered nil. The overburden heap is supporting a variety of grasses and is gradually becoming vegetated by natural seeding. The opencut was neither contaminated with acid nor heavy metals. The pH varied from 6.7 to 8.4 while the copper level was at the limit of detection (0.05 mg ℓ^{-1}).

5.2.2 Mount Burton

The Mount Burton orebody was located 5 km due west of the treatment plant and 200 m east of FR, see Map 5.2. There is no geological plan available for the mine. The orebody occurred in the black graphitic slates of the Acacia Gap Tongue near the contact with the Coomalie Dolomite. It occurred as a near surface deposit with torbernite at the surface, succeeded by pitchblende and pyrite at depth. Malachite, chalcocite and native copper were found in the oxidised zone. The small orebody was mined by the opencut method from the base of the north flank of a low ridge. The opencut is crescent shaped with its southern end penetrating into the ridge and its eastern end rising to the surface. The overburden was piled immediately east of the opencut and alongside Mount Burton Spring Creek, a permanently flowing spring from the dolomite bed. This spring flows alongside the north flank of the overburden heap and the north flank of an embankment separating the opencut from the creek and empties into FR ~ 200 m downstream of the mine. After mining, the opencut was allowed to fill with water to a depth of ~ 10 m.

During the Wet it overflows at its eastern end into Mount Burton Spring Creek.

The water in the opencut had a slightly alkaline pH of 8.5 due, no doubt, to the local dolomite. The water had a low or undetectable heavy metal content.

In contrast the runoff water from the overburden heap had high metal values. The maximum level found for copper was 245 mg ℓ^{-1} in February 1970 while the average value was around 60 mg ℓ^{-1}. Later in the Wet, springs would develop around the base of the overburden heap with an average copper content of 60 mg ℓ^{-1}. Both the runoff and spring water emptied into Mount Burton Spring Creek. This occasionally caused the copper concentration to rise to 0.5 mg ℓ^{-1} in FR immediately below the junction with Mount Burton Spring Creek. No quantitative data are available for the site, but the frequent spot analyses for the area during 1969-70 suggest that this abandoned mine site is causing some pollution to the local environment.

5.2.3 Mount Fitch

The Mount Fitch Prospect is a uranium orebody about 8 km northwest of the treatment plant. A low grade deposit was identified in the dolomite zone of the embayment with minor higher grade lenses in the overlaying slate. The orebody was exposed by opencut mining but not excavated.

The site is close to an old copper mine which has since been covered over by exploration. The opencut is situated on the brow of a ridge and the overburden was dumped immediately below it on top of a stream. Following abandonment of the orebody, the pit was allowed to fill with water. In March 1970 and November 1973 this water was innocuous, and in fact fish were observed in the opencut during the last visit even though the opencut is completely isolated from all flowing waters.

TABLE 5.1

PERCENTAGE OF CONTAMINANTS ENTERING THE EAST BRANCH FROM THE POLLUTED TRIBUTARIES

Date 1974	Diversion channel			Copper Creek			Old Tailings Creek		
	Cu	Mn	Zn	Cu	Mn	Zn	Cu	Mn	Zn
18/12	39	28	91	44	41	5	17	31	3
8/1	76	69	98	13	26	2	11	5	0
26/2	59	50	95	28	26	3	11	22	2
5/3*	53	42	100	46	57	0	1	1	0
16/3*	52	40	100	48	60	0	0	0	0
2/4	72	49	100	26	42	0	1	9	0
9/4*	40	31	100	59	64	0	0	5	0
16/4*	33	33	100	67	67	0	0	0	0
23/4	35	27	100	65	64	0	0	9	0
30/4*	26	35	100	74	66	0	0	0	0

* *Near 'solutions' that failed to meet criteria (see text).*

TABLE 5.2

INSTANTANEOUS PERCENTAGE OF CONTAMINANTS ENTERING THE EAST BRANCH FROM POLLUTED TRIBUTARIES REGARDED AS LINE SOURCES †

Date 1974	Wandering Creek			Copper Creek			Old Tailings Creek		
	Cu	Mn	Zn	Cu	Mn	Zn	Cu	Mn	Zn
21/2	15	4*	58	42	53	0	35	26	0
28/2	18	6*	64	56	34	0	0	23	0
8/3	25	8*	71	3	7	0	57	52*	0
10/3			48						
19/3							0	39	0
2/4				24	51	0	0	0	0
9/4				51	54	0	0	19	0
16/4				72	55	0	0	23	0
23/4				68	62	0	0	0	0
30/4				68	56	0	0	12	0
7/5				58	59	0	0	7	0
14/5				41	50	0	0	0	0
21/5				27	38	0	0	0	0

* *Flow calculated from related measurements exceeded that from either of the other variable. These figures are calculated for a flow equal to the average of the two other determinations.*

† *The average of the flow rates calculated for and then subsequently used in this table were:*

Wandering Creek	:	*10% (range 7-14%)*
Copper Creek	:	*2.5% (range 0.2-5%)*
Old Tailings Creek	:	*11% (range 7-18%)*

TABLE 5.3A

AREAS OF THE EAST BRANCH SUBCATCHMENT

Drainage System	Area (ha x 10^{-2})
(1) Upper East Branch	23.3
(2) Fitch Creek	21.5
(3) Wandering Creek	3.3
(4) Old Tailings Creek	3.0
(5) Weir - confluence	14.3

Increase in flow of East Branch between Old Tailings Creek and railway bridge : 11%

Increase in flow of East Branch between Old Tailings Creek and weir : 18%

TABLE 5.3B

RATED DISCHARGE RATIOS

Date 1974	Diversion channel	Copper Creek		Old Tailings Creek	
	Rating (m^3 s^{-1})	Rating (m^3 s^{-1})	Ratio	Rating (m^3 s^{-1})	Ratio
24/2	7.1	0.11	0.015	0.22	0.031
21/3	22.0	0.34	0.015		
8/3	12.7			0.422	0.033

TABLE 5.4

CONCENTRATION ($mg\ \ell^{-1}$) AND INFERRED MATERIAL BALANCE OF HEAVY METALS ALONG THE DIVERSION CHANNEL

SAMPLING SITE

Date 1974	W7			W5			W6			W1		
	Cu	Mn	Zn	Cu	Mn	Zn	Cu	Mn	Zn	Cu	Mn	Zn
8/1	0.5	1.3	< 0.1	(0.3) 1.6	(0.7) 1.8	0.6	(0.3) (1.3) 1.4	(0.7) (1.1) 1.6	(0.6) 0.7	(0.28) (1.2) (0) 2.4	(0.65) (1.05) (0) 1.7	(0.56) (0.1) 1.2
22/1	< 0.1	0.4	< 0.1	< 0.1	(0.2) 0.3(0.1)	0.1(0.1)	0.1	(0.2) (0.1) 0.4	(0.1) 0.2	0.1 0.5	(0.2) (0.1) (0.1) 0.4	(0.1) (0.1) 0.4
7/2	<0.1	0.4	< 0.1	<0.1	(0.2) 0.8	0.1	0.7	(0.2) (0.6) 0.6	(0.1) 0.4	(0.7) 1.5	(0.2) (0.6) 0.9	(0.1) (0.3) 0.8
12/2	< 0.1	0.3	< 0.1	< 0.1	(0.16) 0.5	0.1(0.1)	0.3	(0.16) (0.34) 0.5	(0.1) 0.4	(0.3) 0.7	(0.16) (0.34) 0.6	(0.1) (0.3) 0.6
19/2	0.2	0.6	< 0.1	(0.1) < 0.1	(0.3) < 0.1	< 0.1	(0.1) 0.6	(0.3) 0.4	0.4	(0.1) (0.5) 0.8	(0.3) (0.1) 0.8	(0.4) 0.5
27/2	0.2	1.1	< 0.1	(0.1) 0.2	(0.6) 0.8	< 0.1	(0.1) (0.1) 0.7	(0.6) (0.2) 0.6	0.7	(0.1) (0.1) (0.5) 0.9	(0.6) (0.2) 0.7	(0.7) 0.5
5/3	0.1	0.8	< 0.1	(0.05) 0.1	(0.4) 0.9	0.1	(0.05) (0.05) 0.4	(0.4) (0.5) 0.8	(0.1) 0.3	(0.05) (0.05) (0.3) 1.0	(0.4) (0.5) 0.7	(0.1) (0.2) 0.5
12/3	0.3	1.3	< 0.1	(0.15) 0.1	(0.65) 0.8	< 0.1	(0.15) 0.6	(0.65) (0.15) 0.7	0.5	(0.15) (0) (0.45) 1.0	(0.65) (0.15) 0.7	(0.5) 0.6
19/3	< 0.1	0.6	< 0.1	0.2	(0.3) 0.2	< 0.1	(0.2) 0.1	(0.3) 0.1	0.1	(0.2) 0.4	(0.3) 0.2	(0.1) 0.3
26/3	< 0.1	0.4	< 0.1	<0.1(0)	(0.2) 0.7	0.1	0.1	(0.2) (0.5) 0.3	(0.1) 0.2	(0.1) 0.1	(0.2) (0.5) 0.5	(0.1) (0.1) 0.5
2/4	< 0.1	0.5	< 0.1	0.4(0.4)	(0.25) 0.7	< 0.1	(0.4) 0.2	(0.25) (0.35) 0.6	0.2	(0.4) 1.0	(0.25) (0.35) 0.5	(0.2) 0.5
9/4	< 0.1	0.5	< 0.1	< 0.1	(0.25) 0.6	< 0.1	0.3	(0.25) (0.35) 0.4	0.2	(0.3) 0.9	(0.25) (0.35) 0.7	(0.2) 0.5
16/4	< 0.1	0.4	< 0.1	< 0.1	(0.2) 0.4	0.1	< 0.1	(0.2) (0.2) 0.6	(0.1) 0.1	0.9	(0.2) (0.2) (0.2) 0.9	(0.1) 0.5
23/4	< 0.1	0.5	< 0.1	0.4	(0.25) 1.0	0.2	(0.4) 0.2	(0.25) (0.75) 0.4	(0.2) 0.1	(0.4) 1.3	(0.25) (0.75) 1.1	(0.2) 0.5
30/4	< 0.1	0.6	< 0.1	0.8	(0.3) 1.0	0.5	(0.8) 0.4	(0.3) (0.7) 1.0	(0.5) 0.3	(0.8) 1.5	(0.3) (0.7) 1.7	(0.5) 0.7
7/5	< 0.1	0.4	< 0.1	0.5	(0.2) 0.9	0.4	(0.5) 0.8	(0.2) (0.7) 1.0	(0.4) 0.5	(0.5) (0.3) 2.0	(0.2) (0.7) (0.1) 2.1	(0.4) (0.1) 0.9
14/5	< 0.1	2.0	< 0.1	1.2	(1.0) 1.7	0.9	(1.2) 1.6	(1.0) (0.7) 1.7	(0.9) 0.9	(1.2) (0.4) 5.0	(1.0) (0.7) 5.0	(0.9) 1.7
21/5	0.1	4.7	0.2	(0.05) 2.5	(2.4) 3.0	(0.1) 1.8	(0.05) (2.5) 4.4	(2.4) (0.6) 3.8	(0.1) (1.7) 2.2	(0.05) (2.5) (1.9) 8.8	(2.4) (0.6) (0.8) 9.6	(0.1) (1.7) (0.4) 2.4

TABLE 5.5

PERCENTAGES OF HEAVY METAL CONTAMINANTS TRANSPORTED DOWN THE DIVERSION CHANNEL THAT ENTER BETWEEN LISTED SAMPLING SITES

Date 1974	W8 - W7			W7 - W5			W5 - W6			W6 - W1		
	Cu	Mn	Zn	Cu	Mn	Zn	Cu	Mn	Zn	Cu	Mn	Zn
8/1	12	38	0	50	62	50	0	0	0	38	0	50
22/1	~5	50	0	~5	25	50	0	0	0	>80	25	50
7/2		23	0		67	12		0	38		10	50
12/2	0	27	0	0	57	17	57	0	50	43	16	33
19/2	12	38	0	0	0	0	63	12	80	25	50	20
27/2	11	75	0	11	0	0	55	25	100	23	0	0
5/3	5	50	0	5	50	20	30	0	40	60	0	40
12/3	15	81	0	0	19	0	45	0		40	0	
19/3	0	100	0	50	0	0	0	0	33	50	0	67
26/3	0	30	0	0	70	20	100	0	20	0	0	60
2/4	0	42	0	40	58	0	0	0	40	60	0	60
9/4	0	42	0	0	58	0	35	0	40	67	0	60
16/4	0	22	0	0	22	0	0	22	20	100	34	80
23/4	0	25	0	31	66	40	0	0	0	69	9	60
30/4	0	18	0	53	42	70	0	40	0	47	40	30
7/5	0	10	0	25	33	44	15	5	11	60	62	45
14/5	0	20	0	24	14	53	8	0	0	68	66	47
21/5	0	25	4	28	6	70	22	8	17	50	60	8

TABLE 5.6

COMBINED COPPER DISCHARGE RESULTS

Date 1973-4	Discharge g s^{-1}			%		
	Road-bridge	Copper Creek	Old Tailings Creek	Road-bridge	Copper Creek	Old Tailings Creek
18/12	30.56	33.8	13.32	39	44	17
8/1	6.24	1.06	0.9	76	13	11
22/1	2.3	3.2	0.3	40	55	5
5/2		7.1	2.0			
6/2	5.25					
12/2	2.31	2.6	0.22	45	51	4
19/2	2.92					
21/2	2.28	0.34	0.24	78	12	10
24/2	2.98	6.3	0.57	30	64	6
26/2	3.60	1.7	0.67	59	28	11
28/2	3.36	0.32	0.20	86	8	6
3/3	3.96	0.5	0.14	86	11	3
3/3	36.08					
3/3	22.61					
5/3	4.1	3.6	0.08	53	46	1
8/3	16.25	2.0	3.04	76	9	15
12/3			0.35			
19/3	2.08	2.4	0.05	46	53	1
21/3		12.94				
22/3			0.675			
23/3	8.46	1.1	0.27	86	11	3
26/3	0.47					
2/4	3.55	1.8	0.100	65	33	2
9/4	3.15	4.7	0.030	40	59	1
16/4	1.98	4.02	0.0032	33	67	0
23/4	2.47	4.6	0	35	65	0
30/4	3.0	8.5	0	26	74	0

TABLE 5.7

POLLUTION LOAD (TONNES) FROM EACH SUBCATCHMENT AREA OF THE EAST BRANCH DURING PERIODS OF INTENSE RAINFALL

Date 1974	Rainfall mm	Flow at roadbridge m^3s^{-1}	Flow at gauging station m^3s^{-1}	Subcatchment area						
				Diversion channel			Copper Creek		Old Tailings Creek	
				Cu	Mn	Zn	Cu	Mn	Cu	Mn
28/1	70.2		263	0.42	0.72	0.54	0.98	0.76	0.16	0.26
24/2	69.4	210		0.21	0.36	0.27	0.49	0.38	0.08	0.13
25/2	0.4			0.22	0.27	0.2	0.35	0.29	0.05	0.09
26/2	0	105		0.23	0.18	0.13	0.22	0.20	0.03	0.06
3/3	97.4			0.48	0.34	0.28	0.28	0.3	0.04	0.1
4/3	0.2	86		0.26	0.18	0.13	0.2	0.28	0.02	0.05
5/3	71.0	110		0.27	0.19	0.13	0.26	0.47	0.02	0.05
6/3	25.2		1131	0.52	0.3	0.12	(0.4)	0.5	0.16	0.09
7/3	38.4			0.88	0.52	0.22	0.64	0.61	0.3	0.14
8/3	62.2	400		2.42	1.5	1.0	2.0	1.3	0.9	0.4
18/3	97.8			0.3	0.3	0.5	0.8	0.8	0.2	0.2
19/3	34.2	150	3310	0.15	0.07	0.12	0.17	0.20	0.04	0.05
Subtotals				6.4	4.9	3.6	6.8	6.1	2.0	1.6

TABLE 5.8

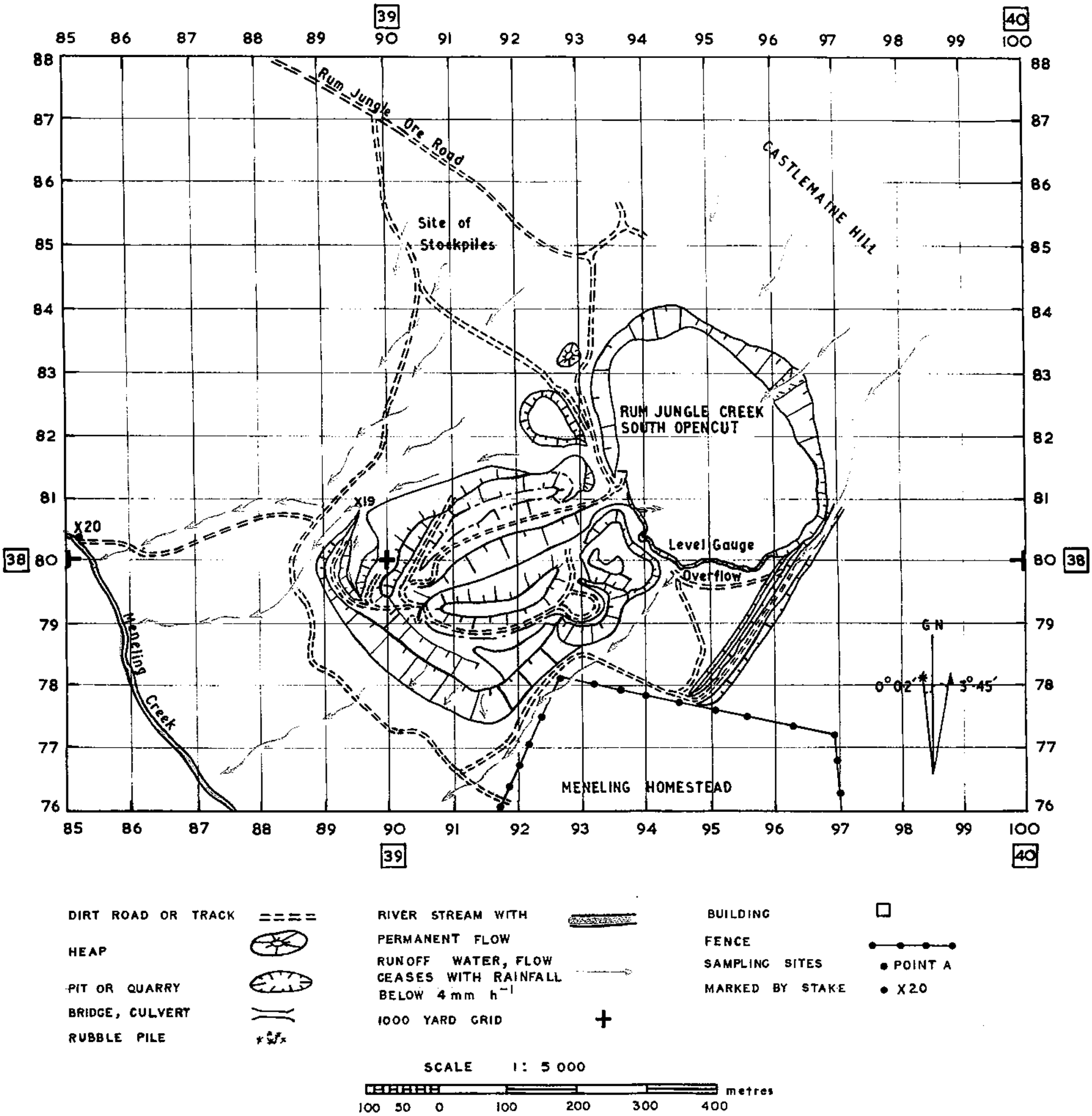
POLLUTION LOAD FROM EACH SUBCATCHMENT AREA OF THE EAST BRANCH (TONNE)

Wet season (November - April) other than days of intense rainfall						
Pollutant	Subcatchment area					Total
	Diversion channel			Copper Creek	Old Tailings Creek	
	Dyson's area	White's area	Intermediate area			
Cu	3	12	16	25	4	60
Mn	10	10	2	21	6	49
Zn	0	8	9	0	0	17

Days of intense rainfall				
Pollutant	Subcatchment area			Total
	Diversion channel	Copper Creek	Old Tailings Creek	
Cu	6.4	6.8	2.0	15
Mn	4.9	6.1	1.6	13
Zn	3.6	0	0	4

Dry season				
Pollutant	Subcatchment area			Total
	Diversion channel	Copper Creek	Old Tailings Creek	
Cu	19	0.5		20
Mn	20	0.5		21
Zn	5.2			5

1:5000 Drawn by R.T. Lowson April 1974



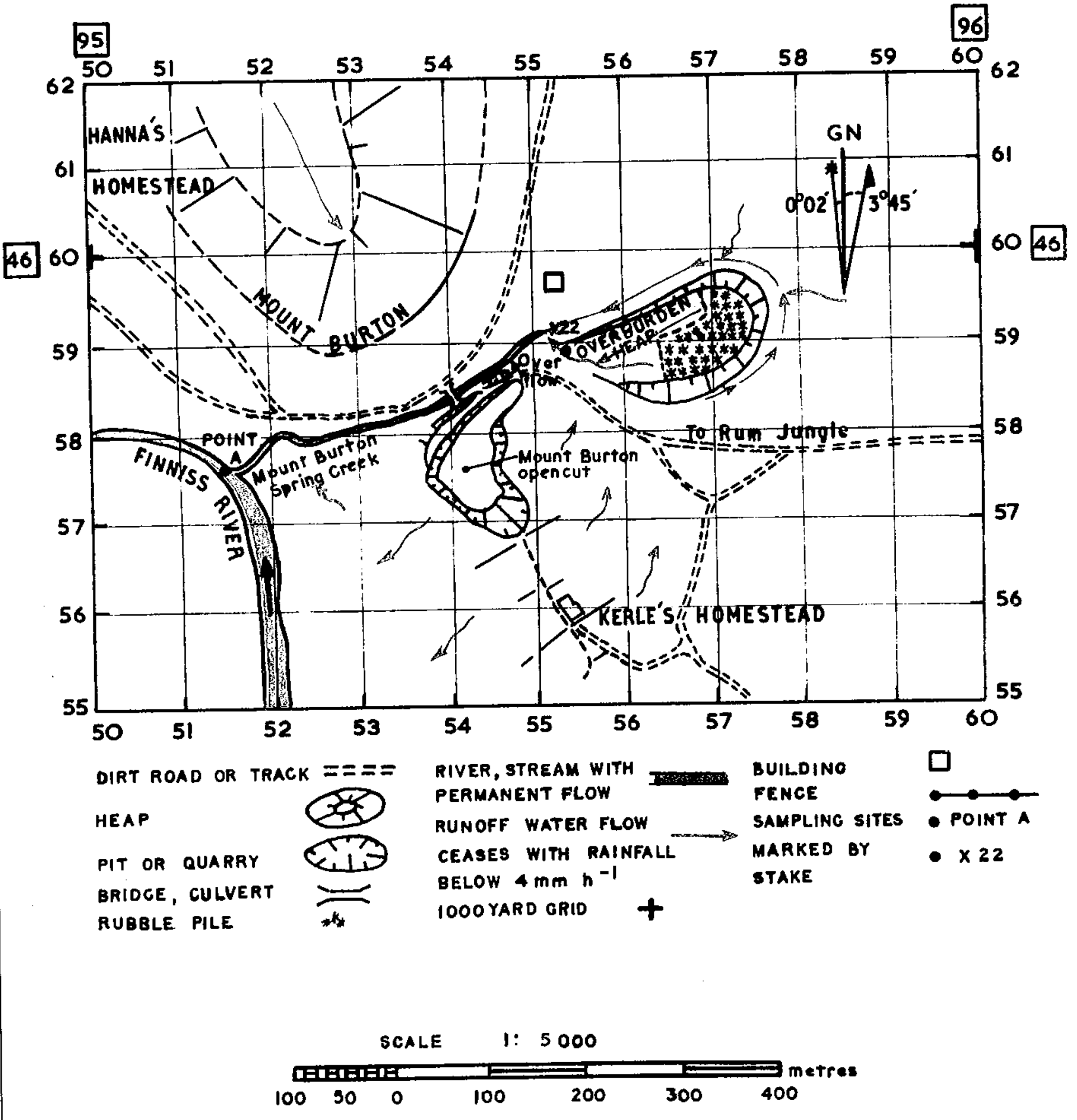
FOR A DESCRIPTION OF THE GRID AND GRID REFERENCING
REFER TO 1:5000 MAP OF THE RUM JUNGLE MINE

RUM JUNGLE CREEK SOUTH MINE

MAP 5.1

1:5000

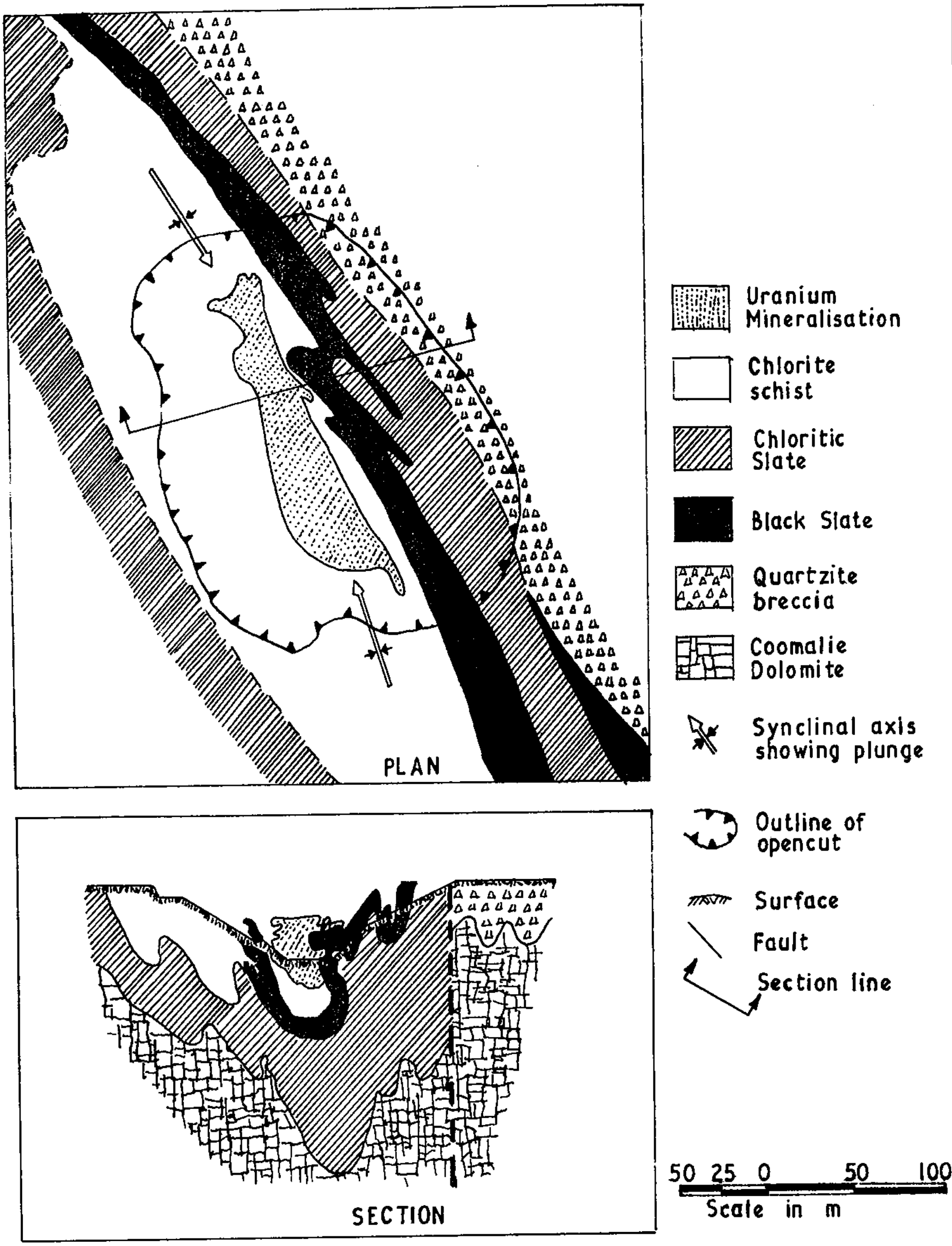
Drawn by R.T.Lowson April 1974



FOR A DESCRIPTION OF THE GRID AND GRID REFERENCING REFER TO 1:5000 MAP OF THE RUM JUNGLE MINE

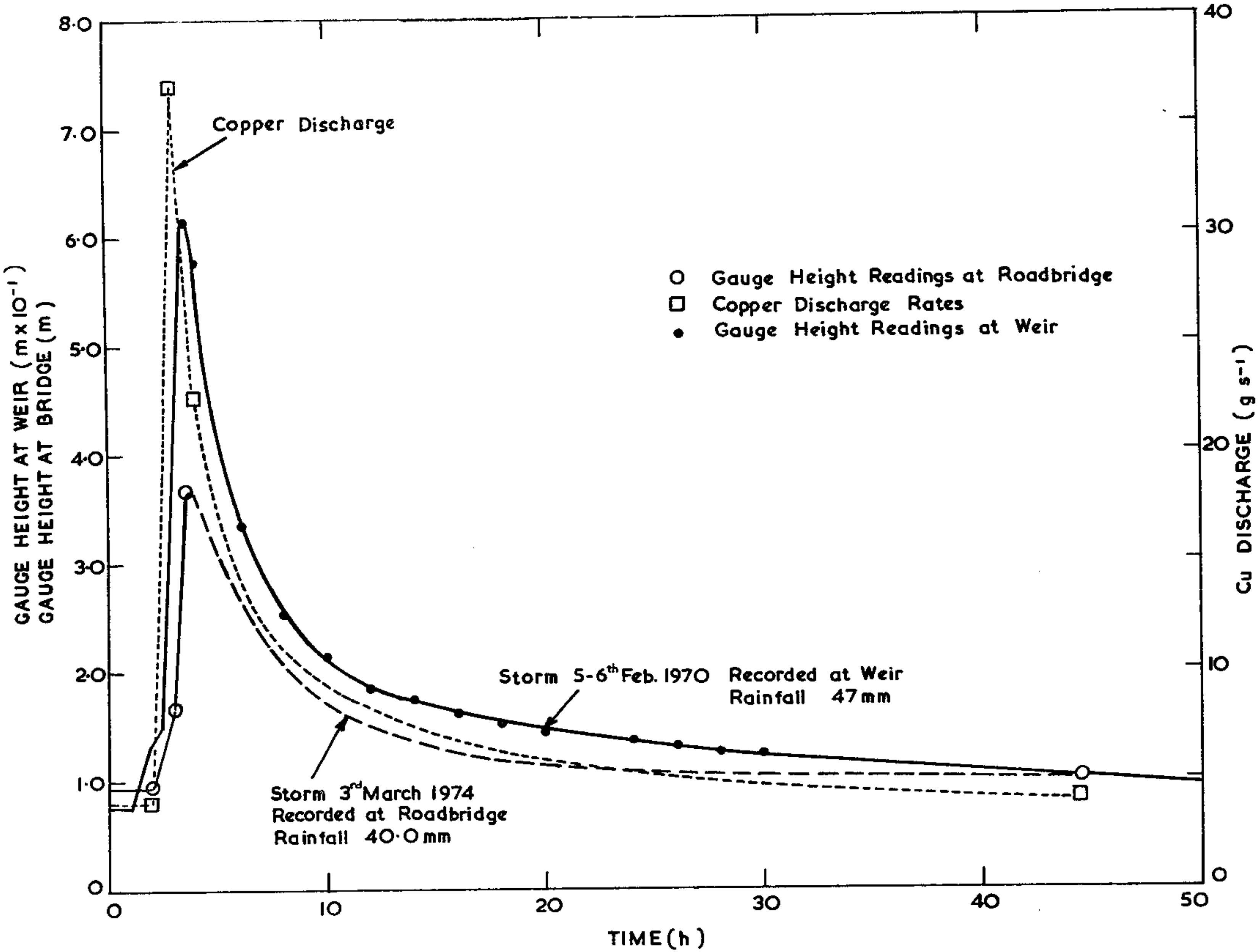
MOUNT BURTON MINE

MAP 5.2



GEOLOGY OF RJCS MINE

FIGURE 5.1



COPPER DISCHARGE FOR STORM 3.3.74.

FIGURE 5.2

RUM JUNGLE ENVIRONMENTAL STUDIES

CHAPTER 6

SOURCES OF POLLUTION

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ABSTRACT

Rainwater falling on overburden heaps provides three sources of pollution to the East Finniss River system. Estimates are made of the contribution of these three sources and these are summed to give the total burden presented to the river system. Estimates are also made of contribution of heavy metals from the seepage and overtopping of opencuts.

CONTENTS

(continued)

CONTENTS (continued)

6. SOURCES OF POLLUTION

6.1 Overburden Heaps

Rain falling on the heaps finds its way into the East Branch (EB) system by one of three ways:

(i) water which passes through the heaps and appears as springs at the base of the heaps,

(ii) water which runs off the surface into runoff channels, and

(iii) water which passes through the heaps and into the local groundwater.

As the ion concentrations and the time dependence of water flow are markedly different for water following these three routes, separate estimates will be made of the heavy metal burden contributed by these three sources and these summed to give the total burden presented to the river system.

6.1.1 Spring water

Well defined springs appear at the base of the east wall of White's overburden heap (see Figure 6.1) and at the base of the south wall and at the northeast corner of Dyson's overburden heap (see Figure 6.3) during the Wet and continue to flow well into the Dry. There is no measureable spring flow from the Intermediate heap except immediately after a heavy storm. Similarly, spring flow of short duration appears at various points around White's and Dyson's heaps after heavy rain.

White's springs

The discharge rates and ion concentrations of the major springs were measured on March 7 and 19, 1974; the results are given in Table 6.1. The spring labelled 4 in Figure 6.1 was gauged at approximately weekly intervals from March 7, 1974, until flow became negligibly small in mid-July. The discharge rate of this spring is shown as a function of time in Figure 6.4 where it can be seen that the time dependence has a simple exponential form over most of the discharge period. The time constant (e folding time) is about 49 days which is long compared to the time between rainstorms (~ every 2 days). It is therefore reasonable to consider the rainfall input to the spring as a step function in time, starting in December and finishing in mid-March. Under these assumptions the time dependence of the spring flow during the Dry will be of the form

$$d(t) = R[1-\exp(-\lambda T)]\exp[-\lambda(t-T)] \qquad ...6.1$$

where T = the time duration of the rainfall period, and

R = the quantity of the rainfall that feeds the spring.

From the shape of the discharge curve given in Figure 6.4 it is again reasonable to take the end of the rainfall period as March 19. With this assumption, equation 6.1 can be integrated analytically to give a total discharge during the Dry of $6.24 \times 10^3 m^3$. With the additional assumption that the rainfall period is 109 days (i.e. starts on December 1) the discharge during the Wet becomes $10.2 \times 10^3 m^3$ giving a total flow from spring 4 of $16.4 \times 10^3 m^3$.

The discharge from the other springs decreased much more rapidly than that of spring 4 so that by mid-April spring 4 was the only measurable source of spring water on White's overburden heap. The changing ratios of discharge rate were not measured so that there is no reliable method of estimating the total spring discharge from the discharge of spring 4. If, however, the time dependence of the other springs is also exponential, then the annual discharge (Wet + Dry) from the n-th spring will have the form

$$O = O_W + O_D = R_n T - R_n[1-\exp(-\lambda_n T)]\exp[-\lambda_n(t-T)]\lambda_n^{-1}$$

where t = time measured from start of Wet,.

λ_n = decay constant of the n-th spring, and

R_n = rainfall fraction that feeds that spring.

If we now assume that $\exp(-\lambda_n T)$ and $\exp[-\lambda_n(t-T)]$ are both small for all springs, then the ratio of the annual discharges from the springs is just the ratio of discharges at peak flow, which we can take as that measured on March 19, 1974. Annual spring flow discharges based on this assumption are given in Table 6.2.

During the period March to July the ion concentrations measured in spring 4 were time independent, allowing the estimates shown in Table 6.2 to be made for the total copper ion burden presented to the river system by this spring during the Dry. If it is assumed that similar copper concentrations held during the Wet, then the estimates given in Table 6.2 can be made for the Wet and for total copper ion burden presented by spring 4. If it is further assumed that the copper concentrations of the other springs have the same relationship to spring 4 throughout the year as they had on March 19, then the estimates given in Table 6.2 can be made of the total copper burden presented to the river system by spring water from White's overburden heap. It should be noted here that copper ion concentrations determined at Darwin by AAEC, were about 30% lower than the values determined by the AAEC at the Research Establishment, Lucas Heights. The values given in Table 6.2 are those determined at Lucas Heights.

Dyson's springs

Figure 6.5 shows the discharge rate as a function of time for the four major springs on the south wall of Dyson's overburden heap. It can be seen that the time dependence of these springs is more complex than that of White's spring and it is necessary to estimate the total discharge during the Dry by numerical integration of the data. Obtaining estimates of discharge during the Wet presents more of a problem. It can be seen from Figure 6.5 that the discharge rates from all four springs have a similar, relatively rapid decay rate at the early part of the Dry and that the time constant of this decay is about 18 days, which is again long compared to the time between rainstorms. If we assume that the discharge is dominated by this relatively rapid decay rate (λ), then the ratio of total discharge in the Wet (O_W) to that in the Dry (O_D) is

$$O_W/O_D = \lambda(T - [\frac{1-\exp(-\lambda T)}{\lambda}])/([1-\exp(-\lambda T)][1-\exp(-\lambda T_1)])$$

where T = the duration of the rainfall period, and

T_1 = time from the end of the rainfall period until the spring dries up.

Since both $T \sim 107$ days and $T_1 \sim 110$ days are long compared to λ^{-1}

$$O_W/O_D \sim \lambda T-1 = 5 \quad .$$

This will give an upper estimate of the spring flow during the Wet.

Table 6.2 shows estimates of the Dry discharge, total discharge and the corresponding copper ion burden presented to the river system by spring water discharge from Dyson's heap. It can be seen that the contribution from Dyson's is small compared to that from White's (~ 10%) and for this reason an accurate estimate is not required.

6.1.2 Runoff

Much less reliable estimates can be made of the annual discharge of runoff water and the metal burden presented to the river system by this source. The reasons for this are the considerable variation in ion concentrations (by up to two orders of magnitude) in samples of runoff water taken from the heaps at different times and the paucity of information on discharge rates of water down the principal runoff channels. The available data consist of:

(i) a number of spot measurements carried out in the 1969-70 Wet,

(ii) a measurement on each of the heaps of the discharge rates and ion concentrations as a function of time throughout a 'typical' rainstorm in 1974, and

(iii) a measurement of the variation in ion concentrations at different points on the surface of each of the heaps during a 'typical' rainstorm in 1974.

Figures 6.6, 6.7 and 6.8 show the time dependence of water discharge and copper concentration in the discharge for the principal runoff channels on White's, Intermediate and Dyson's heaps during rainstorms in 1974 on March 3, 7 and 10. Further data are given in Tables 6.3, 6.4 and 6.5. These data allow estimates to be made of the mass flow of copper as a function of time and the total water discharged as runoff during the storm. Estimates of the total mass of copper presented to the river system as a result of a storm depend very much on estimates of when flow ceased, since the conditions of high concentration and low discharge at the end of the storm lead to significant discharges of copper. For example, the rainstorm of March 3, 1974 on White's heap stopped at about 1800 hours and the runoff discharge had fallen to 1% of its peak value by 1910 hours. The total weight of copper carried away by that time was about 2.2 kg and the total discharge about 1.86 x $10^3 m^3$. If, however, the copper discharge curve is extrapolated to 0900 hours the next day (see, for example, Table 6.3B), the total weight of copper discharge is 5.7 kg and the water discharge 2.3 x $10^3 m^3$. These give estimates of 1.2 and 2.5 mg ℓ^{-1} for the average copper concentration associated with runoff from White's heap after a 'typical' storm.

Similar processes applied to the 1974 rainstorm measurements on Intermediate and Dyson's overburden heaps lead to estimates of 18 mg ℓ^{-1} and 0.2 mg ℓ^{-1} for the average concentration of copper in runoff water. The discharge present in Dyson's principal runoff channel at long times after rainfall (see Table 6.5) indicates that some of the water flow is due to seepage. However, since the total copper burden presented by Dyson's heap is small compared to the other two heaps, this systematic error should not alter significantly the estimates of the total copper burden from the overburden heaps.

Tables 6.6, 6.7 and 6.8 show the ion concentrations in runoff water at different points on the three heap surfaces during a 'typical' storm. These data indicate overall that the metal ion concentration does not build up as the water runs down the surface of the heap. In this sense, the positions down the runoff channel at which the runoff is sampled, do not greatly influence ion concentration measurements. The few high values in Tables 6.6, 6.7 and 6.8 are probably due to local concentrations of pyrites on the surface close to where the measurements were made. To this extent spot measurements can give misleading results.

The spot measurements of ion concentrations carried out from December 1969 to March 1970 provide another means of estimating ion concentrations associated with runoff water. Table 6.9 shows that there is no obvious trend in the ion concentration throughout the year; hence the results can be averaged to give a concentration associated with runoff water during the year. These averages are given in Table 6.9.

The copper concentrations obtained from 'typical' storm estimates are significantly lower than those obtained from yearly averages. This difference can be explained in part by reference to Figures 6.6, 6.7 and 6.8 which show that measurements taken past the peak discharge, yield concentrations higher than the average for the storm; the longer the time after the peak, the higher the concentration. However, the disparity should not be greater than a factor of ten since the bulk of measurements taken in 1969-70 were taken during or shortly after a storm. The disparity could indicate a change in surface characteristics of the heap between 1969-70 and 1974, but for the moment the two sets of values will be used to provide low and high copper burden estimates.

In order to obtain total burdens from average ion concentrations, some estimate of the total runoff water discharge is required. Again, there are at present insufficient data to allow reliable estimates to be made. Measurements of runoff discharge and rainfall in the 'typical' storms of 1974 lead to runoff fractions of 30, 60 and 125% of incident rainfall for White's, Intermediate and Dyson's heaps. The high figure for Dyson's indicates that insufficient consideration has been made for seepage contribution. In estimating total copper burdens, 50 and 25% runoff fractions will be used to obtain some idea of the range of burdens to be expected.

6.1.3 Groundwater

No direct measurements have been made of the rate of flow of groundwater and only one measurement has been made of the quality of groundwater in the vicinity of the overburden heaps. This measurement was made on March 15, 1970 at a point (grid ref. 039374) ~ 250 m west of White's heap, where water was seeping out of the ground. The table below indicates water quality similar to two springs on the east wall of White's heap.

	Concentration mg ℓ^{-1}			
	Co	Cu	Mn	Ni
Spring A	55	125	43	53
Spring B	45	100	42	36
Seepage	25	70	46	22

Springs A and B were located close to the positions of springs 4 and 5 detailed above, but could not positively be identified as the same springs. Observations in the Dry indicate that there is seepage into the diversion channel near Intermediate heap and into Fitch Creek and the diversion channel near White's heap.

It is reasonable then to assume that the ion concentrations in the water passing into the local groundwater from the overburden heaps is the same as that in the spring water which appears at the base of the heaps. It is also reasonable to assume that the metal burden passed onto the groundwater is, in turn, passed on to the EB since, although ion exchange mechanisms could take place between soil and water, such a process is now likely to be in equilibrium. Since there are few data on spring water ion concentrations for the Intermediate heap, the ion concentrations used for groundwater from this heap were taken to be those derived from averaging the 1969-70 runoff concentrations.

The accuracy of this method can be judged from the fact that when it is applied to White's heap, which has a similar composition to the Intermediate heap, the estimated ion concentrations are about 30% below the measured spring water ion concentrations.

The quantity of water passed through to the groundwater follows from a balance between rainfall, evaporation, evapotranspiration, spring water, runoff and groundwater. Since there is little or no vegetation, evapotranspiration will be small. Evaporation will have most impact on runoff estimates, leading to underestimates of the rainfall fraction that follows this route. However, since estimates of runoff discharge are of doubtful accuracy and in the Wet, evaporation rates are only ~ 0.3 mm h^{-1}, loss by evaporation has been neglected.

6.1.4 Total metal burden from the overburden heap

Since from the above discussion, it is clear that at this time there are no reliable data to indicate how rain falling on the heap is apportioned between spring, runoff and groundwater, the total metal burden will be estimated on the assumption that the runoff fraction is either 25 or 50% of the incident rainfall. The rest of the water will pass to the river system, either as spring water or as groundwater, but these will be treated as indistinguishable.

It is also clear that the data presently available are not sufficient to provide estimates of well defined accuracy for the average metal ion concentrations associated with either runoff water or spring and groundwater when the annual metal burden presented to the river system is being calculated. The approach adopted has been to estimate average values which appear reasonable based on available information and, where possible, to indicate the variation that occurs in these average values when the assumptions used in evaluating the data are changed. It is considered that this approach, when applied consistently to the three overburden heaps, should indicate the relative magnitudes of the heaps as sources of pollution. If further, the metal burdens from the three heaps when added to those from other individual sources such as opencuts, are consistent with total metal burdens from the subcatchment areas (Chapter 5) and with totals from the whole EB (Chapter 4) then some confidence can be placed in these estimates of the burdens when comparing the overburden heaps as sources of pollution with other sources, such as the opencuts, tailings dams, etc.

Estimates of the average copper concentrations used to evaluate the total copper burdens presented to the EB from the three overburden heaps in 1973-74 are given in Table 6.10. The value for spring and groundwater for White's heap is a weighted average of the concentrations in the major springs measured on that heap on March 19, 1974. Similarly, the copper concentration value for spring and groundwaters from Dyson's heap is a weighted average of concentrations from the four main springs on that heap that flowed during the 1974 Dry. Since measurements on spring water from these two heaps showed little variation in concentration throughout the Dry, some confidence can be placed in these average values when applied to dry season flow and it does not seem too unreasonable to expect little change in metal ion concentrations during the Wet. The value for spring and groundwater for the Intermediate heap was derived as indicated in Section 6.1.3 above.

Two values are given in Table 6.10 for the copper concentrations associated with runoff water. The low values are derived from measurements made during 'typical' storms in 1974 and the high values from a number of spot measurements made on runoff water during the 1969-70 Wet. The copper burdens in runoff as given by the low values, are credible to the extent that each of these storms was, in fact, typical of all rain storms. On the other hand, the copper burdens given by the high values are credible to the extent that measurements taken throughout the year showed no significant trend and could be taken as samples distributed about the mean values given in Table 6.9. It should be noted that use of average values derived from spot measurements assumes not only that there is no trend throughout the year, but also that there is no trend throughout a storm. Figures 6.6, 6.7 and 6.8 show this latter assumption is not valid, but since the samples were taken when there was significant flow in the runoff channels, the sample value is not likely to be more than a factor of ten larger than the correct value for that particular storm. The major objection to the use of these average values could be the application of data taken in 1969-70, when the rainfall was well below average (~ 0.9 m), to 1973-74 when the rain fall was well above average (~ 2.0 m).

Estimates of the derived copper burden presented to the East Branch based on the above assumptions concerning runoff fractions and average copper ion concentrations, are given in Table 6.10. This table shows that the copper burden presented to the East Finniss system in 1973-74 probably lies between 44 and 80 tonnes. Of this, at least 0.6 tonnes is fed to the river system from spring water from March to July. Estimates for the manganese and zinc burdens were obtained from the copper burden estimates using average Mn/Cu and Zn/Cu ratios for the spring water. These estimates indicate that the manganese burden was between 19 and 33 tonnes and the zinc burden between 31 and 56 tonnes. The relatively high contribution of Dyson's heap to the manganese burden should be noted.

6.2 Opencuts

6.2.1 Introduction

During mining operations groundwater entered each of the opencuts - White's, Intermediate and Dyson's. Each is now essentially full of water and/or tails material and, as a result of the milling operations described in Chapter 2, the contained water is polluted. Seepage and overtopping of these opencuts represents an input of heavy metals directly, or indirectly via the local groundwater regime, to the surface waters. This section estimates the magnitude of the inputs and indicates where the surface expression is thought to occur.

To consider the water balance for the opencuts, it is important to know by what factor the catchment area of the opencut exceeds that of the opencut. The change in water level induced by a known amount of rainfall was used to determine this factor. This approach is complicated by the hydrological connection between the opencuts and the upstream groundwater regimes; an isolated storm leads to an increasing water height over the next few days. The estimates finally used were derived from an overnight storm on 3-4.12.74. Rain started to fall at 1600 hours and continued at a fairly uniform rate of 6 mm h^{-1} until 0100 hours, followed by a more irregular fall of 16 mm over the next 8 hours. Evaporation from a free water surface was taken as nil over this 17-hour period (total rainfall 71.6 mm). The ratio of change-in-height to this rainfall was 1.0 for White's, 1.1 for the Intermediate and 1.8 for Dyson's opencuts.

6.2.2 <u>White's opencut</u>

The quality of water in White's opencut has deteriorated over the years as shown in this table:

Year	Depth m	pH	Concentration mg ℓ^{-1} Cu	Mn	SO_4
1959	0	4.8	3.7	2.7	180
	50	4.8	4.0	2.8	200
1969	0	2.7	52	86	4750
1970	0	2.8	53	115	6000
	50	2.8	53	115	6000
1974	0	2.4	56	150	5700
	50	2.2	60	220	9200

Before 1959, no wastes were discharged to the opencut. It is a matter of conjecture whether the pollution at that time arose from oxidation of the pyritic shales in the opencut boundaries or as a result of groundwater influx to the pit from areas contaminated by seepage through ore stockpiles.

Tailings material was discharged into the opencut from 1965-71 and raffinate from 1968-71. Mixing in the volume of water was induced by the settling tails material and no stratification was observed during this period.

A gauge board was installed in the opencut and readings taken periodically. Figure 6.9 includes a curve showing height variation with time. Also included in Figure 6.9 are height variations recorded in the bore holes in the tails dump area (see Figure 6.10). These heights are taken as being representative of the height of the perched water table.

Table 6.11 lists the water height changes observed, the rainfall (measured at White's overburden heap) and the evaporation (measured at Darwin Airport). Also included are the derived seepage losses.

No detailed measurements are available from December 1973 to mid-March 1974. The change in water height during this period was about twice as much as would be expected from precipitation minus evaporation. Further, the data presented in Table 6.11 indicate that seepage is occurring when the level in White's is lower than that in BH6; it is BH6, rather than its neighbouring bore BH2 (see Figure 6.10), which shows persistently high values of manganese throughout the year. From this it is concluded that the water table height which determines seepage from White's opencut lies between those of BH6-2. If this is so, seepage from early January to about mid-March can be neglected and to an acceptable accuracy a seepage loss of 1.26 m can be inferred from Table 6.11.

The area of White's opencut is 10.5 ha. The seepage loss is equivalent to a volume loss of $1.3 \times 10^5 m^3$ (~ 5% of total water volume) at a pollutant concentration of 60 mg ℓ^{-1} of Cu, 220 mg ℓ^{-1} of Mn and 9200 mg ℓ^{-1} of sulphate ion. Thus the total input from White's opencut of Cu, Mn and SO_4 is 8, 29 and 1200 tonnes respectively.

Note that these figures are lowest value estimates since they ignore the possibility of groundwater flowing through the system (uncontaminated water entering the opencut; contaminated water leaving it). The vertical profile of temperature and dissolved oxygen discussed below indicates no major traverse flow zone so groundwater transverse velocities could be no greater than chemical diffusion velocities which are in the range of 2×10^{-7} to $3 \times 10^{-6} m\ s^{-1}$. Thus an aquifer, 5 m thick, with flow velocities in this range would increase the pollution load from White's opencut by 10-100%.

Vertical temperature and dissolved oxygen profiles were measured in May and November. Both sets of results were essentially the same; those for November are given in Table 6.12. Distributions of this type (clinograde) occur in small, relatively deep lakes in Indonesia [Hutchinson 1957] but the contrast between White's and Intermediate opencuts demonstrates that it is biological activity, rather than limitations on the physical transport of oxygen, which causes the clinograde in White's. Presumably the consumed oxygen appears finally as sulphate. From work reported by Hutchinson it appears unlikely that the transportation of oxygen across the depleted zone at about 3 m could amount to more than 0.2 mg $cm^{-2}\ d^{-1}$ for an annual sulphate production of about 100 tonnes.

This is only about 10% of that lost yearly in seepage. Thus the quality of water in the opencut should improve slowly to an equilibrium level, based on ratios of the 1959 measurements, of 20 mg ℓ^{-1} of copper, 15 mg ℓ^{-1} of manganese and 1000 mg ℓ^{-1} of sulphate ion. Note that at that time - some 25 years from now - seepage from the opencut will still be a significant source of pollution.

6.2.3 Intermediate opencut

Groundwater entering the Intermediate opencut during mining operations was polluted. The opinion at the time was that the pollution originated from White's opencut. After mining operations and while the opencut was refilling, seepage that was heavily contaminated with copper from the heap leach pile also entered it. The quality of the water at present filling the pit is Cu 53, Mn 58, and Zn 6.5 mg ℓ^{-1} at a pH of 3.6.

Figure 6.9 indicates the time variation in water height and Table 6.13 presents the estimated seepage loss and the data on which it is based. Again it is assumed, on the basis of Figure 6.9, that there is no loss from the Intermediate opencut during the Wet although, in this instance, overtopping was observed to occur during the 1973-74 Wet.

The calculated seepage is equivalent to a pollution load of 2.6 tonnes of copper, 2.8 tonnes of manganese, 0.3 tonnes of zinc and about 100 tonnes of sulphate. These values are lower limits for that reason already given in the discussion of White's opencut.

There are insufficient sets of data on the quality of water in the Intermediate opencut for predictions on future trends to be confidently made. The similarity in the height variations for White's and Intermediate opencuts, the apparent increase of manganese concentration relative to copper concentration in 1970-74 both suggest that the Intermediate and White's opencuts have a common aquifer, possibly the EB bed before diversion.

A series of shallow bores were sunk in the vicinity of the trench located between the leach pile and the Intermediate opencut. The original purpose of the trench was to collect some of the lost seepage from the pile. Measurements on the height of water in the shallow bores indicated a gradient to the opencut.

Thus for two reasons the water quality of Intermediate is expected to deteriorate but the secular equilibrium concentrations cannot be predicted from available information.

Table 6.14 lists the vertical profile for temperature and dissolved oxygen in the Intermediate opencut. The results establish that physical mechanisms are adequate for the transportation of oxygen to these depths and that this particular body of water has a low biological productivity.

6.2.4 Dyson's opencut

The Dyson's opencut was used for tailings disposal. The resulting level is such that tailings material is exposed during the Dry and covered during the Wet. For all but the early storms, water precipitation into Dyson's opencut is discharged through an overflow pipe and erosion gully, to EB; Table 6.15 lists concentration of pollutants in the overflow water. The process is not one of flushing out the polluted water resulting from bacterial oxidation of the exposed tails during the Dry, but to a reasonable approximation, is one where the concentration of contaminants is independent of time and flow rate.

The catchment area for Dyson's opencut is about 7.8 ha. Thus the total volume of water that flowed through or seeped from the opencut during the 1973-74 Wet was $1.56 \times 10^5 m^3$. On taking the average concentration of contaminants as 7, 20 and 1500 mg ℓ^{-1} for Cu, Mn and SO_4 respectively, this flow is equivalent to an input of 1, 3 and 230 tonnes of Cu, Mn and SO_4 respectively.

6.2.5 Surface expression of seepage losses

Because of the relative magnitude of the contaminant losses, it is only the fate of the seepage from White's that is of concern. Several areas of surface expression are known. In the diversion channel bed there is a limestone cavern that seeps water throughout the year. Chemical analysis of this seepage strongly suggests that it originates from White's opencut. In a similar way indications are that a geyser in the old EB bed upstream of White's originates from the pit. The western embankment, built across the old river bed, also seeps continuously. Water from this seep contains about the same concentration of copper and manganese at the end of the Dry as does the opencut. During the height of the Wet, results indicate dilution by local runoff.

None of these springs and seeps accounts for much of the calculated seepage loss. As discussed later, the integrated flow of pollutants down Copper and Old Tailings Creeks is consistent with the sources in these catchments if seepage from White's is included. The most likely explanation is that preferential seepage occurs along the fault lines (see Map 2.2) which allows contamination of the perched water tables associated with the two creeks. With the rising water table during the next Wet, the contaminated groundwater is displaced to the flowing creeks. It is interesting to note that BH6 is near one of the fault lines and that water from this bore is always high in manganese (10-30 mg ℓ^{-1}) but, presumably because the pH is near neutral, copper values are low.

6.3 Tailings Dump Area

In 1954-61 about 640 000 tonnes of tailings material were discharged to the southern bank area of Old Tailings Creek. Runoff from this area is contaminated with copper, manganese, sulphate ion, etc.

The concentration of contaminants varies with location (depth of tails materials), rate of rainfall, etc. Only very limited data are available on these variables.

Further, as some of the seepage from White's opencut is believed to find surface expression in this general area, the contribution of heavy metals from the deposited tails material cannot be assessed from a study of water quality.

We assert that tails material deposited in Old Tailings Creek during days of intense rainfall in the 1973-74 Wet provides a representative sample of material from the tails dump. Some of this material (16.82 kg) had 16 ℓ of demineralised water added to it, stirred, and let stand for 24 hours. After evaporation was made good and the mixture stirred again, the water was drained off. The dissolved material in the 16 ℓ of water included 0.23 g of copper, 0.14 g of manganese and 9.6 g of sulphate. The material (1 m^2 surface area) was exposed to unshielded glass-house conditions (up to 30°C diurnal temperature range with dew formation in the evenings) for two months. The soluble material was then 0.29 g of copper, 0.2 g of manganese and 15.4 g of sulphate. About half of these quantities were contained in the water that made the material moist at the start of the glass-house exposure.

It is assumed to be a significant observation that about the same quantity of soluble material was generated in the six months' exposure to atmosphere in the creek bed as that generated in the two months' extreme exposure in the glass-house. Diurnal fluctuations in temperature and humidity are expected to provide a drive for the diffusion of water into the sulphide crystal matrix against the osmotic pressure of the sulphate solute generated by bacterial oxidation to produce these quantities. Thus the annual production of contaminants from tails material is primarily determined by the completeness of the water flush rather than the length of the exposure during the Dry. The tails dump area is effectively flushed by the rising water table. From that point until the next Dry, bacterial oxidation is suppressed by the lack of oxygen.

With this set of assumptions, the production of contaminants from the tails dump is proportionately the same as that for the glass-house exposure (0.0074, 0.0054 and 0.5 g kg^{-1} for Cu, Mn and SO_4 respectively). The estimated annual generation from the tails dump is 4.7, 3.5 and 320 tonnes of copper, manganese and sulphate respectively. Note that by using the quantity of tails material discharged from the mill in arriving at these estimates, account is taken of the tails remaining in the dump area and that deposited in the creek system.

The copper released in the glass-house experiment represented 1.6% of the copper contained in the tails. If this experiment was meaningful then the pollution problem associated with the tails dump area will continue for many years.

A similar glass-house exposure was carried out on sediments from EB at its junction with FR. The production of soluble Cu, Mn and SO_4 was 8.5 µg kg^{-1}, 1.9 mg kg^{-1} and 0.16 g kg^{-1} respectively. Results for radioactivity (^{210}Pb and ^{226}Ra) are presented in Chapter 8.

6.4 The Copper Leach Pile

The Copper Leach pile is centrally located between White's and Intermediate opencuts. It was constructed in 1965 to recover copper from the reject mill grades of copper ore from the Intermediate orebody by bacterially assisted acid leaching. The site was abandoned in 1971 following closure of the treatment plant. The pile consists of a square heap of sulphide ore, 10 m high, attached to an oblong heap of oxide ore 10 m high, as shown in Map 2.4. The heaps have steep walls and flat tops. Data for the heaps are listed in Table 6.16.

The site was located immediately south of the original EB course. The site was smooth with a 2% fall to the flowing river. The ground surface was a very porous silted alluvium and subject to inundation during the Wet. Accordingly the area was surrounded by levees, compacted, and a 100 mm layer of topsoil stabilised by a single pass soil stabiliser (P&H model LA107) using a slow curing bitumen emulsion [Andersen, Herwig & Moffit 1966]. This effectively produced a 100 mm layer of bituminous concrete, a material known to have high seepage rates.

The heaps were constructed by back-dumping onto the sealed area taking care that no equipment was on the sealed area before it had been covered to a depth of 1.3 m by ore. In spite of attempts to control traffic, the top 2 m of the heaps suffered considerable attrition and compaction, accounting for the subsequent poor performance of the heap compared with that of the hand-built Portuguese heaps which had vertical coarse rock drainage channels incorporated in them to assist percolation [Cameron 1963].

A wide collection ditch was built around the side of the sulphide heap, the downstream side of which provided limited storage for the sulphide liquors called the sulphide pond. Three other ponds were built: one to hold the pregnant liquor from the oxidised ore, a second to contain the barren effluent from the launders, and a third to contain supply acid. A small makeup pond was attached to the acid pond. The oxide, barren, acid and makeup ponds were constructed as shallow paddies with levees. The internal surface was sealed with Rivaseal, a thin Terylene-type plastic sheet with a reinforcing layer of Fibreglass sandwiched between two coatings of bitumen. Some trouble was experienced with this sheeting because the outer bitumen coating tended to craze between high and low liquor levels. While the heap was being operated the problem was solved by annual spraying of the surface with bitumen road primer [Andersen, Herwig & Moffit 1966]. The surfaces have not been sprayed since shutdown. It is not clear if all the sulphide pond was also sealed with Rivaseal, although certainly part of it was. Site inspection shows that the bitumen coatings are beginning to break up. The ponds were designed to be above the local water table.

The top of the oxide pile has a number of parallel trenches, 2 m deep, across it which contain the water. The top of the sulphide pile is flat and is surrounded by a ~ 1 m levee. This used to contain all the top surface water but the levee has broken down on the south wall so that rainwater flows off the top surface at this break, runs clockwise around the base of the heap and empties into the sulphide pond.

During operation pregnant liquor was pumped to the launders at $1.59 \times 10^{-2} m^3 s^{-1}$ giving an annual flow of $5.02 \times 10^5 m^3$. Evaporation and seepage losses were reported to be $163.7 m^3 d^{-1}$ in the Wet and $318.2 m^3 d^{-1}$ in the Dry [Andersen & Allman 1968]. Using the values quoted in Chapter 3 for evaporation from an opencut and an overburden heap, annual evaporation was determined to be $3 \times 10^4 m^3 y^{-1}$ (12% of pregnant liquor).

Initially the copper concentration in the pregnant liquor was 9 g ℓ^{-1}. This rapidly dropped over a period of weeks to 4 g ℓ^{-1} and over a year to 1.2 g ℓ^{-1}. It then slowly dropped over a period of 3 years to 0.5 g ℓ^{-1} (January 1970). Some work was then carried out to improve the leach rate until shutdown in 1971. If the average concentration is taken as 1 g ℓ^{-1} and the heap was operated for approximately six years then 3300 t Cu was leached from 6800 t Cu leaving 3500 t Cu in the piles assaying at 0.92% Cu. Approximately 400 t Cu was lost during this period through seepage.

The site was inspected in the 1973-74 surveys to assess the current situation. By the end of the Dry the ponds have dropped to a low level due to seepage and evaporation. The ion concentrations in g ℓ^{-1} are approximately:

	pH	Cu	Mn	Ni	Zn
barren pond	2.7	0.5	0.1	0.04	0.02
oxide pond	2.6	2.5	0.3	0.2	0.05
sulphide pond	2.8	1.5	0.05	0.07	0.05
acid pond	2.8	0.6	0.1	0.07	0.02

When the Wet begins the heaps saturate. Due to the design of the heaps the retention/runoff ratio is high; also runoff is collected by the drains and ponds until the oxide and sulphide ponds form a common lake, which overflows first into the acid pond and then to the old EB bed and Copper Creek. In addition springs develop around the individual piles. Typical concentrations in g ℓ^{-1} are:

	pH	Cu	Mn	Zn
oxide pond	2.7	1.2	0.1	0.1
sulphide pond	2.7	0.3	0.02	0.04
acid pond	3.1	0.2	0.02	0.002
sulphide spring	2.8	0.5	0.02	0.005
oxide spring	3.0	1.8	0.25	0.03

When the Wet ends the dams slowly dry out to their dry season level.

During the 1973-74 Wet approximately 2000 mm of rain fell. The heap has a surface area of 28 065 m^2 and was designed to contain water. However, in view of the broken levee a runoff coefficient of 0.5 was chosen for calculations of total runoff. The barren pond remained independent of the site. The oxide and sulphide ponds formed a common lake which overflowed into the acid pond. Total collection area for these three ponds would include the heap culverts, so total pond rainfall area was 12 195 m^2. However, the surface area of water for evaporation calculations would not have included the culvert area and the evaporation area was 9236 m^3. Since capacity data are available only for the sulphide and oxide ponds, accordingly an estimate had to be made for the volume of the acid pond. Maximum capacity data for the ponds are not available and were assumed to be twice that of the operating capacity. Runoff and leach liquors from the pile drain into the ponds, accordingly the water account is complex; it is summarised by Figure 6.11.

Runoff coefficients, seepage rates and evaporation rates were as determined in the previous paragraphs and Chapter 3. The general conclusions are that 10 t of copper are being annually absorbed by the groundwater system and 32 t of copper are being discharged down Copper Creek. Thus, although the site had been abandoned for three years at the time of inspection, it was still discharging copper to the local waters in amounts similar to those observed during operation. This is because the mechanism of leaching has not altered and, except towards the end of the Dry, the instantaneous amount of water present on any one day is the same now as it was during operation, hence the seepage rates are the same. The only significant difference is that while water was being constantly recirculated and the excess pumped into White's opencut during operation, now there is no recirculation and the heap is leached on a continuous once-through basis, the excess overflowing into Copper Creek. Since the heap still contains 3544 t Cu, continuing discharge of copper from this site at an annual rate of 30-40 t of copper can be expected for the next 25-75 years.

6.5 Summary

Three independent assessments were made of the total quantities of copper, manganese and zinc released from the RJ mine area during the 1973-74 water year. The first involved measurements of flow and concentrations on EB proper. The results obtained were Cu 130 t, Mn 100 t, Zn 30 t. The second method involved measured flows and concentrations at each of the three tributaries that go to make up EB at the mine area. The results for this method were Cu 95 t, Mn 83 t Zn 26 t. The third method involved assessing each source of pollution in a fundamental way. Table 6.17 summarises the set of results obtained. Summing that table gave the results Cu 95-142 t, Mn 70-80 t, Zn 30-56 t. The range of values for this method stems from uncertainties for runoff coefficients and the change in the quality of runoff water with durations of storms.

The three sets of results are in sufficient agreement to permit apportionment of the pollution load to the various sources to be used in assessing abatement proposals.

TABLE 6.1

SPRING DATA FOR WHITE'S OVERBURDEN HEAP

Site	Date	Flow $m^3s^{-1} \times 10^3$	pH	Concentration mg ℓ^{-1}		
				Cu	Mn	Zn
1	19.3.74	15.2	3.60	95	28	40
2	19.3.74	16.2	3.40	114	56	133
5	7.3.74	0.73	3.45	118	43	51
5	19.3.74	1.52	3.40	110	36	45
4	7.3.74	1.23	3.60	90	34	35
4	19.3.74	1.52	3.45	93	32	36
4	Average Values 1)			63 2)	39	37

1) Average values, spring 4, are for flow during 1974 Dry

2) AAEC Darwin Analysis

TABLE 6.2

ESTIMATES OF ANNUAL DISCHARGE OF WATER AND COPPER FROM SPRINGS ON WHITE'S AND DYSON'S HEAPS

Heap	Water discharge m^3		Copper concentration	Copper discharge kg		
	Dry	Wet	mg ℓ^{-1}	Dry	Wet	Total
White's (Spring 4)	6.24×10^3	10.2×10^3 *(1)*	95 *(2)*	593	969	1562
Dyson's	18.1×10^3	90.0×10^3	1.7	30.5	153	183

(1) Estimated from Dry discharge (See Section 6.1.1)

(2) AAEC Lucas Heights Analysis

Estimated total water discharge from White's from all springs = 342 x 10^3m^3

Estimated total copper discharge from White's from all springs = 35.6 tonnes

TABLE 6.3A

ANALYTICAL RESULTS FOR DETAILED SAMPLING OF THE PRINCIPAL RUNOFF ON WHITE'S OVERBURDEN HEAP ON 3.3.74

Sample point	Time	Flow	Concentration, mg ℓ^{-1}						Discharge, g s^{-1}				
	min	m^3s^{-1}	pH	Cu	Mn	U	Zn	SO_4	Cu	Mn	U	Zn	SO_4
1	0		4.55	0.79	0.043	<0.001	0.044	45.7	Initial wave of water				
1	15	0.93	3.80	0.68	<0.092	0.009	0.096	50.0	0.63	<0.09	0.008	0.09	46
3	35	0.25	3.84	1.12	0.14	0.018	0.17	89.0	0.28	0.03	0.004	0.04	22
1	40	0.25*	3.75	1.19	<0.09	0.018	0.15	93.0	0.3	0.02	0.0045	0.04	23
1	55	0.1165	3.82	1.79	0.16	0.026	0.23	149.0	0.01	0.02	0.003	0.03	17
1	195	0.011	3.46	7.68	0.74	0.540	1.92	810.0	0.08	0.008	0.006	0.02	9

* *Estimated*

TABLE 6.3B

DISCHARGES APPROXIMATELY 12 HOURS AFTER A STORM

Date 1974	Flow m^3s^{-1}	Concentration, mg ℓ^{-1}								Discharge, g s^{-1}						
		pH	Cu	Fe	Mn	Pb	Zn	U	SO_4	Cu	Fe	Mn	Pb	Zn	U	SO_4
25/2	0.0015		25		2.5		1.8	0.4	3150	0.038		0.0037		0.0027	0.0006	4.7
26/2	0.0004		52		4.4		12.5	3.0	4300	0.021		0.0018		0.005	0.0012	1.7
6/3	0.009	3.75	5.3	0.8	0.5	0.05	0.5		568	0.048	0.0072	0.0045	0.000 45	0.0045		5.1
19/3	0.03		16	6.0	1.6	0.02	0.9		1840	0.48	0.18	0.048	0.0006	0.027		55.2

TABLE 6.4

CHEMICAL ANALYSIS OF SAMPLES FROM THE INTERMEDIATE PRINCIPAL RUNOFF FOR STORM ON 7.3.74

Time	Flow $m^3s^{-1} \times 10^3$	pH	Concentration, mg ℓ^{-1}					Discharge, mg s^{-1}				
			Cu	Fe	Mn	Zn	SO_4	Cu	Fe	Mn	Zn	SO_4
0*		2.95	260	230	17	11	18 200	Pool of Water				
0		3.20	100	163	2.9	2.1	4840	Initial wave				
15	0.29	3.20	232	474	30	63	13 260	67	137	9	18	3845
35	8.60	3.30	35	35	2.9	6	1300	301	303	25	52	11 180
37	8.60	3.45	41	74	3.5	7	1640	352	636	30	60	14 104
55	115.00	3.35	18	16	1.3	2	755	2070	1840	150	230	86 825
125	0.90	3.23	100	160	8.8	19	4450	90	144	8	17	4005

* Time 0 = 13.25

TABLE 6.5

CHEMICAL ANALYSES OF SAMPLES FROM DYSON'S PRINCIPAL RUNOFF

Date 1974	Time from start of storm min	Flow $m^3s^{-1} \times 10^{-3}$	pH	Concentration, mg ℓ^{-1}						Discharge, mg s^{-1}				
				Cu	U	Mn		Zn	SO_4	Cu	U	Mn	Zn	SO_4
24/2		5.13		0.570	0.86	2.58		0.31	3375	3.0	4.4	13.0	1.6	17 310
26/2		0.18		1.2	1.6	4.30		0.38	5450	0.2	0.3	0.8	0.07	981
				Cu	Fe	Mn	Pb	Zn	SO_4	Cu	Fe	Mn	Zn	SO_4
8/3		2.8	2.95	0.47	380	2.2	<0.04	0.220	3250	1.3	1064	6.2	0.6	9 100
10/3	0	38.0	3.25	0.5	210	0.94	<0.04	0.21	1775	19.0	7980	36.0	8.0	67 450
10/3	30	30.0[a]	2.85	0.27	330	1.4	0.02	0.19	2980	8.0	9900	42.0	6.0	89 400
10/3	45	216.0	3.05	<0.1	46.0	0.19	<0.005	0.065	555	<22	9936	41.0	14.0	119 880
10/3	65	26.5	3.00	<0.1	100	0.5	<0.005	0.089	965	<2.0	2650	13.0	2.0	25 573
10/3	110	6.9	3.15	0.27	330	1.5	0.02	0.17	2970	2.0	2267	10.0	1.0	20 404
3/4		0.267	2.85	0.7		1.3		<0.1		0.19		0.35	<0.03	
29/4		0.07	2.90	0.9		2.0		0.08		0.06		0.14	0.006	
				Concentration gradually rose to										
24/6		0.001		4.5		13.4		<0.1		0.005		0.013	<0.001	
Cease to flow.														

[a] *interpolated*

TABLE 6.6

DETAILED SAMPLING OF WHITE'S OVERBURDEN HEAP

Area	Sample Point	Date 1974	Time	pH	Concentration, mg ℓ^{-1} Cu	Fe	Mn	Pb	Zn	U	SO_4
C	1	15/3	1630	3.85	2.7	0.68	0.24	0.023	0.20		280
NE	3	3/3	1635	3.62	1.3		0.1		0.4	0.046	107
	3	3/3	1911	3.50	7.4		0.8		0.7	0.14	95
	3	6/3	1600	3.65	12.3	1.1	1.12	0.15	2.7		1215
	3	15/3	1520	3.65	36.5	1.4	3.4	0.016	9.0		3300
S	4	3/3	1600	3.61	0.2		<0.09		<0.04	0.005	25
	4	6/3	0911	3.50	1.3	1.2	0.1	0.28	0.09		166
	4	15/3	1530	4.15	0.16	0.95	<0.12	0.08	0.09		20.7
S	5	3/3	1600	3.94	0.3		<0.09		0.05	0.006	27.5
	6	15/3	1540	3.35	4.5	4.2	0.14	0.13	0.15		342
	7	15/3	1540	3.90	0.4	1.3	<0.120	0.024	<0.035		30
	8	15/3	1540	3.70	0.5	1.3	<0.120	0.013	<0.035		31
	9	15/3	1545	5.10	<0.1	0.8	<0.120	<0.005	<0.035		2
	10	15/3	1545	3.95	0.2	2.1	<0.120	0.030	0.035		69
SW	11	15/3	1615	3.85	2.5	0.5	0.22	<0.005	0.34		318
	12	15/3	1615	4.00	1.9	0.8	0.11	<0.005	0.10		102
NW	13	15/3	1600	6.00	<0.1	<0.2	<0.09	<0.005	<0.03		< 4.0
	14	15/3	1615	4.75	<0.1	<0.2	<0.09	<0.005	0.06		24
	15	15/3	1525	3.80	4.5	0.3	0.77	<0.005	0.2		865
W	16	15/3	1545	4.00	<0.1	1.4	<0.09	<0.005	0.033		12.5
	17	15/3	1550	4.15	<0.1	1.3	<0.09	<0.005	<0.03		13.0
	18	3/3	1400	4.90	1.2		<0.09		<0.04	0.004	19.0
Walls	19	3/3	1614	4.70	1.1		<0.09		<0.04	<0.001	4
	20	3/3	1615	3.75	2.4		0.83		0.78	0.14	785
	21	3/3	1616	3.54	0.24		<0.09		<0.04	0.006	45

TABLE 6.7

DETAILED SAMPLING ON INTERMEDIATE OVERBURDEN HEAP, 7.3.74

Site	Area	pH	Concentration, mg ℓ^{-1}					
			Cu	Fe	Mn	Pb	Zn	SO_4
2	Bottom of principal r	3.45	41	74	3.5	0.04	7.0	1640
3	West of principal r	3.85	19	4.7	1.7	<0.04	0.4	2550
4	From area 7	4.30	15	3.0	0.4	0.07	0.6	320
5	From area 6	3.10	55	200	2.5	<0.04	1.0	2030
6	Top of principal r	3.30	35	44	1.2	<0.04	0.9	1110
7	Centre of principal r	3.20	42	84	3.1	<0.04	9.3	1860
8	From area 4	3.25	15	20	2.0	<0.04	2.3	530
9	North wall	3.40	6	8	0.5	0.20	0.8	270
10	North wall	3.50	35	13	8.2	<0.04	8.3	1310
11	North wall	3.45	38	8	7.8	<0.04	3.5	940
12	NE corner	3.45	35	11	5.3	<0.04	2.0	890
13	SE corner	3.20	1.6	9.5	0.7	<0.04	1.9	1060
14	West wall	2.80	72	930	7	<0.04	48	16 750
15	NW corner	3.45	44	18	1.5	<0.04	0.2	2375

r = runoff

TABLE 6.8

DETAILED SAMPLING ON DYSON'S OVERBURDEN HEAP DURING STORM ON 10.3.74

Principal Runoff Sites	Time*	pH	Concentration, mg ℓ^{-1}					
			Cu	Fe	Mn	Pb	Zn	SO_4
6	b	3.35	0.32	180	0.47	<0.04	0.10	1050
	a	3.50	0.15	25	0.12	<0.04	0.06	280
7	b	3.05	0.62	960	1.5	<0.04	0.35	5450
	a	3.25	0.13	250	0.43	<0.005	0.12	1510
8	b	3.20	0.520	540	2.0	0.090	0.32	4350
	a	3.20	0.130	170	0.850	<0.005	0.14	1640
13	a	2.80	0.27	350	0.93	0.017	0.16	2600
10	a	3.00	0.26	700	1.2	0.016	0.31	4230
11	a	3.00	0.29	170	0.58	<0.005	0.11	1190
14	a	3.20	0.110	29	1.1	<0.005	0.11	930
9	b	3.15	0.67	210	2.4	0.085	0.26	2550
9	a	3.15	0.29	180	2.4	<0.005	0.17	2800
5	b	3.20	0.30	28	0.18	<0.040	0.083	280
5	a	3.40	<0.120	9	0.12	<0.040	0.055	203
12	a	3.10	0.160	18	0.11	<0.005	0.036	314

* *Refers to samples collected immediately before 'b' and after 'a' the storm*

TABLE 6.9

COPPER ION CONCENTRATIONS (mg ℓ^{-1}) IN THE PRINCIPAL RUNOFF FROM WHITE'S INTERMEDIATE AND DYSON'S HEAPS MEASURED IN THE 1969-70 WET

Heap	20/10	15/12	24/12	30/12	8/1	13/1	31/1	9/2	3/3	15/3	Av.
White's		70	226	13		6		13			67.
Inter.	800	58	33	75	222			100			215
Dyson's		3	0.16	0.10			0.21		2.1	1.9	1.4

TABLE 6.10

SUMMARY TABLE OF ESTIMATES OF COPPER, MANGANESE AND ZINC BURDENS PRESENTED TO THE EAST FINNISS RIVER SYSTEM BY WHITE'S, INTERMEDIATE AND DYSON'S OVERBURDEN HEAPS, 1973-74

Heap	Incident rain	Copper concentration in runoff		Copper concentration in spring and groundwater	25% Runoff fraction					50% Runoff fraction				
					Runoff water	Spring & groundwater	Copper burden (tonnes)			Runoff water	Spring & ground-water	Copper burden (tonnes)		
		mg ℓ^{-1}					Runoff		Spring & ground-water			Runoff		Spring & ground-water
	$m^3 (\times 10^{-5})$	Low	High	mg ℓ^{-1}	$m^3 (\times 10^{-4})$	$m^3 (\times 10^{-4})$	Low	High		$m^3 (\times 10^{-4})$	$m^3 (\times 10^{-4})$	Low	High	
White's	5.45	1.18	67	104	13.6	40.9	0.16	9.1	42.5	27.3	27.2	0.32	18.3	28.2
Inter-mediate	1.33	17.6	215	215	3.33	9.97	0.59	7.2	21.4	6.65	6.65	1.17	14.3	14.3
Dyson's	1.77	0.2	1.4	1.7	4.43	13.27	0.01	0.06	0.22	8.85	8.85	0.02	0.12	0.15
						TOTALS	0.76	16.4	64.1			1.51	32.7	42.65

TOTAL METAL BURDEN ESTIMATES

Heap	Copper burden		Mn/Cu ratio	Zn/Cu ratio	Mn burden (tonnes)		Zn burden (tonnes)	
	min.	max.			min.	max.	min.	max.
White's	28.5	51.6	0.38	0.61	10.8	19.6	17.4	31.5
Inter-mediate	15.5	28.6	0.17	0.84	2.6	4.9	13.0	24.0
Dyson's	0.17	0.28	31.8	0.79	5.4	8.9	0.13	0.22
				TOTALS	18.8	33.4	30.5	55.7

TABLE 6.11

WATER BALANCE FOR WHITE'S OPENCUT

Date 1974	Height change (mm)	e (mm)	e_o (mm)	Rainfall (r) (mm)	$r-e_o$	Apparent* seepage (mm)	Seepage d^{-1}	Apparent input (mm)	Inflow d^{-1} (mm)
22/3	+34	37.7	30.7	233.6	203	169	24.1		
28/3	0	34.4	28	24.4	-3.6				
1/4	-46	19.7	16	0	-16	30	7.5		
8/4	-46	61.5	50	45.8	-4.2	42	6.0		
15/4	-152	53.2	43	0	-43	109	15.6		
22/4	-107	51.6	42	0	-42	65	9.3		
30/4	-46	54.6	44	11	-33	13	1.6		
7/5	-92	51.6	42	3	-39	53	7.6		
14/5	-91	42.8	35	2	-33	58	8.3		
21/5	-92	49.8	40	0	-40	52	7.4		
28/5	-76	50.0	41	0	-41	35	5.0		
4/6	-122	49.9	40	0	-40	82	11.7		
11/6	-73	46.0	37	0	-37	36	5.1		
18/6	-72	51.2	42	0	-42	30	4.3		
25/6	-75	51.2	42	0	-42	33	4.7		
2/7	-71	39.4	32	0	-32	39	5.6		
9/7	-72	46.0	37	0	-37	35	5.0		
16/7	-68	49.5	40	0	-40	28	4.0		
23/7	-60	41.2	33	0	-33	27	3.9		
30/7	-55	59.6	48	0	-48	7	1.0		
6/8	-40	41	33	0	-33	7	1.0		
13/8	-35	61.2	50	0	-50			15	2.1
20/8	-65	35.8	29	0	-29	36	5.1		
27/8	-45	38.3	31	0	-31	14	2.0		
3/9	-40	52.1	42	1	-41			1	
6/9	-5	18.5	15	40	25	30	10		
10/9	-25	35.2	29	0	-29			4	
17/9	-60	59.8	49	0	-49	11	1.6		
24/9	-25	56.1	46	8	-38			13	
26/9	0	11	9	36	27	27	13.5		
4/10	-35	71.4	58	15	-43			8	
6/10	-8	5.6	4.5	5.6	1.1	9	4.5		
17/10	-67	92.8	75	3	72			5	
20/10	+80	27.9	23	13	-10			90	
28/10	-135	60.8	49	0	-49	86	10.8		
5/11	-40	50.4	41	25	-16	24	3		
12/11	-45	45.8	37	2	-35	10	1.4		
19/11	+80	60.4	49	94	45			25	
28/11	0	64.1	52	87	35	35	3.9		
3/12	0	19.4	16	25	9	9	1.5		
9/12	+8	45.6	37	67.7	31	23	3.8		

* = $(r-e_o)$ - *Height change*

e = evaporimeter reading
e_o = *true evaporation*

TABLE 6.12

VERTICAL PROFILE OF TEMPERATURE (°C) AND DISSOLVED OXYGEN (mg ℓ^{-1})

IN WHITE'S OPENCUT NOVEMBER 1974

Depth (ft)	Location									
	Centre		East Branch outlet*		East Branch inlet*					
			3 m from bank		20 m from bank		3 m from bank		1 m from bank	
	°C	O_2	°C	O_2	°C	O_2	°C	O_2	°C	O_2
0	31.0	7.5	31.5	6.5	31.0	7.2				
5	31.0	7.2	31.5	6.4	30.5	6.8	30.5	6.4	31.0	6.1
7.5			31.5	6.0						
8.5			29.5	4.3						
10	30.0	5.4	29.0	2.5	30.0	4.2	29.0	1.7		
11	29.0	0.5	29.0	1.5	29.0	1.4				
12			27.5	0.5	28.5	0.55				
20	26.0	0.45					28.5	0.65		
35					25.5	0.55				
50 ↓ 200	25.5	0.3								

* *with respect to pre-development river course*

TABLE 6.13

WATER BALANCE FOR INTERMEDIATE OPENCUT

Date 1974	Height change (mm)	e (mm)	e_o (mm)	Rainfall (r) (mm)	$r-e_o$	Apparent seepage (mm) *	Seepage d^{-1}	Apparent inflow (mm)	Inflow (mm) d^{-1}
28/3	-35	34.4	28	27	-1	34	5.7		
1/4	-45	19.7	16	0	-16	29	7.3		
8/4	-45	61.5	50	50	0	45	6.4		
15/4	-120	53.2	45	0	-45	75	10.7		
22/4	-95	51.6	42	0	-42	53	7.6		
30/4	-130	54.6	44	12	-32	98	12.3		
7/5	-115	51.6	42	3	-39	76	10.9		
14/5	-100	42.8	35	2	-33	67	9.6		
21/5	-80	49.8	40	0	-40	40	5.7		
28/5	-95	50.0	41	0	-41	54	7.7		
4/6	-100	49.9	40	0	-40	60	8.6		
11/6	-24	46.0	37	0	-37			13	1.9
18/6	-179	51.2	42	0	-42	137	19.6		
25/6	-19	51.2	42	0	-42			23	3.3
2/7	-18	39.4	32	0	-32			14	2.0
9/7	-65	46.0	37	0	-37	28	4.0		
16/7	-45	49.5	40	0	-40	5	0.7		
23/7	-50	41.2	33	0	-33	17	2.4		
30/7	-30	59.6	48	0	-48			18	2.6
6/8	-55	41	33	0	-33	22	3.1		
13/8	-45	61.2	50	0	-50			5	0.7
20/8	-55	35.8	29	0	-29	26	3.7		
27/8	-25	38.3	31	0	-31			6	0.9
3/9	-15	52.1	42	1	-41			26	3.7
6/9	-5	18.5	15	44	29	34	11.3		
10/9	-25	35.2	29	0	-29			4	1.0
17/9	-55	59.8	49	0	-49	6	0.9		
24/9	-40	56.1	46	9	-37	3	0.4		
26/9	+30	11.0	9	40	31	1	0.5		
4/10	-40	71.4	58	17	-41			1	0.1
6/10	+110	5.6	4.5	6	1			109	55
17/10	-60	92.8	75	3	-72			12	1
20/10	-40	27.9	23	14	-9	31	10.3		
28/10	-5	60.8	49	0	-49			44	5.5
5/11	-4	50.4	41	28	-13			9	1.1
12/11	-111	45.8	37	2	-35	76	10.9		
19/11	+110	60.4	49	103	54			56	8
28/11	0	64.1	52	96	44	44	4.9		
3/12	0	19.4	16	28	12	12	2.4		
9/12	+8	45.6	37	74	37	29	4.8		

** = $(r-e_o)$ - Height change*

e = evaporimeter reading

e_o = true evaporation

TABLE 6.14

VERTICAL PROFILE OF TEMPERATURE AND DISSOLVED OXYGEN IN INTERMEDIATE OPENCUT

Depth (ft)	Temperature (°C)	Dissolved oxygen (mg ℓ^{-1})
0	32	7.1
10	32	6.7
15	31.5	6.6
17.5	30.5	6.8
19	30	7.0
20	29	7.4
25	27	7.5
30	26	6.7
40	25	5.6
50	25	5.2
60	25	5.0
70	25	4.9
80	25	4.7
100	25	4.7
120	25	4.7
140	25	4.7
160	25	4.7
180	25	4.6
200	25	4.5

TABLE 6.15

WATER QUALITY OF OVERFLOW FROM

DYSON'S OPENCUT

Date 1973-4	Flow $m^3\ s^{-1}$	Concentration (mg ℓ^{-1})		
		Cu	Mn	SO_4
4/11	0	8	33	2500
24/2	0.0076	7	21	1500
8/3	0.018	7.2	18	1400
10/3		6.4	16	1300
10/3	0.028	6.1	17	1400

TABLE 6.16

DATA FOR THE HEAP LEACH EXPERIMENT

Ore	Amount, Mg	Original Assay of Cu	Est. Current Assay
sulphide	3.05×10^5 *(a)*	0.7%-2%, average 1.7% *(a)*	0.92 *(d)*
oxide	0.81×10^5 *(a)*	2% *(a)*	

Period of operation	1965-71	
Pumping rate to launders	$1.59 \times 10^{-2} m^3 s^{-1}$	*(b)*
Evaporation and seepage losses	$163.7\ m^3 d^{-1}$ in Wet	*(b)*
	$318.2\ m^3 d^{-1}$ in Dry	*(b)*
Estimated seepage	12%	*(d)*

Plan Area		Volume	
		Normal operation	To overflow
Sulphide heap	21 019 m^2 *(c)*		
Oxide heap	7046 m^2 *(c)*		
Total	28 065 m^2		
Sulphide culvert	1953 m^2 *(c)*		
Oxide culvert	1006 m^2 *(c)*		
Sulphide pond	1894 m^2 *(c)*	1591 m^3 *(b)*	3182 m^3 *(d)*
Oxide pond	2664 m^2 *(c)*	3500 m^3 *(b)*	7000 m^3 *(d)*
Acid pond	4678 m^2 *(c)*	7000 m^3 *(d)*	14 000 m^3 *(d)*
Sum of ponds	9236 m^2		24 180 m^3
Barren pond	2427 m^2 *(c)*		

(a) *Andersen, Herwig & Moffitt* [*1966*]

(b) *Andersen & Allman* [*1968*]

(c) *AAEC aerial survey*

(d) *Estimation given in text (Section 6.4)*

TABLE 6.17

ANNUAL RELEASE OF HEAVY METALS (IN TONNES) FROM EACH SOURCE IN THE RUM JUNGLE AREA (1973-74)

Source	Annual release (tonnes)		
	Cu	Mn	Zn
Dyson's opencut	1	3	
Dyson's waste rock	0.2	5	
White's opencut	8	30	
White's waste rock	29-53	11-19	17-31
Intermediate opencut	3	3	0.3
Intermediate waste rock	16-30	2.5-4.5	13-25
Heap leach pile	32-42		
Tailings area	5	3.5	
Old Acid Dam		12	
TOTAL	95-142	70-80	30-56

KEYS

Figure 6.1

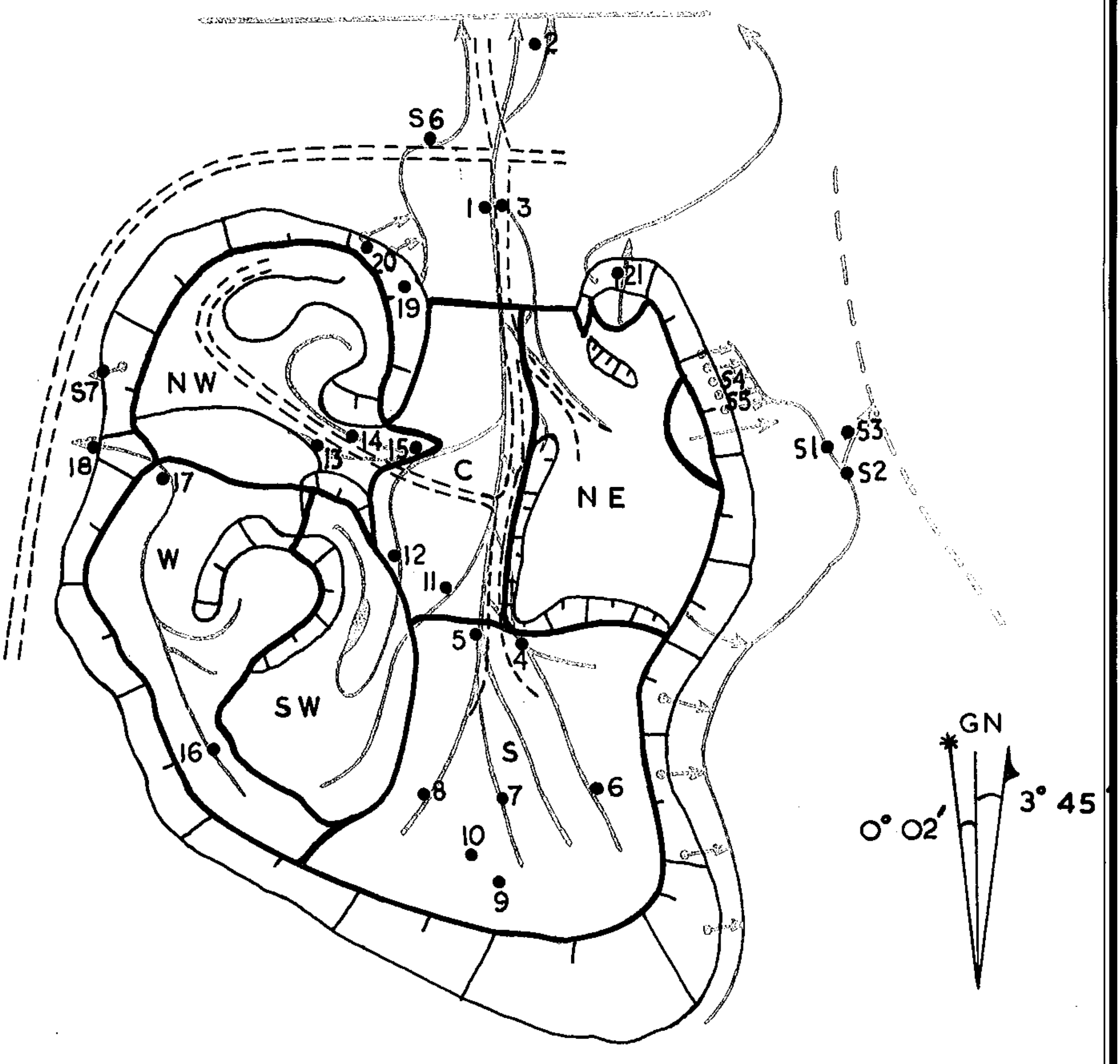
S1 •	etc	Spring sites	
1 •	etc	Sample points	
C		Central	Catchment areas
SW		South west	Catchment areas
W		West	Catchment areas
NE		North east	Catchment areas
NW		North west	Catchment areas
S		South	Catchment areas

Figure 6.2

1,2,....8	Catchment areas

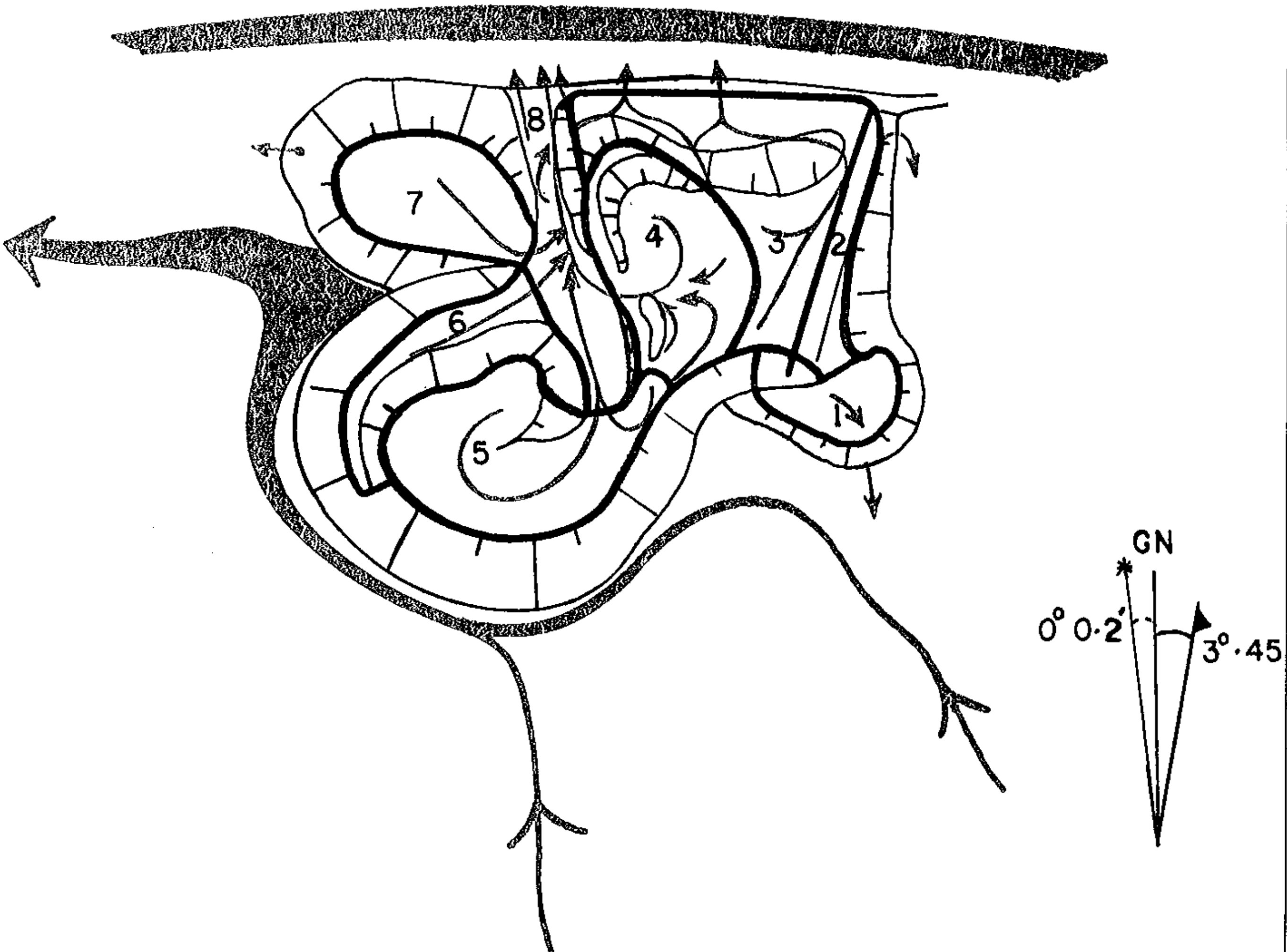
Figure 6.3

S1•	etc	Spring sites
1 •	etc	Sample points



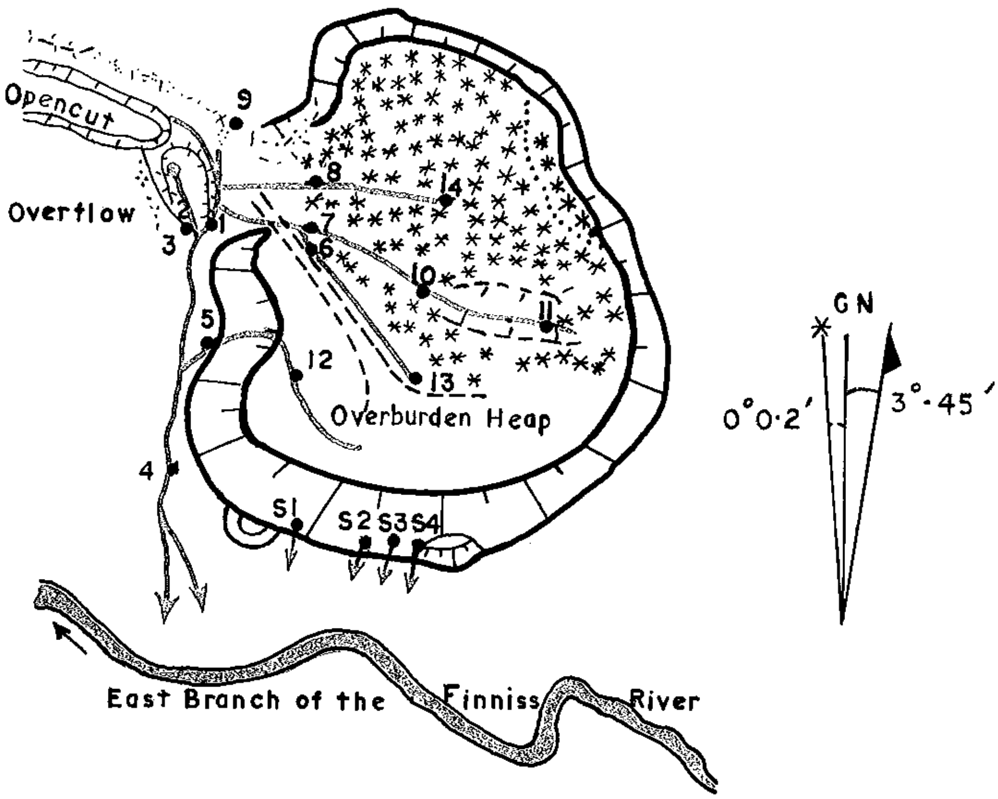
DRAINAGE PATTERN ON WHITE'S OVERBURDEN HEAP

FIGURE 6.1



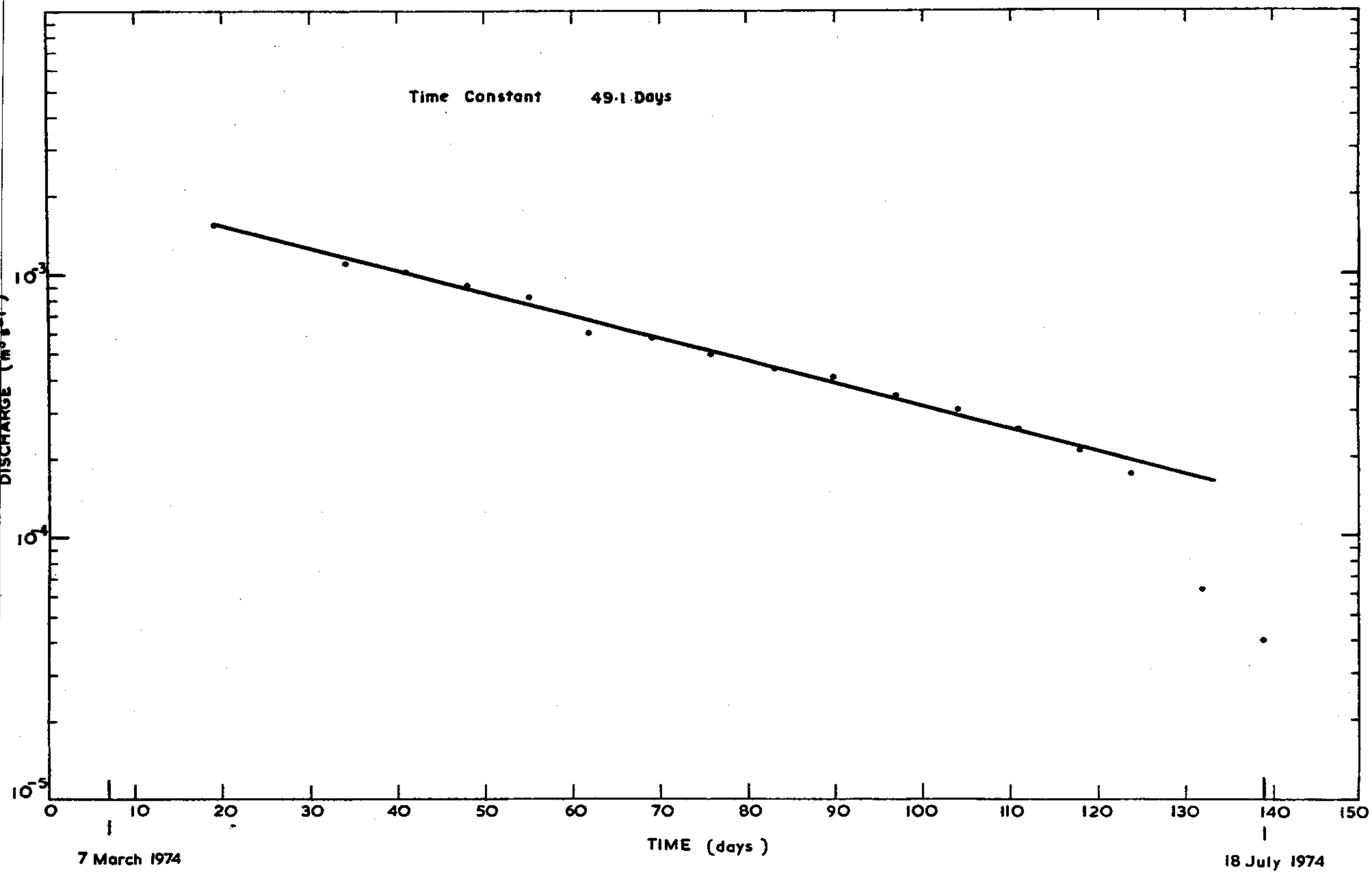
WATER FLOW DISTRIBUTION ON INTERMEDIATE OVERBURDEN HEAP

FIGURE 6.2



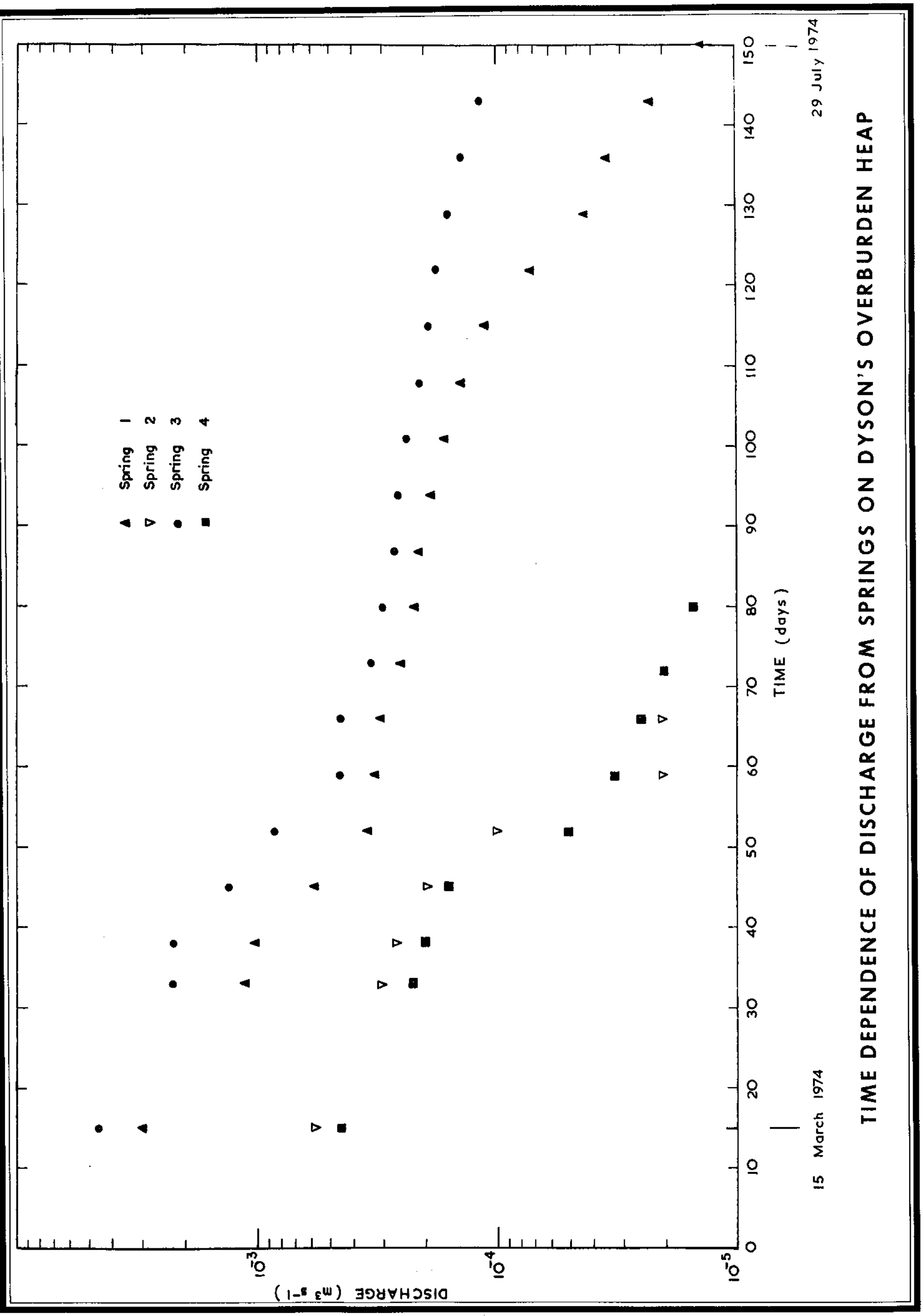
WATER FLOW DISTRIBUTION FOR DYSON'S OVERBURDEN HEAP

FIGURE 6.3



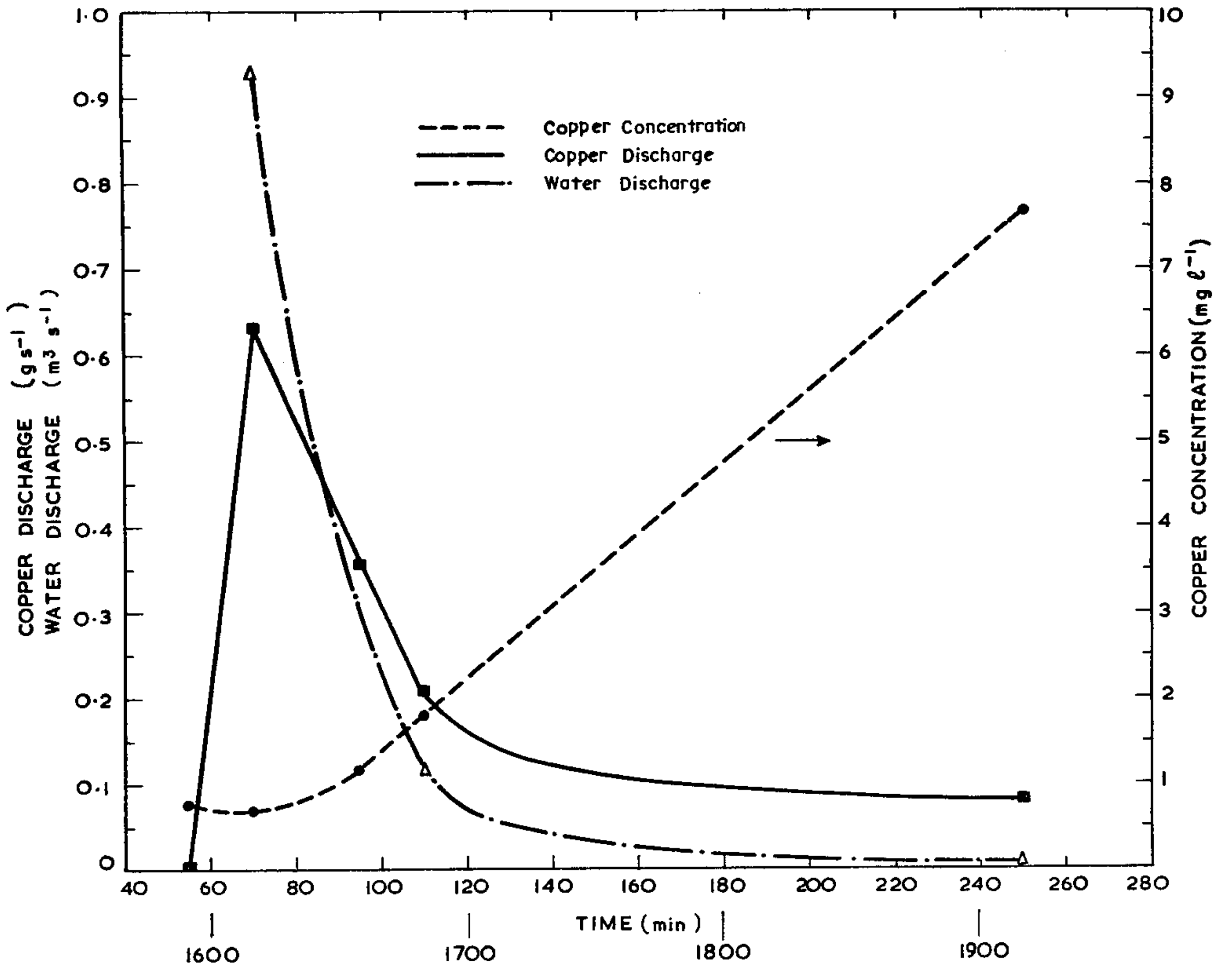
TIME DEPENDENCE OF SPRING(4) ON WHITE'S OVERBURDEN HEAP

FIGURE 6.4



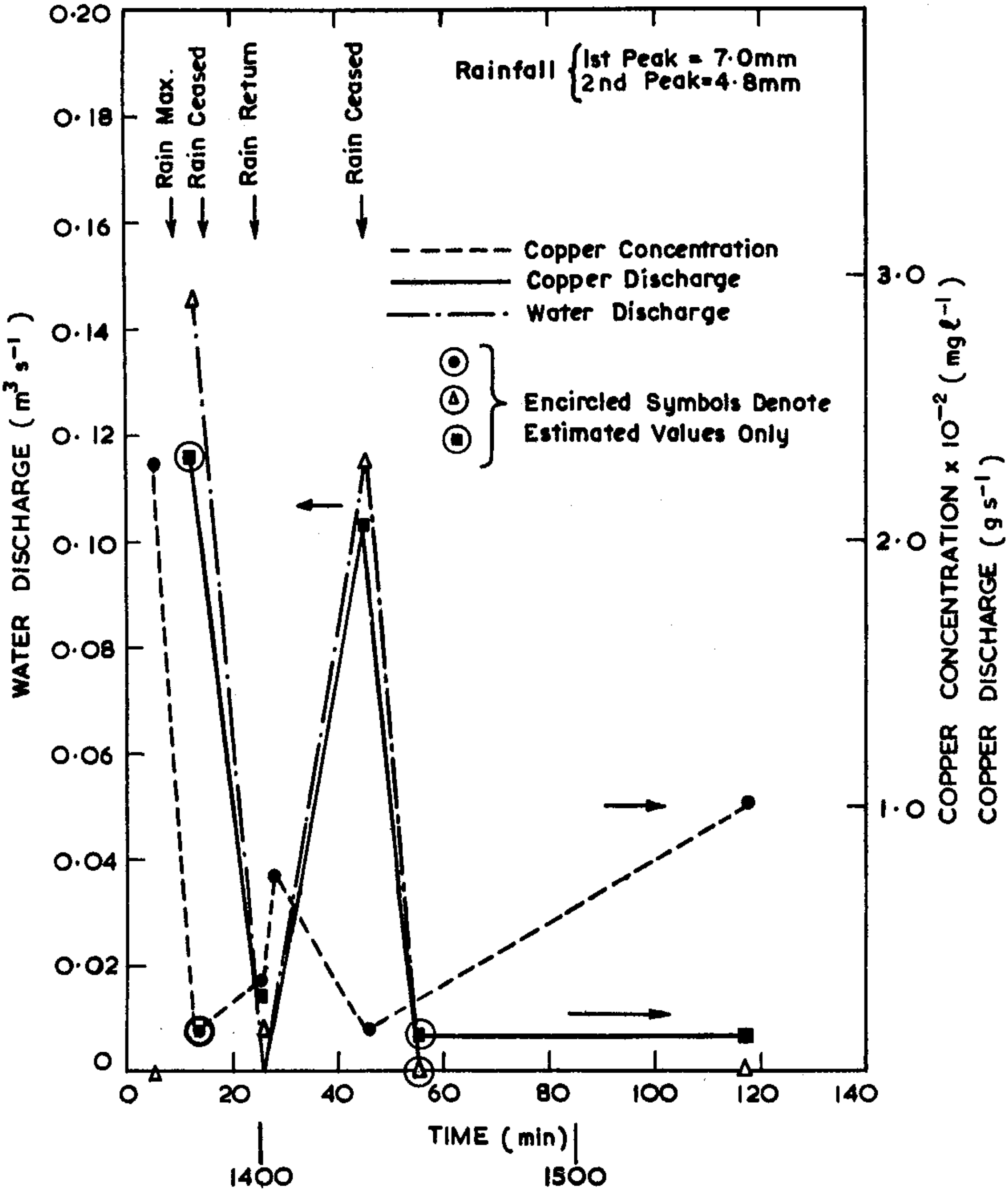
TIME DEPENDENCE OF DISCHARGE FROM SPRINGS ON DYSON'S OVERBURDEN HEAP

FIGURE 6.5



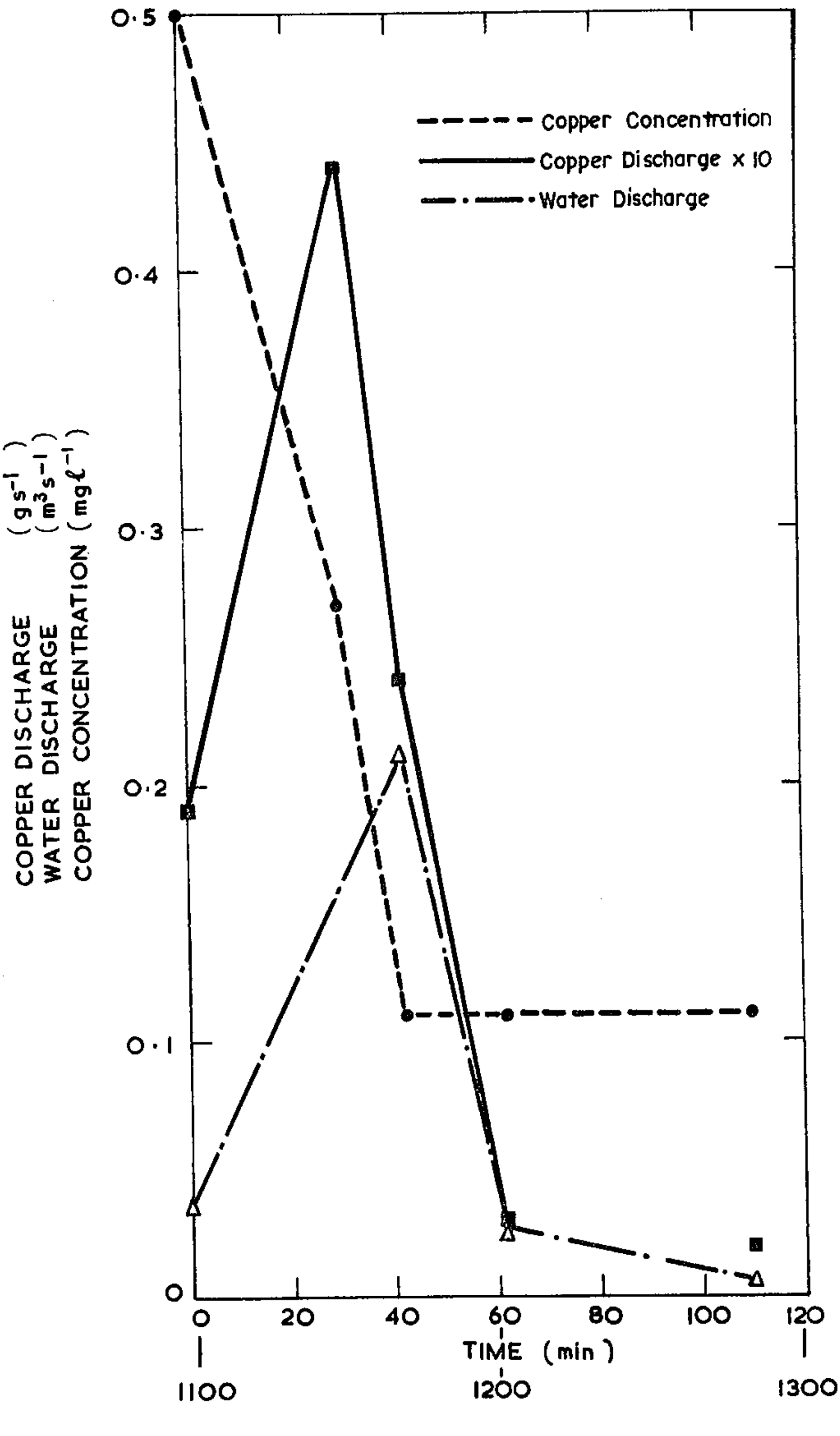
DISCHARGE RATES AND CONCENTRATIONS FOR RUNOFF DISCHARGE FROM WHITE'S HEAP 3-3-74

FIGURE 6.6



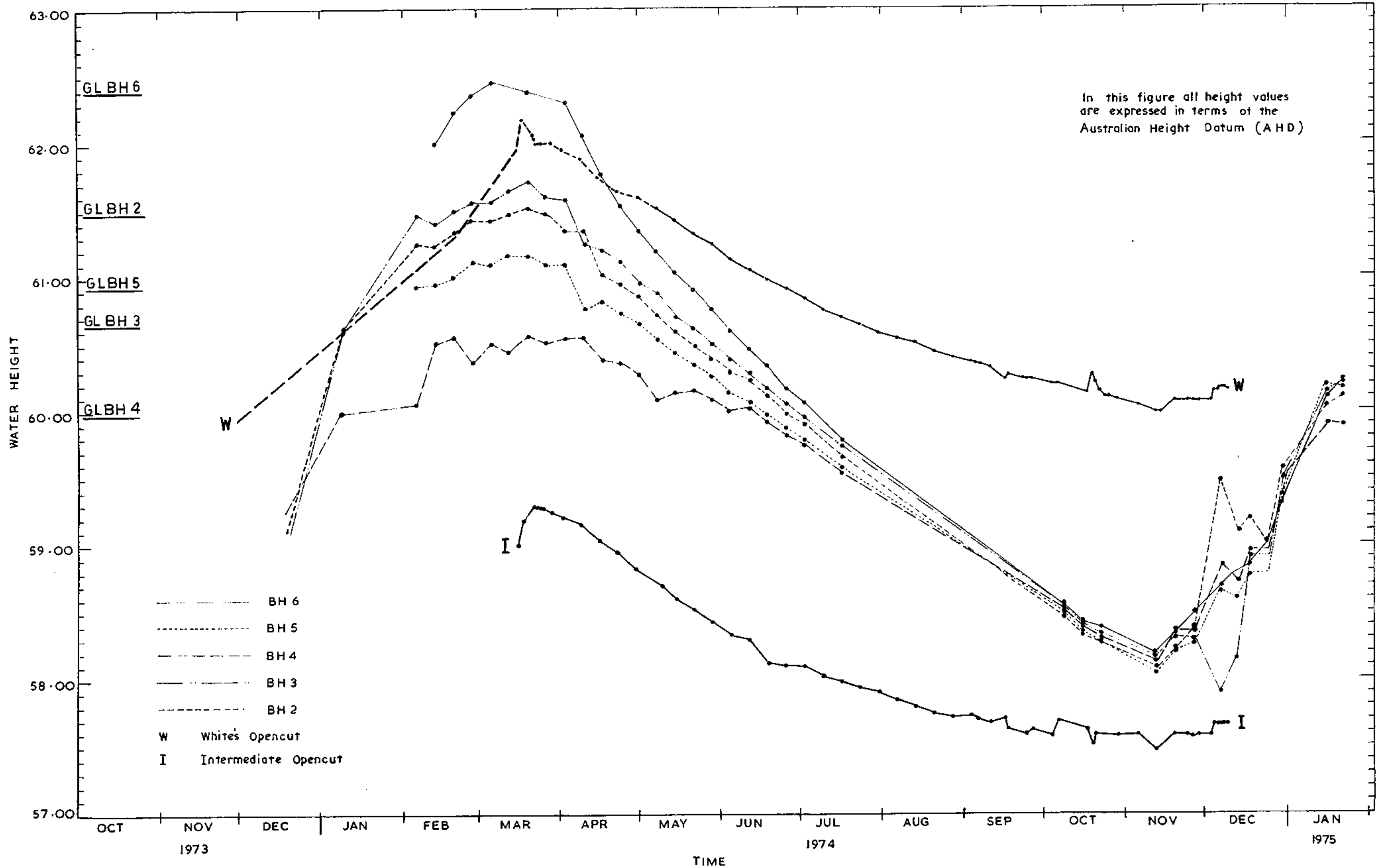
DISCHARGE RATES AND COPPER CONCENTRATIONS FOR RUNOFF DISCHARGE FROM INTERMEDIATE HEAP 7-3-74

FIGURE 6.7



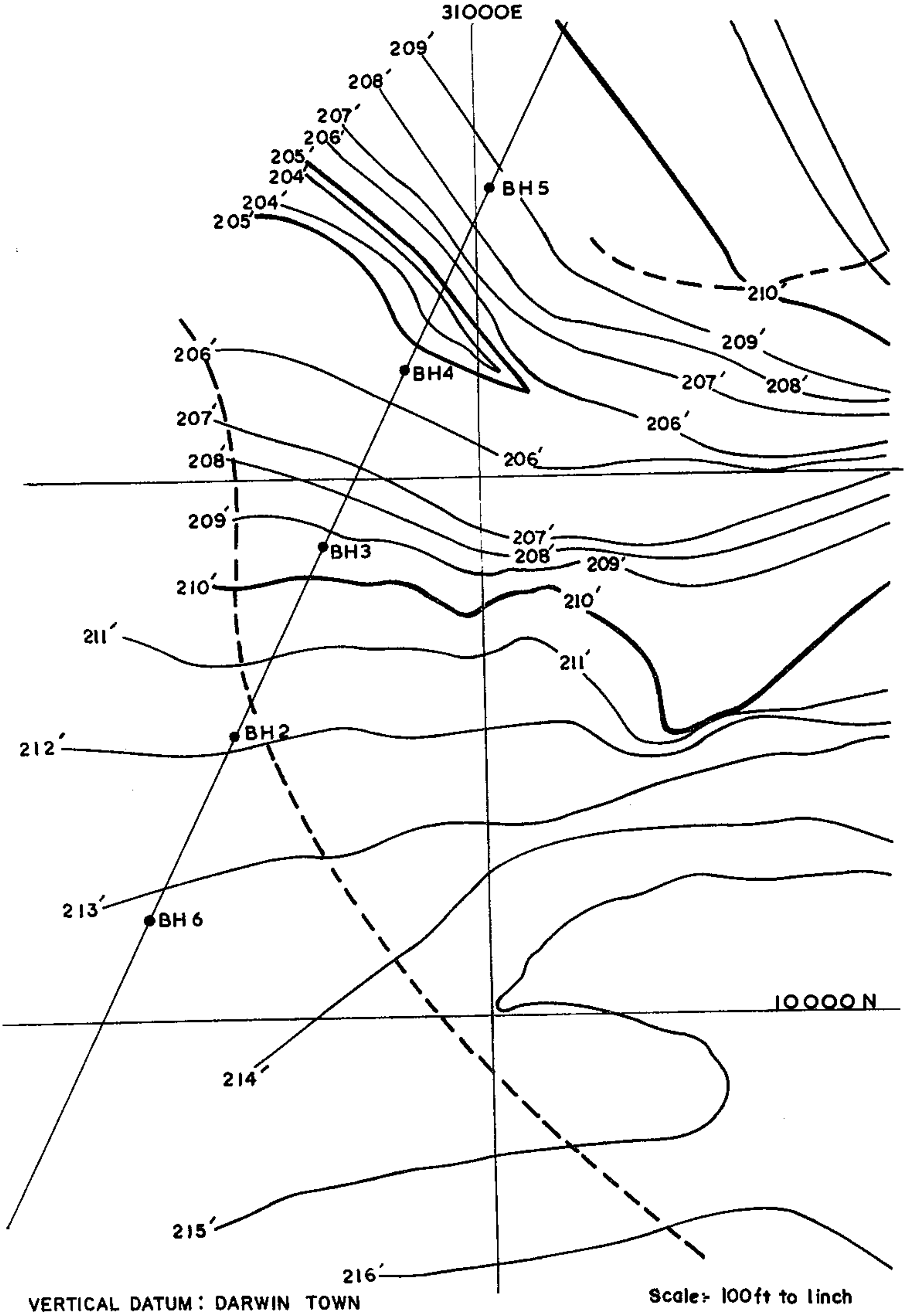
DISCHARGE RATES AND COPPER CONCENTRATIONS FOR RUNOFF DISCHARGE FROM DYSON'S HEAP 10-3-74

FIGURE 6.8



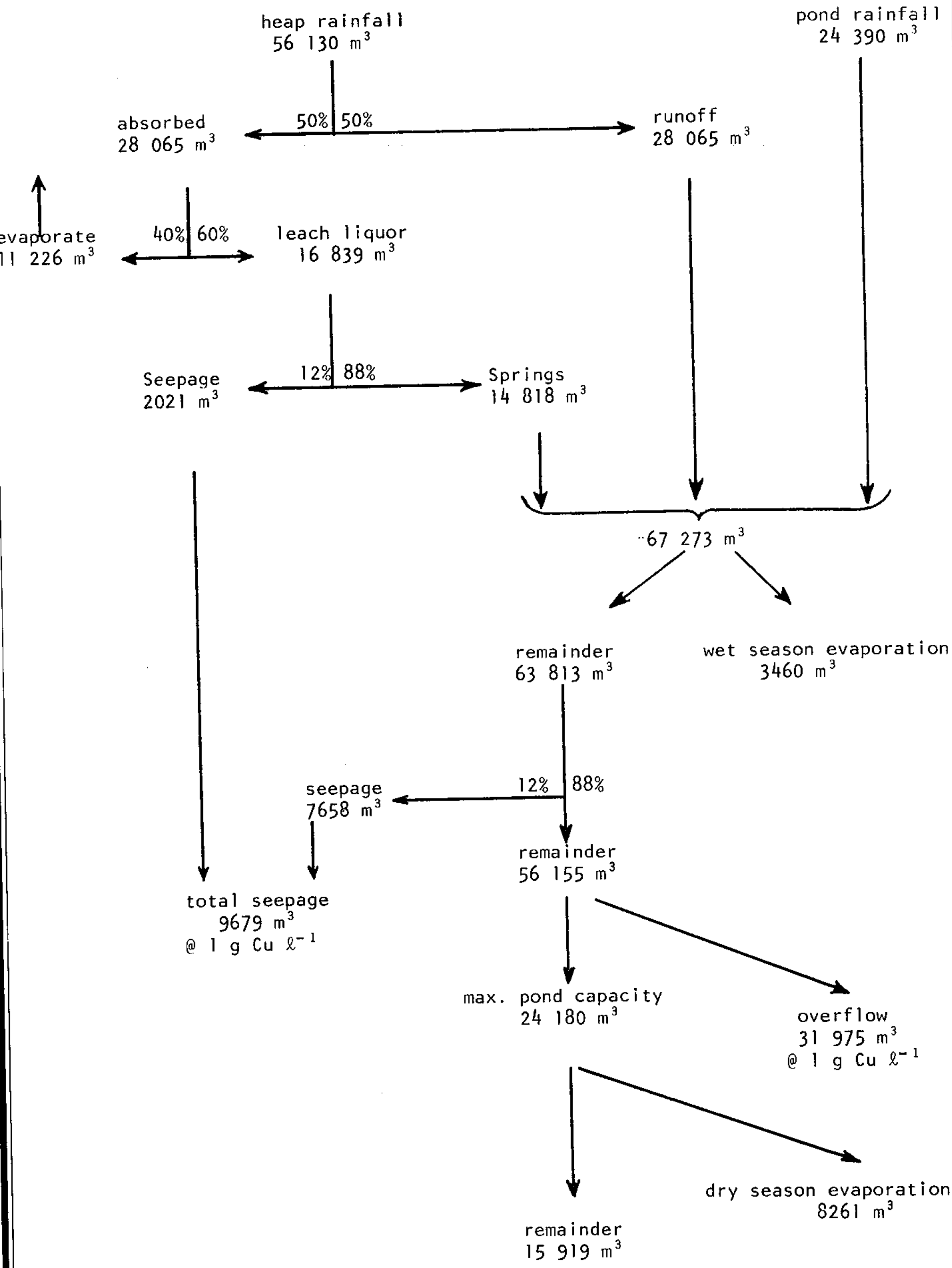
CHANGE IN WATER HEIGHT IN BORE HOLES (BH1 - BH6), WHITE'S OPENCUT (W) AND INTERMEDIATE OPENCUT (I)

FIGURE 6.9



LOCATION OF BORE HOLES IN TAILINGS DUMP AREA

FIGURE 6.10



WATER ACCOUNT FOR THE 73-74 WET

FIGURE 6.11

RUM JUNGLE ENVIRONMENTAL STUDIES

CHAPTER 7

BIOLOGICAL INDICATIONS OF POLLUTION OF THE FINNISS RIVER SYSTEM ESPECIALLY FISH DIVERSITY AND ABUNDANCE

by

R.A. JEFFREE

N.J. WILLIAMS

ABSTRACT

A study was conducted on the effects of pollution in the Finniss River system on the distribution and abundance of aquatic animals.

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CONTENTS (Continued)

CONTENTS (Continued)

7. BIOLOGICAL INDICATIONS OF POLLUTION OF THE FINNISS RIVER SYSTEM, ESPECIALLY FISH DIVERSITY AND ABUNDANCE

7.1 Introduction

The Finniss River (FR) system of the far north of NT contains a freshwater fish fauna* of approximately 20 species, as well as many invertebrates†. Concurrently with an extensive investigation of the chemical nature of pollution known to result from the aftermath of mining and milling for copper and uranium at Rum Jungle (RJ), information was gathered on the direct effects of the pollution on the distributions and abundances of the aquatic animals.

A preliminary survey of the fishes was conducted by A.H. Midgley in August 1973 under contract to the Australian Atomic Energy Commission. That survey pointed to the likelihood of a depletion in number of species in FR downstream of the confluence with the East Branch (EB) and an absence of fishes in EB downstream of the mined area.

The study of fish was indicated partly because of the ready appreciation of their importance by the public at large but in the main for the following interrelated reasons:

(i) fish are known to be intolerant of heavy metals,

(ii) the number of species is large, with great diversity in structure, physiology, behaviour, foods, and size, and

(iii) they are highly mobile, being able quickly to recolonise any stream section should the pollutant levels fall to allow it.

No collecting could be made during the Wet because access roads become bogs and the river flows swiftly. Four field trips were able to be conducted: one towards the end of the 1973 Dry, (October-November) and three during the 1974 Dry(May-June, August-September, November).

The fish species found are listed in Table 7.5. Elsewhere in this report only the genus has been used to indicate genus and species. It became apparent that two species of *Neosilurus* occurred, a small headed, short snouted, yellow tailed species and another (more common) which was more uniformly brown. Great variation occurred in body and head shape of the *Hephaestus* and two species are thought to have occurred. However, for all the comparisons the simplification is made that only one species occurred in each genus.

As many specimens as possible of fishes and invertebrates have been lodged with the Australian Museum.

---

* Pollard [1974] has surveyed the fishes of the Alligator Rivers area of the NT. No clearly different form has been found in the FR system which has not been recorded by Pollard.

† Invertebrates were identified mainly from W. Williams' [1968] handbook except for crustaceans when reference was made also to Riek [1951a, 1951b, 1953 and 1969].

7.2 Sampling

Six sites were occupied regularly along the FR proper. Two were upstream of EB, the major channel for input of pullutants, and four downstream, the most downstream site being below the confluence with another major perennial tributary, Florence Creek (FC). Map 7.1 locates these six sites where nearly all collecting was carried out. Sampling along EB was usually confined to seining and scooping using nets. After the first field trip, trip 1, searching and sampling were mainly limited to those EB sites marked on Map 7.1.

In order to attempt a comprehensive and partly quantitative collection of the fish species present in FR, the following methods of collecting were used where possible:

- entangling during the night in enmeshing nets of bar mesh sizes ranging from 12 mm to 75 mm set in the pools;
- poisoning during the daytime using the insecticides rotenone and pyrethrins in channels, embayments, and isolated pools;
- trapping overnight using fyke nets of bar mesh size about 3 mm set in the shallower parts of pools;
- seining during the daytime using mosquito or finer netting ('marcasite', a Terylene fabric);
- searching and scooping by spotlight at night;
- angling in the daytime using lures and small baited hooks;
- scooping and simply observing at any time.

Methods which could be used at all six sites were enmeshing, poisoning and spotlighting, and these yielded the most useful numerical data for comparing the sites. Fishing effort by enmeshing and spotlighting was nearly uniform over the sites during any trip.

Invertebrates were sampled qualitatively mainly by searching, especially in very shallow water where stones occurred, and by placing artificial substrates (trays of stones, baskets of pipes). Other invertebrate material was obtained during netting, spotlighting and poisoning.

7.3 Fishes in the Finniss River

7.3.1 Description of the Finniss River

The FR proper consists typically of a series of long still pools of about three metres depth with flat bottoms, fringed with trees, shrubs and bamboo, and connected by shallower sections running over gravel, sand, and root networks or amongst a tangle of *Pandanus* palms. The more downstream pools have greater maximum depths than the more upstream ones. The banks of the pools are usually steep and concave below water level, often with a slope as great as about 80° at the water surface. The relative amount of shoreline occupied by *Pandanus* palms is at a minimum closely downstream from the FR-EB junction. During the Wet the river rises and there is repeated overbank flow; this makes the speed of flow along the river, and the depth, more uniform than is the case during the Dry. Table 7.1 contains a summary description of the sites, where most samples were taken, as they appear during the Dry. Adjacent to both perennial and intermittent streams of the FR system are some waterholes, usually not connected to a stream during the Dry.

Table 7.2 shows the concentrations of selected inorganic constituents during the periods of the four field trips. The transition elements, 'heavy metals', have low concentrations at sites upstream of the FR-EB junction and in FC at all times; during the cessation of flow in EB all sites show low values.

The pH in FR ranged from 6.5 to 7.5 at and just downstream of the EB junction with one exception. When EB was flowing the pH fell to as low as 5.5

Temperatures ranged uniformly along the river from about 16°C during trip 2 (midwinter) to about 30°C during trips 1 and 4 (early summer, before the Wet).

7.3.2 Influence of the method of catching

The species caught varied with the method used; for example the species *Fluvialosa, Hephaestus, Hexanematichthys, Lates, Megalops* and *Toxotes* were taken almost solely by enmeshing nets out of the three main methods; and *Craterocephalus* by poisoning. Table 7.5 shows the distribution of species over the methods, grouped for all sites and for trips 1 to 4 (no spotlighting was done during trip 1). For these comparisons catches made in 12 mm enmeshing nets have been excluded.

Spotlighting and poisoning showed the greatest tendency towards sampling the same species, whereas enmeshing and spotlighting showed the least tendency (Figures 7.1 and 7.2). It is concluded that the two methods of enmeshing and of spotlighting are largely independent methods for determining the species composition at any sampling site.

7.3.3 Taken in enmeshing nets

7.3.3.1 Mesh size 25 mm and greater

The accumulated number of species caught increased from trip 1 to 4 at each site. There were differences between the sites both in the number of species taken during each trip, and in the accumulated number of species (Figure 7.3). Those sites closest downstream of the EB junction showed lower values than those upstream or far downstream. Even those species found most ubiquitously showed a less frequent occurrence in the nets downstream of the junction (Figure 7.4). Certain species showed this disparity very clearly, e.g. *Amniataba, Neosilurus, Strongylura* and *Toxotes*.

At both sites 6 and 2 the number of species declined over the 1974 Dry, to approximately half the initial values (Table 7.6 and Figure 7.3). However, at site 2 the numbers of individuals were always very low excepting in the single species *Megalops* (Table 7.7); hence no obvious importance can be attached to the decline in number of species at site 2. At all sites most distant from (or upstream of) the point of entry of pollutants, i.e. sites 6, 5, 2 and 1, the numbers of individuals (of the most abundant of the species in the catches, Table 7.7) declined by at least 50% from trips 3 to 4, but only site 6 showed this decline markedly over all species (Figure 7.5, logarithmic scale). Site 6 showed a decline over the Dry in number of individuals for every species which in any of the trips yielded 4 or more individuals, and for the rarer species no increase.

These declines may be partly attributable to depletion by the fishing effort especially for site 6 because, although site 6 has a downstream connexion with a much larger pool which presumably offers a much larger stock of fish, this connexion at its shallowest part was only about 6 cm. Apparently only a small stock was in fact available to the nets at site 6, but to attribute the decline solely to the fishing effort would seem to require the netting to be too effective (catching about 6 of every 7 catchable fish present). Other factors of natural mortality or behaviour must therefore have contributed to the decline.

Figure 7.6 shows that the relationship between the number of species caught and the number (log_{10}) of individual fish caught was similar for all sites and all trips. Site 1 showed relatively more individuals; this is explained by the very high catches of the three species *Fluvialosa, Megalops,* and *Neosilurus*, which numerically dominate those catches. This constancy of numerical relationship masks the fact that some species, e.g. *Amniataba, Hephaestus, Neosilurus* and *Toxotes* which were abundant at sites upstream from the EB junction, were absent immediately downstream of it. The samples enmeshed at the sites differed not only in the numbers of individuals of the species found, but also in their species compositions.

Some parameters of the habitats - the pools in which the enmeshing nets were placed - were examined for their relationships with the catches. Length of the pool, width, area, central area (meaning the total area minus a strip 3 m wide around the periphery), and amount of overhanging vegetation within about 50 cm of the water surface were chosen. Other parameters which might be expected to be significant by functioning as sheltering or spawning places for the fish species present, would include extent of undercut banks, amount of logs, amount of submerged roots as sheltering places; but it was not possible to estimate them. Those relationships found after transforming the data to eliminate pronounced curvilinearity are shown in Table 7.8. The significance of the correlations corresponds in some cases to an obvious correlation between the habitat parameters themselves. The parameter 'amount of closely overhanging vegetation' (length of pool multiplied by degree so vegetated) correlates significantly for trips 1 to 3 with number of species caught, with number of individuals of all species caught, with numbers of individuals of *Fluvialosa* caught, but for trip 4 only with number of species. Species other than *Fluvialosa* and *Megalops* were not usually caught in sufficient numbers to allow such comparisons.

The sample linear regressions of estimated numbers of species ($\hat{Y}$) on amount of closely overhanging vegetation (X) for the four trips are:

Trip 1	$\hat{Y} = 0.3 + 4.3\ X$
Trip 2	$\hat{Y} = 2.0 + 4.7\ X$
Trip 3	$\hat{Y} = 2.0 + 4.2\ X$
Trip 4	$\hat{Y} = 2.8 + 2.5\ X$.

Trip 1 is not discussed further owing to the great difference in the fishing effort between it and the subsequent trips which all had a similar fishing effort. The slope of the sample regression line decreases from trip 2 to trip 4, i.e. over the Dry, indicating that the amount of closely overhanging vegetation becomes less of a 'determinant' of number of species as the time elapsed, since the Wet, increases.

A partial recovery of the fish fauna during the Dry would be indicated if the distributions of the fishes came to correspond less to the distance from the point source of pollution or to any parameter highly correlated with such a distance. The following points favour a partial recovery:

- (i) the reductions in slopes of the sample regressions of numbers of species on amount of closely overhanging vegetation;
- (ii) the lack of correspondence of numbers of *Fluvialosa* with distance from the point of pollutant input, i.e. the recovery at site 4 during trip 4 (Table 7.7); and
- (iii) the lack of correlation of catch in number with amount of closely overhanging vegetation in trip 4 (Table 7.8).

Points (i) and (iii) depend partly on the occurrence and abundance of *Fluvialosa*, so the evidence for recovery is not strong.

7.3.3.2 Mesh size 12 mm

These catches were sparser in individuals and species than those of the sets of nets of 25 mm and greater. A total of eleven species were taken. There is no correlation between either number of species or total number of individuals and any of the environmental parameters. However, the numbers of *Nematocentrus* showed a generally inverse relationship compared with the catches made in the nets of larger mesh size: this species was generally most abundant at sites 4 and 3, those just downstream of the input of pollutant. The catches for *Nematocentrus* are plotted in Figure 7.7.

These greater abundances of *Nematocentrus* at sites 4 and 3 both relative to other species at these sites, and to the abundance of *Nematocentrus* at other sites, remain unexplained but indicate that the species is more tolerant of exposure to the pollutant complex. The following explanations are therefore suggested, some or all of which may be valid:

- the species is more tolerant of exposure by immersion, rather than by ingestion;
- its diet consists largely of allochthonous items;
- it is favoured by deep or moderately deep water near banks with little overhanging vegetation; and
- other species are insufficiently abundant to reduce its abundance by competition or predation.

7.3.4 Observed by spotlighting

There was a marked reduction in the number of species observed at sites 4, 3, and 2 compared with the sites upstream or farthest downstream of the EB junction (Figure 7.8). The three species *Mogurnda*, *Melanotaenia*, and *Nematocentrus* were observed at nearly all sites and were generally the most common - even at those sites with many other observed species. Figure 7.8 also shows that the number of species observed increased from trips 2 to 4, in general for all sites. This could have resulted from greater skill in searching, but at least two other causes may be involved:

(i) seasonal factors such as higher water temperature, and

(ii) recovery of the fauna (especially at sites 4,3, and 2) by immigration or reproduction over the Dry during which the FR flows continuously past the nondischarging EB.

There is some evidence from the catches made in enmeshing nets that a partial recovery occurred in that set of species (Section 7.3.3.1).

Since a similar effort was expended at all sites in searching by spotlighting, it is concluded that most species of those available to the method of spotlighting were either rare or absent at those sites most nearly below the EB junction.

7.3.5 Taken by poisoning

Some catches were numerically strongly dominated by one species, others were less so. Figure 7.9 gives examples of the types of relationships found between the number of individuals of a species and the rank of that species in abundance in any poisoning. For assemblages a number of derived parameters called diversity indices, have been used to describe the composition numerically. Heip & Engels [1974] discuss and compare the usefulness of using one or more parameters of diversity.

In this investigation an 'evenness component' was used as an index of diversity additional to the number of species. Evenness components are the values of the slopes of the sample regressions of $\log_{10}$(number of individuals) with rank of the species where the most numerous has rank 1, and so on. As the evenness component becomes more negative the distribution of individuals amongst the species becomes less even.

Tables 7.9A and 7.9B list the numbers of species and the evenness components for the catches. Three of the catches were from pools with only a shallow narrow neck connecting them with the mainstream; of these three, one was at site 1 and had moreover been only recently connected owing to a rise in mainstream level. Since all other catches were from pools or embayments with more permanent, or wider and deeper connexions, or from channels of the mainstream, these three poisoning catches were eliminated in constructing Table 7.9B. This table shows that upstream of the EB junction and in FC (also upstream of any pollutant) evenness did not attain such high absolute values as downstream of it, and that the numbers of species were greater, i.e. species diversity was in both respects greater where there was no input of pollutants. Neither number of species nor evenness can be shown to change with advance through the Dry.

A number of habitat parameters were examined for correlations with numbers of species and numbers of individuals. Four of these parameters: depth of connexion with the mainstream, maximum depth, amount of shading, and coarseness of the substrate, showed no correlations, but two parameters did. These are $\sqrt{(\text{area})}$ and another parameter called $\log_{10}$(breakup x area). For this parameter all habitats were ranked for heterogeneity of structure and extent of potential shelters for small fish, where 'breakup' is the proportion of the substrate which consists of undercut bank and is occupied by logs, roots, and litter as estimated by observation using polarising spectacles. The ranked habitats were divided into four groups where successive groups were related by the factor 1.5, so that they were assigned the four values of 8, 12, 18, 27. We are not especially confident that any particular habitat would not properly belong in an adjacent group, but are certain that it could not be placed two groups away. For the two parameters all the sample correlation coeffients are positive although few of the separate values differ significantly from zero. For numbers of individuals only one single sample correlation coefficient is significant, i.e. that of those collections taken upstream of all pollutants, with $\log_{10}$(breakup x area). For numbers of species the sample correlations with $\log_{10}$(breakup x area) are in general more significant, i.e. the probabilities are lower, than those sample correlations with √(area).

Adjusted numbers of species were derived based on the sample regression for trip 4 since that trip occurred the greatest time after cessation of flow in EB. These adjusted values are plotted in Figure 7.12A. In Figures 7.12A and 12B sample means have been calculated firstly for each trip if necessary, and then for each site. Figure 7.12B plots the accumulated number of species against the accumulated effort (the number of pools poisoned with each adjusted for its habitat parameter $\log_{10}$(breakup x area)) and shows that for any convex curve site 3 clearly yielded fewer species than other sites.

A decline over the Dry (with evenly spaced trips) in numbers of individuals per poisoning is shown by Figure 7.10. The regression of $\log_{10}$(number of individuals) (Y) on trip X over the Dry is

$$\hat{Y} = 2.5 - 0.2 X .$$

Correlations between the adjusted number of individuals and the habitat parameters of √(area) and $\log_{10}$(breakup x area) are listed in Table 7.10. For most poisonings there was a large majority of one or more of the species *Mogurnda, Nematocentrus*, or *Melanotaenia*. Partitioning the catches to allow analyses for the separate species may show that more sample correlations with habitat parameters are significant.

From Table 7.12 it can be seen that of the parameters correlated with numbers of species the more significantly correlated one, $\log_{10}$ (breakup x area), had the more constant values. Further, a one-sample runs test applied to the distributions of the occurrences of the species over the poisoned pools and embayments (when they were arrayed greatest to least value of the parameter $\log_{10}$(breakup x area)) showed no deviation from randomness. The only non-random tendency was with numbers of species as indicated by the sample correlation coefficients (Table 7.11, upper part). Although the data are limited, the indication from the increase in the sample correlation between number of species and $\log_{10}$(breakup x area) from trips 2 to 4 for all sites towards a value as great as that for the sites with no pollutant (sites 6, 5, and FC) is that there is recovery through the Dry towards a more normal or unpolluted state.

7.3.6 Total numbers of fish species by all methods

Figure 7.13 plots the total number of species found at each site for each trip by all methods. There is of course no weighting for effort, but these most inclusive data are consistent with the evidence from enmeshing, spotlighting, and poisoning, when these three were considered separately.

7.4 Fishes in the East Branch

7.4.1 Description of the East Branch

Tables 7.3 and 7.4 briefly describe those places where most collections were taken. EB flows into FR at the beginning of the Wet and usually ceases in the early Dry, about June (see Chapter 3). A small flow at a rate measured in litres per minute may persist in several sections of EB or from tributary springs without surface discharge into FR. The stream contains numerous permanent pools of sizes and depths as great as those listed in Table 7.3. No rooted emergent or submerged plants were found. Vegetation along the banks which consisted of trees, herbs, and grasses was not dense. Live *Pandanus* palms were rare; some dead *Pandanus* stumps occurred at EB site 4 and upstream. Shallow gullying, gently sloping banks, and large deposits of non-vegetated sand along the banks indicate that erosion and consequent deposition were appreciable and continuing because the soil is not stabilised by roots.

Table 7.4 lists the concentrations of the major inorganic constituents found in EB during the periods of the field trips. Values for the heavy metals Cu(II), Zn, Co and Ni are generally very high, while the pH is as low as 3 in the middle reaches. During the early part of the Dry, EB discharged a solution of heavy metals lethal to most aquatic organisms into FR where the perennial stream dilutes it greatly. During the Wet the concentrations of heavy metals reached low levels (Chapter 3).

7.4.2 Fish species in the East Branch and tributaries

Apart from the fishkills (Table 7.19) in the stream section downstream of the mined area, a number of species of fish were found in tributaries. These are listed in Tables 7.13 and 7.14B. By virtue of their physical and structural characteristics, the pools of the EB system could be expected to contain a number of species of fish at least similar to that found by poisoning at site FC with little effort (seven species, (Table 7.5D)) but fish are virtually absent. The concentrations of the metal ions Cu(II), Co, Ni and Zn are too high to allow their survival (Table 7.4).

7.5 Invertebrates in the East Branch and the Finniss River

Tables 7.14A, 7.14B, 7.15A, 7.15B Part 1, and 7.15B Part 2, list the invertebrates of FR and EB. Some families of insects occur abundantly in EB; nearly all of them have a rather impervious cuticle and obtain atmospheric or dissolved oxygen through bubbles. Two phyla, Mollusca and Porifera, and a major class of Arthropoda, Crustacea, occurred in FR but were not found in EB downstream of the mined area. Within the Insecta, many groups (Orders and Families) known of general importance to fish as dietary items and as indicators of an unpolluted state, occurred in FR but were not found in EB. The following list summarises the groups found exclusively in FR proper:

Mollusca	-	bivalves, snails, limpets;
Porifera	-	sponges;
Crustacea	-	shrimps of two families, crayfish, crabs; and
Insecta	-	mayflies of three families, caddisflies of three families, dragonflies, damselflies, flies and midges of three families, moths.

7.6 Fishkills*

Minor to moderate fishkills were observed on 8-9.11.73 and 19-20.11.74 in FR downstream of the EB junction, on 22-23.5.74 in the EB at EB sites 3 and 4, and on 8.6.74 at EB site 8A1.

7.6.1 Finniss River, November 1973

Chance observation that EB well upstream of the FR junction had risen led to the first recorded fishkill at the junction. The streams mixed forming a cloudy precipitate, together with formation of a stable foam (see Plate 7.2). Along the shore many dead fish were recovered and moribund ones scooped up. Table 7.16 lists the species found over a shore length of approximately 500 m.

The concentration of copper reached a very high level, presumably momentary, at 50 mg dm^{-3} (see Table 7.2 for fuller details and comments). Downstream as far as the FC confluence the copper concentration was

* As used in American Public Health Association 'Standard methods for the analysis of water and waste water' 13th ed. Wash. D.C. 1971.

measured at 0.1 mg dm^{-3} two weeks after the fishkill was observed. At site 3 the copper concentration was still 0.9 mg dm^{-3} three days after the fishkill. Cobalt, nickel and zinc were discharged from EB in appreciable quantities as well as large amounts of sulphate and acidity (see also Section 7.3.1).

Catches made with 12 mm enmeshing nets at sites 3 and 2 before and after this observed flow by EB are shown in Table 7.17. Unfortunately, since nets of appreciable fishing power of other mesh sizes could be used only after the date of the fishkill no additional comparison is possible. The reduction in number of individuals and in number of species at each site within one week of the entry of pollutants is clear.

It was possible to follow the progress of the fishkill for only 6 hours. During that time it did not extend further than 2 km downstream. Overnight further rains fell in the area. causing a sharp rise in the FR which ameliorated the pollution at the acutely affected site 4.

7.6.2 Finniss River, November 1974

Observations could be made only after two or three days had elapsed since EB began to flow into FR. It was not known, from the occurrence of the thunderstorms, on which day flow first occurred. Table 7.16 lists the species found over a total distance of 4 km where observations were scattered along the river at points of access.

The concentrations of copper, cobalt, nickel and zinc were raised by the inflow from EB, although the dramatically high concentrations noted for the first fishkill were not observed. An increase in the concentrations of these metals was again observed as far downstream as site 1 several days after the observed fishkill.

Catches made at site 2 with enmeshing nets of 12 mm and of 25 mm and greater are listed in Table 7.18. The reductions in number of individuals and in number of species were slight but agreed with the 1973 results for sites 3 and 2. No rise in FR occurred to possibly ameliorate the pollution, within the period of observation.

7.6.3 East Branch, May-June 1974

Table 7.19 lists the species found dead or moribund at EB sites 3, 4 and 8A1. Several specimens only were found at EB site 8A1. Nothing is known of the possible extension by these species of their range into EB site 8A1 during the Wet. Observations during the Dry indicated that they did not usually occur. Table 7.4 gives the water quality over the periods of the field trips.

On 22.5.74 both live and dead fish were observed at EB site 4. A shoal of many hundreds of *Melanotaenia* were swimming actively within several metres of the junction with a small tributary creek. Several individual *Mogurnda* were seen to pass to and from the small creek through the connexion which was about 1.5 cm deep. On 23.5.74 no live fish were found in EB; the connexion was broken. Downstream of this point, dead fish were recovered both upstream and downstream of the junction with another creek (EB site 2A) with EB, at EB sites 3 and 2. Specimens of *Melanotaenia* swam weakly, losing position in the slow flow below that creek. *Melanotaenia* were abundant and vigorous in both of the tributary creeks.

It is suggested that during the Wet, either sections of EB become temporarily inhabitable by fish, depending on the relative flows from tributary creeks, or that a combination of downstream drifting at night, flushings during rainstorms, and contractions of the available stream habitat lead to the penetration of some species of fish into EB where they subsequently die.

7.7 Discussion and Conclusions

The high concentrations of heavy metals and the low pH of EB (Table 7.4) would indicate that few aquatic species of animal can survive in the EB downstream of the mined area. This has been confirmed. Hart's [1974] extensive literature survey reported that zinc and copper were lethal (i.e. killed 50% of a sample of individuals over a fixed period) to fish for example, at concentrations as low as 0.1 mg dm^{-3} and deleteriously affected fish down to 0.01 mg dm^{-3}. The effect also depended on the concentrations of other ions; in particular a low pH (below neutral) enhanced the toxicity. Giles [1974] found that copper at about 0.1 mg dm^{-3} and zinc at about 0.3 mg dm^{-3} were lethal to species of the Alligator Rivers area; the same or very similar species occur in the FR system.

Erosion of the stream banks, absence of rooted aquatic plants, and destruction of closely overhanging *Pandanus* palms have been observed along EB. Some species of fish and crustaceans have been taken from unpolluted EB tributaries and these and similar species, as well as a rich assemblage of other invertebrates would be expected naturally to be found in EB too.

In FR proper, a correlation between the number of species of fish with the position relative to the input of pollutants coincides with a correlation with amount of closely overhanging vegetation; nearly all that vegetation is of *Pandanus* palms. This might indicate that the closely overhanging vegetation provides some component essential to the ecology of the fish species, not only of those species taken in enmeshing nets of large mesh size but also those species observed by spotlighting. However, this is a large assemblage of diverse species: the possibility that the reduced amount of closely overhanging vegetation directly and solely caused the general lack of fish is rejected. The possibility exists that the pollutants not only directly caused the lack of fish but altered other conditions (e.g. foods, bank structure) necessary for the presence of the fish. No literature on the tolerances of *Pandanus* could be located.

During the Wet, appreciable loads of heavy metals enter FR and reach 30 km downstream at levels which may still be deleterious to the fish although not rapidly lethal (Table 7.2: trip 1, site 1; trip 3, site 3; trip 4, site 1). The perpetual flow of FR past the junction with the seasonal EB leads to the inference that the strip of river affected adversely by the flow from EB will be reduced in extent, by flushing, as the Dry continues. Some tentative evidence was found for this from both the enmeshing and poisoning data.

Whilst the pollutants are most concentrated, during the first thunderstorms (over the EB catchment) at the end of the Dry, and also during the Wet at times when the flow rates fluctuate so as to increase the relative contribution of EB, their effects on the populations of fishes can be expected to be greater than the strict geographical limits of the damaging concentrations. Natural dispersal or migration by the fish along the river will result in the polluted section's becoming a sink for fish. The dividing up of the river into two sections separated by the sink will adversely affect especially those fish which might normally undergo any general movement or migration at times of high pollutant concentrations.

Other species may be affected by having access to more favourable localities restricted; for example if different sections of the river should contain different relative amounts of especially favourable habitat, but the current knowledge of the fishes' biology is too limited to allow more than this general comment.

Additionally, no information is available on the possible deposition of heavy metals in FR (onto sediments, algal or other surfaces) at times of higher concentration, and their release at lower concentrations over a more extended period; nor do we have information on the effects on land fauna which use EB as a source of water.

The aquatic fauna of EB has been almost wholly destroyed in the 10 km section downstream of the mined area, but in FR the effect has been less severe. Fishkills will regularly occur at the beginning of each Wet whenever a flush through EB does not coincide with a high flow in FR and provided that the fish populations have been able to be reconstituted from adjacent unpolluted zones (e.g. sites just upstream from the junction). Throughout the Dry the FR fish fauna is considerably reduced in number of species and in their abundances, and altered with respect to their relative abundances, over the first 15 km downstream of the EB junction, and is less affected over the next 15 km. At the level of precision of the biological observations made on the fauna, no effect of pollution could be detected at the site below the entry of Florence Creek.

TABLE 7.1

DESCRIPTION OF THE SITES SAMPLED ALONG THE FINNISS RIVER

Site	Distance from EB junction (negative if upstream of the junction)	Dimensions of pool m			Main vegetation at banks (percentages show approximate length of bank occupied)	Connexions with next pools
		Length	Range of width	Range of greatest depth along the pool		
6*	-18 km	250	10-25	2-2.6	Densely lined with *Pandanus* palms (100%)	Upstream: tangle of *Pandanus*. Downstream: riffle and channels through sand and roots.
5	-0.1 km	600	15-25	2.2-3.0	Densely lined with *Pandanus* (85%), many *Melaleuca* trees, and some patches of bamboo.	Upstream: tangle of *Pandanus*. Downstream: broad band over sand to site 4.
4	0.4 km	150	12-25	1.9-2.2	Numbers of *Pandanus* and *Melaleuca*, and some patches of bamboo.	Upstream: broad band over sand from site 5. Downstream: channels through sand and roots.
3a	1.8 km	150	15-20	1.8-3.0	*Pandanus* (30%) bamboo (30%), with some *Melaleuca*.	Upstream and downstream: channels through sand and roots.
3b	3.0 km	300	15-20	2.1-3.0	Similar to 3a.	Similar to 3a.
2	16.5 km	250	15-20	2.5-4.7	*Pandanus* (50%) few *Melaleuca*, few patches of bamboo.	Upstream: rapids and waterfall 1 m high from channels through sand and roots. Downstream: channels through sand and roots.
1	30 km	300	18-50	4-6.5	*Pandanus* (50%) many *Melaleuca*, some patches of bamboo, and other species totalling 100%.	Upstream: 1 m deep at constriction to further large pool which receives FC Downstream: channels through *Pandanus* and other species, with riffles.

* *See Plate 7.3*

TABLE 7.2

WATER QUALITY OF THE FINNISS RIVER AND FLORENCE CREEK

(filtrate, 0.45 μm pores)

Trip	Site	Na	Ca	Mg	Cl	SO_4	Al	Mn	Cu	Zn	Co	Ni	Explanatory Note
		Concentrations (or ranges) in mg dm^{-3}											
1	6		< 10	1.5		< 0.4	< 0.02	< 0.003	< 0.003	< 0.003	< 0.004	< 0.004	
			22	27		5.5	0.2			0.003		0.004	*(1)*
	5		< 10	4.2		3	0.07	< 0.03	< 0.03	< 0.03	< 0.04	< 0.04	
			24	31		25	0.2		0.06				*(1)*
	4		19	19		4	0.2	0.04	< 0.02	< 0.02	< 0.04	< 0.04	*(2)*
			72	75		820	6.6	7.9	53	0.75	6.6	6.4	*(3)*
			67	5.3					0.1	< 0.005	< 0.04	< 0.04	
			78	6.8					0.5	0.03	0.04		*(4)*
	3		19	21		2.4	0.1	< 0.03	< 0.03	< 0.02	0.04	0.04	
			8	3		3	0.2	< 0.03	< 0.03	< 0.02	< 0.04	< 0.04	
			19	18		23	0.6	0.1	0.3				*(3)*
			< 10	4.6		20	0.5	0.1	0.9	0.03	0.08	< 0.04	*(5)*
			27	6.3		19	0.1	0.04	0.1	0.02	< 0.02	< 0.04	*(4)*
	2		< 10	5.9		12	0.2	0.04	0.02	0.01	< 0.01	< 0.04	
			12	8.2		33	0.4	0.06	0.09	0.03			*(4)*
	1		< 10	2.8		6	0.5	< 0.03	< 0.03	< 0.03	< 0.04	< 0.04	*(5)*
			< 10	5.6		16	0.3	0.07	0.1	0.05	< 0.01	< 0.04	*(4)*
2	6		20			< 1	< 0.03	0.05	< 0.005	< 0.005	< 0.005	< 0.005	
	5		14			< 1	< 0.03	0.03	0.03	< 0.005	0.01	< 0.005	
			17					0.05			0.02	0.01	*(6)*
	4		17			54	0.4	0.6	0.02	0.01	0.1	0.1	
			18			69	2	0.9	0.7	0.2	0.2		*(7)*
	3	3	18	30	6	51		< 0.1	< 0.1	< 0.1		< 0.1	
		4	20	31		53		0.3					
	2		14			52	< 0.03	0.3	0.2	< 0.005	0.06	0.02	
	1	3	4	8	6	13		< 0.1	< 0.1	< 0.1		< 0.1	
3	6				2.7	3		< 0.01	< 0.01	< 0.01	0.01	< 0.01	
	5		22		3.4	10		0.03	0.01	0.05	< 0.01	< 0.02	
	3		23		1.3	125		0.6	1.0	0.8	0.4	0.4	*(8)*
	2		17		3.1	< 1		< 0.04	< 0.01	< 0.01	< 0.01	< 0.01	
			20			3							
	1a		15		3.7	27		0.3	< 0.01	< 0.01	< 0.01	< 0.01	*(9)*
	1		2.1		3.0	< 1		0.06	< 0.01	< 0.01	< 0.01	< 0.01	
			2.8		3.5	1.7		0.1			0.02		
	FC		0.6		2.8	< 1		< 0.01	< 0.01	< 0.01	< 0.02	< 0.01	
4	6	3.0	21	29	3.3	< 2.5	< 0.01	< 0.005	0.03	< 0.005	< 0.01	0.04	
	5	3.1	12	22	3.3	< 2.5	0.01	0.02	< 0.005	< 0.005	0.01	< 0.01	
		3.3	22	34	3.7	3.0			0.02	0.02	0.03	0.03	
	4	4.3	20	32	4.4	4.0	0.04	0.04	0.02	0.03	0.02	0.04	*(10)*
	4	2.9	18	26	3.3	30	0.3	0.16	0.3	0.06	0.04	0.04	*(11)*
	3	3.3	23	35	3.8	< 2.5	0.01	< 0.005	< 0.005	0.01	0.03	0.04	*(10)*
	3	3.0	13	26	3.3	26	0.06	0.15	0.2	0.04	0.04	0.05	
		3.6	19	28	4.0		0.1	0.16	0.3	0.05	0.05	0.08	*(11)*
	3a	3.5	20	31	3.8	33	0.09	0.2	0.3	0.04	0.08	0.06	*(11)(12)*
	3b	2.9	15	23	3.4	19	0.09	0.1	0.1	0.04	0.04	0.03	*(11)(12)*
	2	3.9	18	32	3.8	15	< 0.01	0.01	< 0.005	0.01	< 0.01	0.04	*(10)*
	2	3.5	20	34	4.2	22	0.01	0.06	0.03	0.01	0.02	0.03	*(11)*
	1a	4.5	13	19	4.3	14	0.05	0.1	0.03	0.09	< 0.01	0.05	*(9)(14)*
	1	3.4	7.4	13	3.2	4.8	0.09	0.05	0.01	0.06	< 0.01	< 0.01	*(14)*
	FC	2.5	0.8	1.6	2.6	9.0	0.08	0.05	0.07	0.06	0.04	< 0.01	
		3.2	1.1	2.6	2.7	15	0.2	0.06	0.1	0.09	0.05	0.02	

(1) The higher values occurred after rainfall in the catchment.

(2) Before the fishkill of 8-9.11.73 at site 4.

(3) During the fishkill of 8-9.11.73 at site 4.

(4) 8 to 16 days after the fishkill of 8-9.11.73 at site 4.

(5) 3 days after the fishkill of 8-9.11.73 at site 4.

(6) Site 5 receives a small pollutant load from Mount Burton Spring Creek (See Chapters 2 and 4).

(7) The concentrations near the end of the Wet fluctuate depending on the relative contributions of FR, Mount Burton Spring Creek, and EB.

(8) A thunderstorm occurred the previous day in the EB catchment.

(9) This sample was taken upstream of the FC confluence.

(10) Before the fishkill of 19-20.11.74 at sites 4 and 3.

(11) During the fishkill of 19-20.11.74 at sites 4 and 3.

(12) This sample was taken 2 km downstream of site 3.

(13) This sample was taken 4 km downstream of site 3.

(14) 4 days after the fishkill of 19-20.11.74 at sites 4 and 3.

TABLE 7.3

THE EAST BRANCH SITES SAMPLED

EB Site	Locality	Description
1	Large pool held at rocks, and shallow stream downstream to the FR junction	Pool 15 m wide, 40 m long, and 1.5 m deep (at least). Large sandbanks forming upstream end. Bottom of sand and tailings. Small number of *Pandanus* palms at steep left bank. Downstream EB is much shallower over gravelly sand occasionally with depths up to 50 cm. Banks gently sloping and appear eroded.
2	Downstream end of pool where creek of EB site 2A enters.	Pool 10 m wide, 100 m long and 1.5 m deep. Bottom and banks of fine sand and tailings. A fringing grass extends runners part of the way across the water.
2A	Creek from permanent spring.	Channel up to 50 cm wide, 100 m long, 50 cm deep. Surrounded by *Pandanus* and other trees. Much leaf litter on the bottom of fine sand.
3	Upstream end of pool EB site 2.	Rocks form banks, depth to 1.5 m.
4*	Immediately downstream of weir and stream gauging station of Water Resources Branch of Department of Northern Territory.	Pool 10 m wide, 120 m long and 1.5 m deep at one point only, mostly much shallower. Bottom of sand and tailings. Bank vegetation nearly absent. Dead *Pandanus* palms fringing the pool held by the weir. Banks sloping and appear eroded.
5	Ford and pool near railway bridge.	Riffles with pools of widths to 5 m and depths to 1 m. Bottom of gravel, sand, and tailings. Banks generally firm with herbs and grasses.
6	Batchelor-RJ mine roadbridge.	Pool 5 m wide, 30 m long, and 1.5 m deep. Bottom and banks of soft sand and silt. Few grasses and herbs at banks which are gravelly and firm.
8A1	'Sweet Dam', pool held by artificial gravel wall in Fitch Creek at its junction with EB.	Pool about 50 m wide, 100 m long, with large area deeper than 1 m. Bottom of silt and sand.
8A2	*Pandanus* swamp, a spring forming area, tributary to Fitch Creek.	Shallow dispersed patchwork totalling roughly 300 m^2 of water surface, depth up to 0.5 m. Herbs and grasses abundant with *Pandanus* palms.

* *See Plate 7.1*

<u>TABLE 7.4</u>

<u>WATER QUALITY OF THE EAST BRANCH</u>

(filtrate, 0.45 µm pores)

Trip	EB Site	Concentrations in mg dm^{-3}											Explanatory Note
		Na	Ca	Mg	Cl	SO_4	Al	Mn	Cu	Zn	Co	Ni	
1	9*		95	14		8	1.8	1.3	0.01	0.03	< 0.01	< 0.03	
	8A2		16	57		4	0.3	< 0.01	0.01	< 0.003	< 0.01	< 0.03	
	6		270	520		5000	85	50	65	12	24	24	
	6		150	480		3200	70	1.5	45	9	8	7	*(1)*
	5	32	200	220	55	2000	15	45	130	2.8	15	12	
	4		140	150		2200	31	23	250	2.0	21	23	
	4		80	65		900	18	8	40	2.1	6	4	*(1)*
	2A		37	32	6.0		< 0.02	< 0.03	< 0.03	< 0.03	< 0.04	< 0.05	
	1		120	120		1500	12	12	100	1.6	11	12	*(2)*
2	9		16	10				< 0.1	< 0.1	< 0.1			
	6		75	300				1.0	9	2.4		3.5	
	6							29	30	8			*(3)*
	5				17	830		9	7	1.1	2.8		
	5				31	1100		12	10	1.2			
	2A		30	30	6	2.0	< 0.03	< 0.005		< 0.005	0.007	0.01	
	1		70			700	0.5	8	2.6	0.6	1.8	1.9	
3	9		21			75		0.4	1.5	0.1	0.2	0.2	
	6		200		43	3300		31	32	11	12	15	
	6		160		16	6000		28	55	44	19	34	*(4)*
	5		160		43	1600		10	3.8	2.6	2.8	8	
	5		160		44	1500		12	3.2	2.6	3.3	2.5	*(4)*
	4		150	260	39	1400		12	1.9	2.0	2.4	7	
	4		140		40	1400		11	2.2	2.0	2.9	1.8	*(4)*
	3		120		33	1200		11	1.3	1.4	1.8	5	
	2		110		30	1100		10	0.9	1.2	1.6	5	
	1		38		10	280		1.5	0.03	0.02	0.1	0.2	
	1		50		12	350		2.2	0.19	0.05	0.3	0.2	*(4)*
4	9	4	3.6	8	8	35	0.4	0.3	0.8	0.1	0.1	0.1	
	8A2	4	2.9	11	7	10	0.03	0.02	< 0.005	0.05	0.03	0.03	
	6	12	94	330	10	1800	37	13	19	5	4	5	
	5	15	110	230	14	1400	22	10	46	2.4	6	5	
	4	13	86	210	16	1200	21	9	18	2.1	2.6	2.6	
	2A	2.2	26	33	2.5	<2.5	0.07	< 0.005	< 0.005	< 0.005	0.02	0.04	
	2	11	80	190	12	1100	18	8	16	2.1	3.1	2.4	
	1	10	64	160	6	860	6	7	13	1.0	2.1	1.9	
	1	6	40	76	7	440	0.08	2.5	2.1	0.8	1.0	0.9	*(5)*

* *Site 9 is at the upper limit of influence by the mined area.*

(1) *Five days after the FR fishkill of 8-9.11.73.*

(2) *During the FR fishkill of 8-9.11.73.*

(3) *At these middle reaches, the values increased sharply during the decline in flow rate of the stream near the beginning of the Dry.*

(4) *One day after a 20 mm thunderstorm in the mined area. At EB sites 5, 4 and 1 there was no evidence from discoloration or flow that the storm had occurred.*

(5) *After the FR fishkill of 19-20.11.74.*

TABLE 7.5

THE METHODS BY WHICH THE SPECIES OF FISH WERE TAKEN

A TRIP 1

	Site					
	6	5	4	3	2	1
Ambassis macleayi	af	c	d	b		bd
Amniataba percoides		ag	d	a	ab	bd
Craterocephalus stercusmuscarum	c	c	d	b	b	
Fluvialosa erebi	a	a		a	a	a
Glossamia aprion	ac	ag			ab	d
Glossogobius giurus						
Hephaestus sp.	a	ag			a	a
Hexanematichthys leptaspis		a				
Lates calcarifer						
Madigania unicolor	c			g		
Megalops cyprinoides	a	a			a	a
Melanotaenia nigrans	c	c	c	bc		
Mogurnda mogurnda		c	d	abdg		d
Nematocentrus sp.	af	ac	ad	a	a	d
Neosilurus sp.	a	a				a
Oxyeleotris lineolatus						
Prototoxotes lorentzi		a				a
Quirichthys sp.						
Strongylura krefftii		a			a	a
Synbranchus bengalensis						
Toxotes chatareus	a	ag				
Total number of species	11	15	6	8	8	11

TABLE 7.5 (Continued)

THE METHODS BY WHICH THE SPECIES OF FISH WERE TAKEN

B TRIP 2

	6	5	4	3	2	1
Ambassis macleayi	a	cde			d	a
Amniataba percoides	a	a	a		d	a
Craterocephalus stercusmuscarum	d			d		
Fluvialosa erebi	a	a			ad	a
Glossamia aprion	d	ad			a	
Glossogobius giurus	e	d				d
Hephaestus sp.	a	a	a			a
Hexanematichthys leptaspis		a	a	a		
Lates calcarifer	a				a	a
Madigania unicolor		a	d	a	ad	a
Megalops cyprinoides	a	a	a		a	a
Melanotaenia nigrans	de	cde	de	e	d	
Mogurnda mogurnda	de	d	de	ad	d	d
Nematocentrus sp.	ade	cde	ae	ad	d	
Neosilurus sp.	ad	a				a
Oxyeleotris lineolatus	d				d	
Prototoxotes lorentzi						d
Quirichthys sp.						
Strongylura kreffti	a	a	a		a	a
Synbranchus bengalensis						
Toxotes chatareus	a	a				a
Total number of species	16	15	9	6	12	13

TABLE 7.5 (Continued)

THE METHODS BY WHICH THE SPECIES OF FISH WERE TAKEN

C TRIP 3

	6	5	4	3	2	1
Ambassis macleayi	ab	d		b	d	
Amniataba percoides	a	a				ae
Craterocephalus stercusmuscarum	c	d		d		
Fluvialosa erebi	a	a	a		a	a
Glossamia aprion	acde	a	b		a	a
Glossogobius giurus	bd				b	de
Hephaestus sp.	ad	a	a			a
Hexanematichthys leptaspis						
Lates calcarifer		a			a	a
Madigania unicolor	d	a	a	a		de
Megalops cyprinoides	a	a	a	a	a	a
Melanotaenia nigrans	cde	d		bde	de	
Mogurnda mogurnda	de	d		bde	de	cd
Nematocentrus sp.	acd	ad	ab	abde	de	acde
Neosilurus sp.	abd	a	b			a
Oxyeleotris lineolatus	abd					ad
Prototoxotes lorentzi						
Quirichthys sp.	ce					
Strongylura kreffti	a	a	a	a	a	
Synbranchus bengalensis						
Toxotes chatareus	a	a				
Total number of species	17	15	8	8	10	12

TABLE 7.5 (Continued)

THE METHODS BY WHICH THE SPECIES OF FISH WERE TAKEN

D TRIP 4

	6	5	4	3	2	1	FC
Ambassis macleayi	b	e		d		e	d
Amniataba percoides		ad		d	d	a	
Craterocephalus stercusmuscarum	bc	c					d
Fluvialosa erebi			a			a	a
Glossamia aprion		ad	a	a	d		d
Glossogobius giurus	e	cde		d	e	d	e
Hephaestus sp.	a	a				a	a
Hexanematichthys leptaspis							
Lates calcarifer			a		a		
Madigania unicolor		a	a	a			
Megalops cyprinoides	a	a	a	a	a	a	a
Melanotaenia nigrans	de		d	de	de		e
Mogurnda mogurnda	de	de	d	d	d	d	d
Nematocentrus sp.	acde	cde	ad	ade	de	de	cde
Neosilurus sp.	a	a	a		a	a	d
Oxyeleotris lineolatus							
Prototoxotes lorentzi						a	
Quirichthys sp.	bce						
Strongylura kreffti	a	a	a		a	a	a
Synbranchus bengalensis	d						d
Toxotes chatareus	a	a					a
Total number of species	13	13	10	9	10	11	14

a Enmeshing
b Fyke netting
c Seining
d Poisoning
e Spotlighting
f Scooping
g Angling

TABLE 7.6

NUMBERS OF SPECIES OF FISH TAKEN BY ENMESHING NETS OF BAR MESH SIZE 25 MM AND GREATER FOR TRIPS 2 TO 4

Trip	Sites					
	6	5	4	3	2	1
2	9	10	3	1	6	10
3	9	10	4	1	4	8
4	5	8	5	3	3	7

TABLE 7.7

NUMBERS OF INDIVIDUALS IN THE GENERALLY MOST ABUNDANT SPECIES OF FISH AS TAKEN BY ENMESHING NETS OF BAR MESH SIZE 25 MM AND GREATER FOR TRIPS 2 TO 4

Site	Trip	*Amniataba*	*Fluvialosa*	*Hephaestus*	*Megalops*	*Neosilurus*	*Toxotes*
6	2	3	35	25	24	21	4
	3	1	6	13	6	20	1
	4	0	0	2	2	2	1
5	2	13	32	5	30	14	17
	3	3	39	3	16	16	4
	4	2	0	3	11	16	1
4	2	0	0	2	5	0	0
	3	0	2	1	6	0	0
	4	0	23	0	4	0	0
3	2	0	0	0	0	0	0
	3	0	0	0	0	0	0
	4	0	0	0	3	0	0
2	2	0	1	0	29	0	0
	3	0	5	0	17	0	0
	4	0	0	0	5	2	0
1	2	12	54	6	30	24	1
	3	12	78	2	45	49	0
	4	2	69	2	5	24	0

TABLE 7.8

SIGNIFICANT CORRELATIONS OF DATA FROM ENMESHING WITH HABITAT PARAMETERS.

ALL CORRELATION COEFFICIENTS WERE POSITIVE

	Trip	Habitat Parameter				
		√(Area)	Width	√(Central area)	Length	Length x degree vegetated
Number of species	1	x		x	xx	xx
	2				x	xx
	3					xx
	4				x	xx
Log_{10} (catch in number)	1	xx		xx	xx xx	xx xx
	2					xx
	3	x		x	x	xx
	4	x	x	x		
Log_{10} (catch of *Megalops* in number)	1	xx		xx	xx	xx
	2					
	3					
	4					
Log_{10} (catch of *Fluvialosa* in number)	1				x	xx
	2				x	xx
	3	xx	x	xx	xx	xx xx
	4					

x   *P lies between 0.1 and 0.05*

xx   *P lies between 0.05 and 0.01*

xx
xx   *P is less than 0.01*

} *for 4 degrees of freedom*

TABLE 7.9A

POISONINGS: NUMBERS OF SPECIES AND EVENNESS COMPONENTS DESCRIBING THE CATCHES

	Trip	Number of species	Evenness component
Site 6	2	3 (1)	-1.02 (1)
	2	6	-0.32
	3	9	-0.19
	4	6	-0.26
	4	3	-0.72
Site 5	2	6	-0.26
	3	3	-0.69
	3	4 (2)	-0.54 (2)
	3	3 (2)	-0.49 (2)
	4	5	-0.22
Site 4	2	3	-1.07
	4	3	-0.24
Site 3	2	4	-0.60
	3	2	-1.08
	3	3	-0.50
	4	4	-0.32
	4	5	-0.42
Site 2	2	6	-0.26
	2	6	-0.43
	3	3	-0.36
	3	4	-0.53
	4	6	-0.31
	4	2	-0.97
Site 1	1	5	-0.34
	2	3 (3)	-0.88 (3)
	3	1 (3)	
	3	5	-0.44
	4	3	-0.48
	4	2	-0.56
Florence Creek	4	7	-0.16
	4	6	-0.31

(1), (2) *These little pools had very shallow openings to the mainstream.*

(3) *This pool was connected to the mainstream owing to a very recent rise in the river.*

TABLE 7.9B

POISONINGS: RANGES AND MEANS FOR NUMBERS OF SPECIES AND EVENNESS COMPONENTS FOR TRIPS 2-4. POOLS WITH VERY SHALLOW OR VERY RECENT CONNEXION WITH THE MAINSTREAM HAVE BEEN ELIMINATED

Site	Number of species		Evenness component	
	Range	Mean	Range	Mean
6	3 9	6.0	-0.72 -0.19	-0.37
5	3 6	4.5	-0.69 -0.26	-0.43
4	3	3.0	-1.07 -0.24	-0.66
3	2 5	3.6	-1.08 -0.32	-0.58
2	2 6	4.5	-0.97 -0.26	-0.48
1	2 5	3.3	-0.88 -0.44	-0.59
FC	6 7	6.5	-0.31 -0.16	-0.24

TABLE 7.10

POISONINGS: CORRELATION COEFFICIENTS (τ) FOR ADJUSTED*

NUMBER OF INDIVIDUALS WITH HABITAT PARAMETERS

	Degrees of freedom	τ	P
With $\log_{10}$(breakup x area)			
Trip 2 all sites	6	0.21	> 0.1
Trip 3 all sites	8	0.28	> 0.1
Trip 4 all sites except FC	8	0.26	> 0.1
Sites 6 & 5 all trips	8	0.57	0.1-0.05
Sites 6 & 5 and FC all trips	10	0.61	0.05-0.02
Trip 4 all sites including FC	10	0.41	> 0.1
With $\sqrt{(\text{area})}$			
Trip 2 all sites	6	0.30	> 0.1
Trip 3 all sites	8	0.27	> 0.1
Trip 4 all sites except FC	8	0.08	> 0.1
Sites 6 & 5 all trips	8	0.46	> 0.1
Sites 6 & 5 and FC all trips	10	0.53	0.1-0.05
Trip 4 all sites including FC	10	0.33	> 0.1

* *From regression* $\hat{Y} = 2.49 - 0.22\,X$, *where X is the number of the field trip and Y the number of individuals.*

TABLE 7.11

POISONINGS:CORRELATION COEFFICIENTS (τ) FOR NUMBER OF SPECIES WITH HABITAT PARAMETERS FOR TRIPS 2, 3 AND 4

	Degrees of freedom	τ	P
With $\log_{10}$(breakup x area)			
Trip 2 all sites	6	0.31	> 0.1
Trip 3 all sites	8	0.59	0.1-0.05
Trip 4 all sites except FC	8	0.57	0.1-0.05
Sites 6 & 5 and FC all trips	10	0.52	0.1-0.05
Trip 4 all sites including FC	10	0.61	0.1-0.05
Trip 2 sites 4, 3, 2, 1	3	0.52	> 0.1
Trip 3 sites 4, 3, 2, 1	4	0.17	> 0.1
Trip 4 sites 4, 3, 2, 1	5	0.89	0.01-0.001
With $\sqrt{(area)}$			
Trip 2 all sites	6	0.06	> 0.1
Trip 3 all sites	8	0.60	0.1-0.05
Trip 4 all sites except FC	8	0.42	> 0.1
Sites 6 & 5 and FC all trips	10	0.49	0.1
Trip 4 all sites including FC	10	0.50	0.1-0.05
Trip 2 sites 4, 3, 2, 1	3	0.19	> 0.1
Trip 3 sites 4, 3, 2, 1	4	0.34	> 0.1
Trip 4 sites 4, 3, 2, 1	5	0.34	> 0.1

TABLE 7.12

POISONINGS: MEAN VALUES OF 'EFFORT' (AS HABITAT PARAMETERS) BETWEEN TRIPS, AND THEIR SAMPLE STANDARD DEVIATIONS(s)

	$\bar{x}$	s
Log_{10}(breakup x area)		
Trip 2 all sites	2.09	0.44
Trip 3 all sites	2.24	0.38
Trip 4 all sites except FC	2.14	0.35
Sites 6 and 5 all trips	2.30	0.43
Sites 6 and 5 and FC all trips	2.33	0.40
Trip 4 all sites including FC	2.20	0.35
√(area)		
Trip 2 all sites	2.96	0.99
Trip 3 all sites	2.84	1.50
Trip 4 all sites except FC	2.99	0.89
Sites 6 and 5 all trips	3.64	1.28
Sites 6 and 5 and FC all trips	3.75	1.26
Trip 4 all sites including FC	3.21	1.05

TABLE 7.13

FISH SPECIES OCCURRING IN THE STREAMS OF THE EAST BRANCH DRAINAGE BASIN, WHERE NO FISHKILLS WERE KNOWN TO HAVE OCCURRED

Place	Species
EB site 2A, a permanent spring creek about 50 cm wide and 100 m long.	*Melanotaenia* *Mogurnda*
Intermittent creek, downstream of EB site 2A, with large permanent pool of diameter about 20 m.	*Melanotaenia* *Mogurnda*
Intermittent creek at EB site 4 with small pools, perhaps permanent, of diameter about 1 m.	*Melanotaenia*
EB site 8A2, a permanent spring whose flow intermittently forms a creek, a patchwork totalling about 300 m^2.	*Ambassis* *Melanotaenia* *Mogurnda* *Synbranchus*
EB site 2, at the inflow from EB site 2A.	*Melanotaenia*(1)(2) *Mogurnda*(1)

(1) Observed and captured at end of 1973 Dry only. During 1974 flow in EB did not cease at this point, apparently resulting from the high rainfall of the previous Wet.

(2) These individuals were all small - no large specimens at EB site 2A were seen.

TABLE 7.14A

CRUSTACEANS COLLECTED FROM THE EAST BRANCH BY ALL METHODS

Trip:	Trip 1	Trip 2				Trip 3		Trip 4
EB site	2A	2A	3	4	8A1	2A	4	2A
*Caradina gracilirostris**							+	
Caradina sp. 1	+	+				+		+
*Paratelphusa transversa**			+	+	+			

* *All specimens found were dead ones.*

TABLE 7.14B

AQUATIC FAUNA, MOSTLY INVERTEBRATES, COLLECTED FROM THE EAST BRANCH BELOW THE MINED AREA OF RUM JUNGLE

(Each taxonomic category refers to one species unless another number occurs. 'Ima' means imagos or adults, 'Nym' means larvae or nymphs. Fish are superscripted 'f', crustaceans 'c')

EB Site	Trip 1	Trip 2	Trip 3	Trip 4
1	Dytiscidae-4 ima -1 nym Gerridae Gyrinidae Megaloptera Nepidae-2 Notonectidae	*Melanotaenia*^{f} (moribund) *Craterocephalus*^{f} (moribund)	Gerridae	Gerridae Gyrinidae Veliidae
2	Dytiscidae-2 ima Hemiptera-2 nym Hydrophilidae Odonata*	*Ambassis*^{f} (dead) *Melanotaenia*^{f} (dead) Gerridae Gyrinidae	Gerridae	Gerridae Gyrinidae Veliidae
2A	Atyidae^{c} Orthoptera	*Melanotaenia*^{f} Atyidae^{c} Gerridae Gyrinidae Hydrometridae	*Mogurnda*^{f} Atyidae^{c} Dytiscidae Trichoptera	Atyidae^{c} Gyrinidae Hydrometridae
3	Dytiscidae-5 ima -1 nym	*Ambassis*^{f} (dead) *Craterocephalus*^{f} (dead) *Melanotaenia*^{f} (alive and dead) Potamidae^{c} (dead)	Dytiscidae Gerridae Gyrinidae Hydrophilidae	Dytiscidae-3 ima Gerridae
4	(Not occupied)	*Ambassis*^{f} (dead) *Melanotaenia*^{f} (alive and dead) *Mogurnda*^{f} (alive and dead) *Neosilurus*^{f} (dead) Potamidae^{c} (dead)	Atyidae^{c} (dead) Dytiscidae-2 ima Gyrinidae Hydrometridae Notonectidae	Araneae Dytiscidae Gerridae Notonectidae
5	(Not occupied)	Belostomatidae Gerridae Gyrinidae Hydrophilidae	Gerridae Gyrinidae Hydrometridae Hydrophilidae Notonectidae	Dytiscidae Gerridae Hydrophilidae Notonectidae
6	Dytiscidae-4 ima -1 nym Hydrophilidae Nepidae Notonectidae Veliidae	Dytiscidae-2 ima Gerridae Gyrinidae Hydrophilidae Nepidae Notonectidae	Gerridae Gyrinidae	Dytiscidae Gerridae Notonectidae Veliidae

* *Only one specimen was found in the EB downstream of the mined area.*

TABLE 7.15A

CRUSTACEANS COLLECTED FROM THE FINNISS RIVER BY ALL METHODS

	Trip 1						Trip 2						Trip 3						Trip 4						
	Sites						Sites						Sites						Sites						
	6	5	4	3	2	1	6	5	4	3	2	1	6	5	4	3	2	1	6	5	4	3	2	1	FC
Cherax quadricarinatus	a	a					ac	ac			ab	a	bc	b		c	b	bc	abh	ab		c	b	i	b
Macrobrachium tolmerum	e		bdf	d	d	b	bc	c			b		c	b			b	bce	bc	bce	d		bc	b	bc
M. glypticum	g																		h					h	
M. rosenbergi	e		f																				c	abc	
Caradina gracilirostris	eg		f										ce						bc	b					
Caradina sp. 1																			c						
Paratelphusa transversa														b											

a Enmeshing
d Fyke netting
g Collecting from riffles
b Poisoning
e Seining
h Collecting from artificial riffle-patches
c Spotlighting, scooped
f Collection of dead specimens
i Collecting from artificial reefs

TABLE 7.15B - PART 1

INVERTEBRATES OF THE FINNISS RIVER AT TWO RIFFLE AREAS NEAR SITES 6 AND 1, TAKEN BY SEARCHING AND BY EXAMINATION OF 'ARTIFICIAL RIFFLE' (STONES IN PLASTIC TRAYS SET INTO THE NATURAL RIFFLE)

	November 1974				September 1974
	Site 6		Site 1		Site 1
	Artificial Riffles	Natural Riffle	Artificial Riffles	Natural Riffle	Natural Riffle
Mollusca					
Gastropoda sp.1	+				
Corbiculina sp.1	+				
Crustacea					
Macrobrachium glypticum	+	+	+		
Insecta					
Ephemeroptera					
Leptophlebiidae sp.1	+	+	+	+	+
Leptophlebiidae sp.2	+	+	+	+	
Jappa sp.1	+				
Baetidae	+	+	+	+	+
Other sp.	+				
Lepidoptera sp.1		+		+	
Plecoptera sp.1		+			
Trichoptera					
Hydropsychidae sp.1	+	+	+	+	+
Psychomyiidae sp.1	+	+	+		+
Psychomyiidae sp.2			+		
Diptera					
Chironomidae sp.1			+	+	
Muscidae sp.1	+				
Simuliidae sp.1				+	
Coleoptera					
Imago sp.1		+	+		
Larva sp.1	+				

TABLE 7.15B

PART 2 AQUATIC INVERTEBRATES OF THE FINNISS RIVER NOT LISTED IN PART 1, WHICH WERE COLLECTED FROM AREAS ADJACENT TO RIFFLE

	Site 6	Site 1
Porifera sp.1	+	
Insecta		
Zygoptera sp.1	+	+
Anisoptera sp.1	+	
Mollusca		
Mytelidae sp.1	+	+
Limpet sp.1	+	
Crustacea		
Macrobrachium sp.1	+	+
Cherax sp.	+	+
Atyidae sp.1	+	+

TABLE 7.16

SPECIES OF FISH RECOVERED DURING THE FISHKILLS OF 1973 AND 1974 IN THE FINNISS RIVER BELOW THE JUNCTION WITH THE EAST BRANCH

Species	8-9.11.1973	19.11.1974
Ambassis	+	
Amniataba	+	+
Craterocephalus	+	
Glossamia	+	+
Glossogobius	+	+
Madigania		+
Megalops		+
Melanotaenia	+	+
Mogurnda		+
Nematocentrus	+	+
Neosilurus	+	+
Oxyeleotris		+
Strongylura	+	
Total number of species	9	10

TABLE 7.17

CATCHES IN 12 MM ENMESHING NET BEFORE AND AFTER THE FISHKILL OF NOVEMBER 1973 IN THE FINNISS RIVER

Fish species	Numbers in the catches			
	Site 3		Site 2	
	Before (6-7.11.73)	After (14-15.11.73)	Before (7-8.11.73)	After (26.11.73)
Amniataba	1		1	
Fluvialosa	1		8	
Megalops			1	
Mogurnda	1			
Nemotocentrus	18	7	2	
Strongylura			3	1
Number of species	4	1	5	1
Number of individuals	21	7	15	1

TABLE 7.18

CATCHES IN ENMESHING NETS OF 12 MM AND OF 25 MM AND GREATER BEFORE AND AFTER THE FISHKILL OF NOVEMBER 1974 IN THE FINNISS RIVER, AT SITE 2.

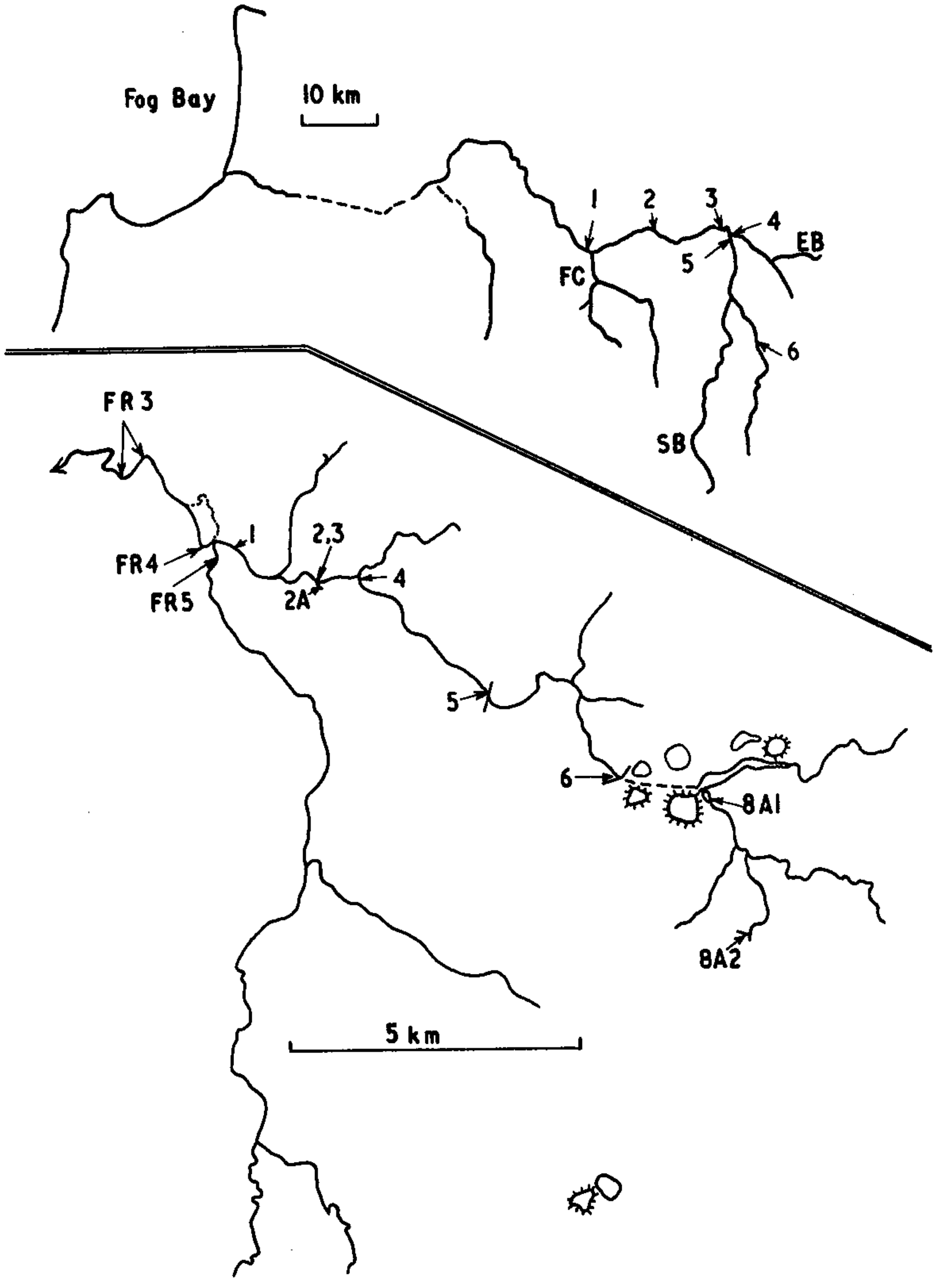
Net size	Fish species	Numbers in the catches	
		Before (7-8.11.74)	After (20-21.11.74)
12 mm	*Strongylura*	5	3
25 mm and greater	*Lates*	2	1
	Megalops	5	5
	Neosilurus	2	
Number of species		4	3
Number of individuals		14	9

TABLE 7.19

FISHKILLS IN THE EAST BRANCH:

SPECIES FOUND DEAD OR MORIBUND

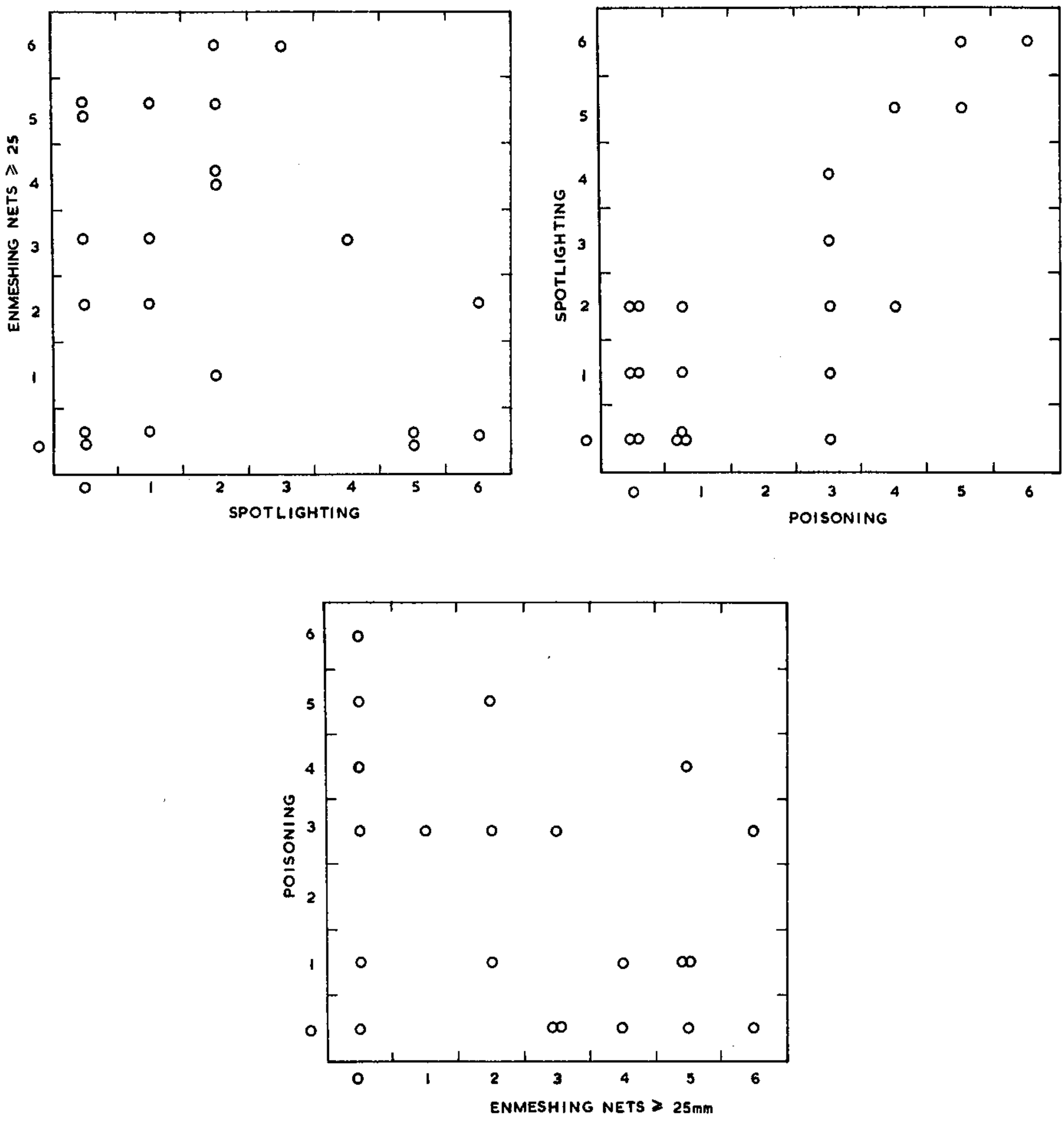
EB sites 3 and 4 22-23.5.1974	EB site 8A1 8.6.1974
Ambassis	*Melanotaenia*
Craterocephalus	*Mogurnda*
Neosilurus	
Melanotaenia	
Mogurnda	



Upper: The FR system showing the 6 sites regularly fished. EB is the seasonal East Branch, SB is the seasonal South Branch, FC is the perennial Florence Creek.
Lower: The EB joining the FR between the regularly fished sites 5 and 4, showing the 9 EB sites mentioned in the text. The mined area of RJ is at the right with the overburden dumps marked with radiating strokes.

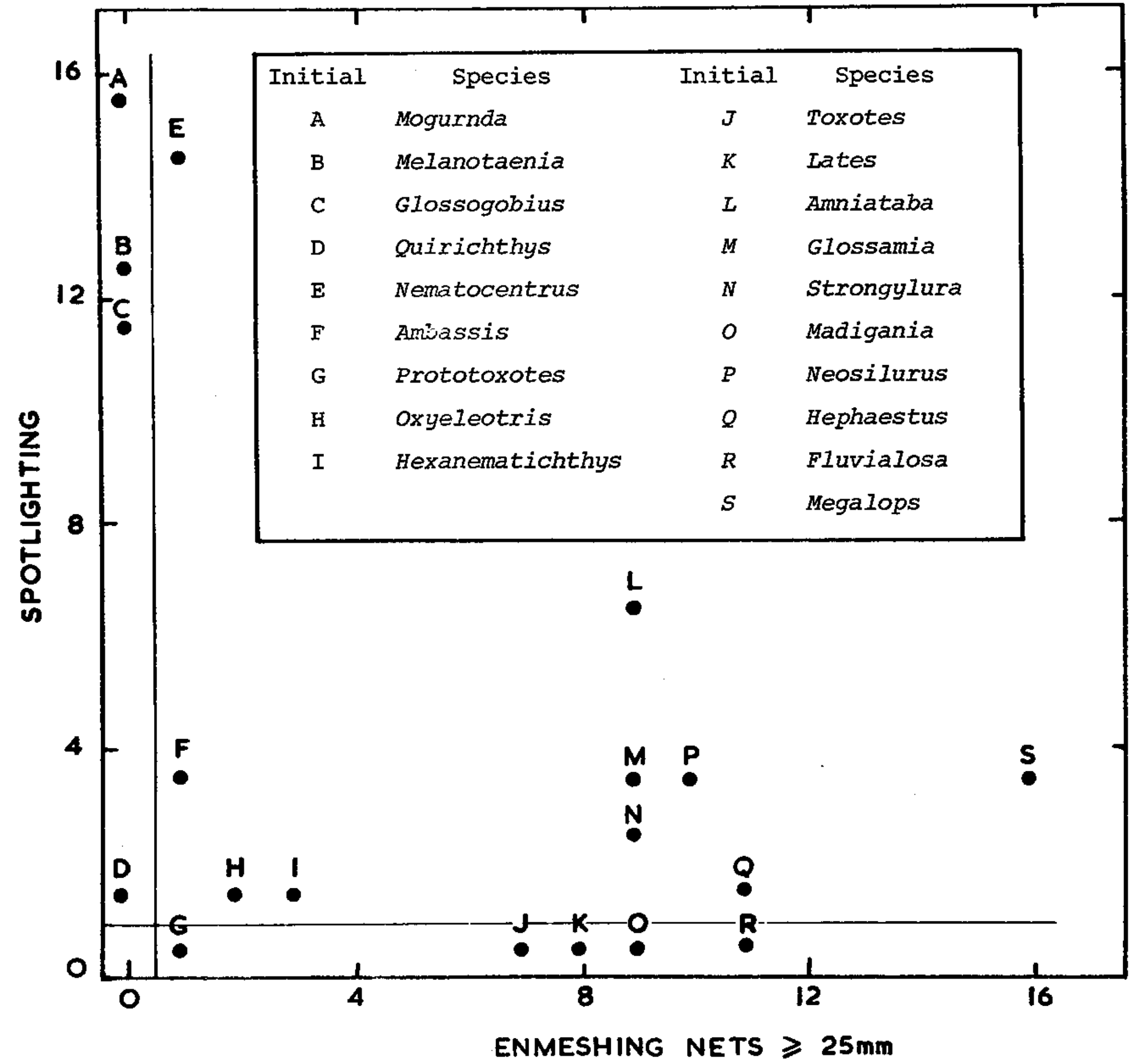
REGULAR FISHING SITES ON THE FR SYSTEM

MAP 7.1



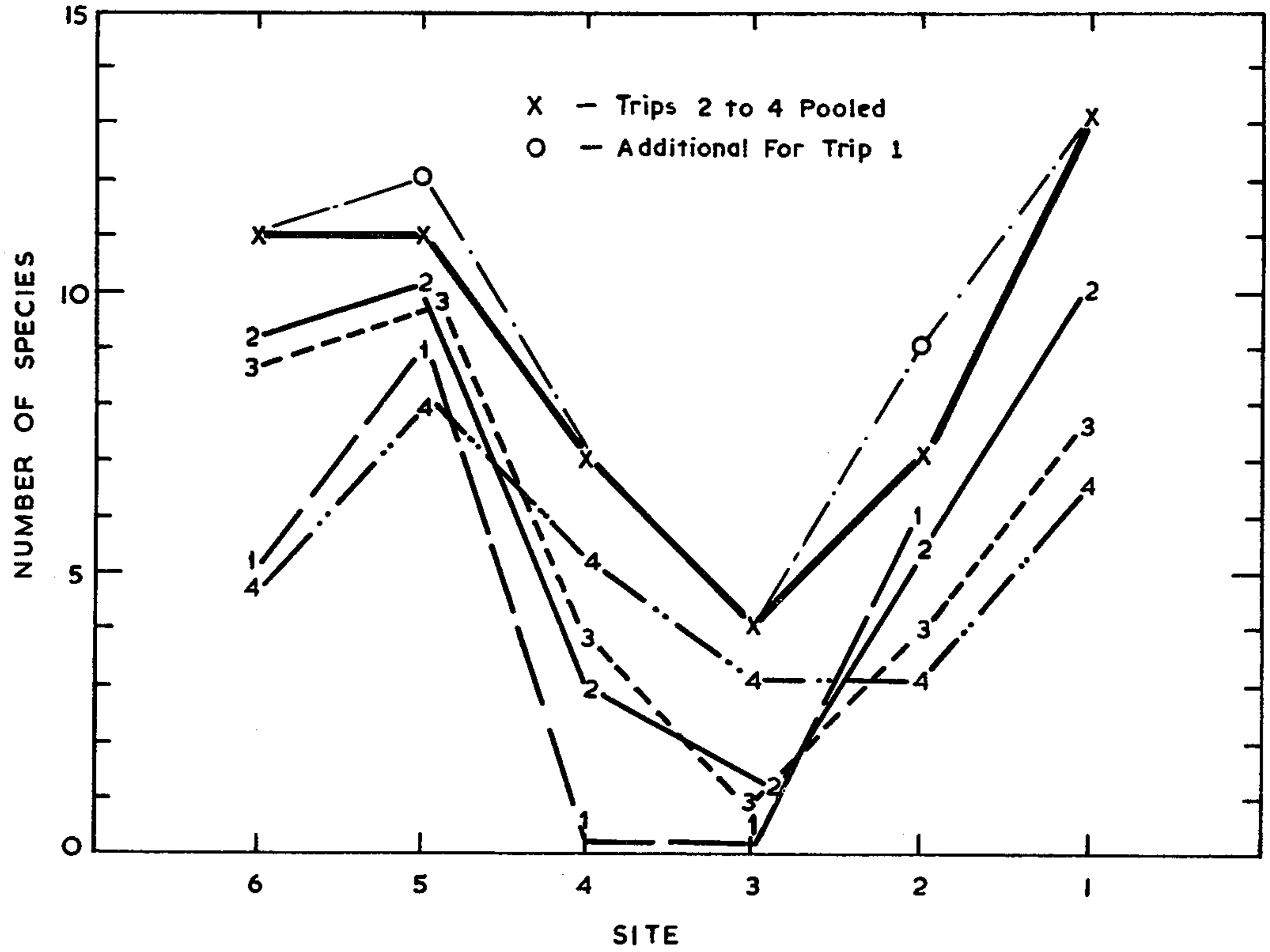
THE NUMBER OF TIMES THE FISH SPECIES WERE CAUGHT FOR EACH PAIR OF THE THREE METHODS OF FISHING, GROUPED OVER TRIPS 2 TO 4

FIGURE 7.1



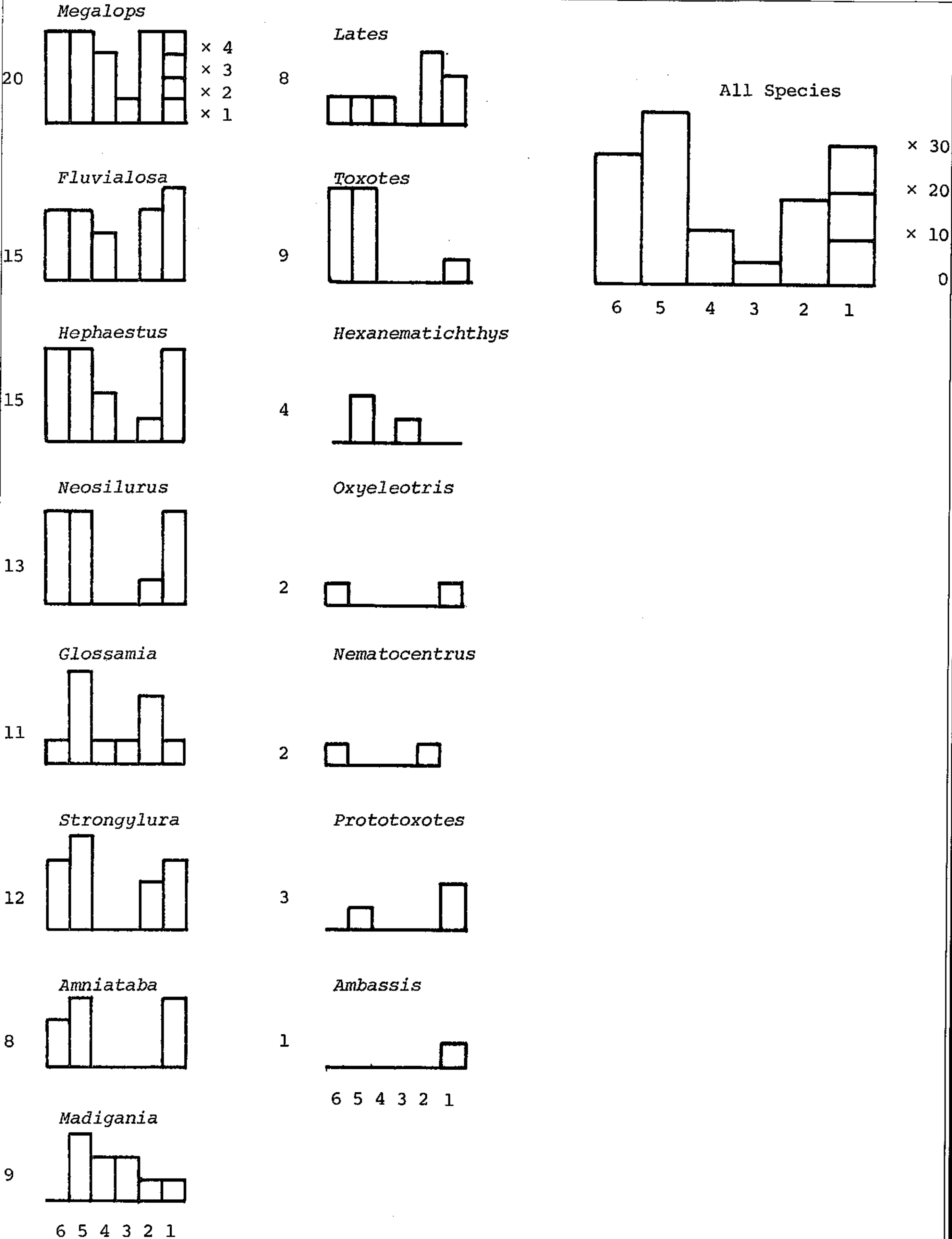
NUMBER OF TIMES FISH SPECIES CAUGHT IN ENMESHING NETS ≥25 mm AND/OR OBSERVED BY SPOTLIGHTING WERE TAKEN BY BOTH METHODS FOR THE 6 SITES AND TRIPS 2-4

FIGURE 7.2



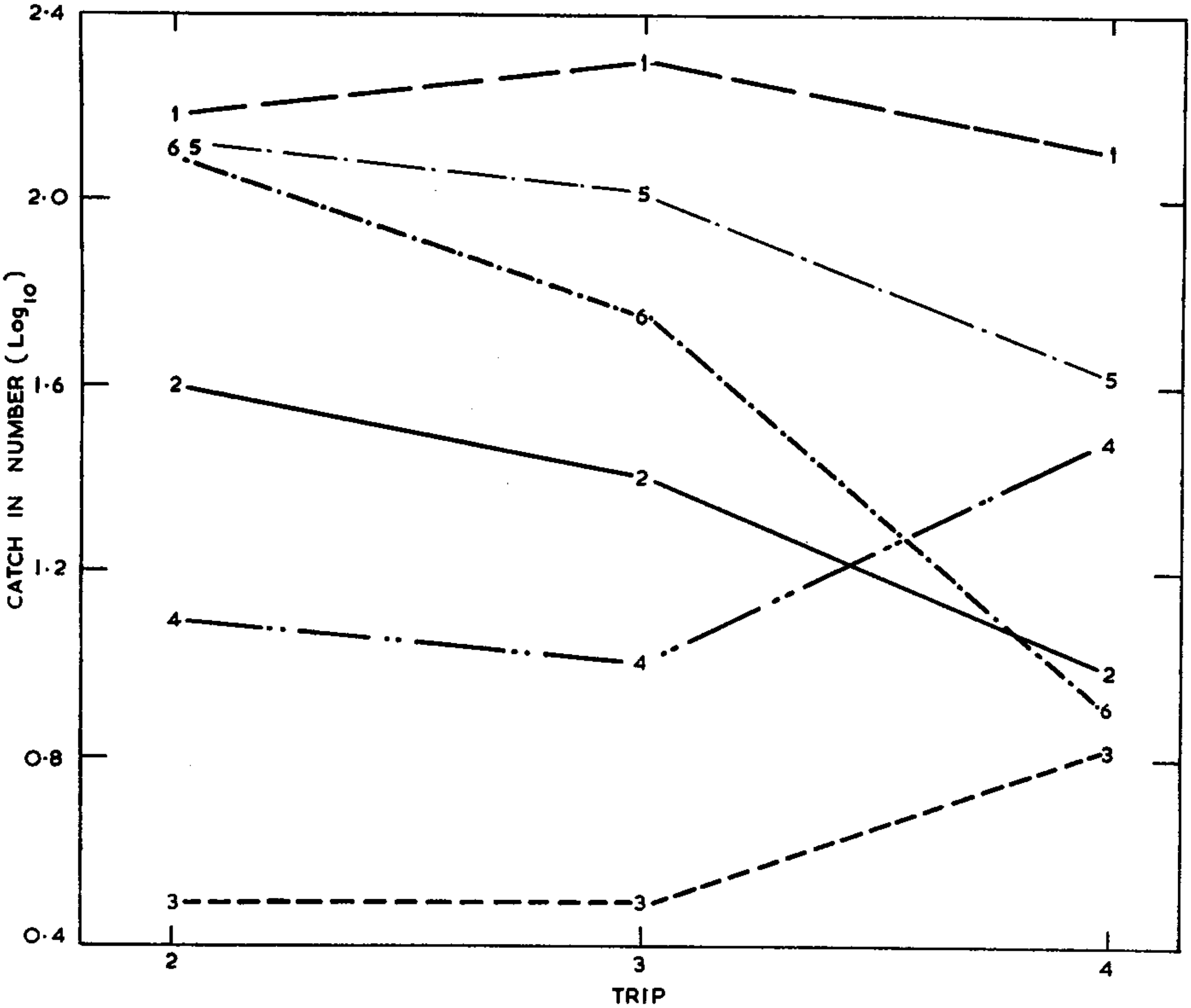
NUMBERS OF SPECIES OF FISH TAKEN IN ENMESHING NETS OF 25 mm AND GREATER DURING THE 4 TRIPS AT THE 6 SITES

FIGURE 7.3



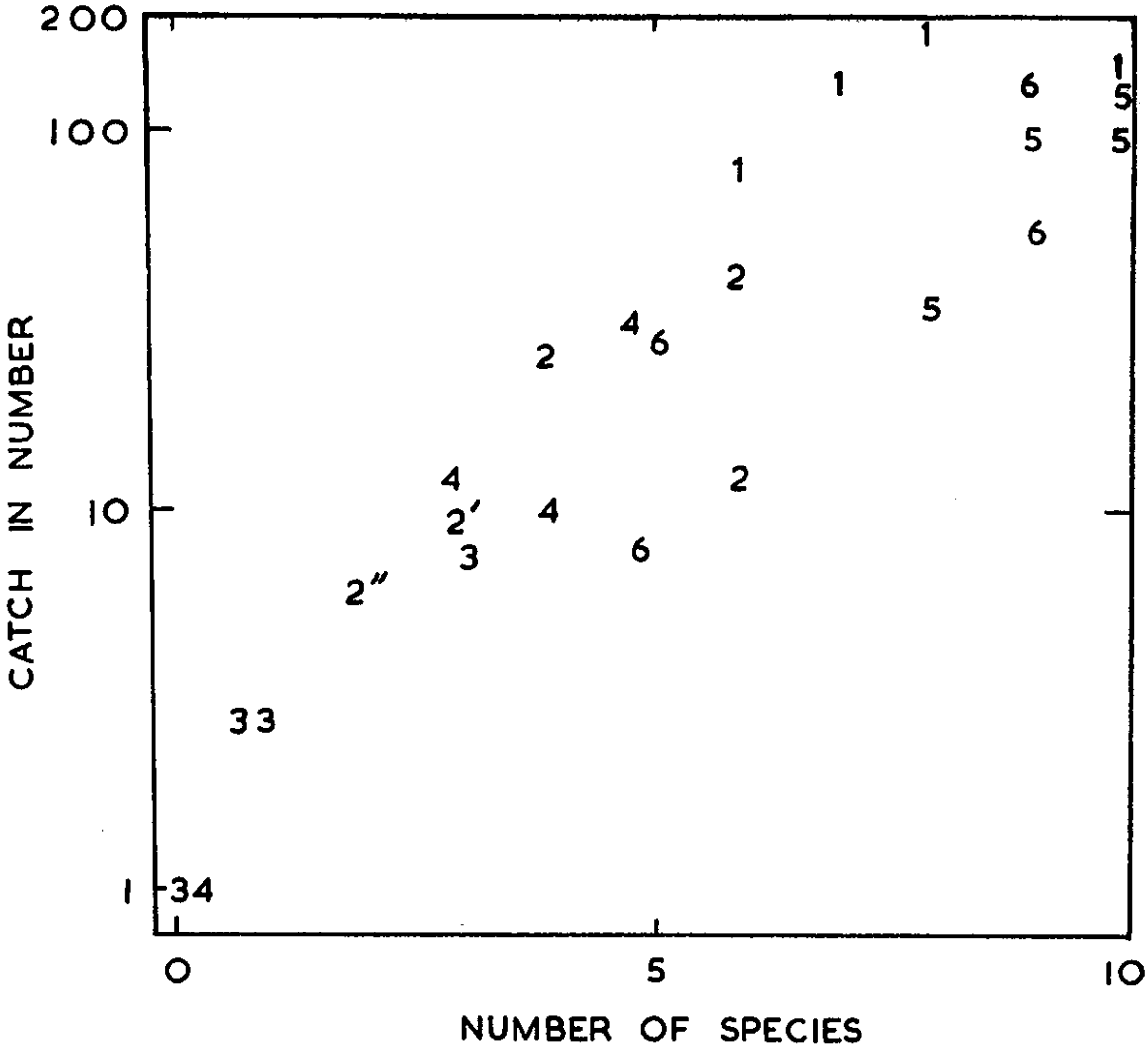
HISTOGRAMS OF THE NUMBER OF TIMES THE SEPARATE SPECIES OF FISH WERE TAKEN BY ENMESHING NETS ⩾ 25 mm DURING ALL 4 TRIPS AT THE 6 SITES SEPARATELY

FIGURE 7.4



CATCHES OF FISH IN ENMESHING NETS ≥25 mm FROM TRIPS 2-4, WHEN THE EFFORT WAS MOST SIMILAR, FOR EACH SITE SEPARATELY

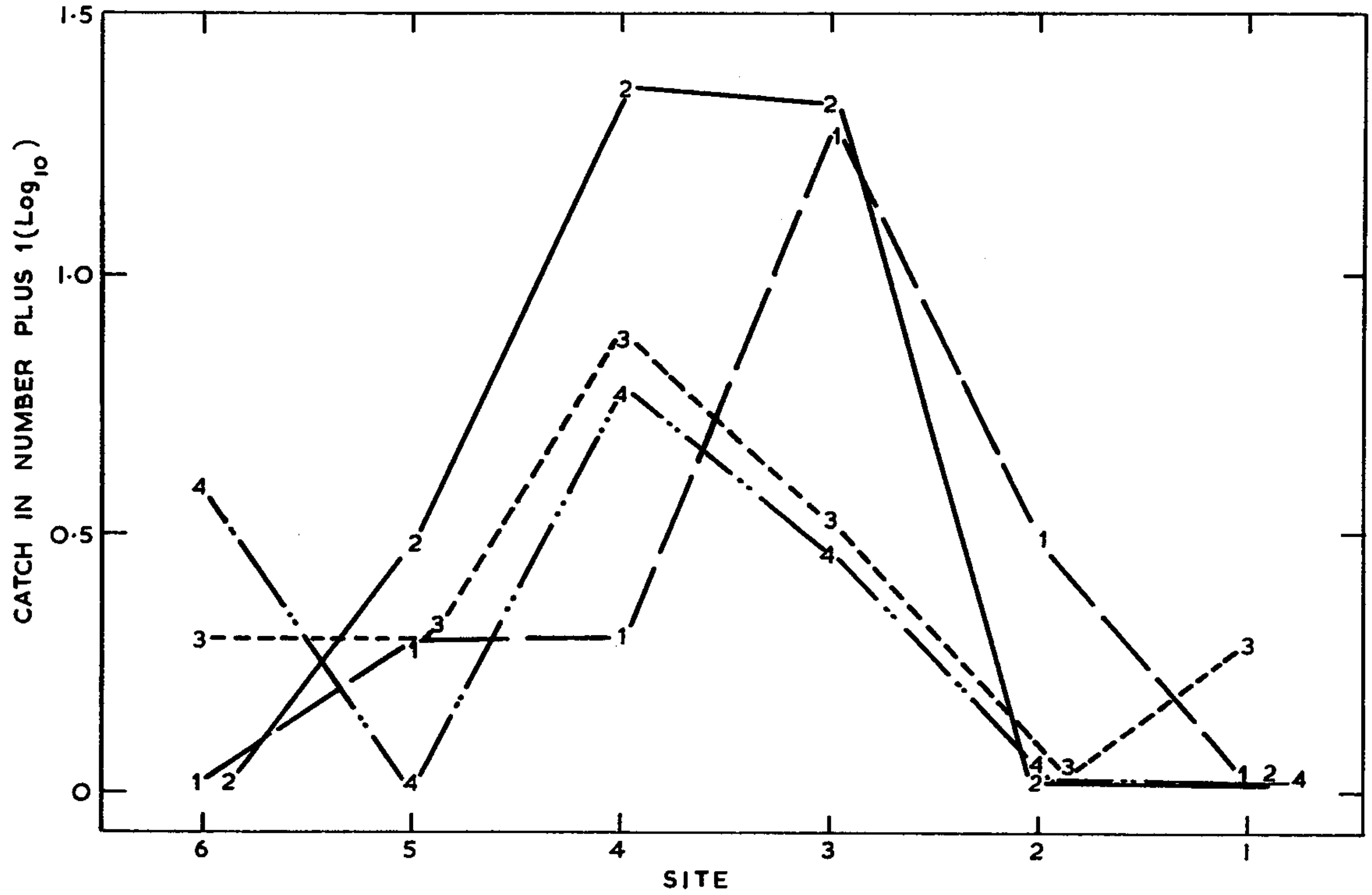
FIGURE 7.5



Catches are labelled by site number. Catches 2' and 2" were taken at site 2 during trip 4, before and after fishkill respectively

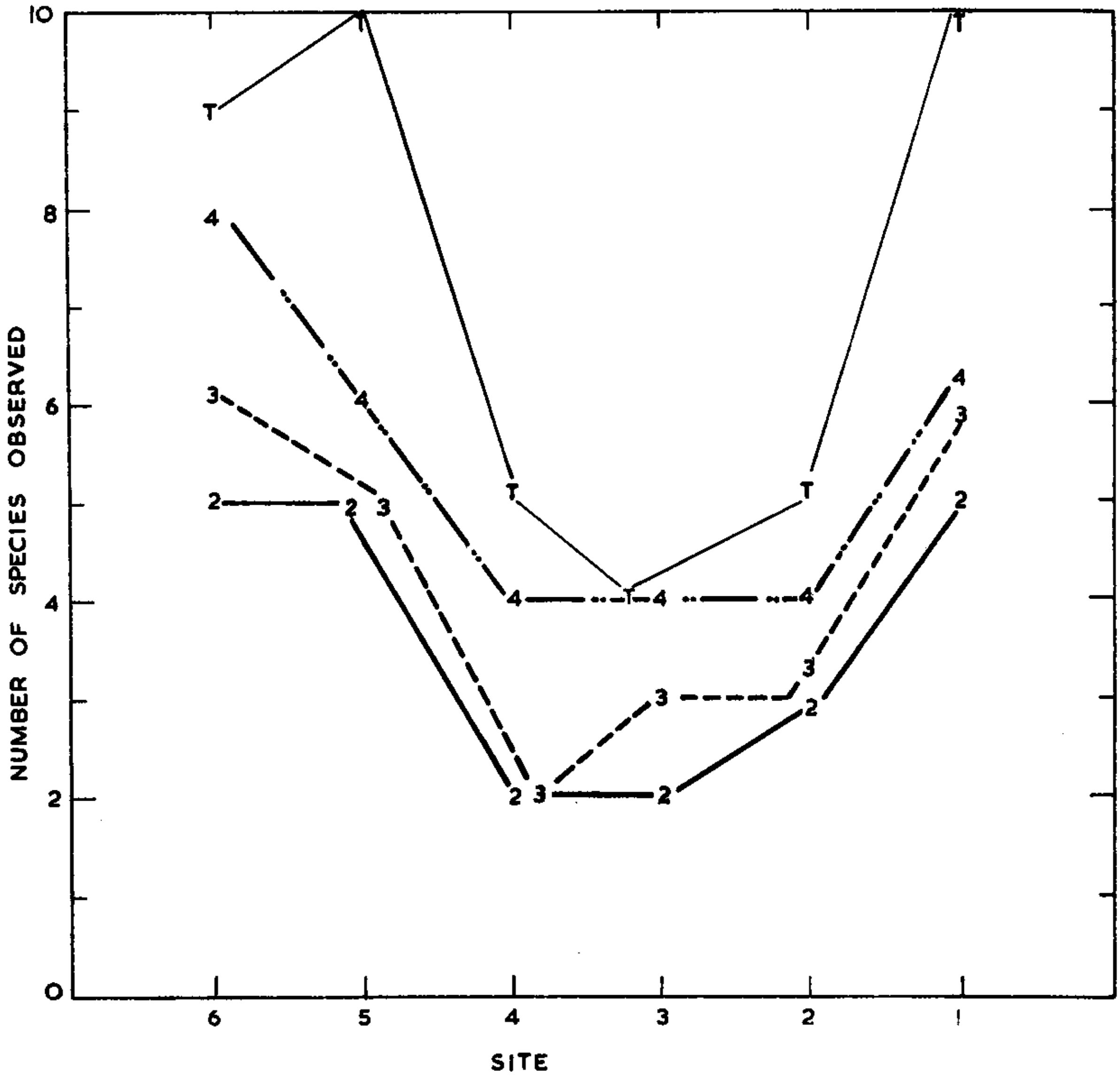
THE APPROXIMATELY CONSTANT RELATIONSHIP BETWEEN CATCH IN NUMBER AND NUMBER OF SPECIES OF FISH IN THE CATCH BY ENMESHING NETS ≥25 mm, FOR ALL TRIPS.

FIGURE 7.6



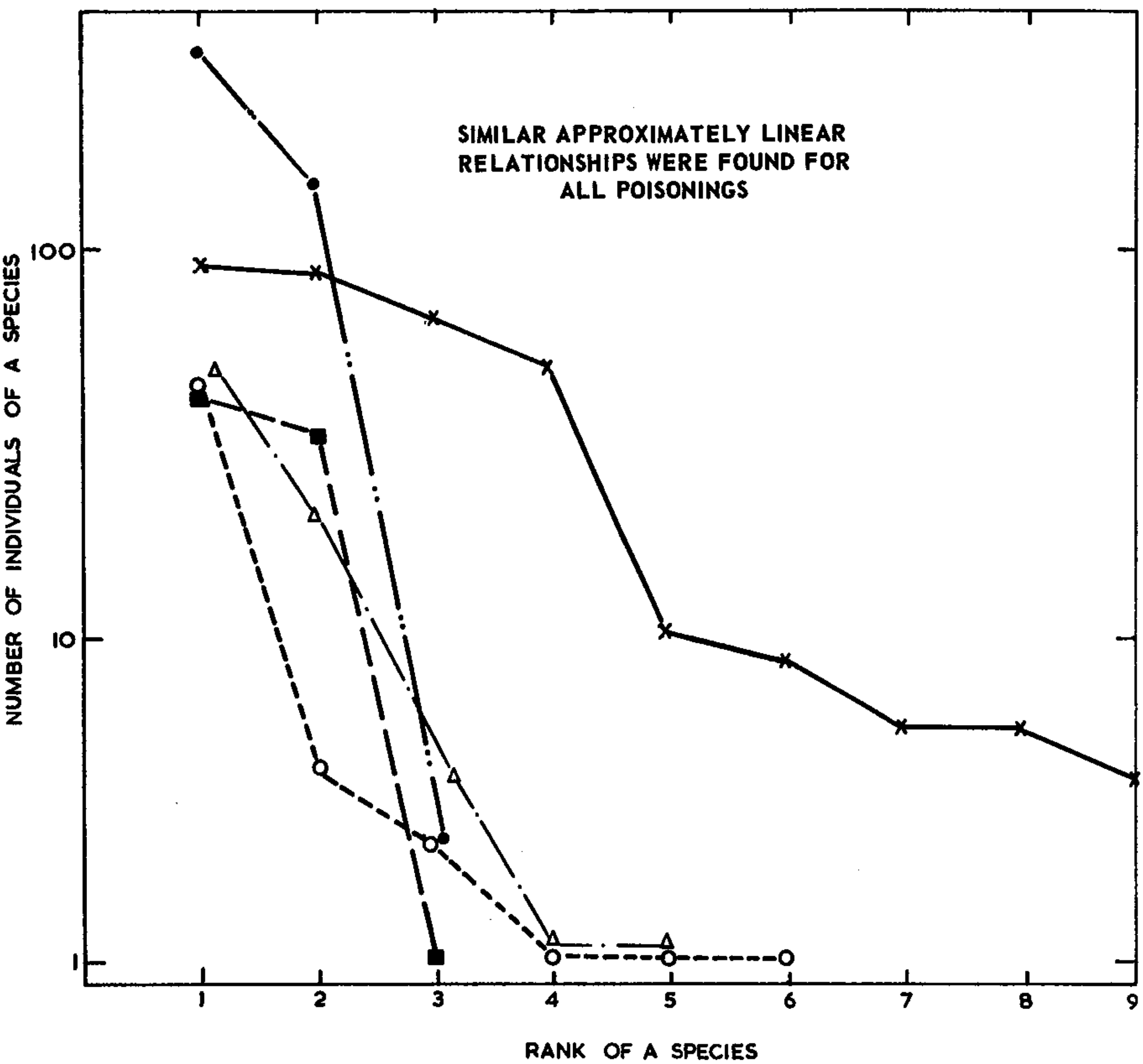
THE CATCHES OF Nematocentrus IN A 12 mm NET DURING TRIPS 1-4

FIGURE 7.7



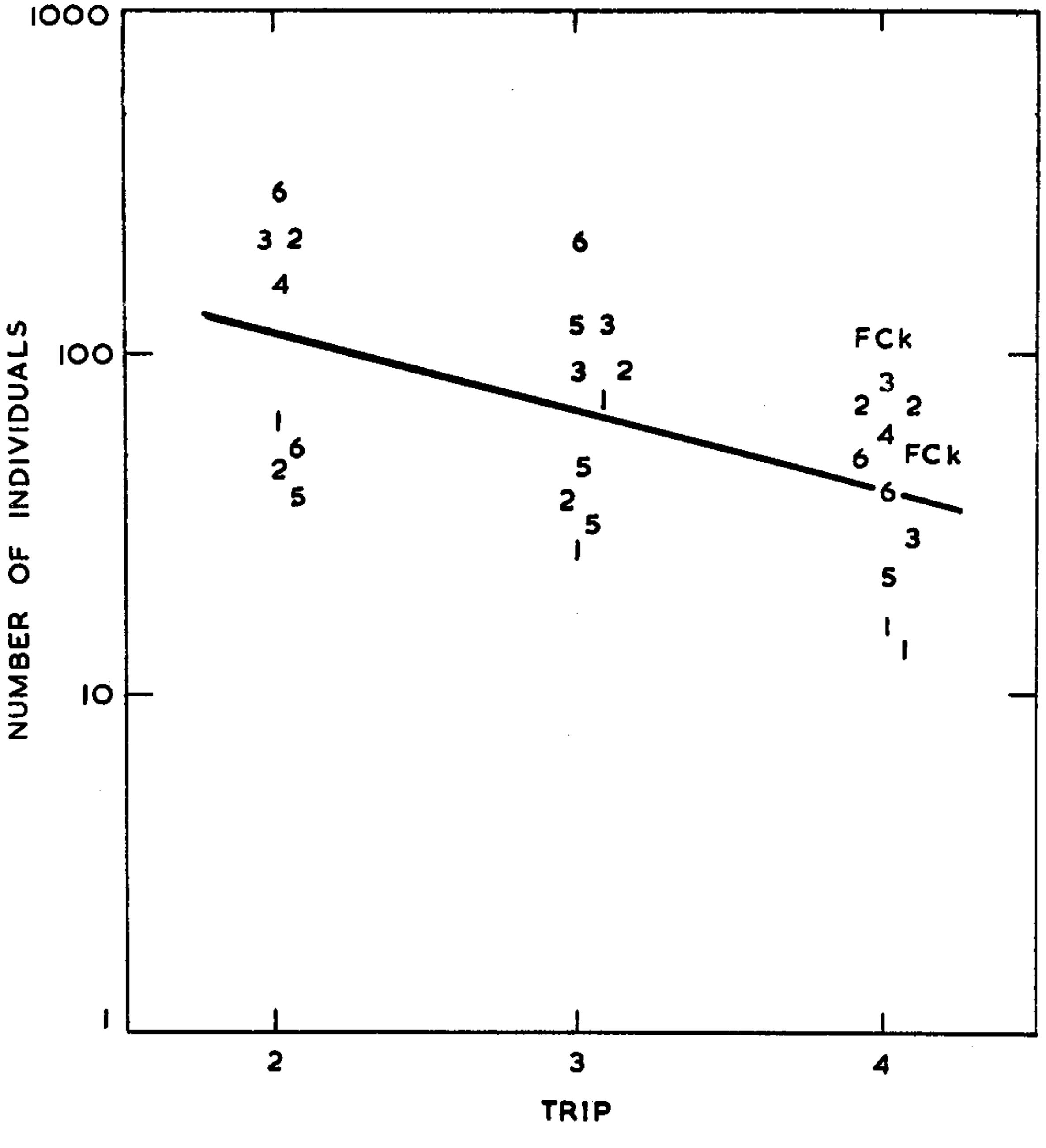
NUMBERS OF SPECIES OF FISH OBSERVED BY SPOTLIGHTING DURING TRIPS 2-4, AND THE TOTAL NUMBERS OF SPECIES

FIGURE 7.8



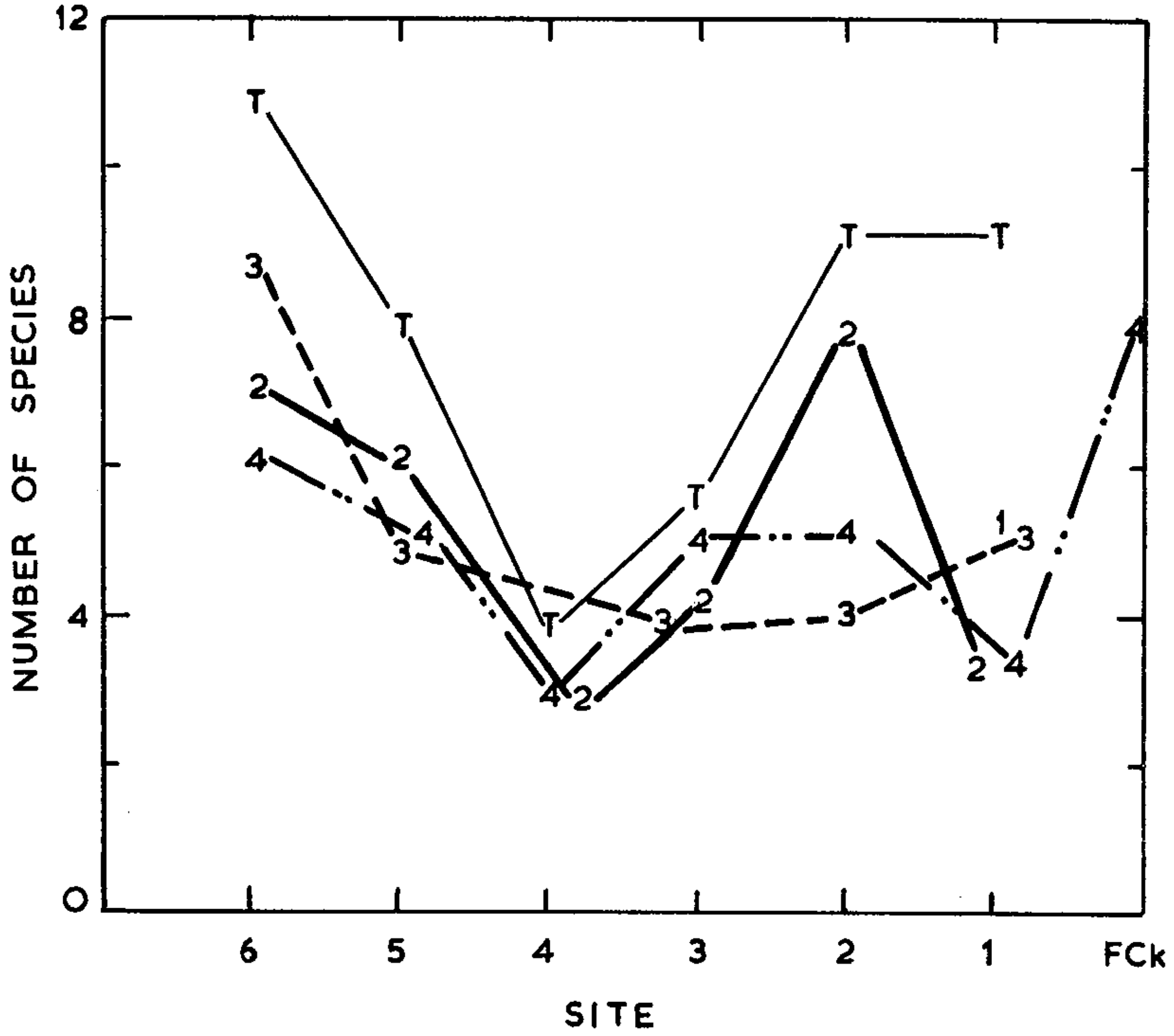
THE DISTRIBUTIONS OF NUMBERS OF INDIVIDUALS AMONG THE SPECIES OF FISH TAKEN BY POISONINGS AT SITE 6

FIGURE 7.9



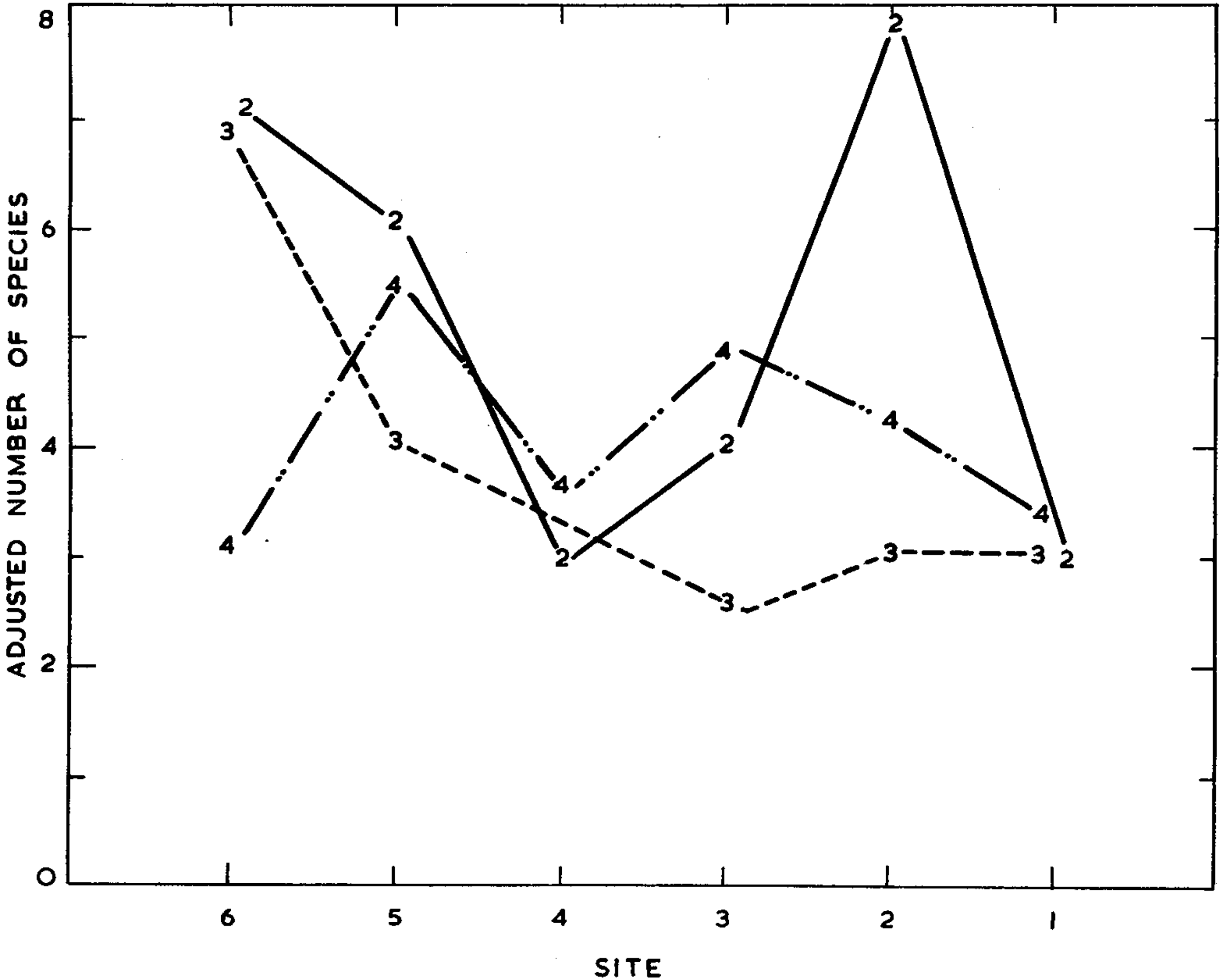
THE DECLINE IN NUMBERS OF FISH TAKEN BY POISONINGS DURING TRIPS 2—4 AT THE 6 SITES AND FC

FIGURE 7.10



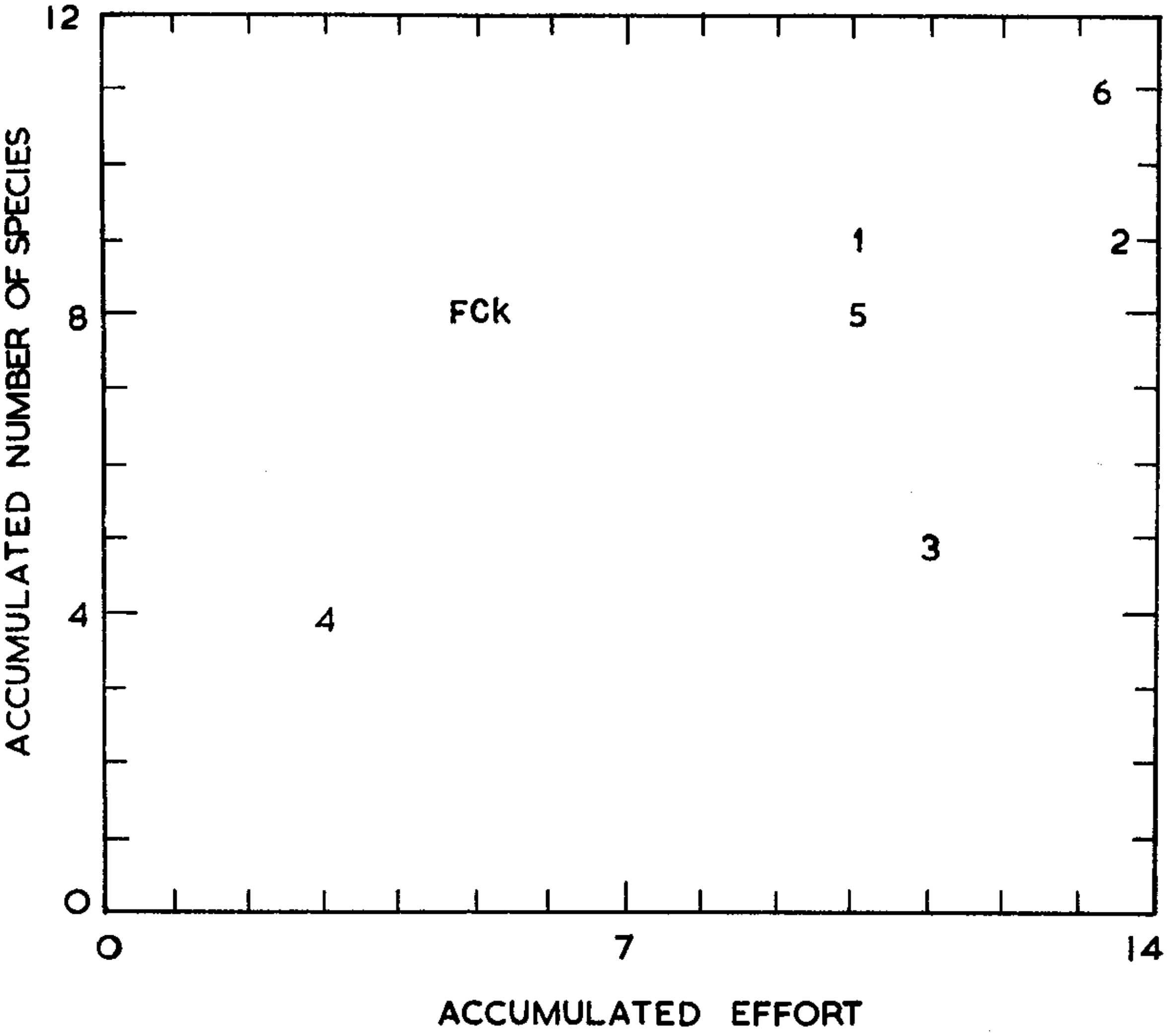
NUMBERS OF SPECIES OF FISH TAKEN BY POISONINGS AT THE SITES FOR TRIPS 2–4, AND THE TOTAL NUMBERS OF SPECIES

FIGURE 7.11



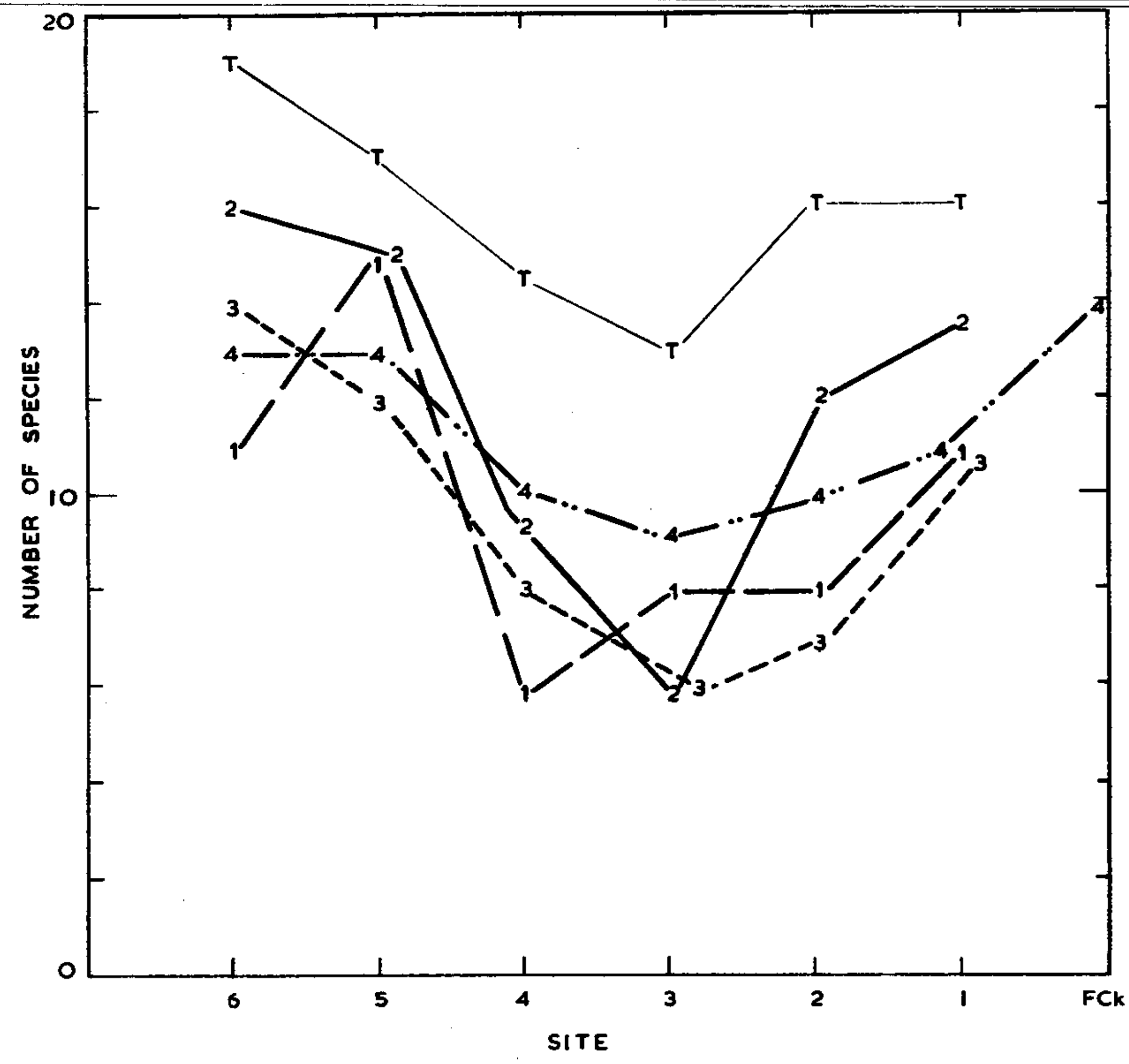
ADJUSTED NUMBERS OF SPECIES OF FISH TAKEN BY POISONINGS DURING TRIPS 2-4. THE ADJUSTMENT ALLOWS FOR A CORRELATION BETWEEN NUMBER OF SPECIES AND THE HABITAT PARAMETER $\log_{10}$ (BREAKUP × AREA) DURING TRIP 4

FIGURE 7.12(a)



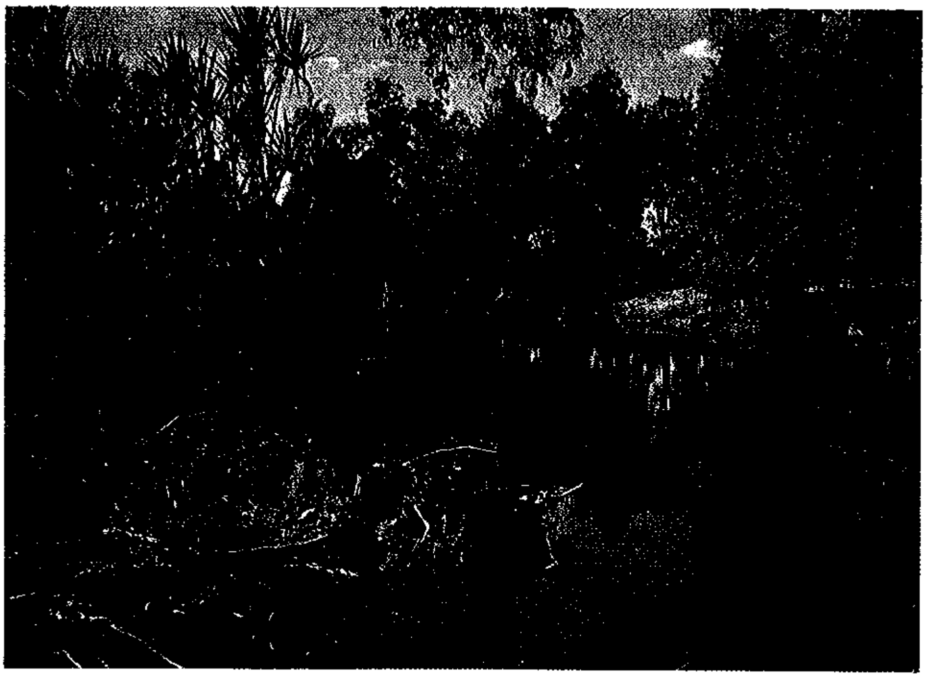
THE INCREASE IN NUMBER OF SPECIES OF FISH WITH ACCUMULATED EFFORT AS $\log_{10}$ (BREAKUP × AREA), FOR TRIPS 2-4 POOLED

FIGURE 7.12(b)



TOTAL NUMBER OF SPECIES RECORDED DURING TRIPS 1-4 BY ALL METHODS, AND TOTAL NUMBERS OF SPECIES BY POOLING ALL TRIPS

FIGURE 7.13

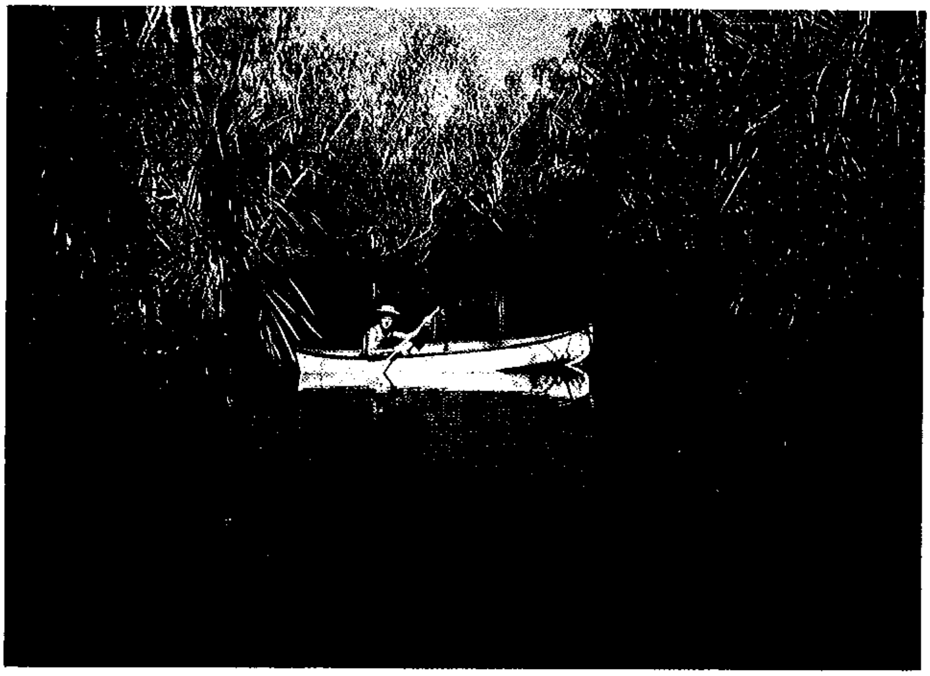


Pool in the EB held by the stream gauging weir at EB site 4. Stumps of dead Pandanus palms, lower left; eroded and grassless bank right of centre.

PLATE 7.1

Part of the FR immediately downstream of the junction with the EB during the fishkill of 8-9.11.1973.

PLATE 7.2



Dense fringing growths of *Pandanus* palms with some paperbarks along the shores at the unpolluted site 6

PLATE 7.3

RUM JUNGLE ENVIRONMENTAL STUDIES

CHAPTER 8

THE FATE OF THE DISCHARGED HEAVY METALS

by

D.R. DAVY
B.G. O'BRIEN

ABSTRACT

Measurements were made in order to deduce the fate of heavy pollutants which were discharged during milling operations. The extent to which these metals have accumulated in the Finniss River floodplains and the significance of the accumulation with respect to the pastoral use of the plains are discussed. The metals investigated were copper, manganese, zinc and radium.

CONTENTS

8. FATE OF DISCHARGED HEAVY METALS

8.1 Introduction

In this and the following chapter an attempt is made to deduce, from measurements made in 1974, the fate of the pollutant heavy metals discharged in significant quantities during milling operations (1954-71), together with those leached from the mine area since shutdown. The main issues are the extent to which these metals have accumulated in the Finniss River (FR) floodplains, and the significance of the accumulation with respect to the pastoral use of the plains.

The metals investigated were copper, manganese, zinc and radium-226. Each of these metals has a unique history of discharge levels, a fact which should be kept in mind when examining the results.

The major source of manganese has always been the raffinate. From 1954-61 about 800 tonnes of manganese entered the East Branch (EB) and would have been transported to the floodplains during the early flooding of the plains. From 1961-67 about 1000 tonnes of manganese was discharged and, during this period, under peak flood conditions. Since 1967 about 500 tonnes of manganese has entered the FR system at a roughly uniform concentration throughout the Wet.

The copper discharged in the raffinate is not known with any precision. If Table 2.4 is representative of raffinate throughout the life of the mill, then the quantities related to the periods listed above are 300, 400 and 450 tonnes respectively. To these estimates must be added the copper lost as seepage from the Heap Leach pile from 1964-67. On the basis of Section 6.4 this has been set at a maximum of 200 tonnes. The discharge of this copper would have been distributed reasonably uniformly over each of the Wets.

For the purpose of this chapter it can be assumed that all discharged zinc originated from Intermediate and White's overburden heaps and that during 1964-74 about 200 tonnes was discharged at a fairly uniform seasonal rate.

The discharge of radium over the mining operations had two components - one related to the radium content of raffinate and the other, the leaching of radium from tails material by natural waters. The only field results on the radium content of raffinate relate to the overflow from Dyson's opencut when that pit was the receptor for the tails slurry and raffinate. Reported results range from 410-820 pCi ℓ^{-1} for samples collected during the Wet and from 320-11 100 pCi ℓ^{-1} for samples collected during the Dry. One result reported for the head of the Old Acid Dam (which included the overflow from Dyson's as part of its catchment) during the Dry was 1000 pCi ℓ^{-1}. The radium contents of raffinate from laboratory work when ore from RJCS was being processed were 26 200 pCi ℓ^{-1} (pH 1.3) and 14 600 pCi ℓ^{-1} (pH 1.7) [Alfredson & Ryan 1975]. The laboratory results should be the most reliable. If the raffinate averaged 20 000 pCi ℓ^{-1} during the milling operations then about 40 Ci were discharged from this source during 1954-61 at a fairly uniform rate during each Wet and a further 50 Ci was discharged in raffinate during 1961-67 under peak flood conditions.

Nothing is known of the fate of the radium present in the raffinate that was discharged to White's opencut. Present levels ($\sim$ 3 pCi ℓ^{-1}) in the pit indicate that some efficient removal mechanism (over and above seepage losses) was at work but there is no clue whether this was associated with recirculation through the mill, its use as a leachant for the Heap Leach pile, or the complex chemical reactions that must have gone on in the opencut. It is assumed here that no substantial quantities were released to EB as a result of waste operations during the period 1967-71.

Tails material discharged to the bank of Tailings Creek contained about 380 Ci of radium at a concentration of about 6 x 10^5 pCi kg^{-1}. The 16 kg sample of tails material collected from Tailings Creek (see Section 6.3) had a radium content of 330 pCi kg^{-1} and so is virtually radium free. This sample, which resulted from deposition after over-topping of the creek bank, should have been very representative of the coarser fraction of tails material (the sands fraction). It is probable that the finer tails (slimes fraction) has been either eroded away and subsequently deposited in the lower reaches of the FR, or transported to the deeper sections of the tails dump. Slimes carry a disproportionate amount of the total radium in the tails. An attempt to obtain samples of tails material at depth (bore hole BH1) was unsuccessful as continuous cave-ins occurred with the rotary percussion drill that was used.

The radium content of water obtained at depth during this drilling was low ($\sim$ 6 pCi ℓ^{-1}) indicating that little leaching is now occurring. Thus the quantity of radium released from the tails dump is unknown. The quantity remaining is being investigated. Since the leaching of surface tails material is virtually complete it is probable that most of it was released within a few years of deposition. In that case, the release history of radium differs from that of the other heavy metals in that only a small percentage of the total release has occurred over the last 8 years.

Nothing is known of the discharge history for lead-210. The major, if not the only, source would have been tails material for which there is little evidence for significant leaching of ^{210}Pb (see Chapter 9). Released ^{210}Pb would therefore be mainly confined to the FR system as a result of sedimentation.

In summary the distribution of zinc on the floodplains is the result of a more or less uniform release rate over an 11-year period. The distribution of manganese will reflect, more so than that of any other metal, the effect of storage during the Dry and subsequent release under peak flood conditions, while the distribution of copper should be intermediate between that of zinc and manganese. For radium, redistribution and removal mechanisms have been operative for an 8-year period without any significant fresh input from the mine area.

A second major factor to be kept in mind in considering the distribution of heavy metals on the floodplains is the FR course across the plains. Maps of the area show a north and a south string of waterholes with the southern string being closer spaced. It is this more continuous southern branch that is marked 'Finniss River'. Observations made during September 1974 led to the conclusion that it would be more apt to brand the north branch as the FR. All the evidence for this is circumstantial, the more important clues being:

- Water was flowing in and out of the north branch waterholes but not in the south branch waterholes. At the west end of the waterholes, the flow was essentially northwards to swamps which in turn are drained to the east end of the next waterhole.
- The banks at the ends of the waterholes in the north branch were steeper than those in the south branch.

- The vegetation of the north branch was denser, more varied more damaged and contained more flood debris than that of the south branch. This was particularly true of bamboo thickets.
- Paperbarks occurred extensively on both banks of the south branch but predominantly to the south of the north branch.
- The north branch was reputed to be a better fishing area for barramundi than the south branch.

Most of the sampling that was done related to the north branch not because we judged it to be more important but because of the abnormally high rainfall during the 1973-74 Wet which flooded paperbark forests making them difficult to penetrate with any form of transport.

Between both branches and the section of FR that is influenced by tidal movement there is a 5 km stretch of meadows to which parra grass has been introduced. Some sampling was done on the perimeter of this area (using a balloon-tyred tricycle) but most of it could not be approached. Results for the perimeter samples suggest that this area is a substantial sink for released heavy metals.

8.2 Sampling Program

Sampling was concentrated on pasture grasses (sedge and parra) and the soil that supported them. Higher priority went to depression areas (sedge meadows) at right angles to the river course since the landward extremities provide baseline data with respect to sections closer to the river. In most cases sampling was done within the paperbark fringe and thus was restricted more to the areas that are flooded for the longest period each year (i.e. the sedge meadows).

Within each depression some sites had soil samples collected both at the surface and at the horizon (judged by colour and texture) that marked the transition to a zone permanently below the water table. Sometimes this was done by trenching, more often by auger-drilling. The depth involved was always less than 1 m.

Some grab sampling of sediments from the waterholes was done to obtain a general idea of how levels of heavy metals changed down the 100 km length of river. In retrospect this sampling was not detailed enough since results on radium levels in river water which showed marked changes corresponding to bends in the river, were not anticipated.

8.3 Results

Table 8.1 lists the results of chemical analyses for all samples other than stream sediments. The majority of these results are reproduced on Map 8.1 (soil samples) and Map 8.2 (pasture grasses). Leaves from paperbark trees were collected from those sites where heavy grazing precluded the collection of grass samples.

Several general conclusions follow from these results.

- Grass samples with a high concentration of one of the measured contaminants had abnormally high concentrations of each of the other measured contaminants.
- The highest concentrations of contaminants occur near the river bed particularly at sites where the waterholes discharge onto the plains (see also Map 3.1).
- The first sedge meadow encountered after FR ceases to be a continuous channel (top right hand corner Map 8.1 and Map 8.2) is contaminated along its entire length (3 km). It is probable that this resulted from a slug of wastes released from the mine area flowing over local floodwater.
- Areas containing remnant dead vegetation have high concentrations of contaminants.

Table 8.2 lists the concentration of contaminants in soil from the surface (2-5 cm) and at depth (< 1 m) for sites where both were sampled. The results indicate that little or no manganese, copper or zinc has migrated with rain infiltration to the water table. The situation for radium is far less clear. Frequently the concentration of radium increases markedly with depth. For those sites where both values are similar and relatively high, there would be some continuing input of radium from the river during periods of low flow as a result of leaching of tails slimes deposited in the creek bed.

The area sampled was not extensive enough nor the depth distribution defined precisely enough for an accurate assessment of the quantity of released contaminants confined within the floodplains. An indication of the overall position can be obtained in the following way. From the sampling done, the land units involved, the vegetation and the areas still inundated in September 1974, it appears that about 100 km^2 of floodplain was influenced by RJ operations.

If the unique discharge histories for each of the contaminants are taken into account it seems likely that the average concentration of the contaminant for the sites sampled would overestimate the average for manganese over the 100 km^2 area and underestimate it in the case of zinc. The averages for the concentrations of copper, manganese and zinc in the surface samples were 36, 140 and 14 $\mu g\ g^{-1}$ respectively and 0.27 $pCi\ g^{-1}$ for radium. Preoperational levels for these contaminants would have been in the region of 2, 10, 3 $\mu g\ g^{-1}$ and 0.02 $pCi\ g^{-1}$ respectively. Thus the greater than normal concentrations of Cu, Mn and Zn over the 100 km^2 area are respectively 90, 300 and 30 tonnes per cm depth of contaminated soil. The stated 'surface' soil averages apply to the top 2-5 cm; if similar values hold for, say, 0-10 cm then almost all the manganese (2300 tonnes) and zinc (200 tonnes) and about two thirds of the copper (1300 tonnes) discharged from RJ still remain on the floodplains. The situation for radium is quite different. Only a few per cent, of the ~ 100 Ci that was released, remain in the surface soil; the remainder has migrated through the soil profile or been removed from the area, or, less likely, is yet to arrive.

Figure 8.1 displays the variation in the contaminant concentration for grasses as a function of levels in the supporting soil. Obviously only some of the variability is accounted for by variations in the soil concentrations but in each case a biological concentration factor of 10 is indicated for pasture grasses when results are based on dry weight.

Some further evidence for the relative mobility of radium with respect to that for other contaminants is provided by Figures 8.2, 8.3, 8.4 and 8.5 which depict the concentrations (and by inference, the concentration gradients) of ^{226}Ra, ^{210}Pb, SO_4 and Mn in the soil profiles associated with bore holes BH2-6 located in the tails dump area (refer Section 6.3). As discussed previously, seepage from White's opencut is believed to enter that region in the general area of BH6. The ^{226}Ra and SO_4 contaminants from that source have dispersed in much the same way while the Mn and ^{210}Pb have dispersed much less.

8.4 Discussion

The significance of the heavy metal contamination of the floodplains is related to the plant-to-animal transfer of them.

The functional forms of the trace elements and their concentrations must be maintained within fairly narrow limits if the growth, health and fertility of animals are to remain unimpaired. Underwood [1971] has reviewed this topic in detail and the following summary is from that source.

Copper In Western Australia, sheep and cattle grazing pastures containing 3-4 μg g^{-1} copper or less, and with molybdenum concentrations usually below 1.5 μg g^{-1}, exhibit a wide range of copper deficiency symptoms and subnormal concentrations of copper in the liver. Pastures containing 4-6 μg g^{-1} dry weight, and which are similarly relatively low in molybdenum, provide sufficient copper for cattle.

Copper and molybdenum are antagonistic and the action of molybdenum in blocking the metabolism of copper is augmented by high levels of sulphate. Pastures in parts of England containing 7-14 μg g^{-1} copper (dry weight) can result in subnormal status in cattle.

In all animals, the continued ingestion of copper in excess of requirements leads to some accumulation in the tissues, especially in the liver. Sheep are the most susceptible of all domestic livestock to copper toxicity, pastures with 10-15 μg g^{-1} copper and 0.1 to 0.2 μg g^{-1} molybdenum (dry weight) inducing chronic copper poisoning. Cattle appear to be less so and copper pasture levels as high as 80 μg g^{-1} could be acceptable.

For a given set of conditions, the copper content of cattle tissue exhibits marked individual variation. On a normal diet, the copper content of cattle flesh, kidney and liver is in the region of 3, 20 and 200 μg g^{1} (dry weight). For 23 beasts on a normal diet, the liver content ranged from 23 to 409 μg g^{-1} and for 51 beasts on a copper deficient diet, the range was 3 to 32 for an average of 11.5 μg g^{-1}.

Zinc The minimum zinc requirements of sheep and cattle vary with the criteria of adequacy employed and, apparently, also with the type of diet consumed. Different workers have reported that signs of zinc deficiency, responsive to zinc treatment, occur in cattle where the pasture contains 18-42 μg g^{-1}, 19-83 μg g^{-1} and an estimated 28-50 μg g^{-1} zinc. Zinc is relatively nontoxic to birds and mammals and a wide margin of safety exists between normal intakes and those likely to produce deleterious effects. Lambs and feeder cattle are somewhat less tolerant of high zinc intakes than are rats, pigs and poultry, in which 1000 μg g^{-1} zinc causes depressed feed consumption.

Manganese The requirements of cattle for body growth appear to be substantially lower than the requirements for normal bone growth and fertility. It appears that a diet containing 25-30 μg g^{-1} (dry weight) is adequate in all respects. Manganese is among the least toxic of the trace elements to mammals and birds. The adverse effects of excess manganese on growth are mainly a reflection of depressed appetite. A relationship between manganese, iron metabolism and hemoglobin formation is apparent from studies with lambs, cattle and pigs, with an intake containing 45 μg g^{-1} influencing the iron uptake by anaemic lambs, and levels between 50-125 μg g^{-1} affecting hemoglobin formation in mature rabbits and baby pigs.

The average concentrations of copper, manganese and zinc in the pasture grasses sampled were 33, 580 and 68 μg g^{-1} (dry weight); that for radium 0.95 pCi g^{-1} (dry weight). With our present understanding we expect that the level of copper, manganese and zinc will become worse with time if no remedial action is taken at the RJ site.

No assessment of the molybdenum status of FR area has been made. From work done in the Alligator Rivers area, an area with similar floodplains, it is expected to be low; (for example the Mo content of water from the Magela Creek during the 1974-75 Wet was < 0.1 μg ℓ^{-1}).

It is expected that present levels of copper and manganese in pasture grass would be causing pathologically detectable effects in grazing stock, but these have not been investigated. Presumably the risk would be markedly increased if, for example, two consecutive years with well above average rainfall (as occurred in 1973-74 and 1974-75) were followed by years with below average rainfall. For this series of events, cattle would be forced to graze areas that are more heavily contaminated than the average.

The results reported in this chapter are based on metal extraction from soil samples using hot 10% nitric acid for 20 minutes. The volume of acid is fixed at 2.75 times that of the volume of ashed soil sample. This method of extraction is meant to approximate to the biologically available material. The possibility exists that whereas the method efficiently extracts Cu, Mn and Zn, a much harsher technique (e.g.

hydrofluoric-perchloric acids) is needed to extract all the radium. This is being investigated.

The work reported here was a preliminary enquiry, its results warrant a more scientific study which is being attempted in the form of a comparative study of the Finniss and Magela floodplains. By this means it is hoped to place the waste management requirements for uranium mining-milling in the Alligator Rivers area on a more scientific basis.

TABLE 8.1

DISTRIBUTION OF RADIOACTIVE AND STABLE ELEMENTS IN SOIL, PASTURE GRASSES AND PAPERBARK LEAVES ACROSS THE FINNISS PLAINS

Locations (1:50000)	Concentration in Ash							Concentration in Dry Material																				
	Soil - Surface							Sedge Grasses							Parra Grass							Paperbark Leaves						
	$\mu g\ g^{-1}$					*pCi g^{-1}		$\mu g\ g^{-1}$					pCi g^{-1}		$\mu g\ g^{-1}$					pCi g^{-1}		$\mu g\ g^{-1}$					pCi g^{-1}	
	Ca	Mg	Cu	Zn	Mn	^{226}Ra	^{210}Pb	Ca	Mg	Cu	Zn	Mn	^{226}Ra	^{210}Pb	Ca	Mg	Cu	Zn	Mn	^{226}Ra	^{210}Pb	Ca	Mg	Cu	Zn	Mn	^{226}Ra	^{210}Pb
6-518620	2.2	2.6	3	6	260	0.14	2	1.8	1.6	18	37	236	0.4	2.0														
6-520607	0.7	0.2	3	4	33	0.04	3	2.6	1.9	16	42	207	0.2	1.0														
6-516604	1.1	0.3	8	9	68	0.005	4.4	1.9	2.2	20	41	410	0.1	1.4								7.7	2	1.2	12	33	0.004	<0.1
6-517600	1.4	0.6	7	10	75	0.02	2.1															11.3	4.9	2.1	13	428	0.02	1.5
6-517595	1.5	0.6	30	35	290	0.25	3.6															10.4	3.6	3.8	29	910	0.1	<0.1
6-517590	0.6	0.4	40	30	120	3.04	7.4	1.9	3.3	150	109	1150	6.0	1.5								17.5	7.2	4.5	25	80	0.2	<0.1
6-520583																						17.3	2.5	3.9	13	14	0.03	<0.1
6-525575	4.2	0.9	300	70	250	0.49	10															11.2	4.4	5.5	16	92	0.3	0.2
6-508595	2.1	1.3	17	7	165	0.06	2.5	2.5	2.5	25	60	610	0.35	0.3														
6-505590	1.2	0.8	2	6	70	0.02	3.5	2.3	3.0	30	50	660	0.6	1.3														
6-500585	1.2	0.5	6	5	70	0.05	2.6	2.3	2.4	23	50	500	0.5	0.9														
6-495584	0.9	0.7	5	5	50	0.03	2.6	1.8	1.6	22	30	400	0.8	1.0														
6-486582	0.9	0.6	4	7	60	0.06	3.6	1.6	2.2	20	40	400	0.2	0.4														
6-485575	2.3	1.8	185	34	350	0.87	5.5	2.7	2.7	95	75	1450	0.6	2.2														
6-481569	1.6	0.8	160	40	425	0.61	3.9	4.6	5.7	100	100	1200	4.4	2.3														
6-485570	2.0	0.9	120	30	350	0.32	2.9	3.5	4.2	60	90	1600	2.0	1.8														

TABLE 8.1 cont.

Locations (1:50000)	Concentration in Ash: Soil - Surface ($\mu g\ g^{-1}$)					*$pCi\ g^{-1}$		Concentration in Dry Material: Sedge Grasses ($\mu g\ g^{-1}$)					$pCi\ g^{-1}$		Parra Grass ($\mu g\ g^{-1}$)					$pCi\ g^{-1}$		Paperbark Leaves ($\mu g\ g^{-1}$)					$pCi\ g^{-1}$	
	Ca	Mg	Cu	Zn	Mn	^{226}Ra	^{210}Pb	Ca	Mg	Cu	Zn	Mn	^{226}Ra	^{210}Pb	Ca	Mg	Cu	Zn	Mn	^{226}Ra	^{210}Pb	Ca	Mg	Cu	Zn	Mn	^{226}Ra	^{210}Pb
6-469620	0.4	0.5	1.2	4	15	0.03	2.5	12.9	2.5	13	75	315	0.6	0.6														
6-466604	0.7	0.5	2.5	3	10	0.02	2.7	1.7	2.6	10	55	215	0.1	0.6														
6-465596	0.9	0.5	2.5	6.5	55	0.04	1.2	1.6	1.6	16	34	320	0.3	0.2	2.2	2.8	18	47	256	0.3	<0.1							
6-470581	1.4	0.7	5.4	13	100	0.3	1.4								2.2	3.6	50	50	240	0.7	0.4							
6-467577	1.8	0.9	100	30	860	0.3	3.6																					
6-330540	4.1	1.7	1.5	12	90	0.17	1.6	6.3	6.3	33	200	2100	2.0	0.5														
6-355560															3.4	6.4	40	130	560	1.5	0.7							
6-373555								5.2	5.2	55	130	880	1.5	0.7	4.1	4.4	57	130	758	1.4	0.6							
6-312546†								6.3	6.6	6	90	156	0.25	0.2														
6-486480	1.3	0.6	2.0	3	11	0.02	1.6								2.7	1.7	7	100	150	0.2	0.5							
6-486494	2.3	1.1	2.0	3	7	0.06	1.0								4.2	2.4	8	60	260	0.2	0.2							
6-486508	2.6	0.6	2.0	5	35	0.46	1.5								2.9	2.9	9	22	240	0.1	0.2							
6-486528	2.8	1.3	15	6	60	0.06	3.4								3.2	3.2	15	100	520	0.2	0.2							
6-486538	2.6	1.1	6.0	8	35	0.11	2.9								1.6	2.2	20	40	100	0.4	0.3							
6-599608															1.0	0.8	13	18	238	1.3	0.6							
6-430585	2.7	0.4	3	6	35	0.06	1.7								3.3	2.5	14	45	730	0.3	0.5							
6-442585	1.7	0.4	6	6	40	0.02	2.3								2.1	2.7	13	30	315	0.1	0.5							
6-450583	1.3	0.9	4	5	18	0.04	0.3								2.1	3.4	16	50	310	0.1	0.3							

* *^{226}Ra and ^{210}Pb analyses expressed in $pCi\ g^{-1}$ dry weight*

† *Saline - sedge grasses*

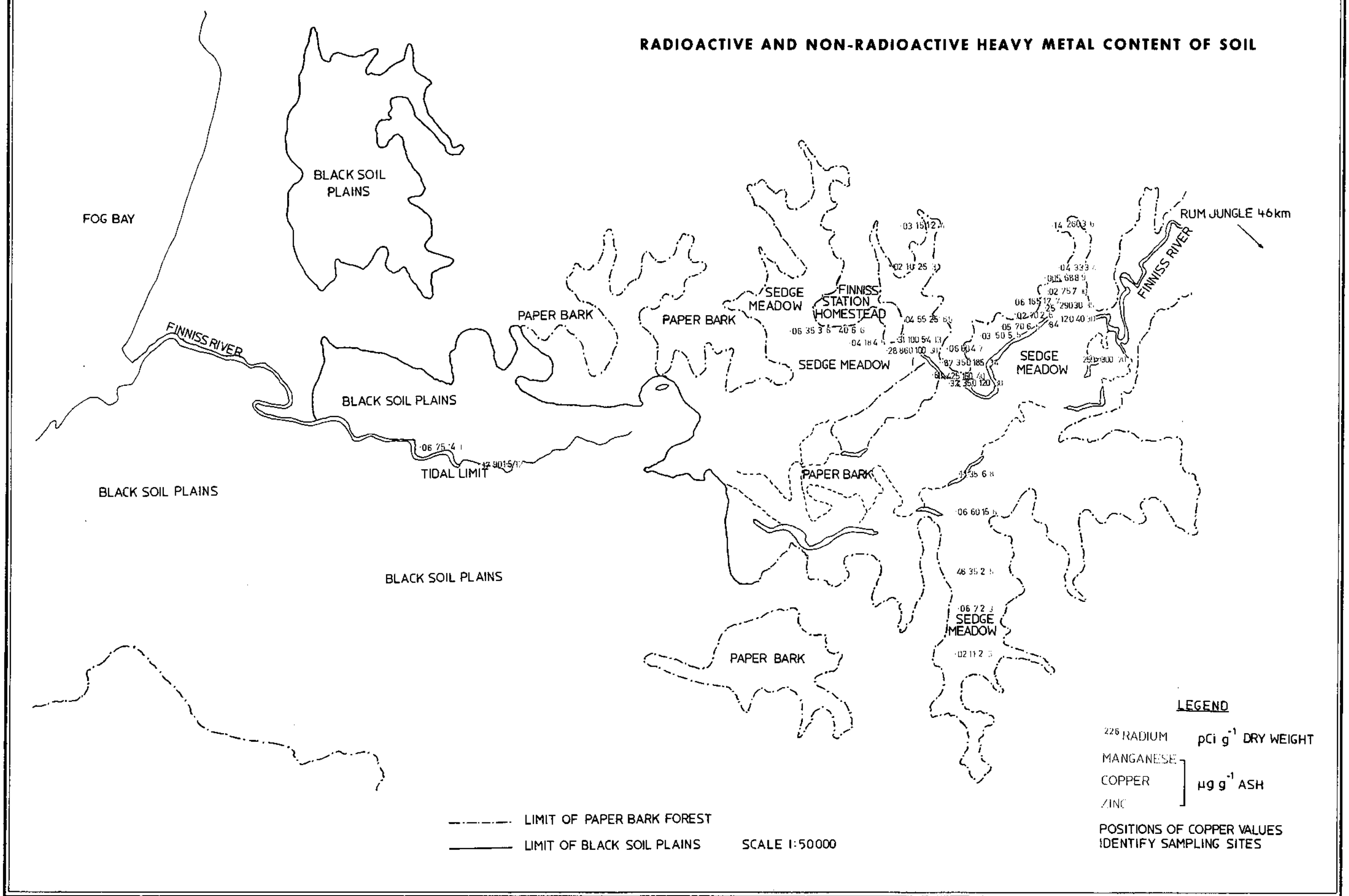
TABLE 8.2

VERTICAL DISTRIBUTION OF RADIOACTIVE AND STABLE ELEMENTS IN SOIL

Locations (1:50000)	Soil															
	Concentration in Ash															
	Surface 2-5 cm							Depth Sample								
	$\mu g\ g^{-1}$					*$pCi\ g^{-1}$			$\mu g\ g^{-1}$					*$pCi\ g^{-1}$	
	Ca	Mg	Cu	Zn	Mn	^{226}Ra	^{210}Pb	Depth (cm)	Ca	Mg	Cu	Zn	Mn	^{226}Ra	^{210}Pb
6-518620	0.7	0.2	3	4	33	0.04	3.0	77	1.7	0.4	2.0	6	25	0.44	1.0
6-517590	0.6	0.4	38	28	120	-	7.4	77	0.6	0.2	5.0	6	23	0.84	3.0
6-508595	2.1	1.3	17	7	165	0.06	2.5	55	0.6	0.6	1.2	6	11	0.50	1.6
6-485575	2.3	1.8	185	34	350	0.87	5.5	81	1.8	0.7	1.7	6	24	0.69	1.1
6-481569	1.6	0.8	160	40	425	0.61	3.9	40	1.4	0.7	1.7	7	20	0.64	0.8
6-485570	2.0	0.9	120	30	350	0.32	2.9	35	0.6	1.1	1.6	6	11	0.73	1.2
6-469620	0.4	0.5	1.2	4	15	0.03	2.5	70	0.9	0.5	1.4	3	8	0.35	1.2
6-486508	2.6	0.6	2	5	35	0.46	1.5	35	2.8	0.7	1.0	4	15	0.43	1.3

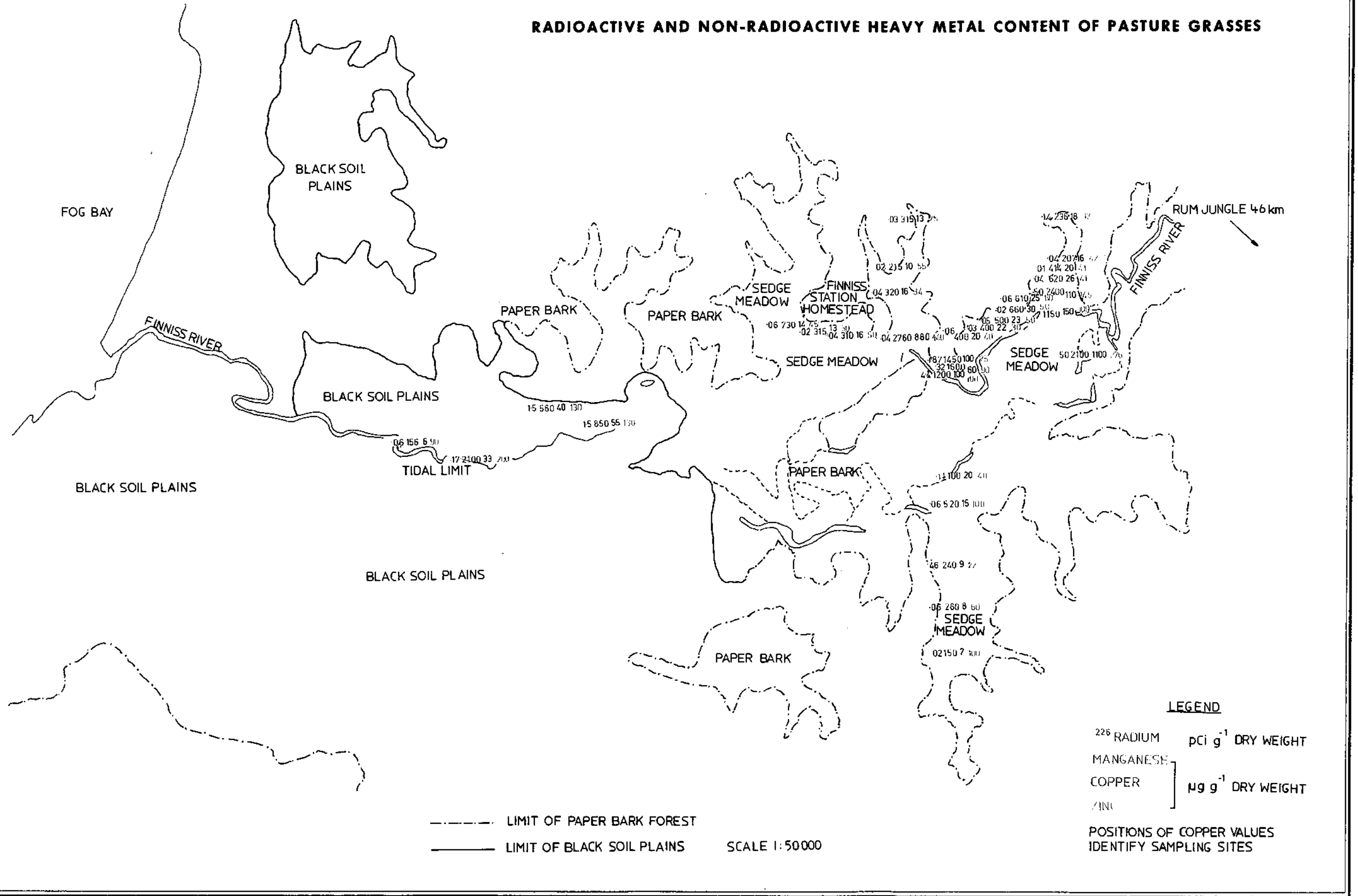
* *^{226}Ra and ^{210}Pb analyses expressed in $pCi\ g^{-1}$ dry weight.*

RADIOACTIVE AND NON-RADIOACTIVE HEAVY METAL CONTENT OF SOIL

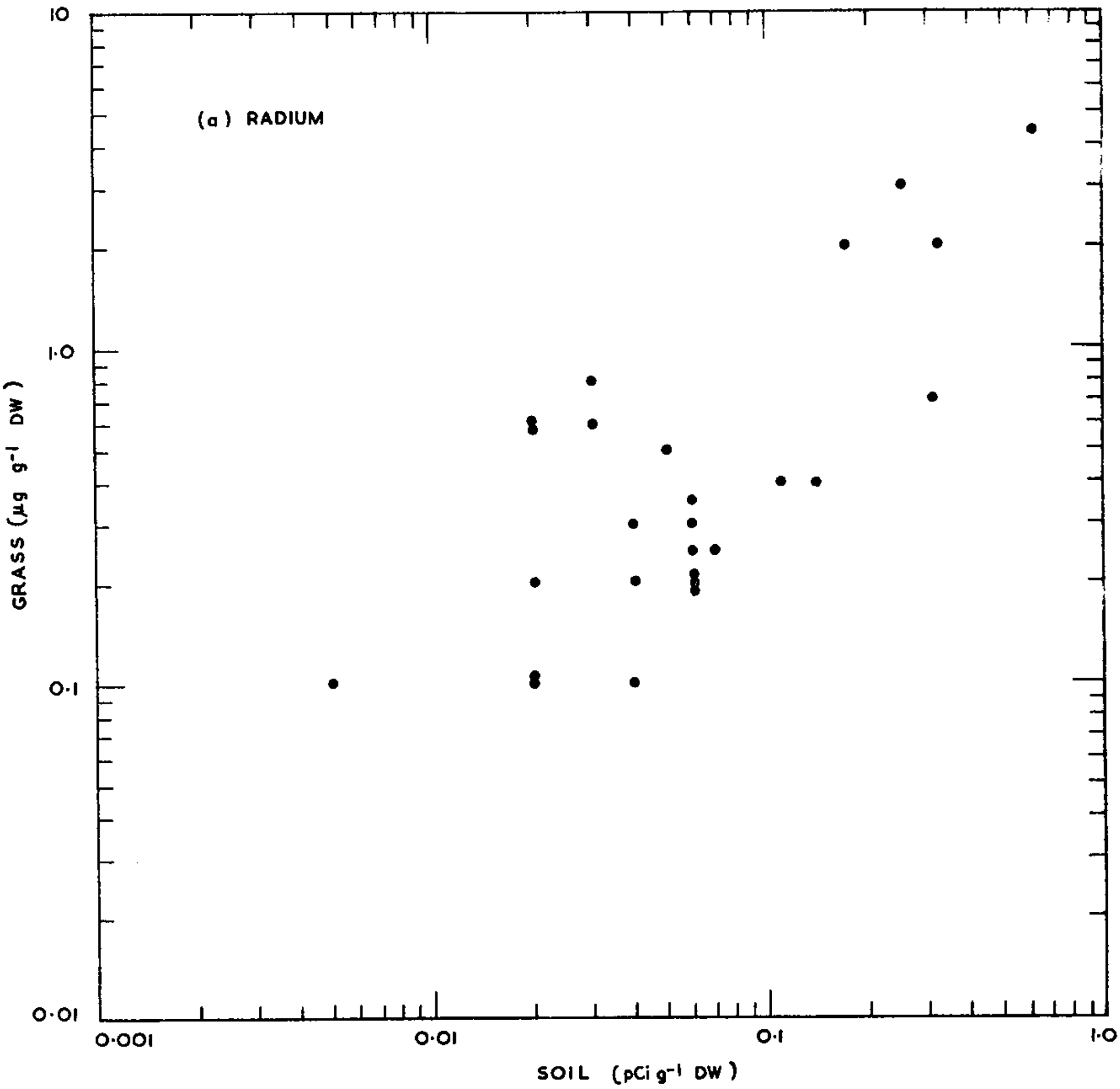


MAP 8.1

RADIOACTIVE AND NON-RADIOACTIVE HEAVY METAL CONTENT OF PASTURE GRASSES

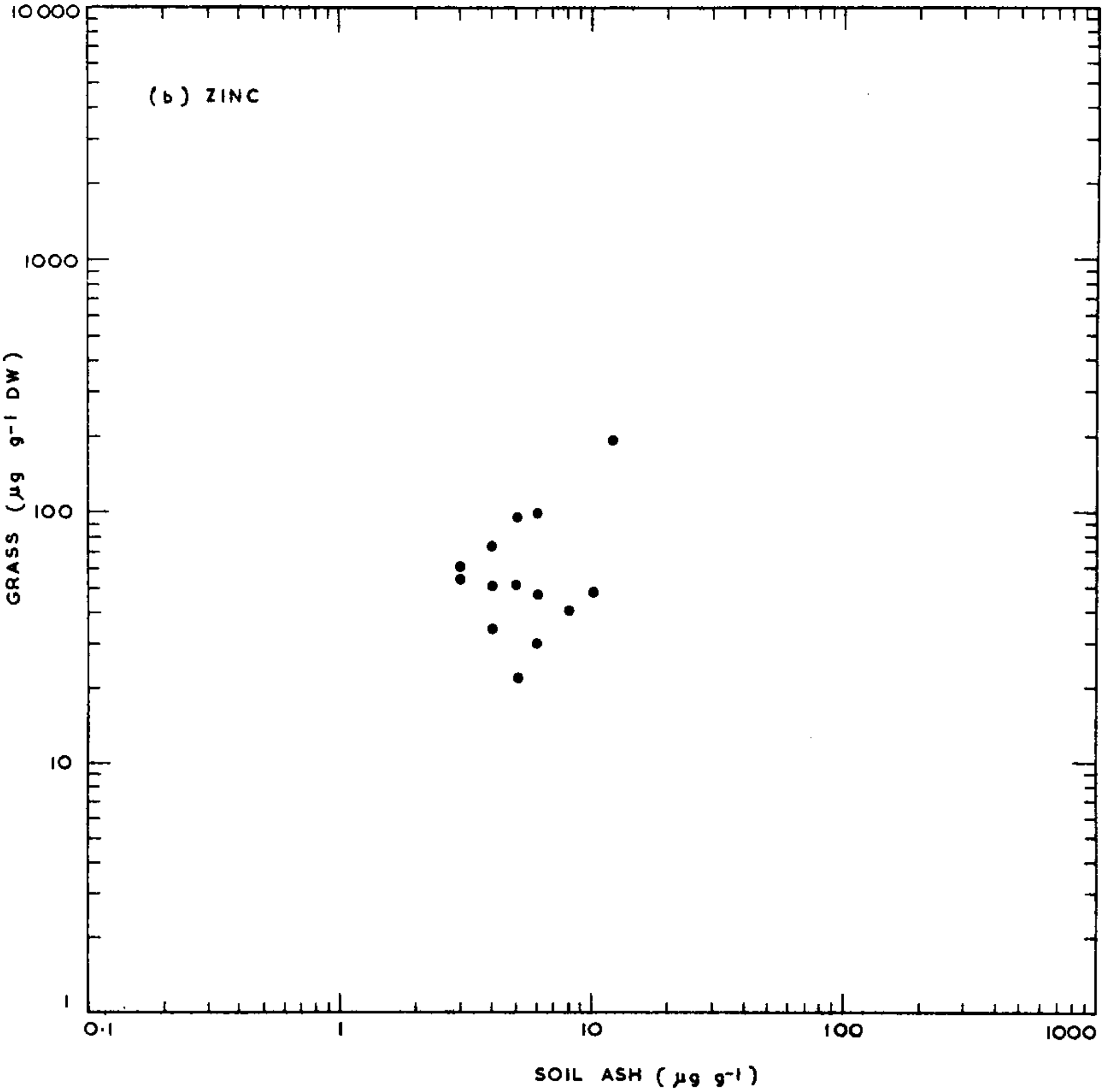


MAP 8.2



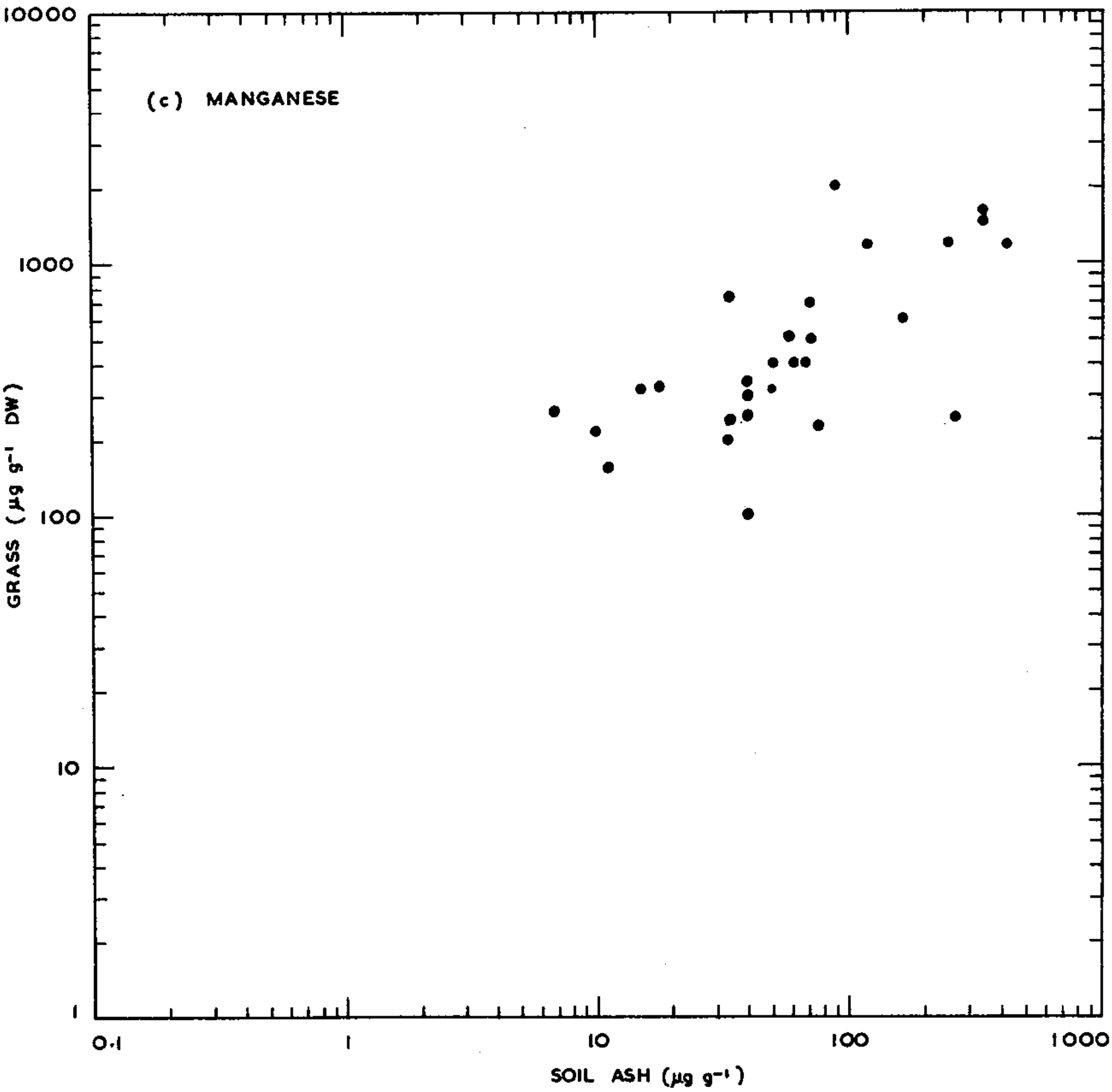
VARIATION IN THE CONTAMINANT CONCENTRATION FOR GRASSES AS A FUNCTION OF LEVELS IN THE SUPPORTING SOIL FOR RADIUM

FIGURE 8.1(a)



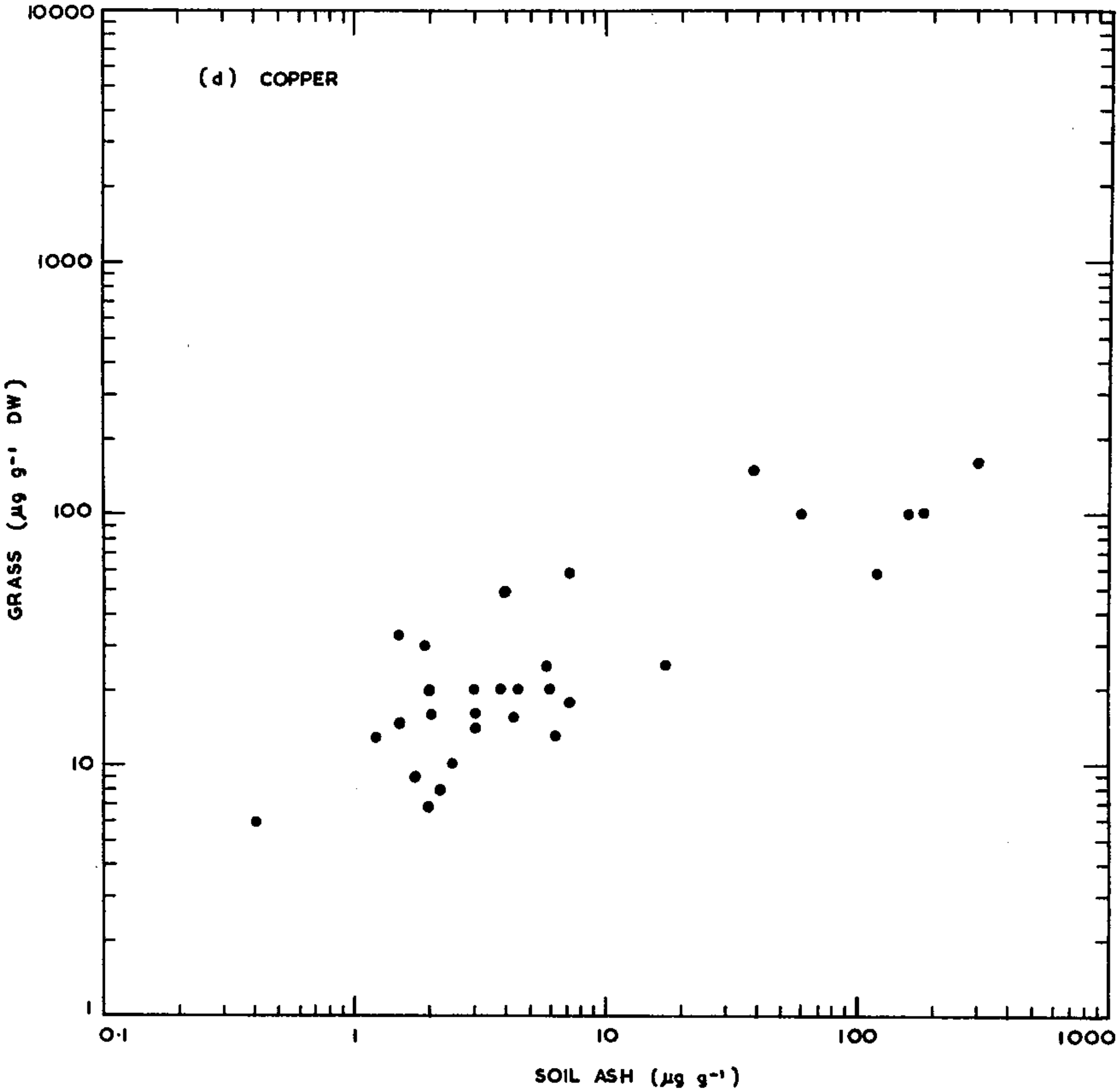
VARIATION IN THE CONTAMINANT CONCENTRATION FOR GRASSES AS A FUNCTION OF LEVELS IN THE SUPPORTING SOIL FOR ZINC

FIGURE 8.1(b)



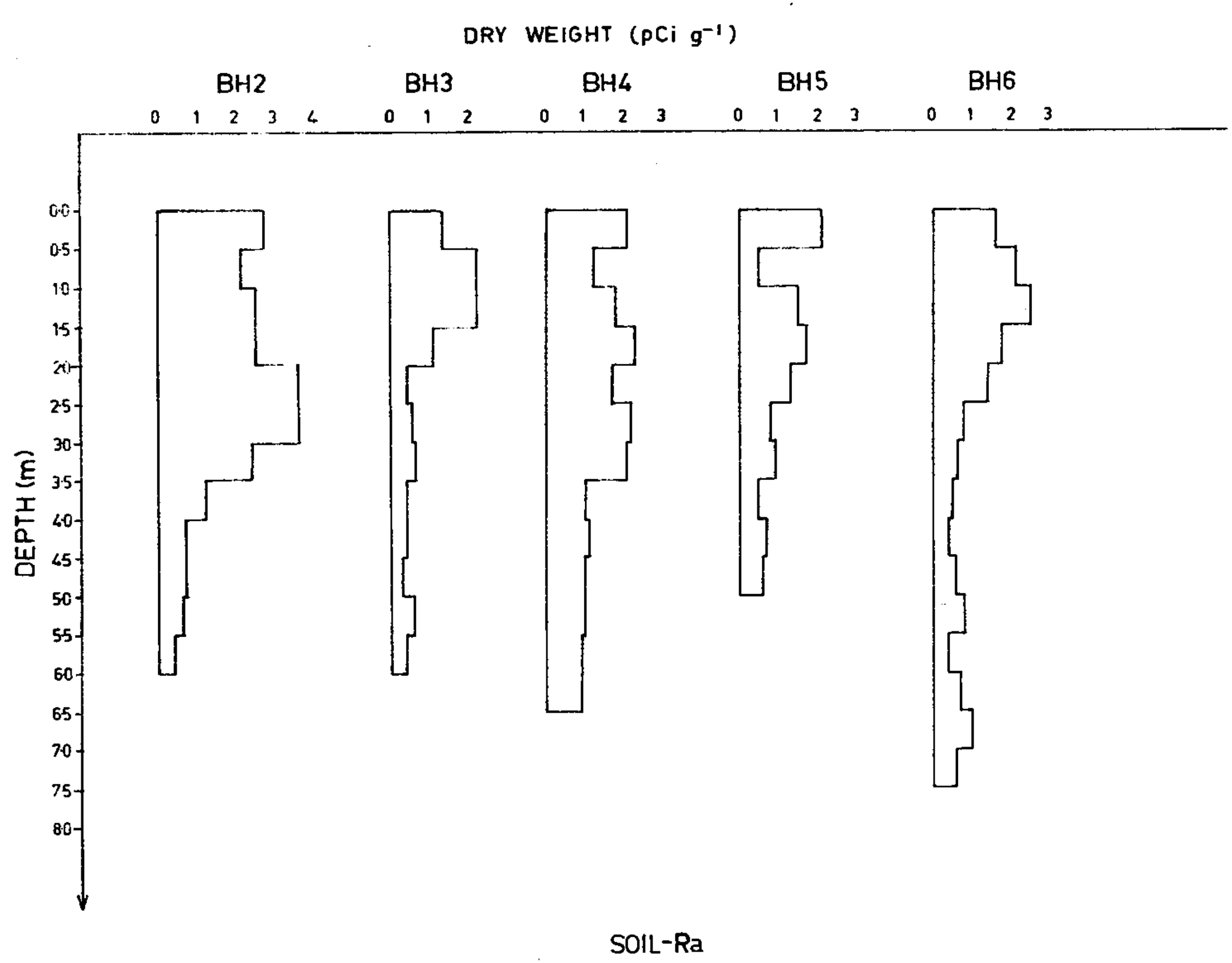
VARIATION IN THE CONTAMINANT CONCENTRATION FOR GRASSES AS A FUNCTION OF LEVELS IN THE SUPPORTING SOIL FOR MANGANESE

FIGURE 8.1(c)



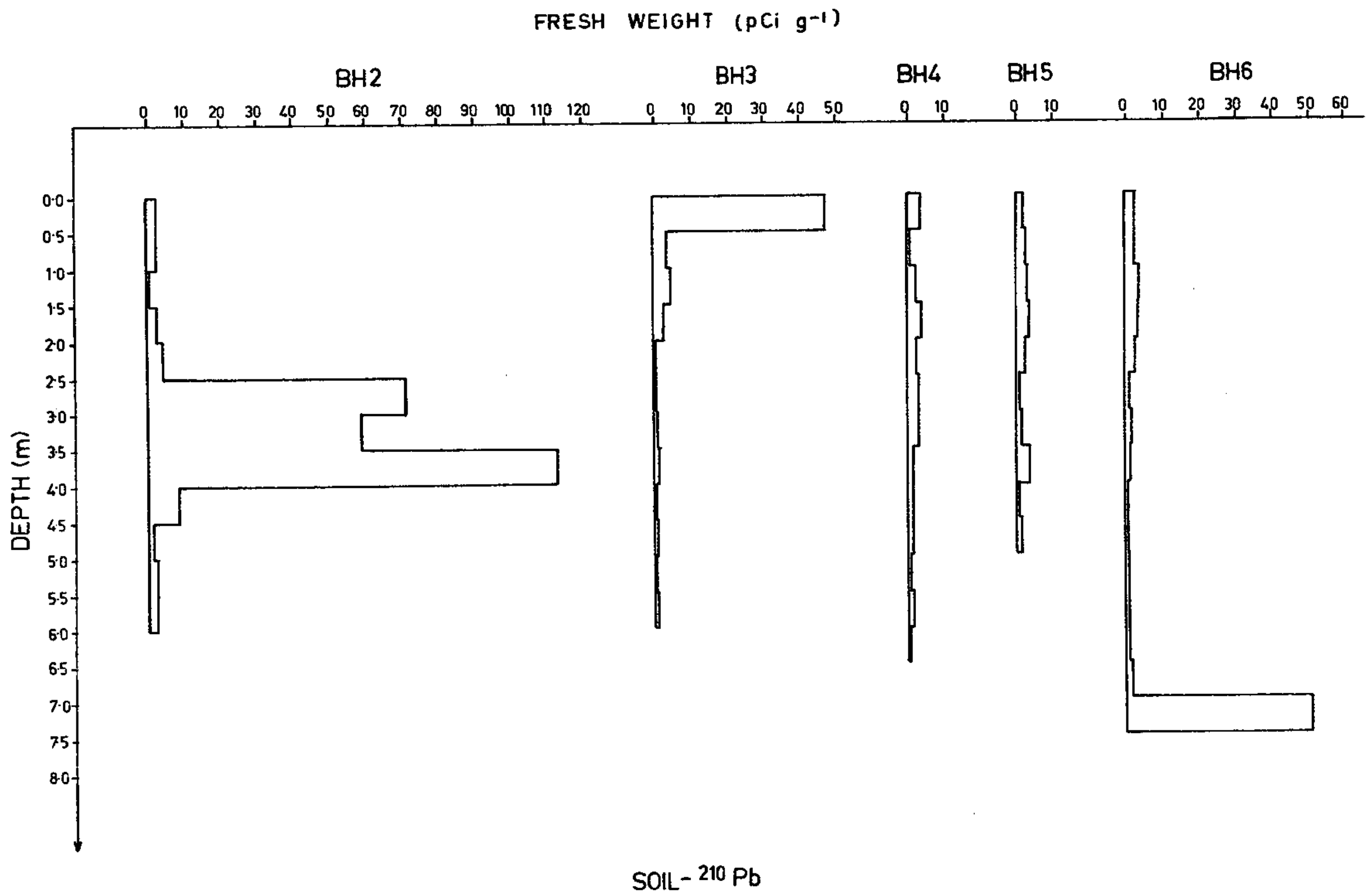
VARIATION IN THE CONTAMINANT CONCENTRATION FOR GRASSES AS A FUNCTION OF LEVELS IN THE SUPPORTING SOIL FOR COPPER

FIGURE 8.1(d)



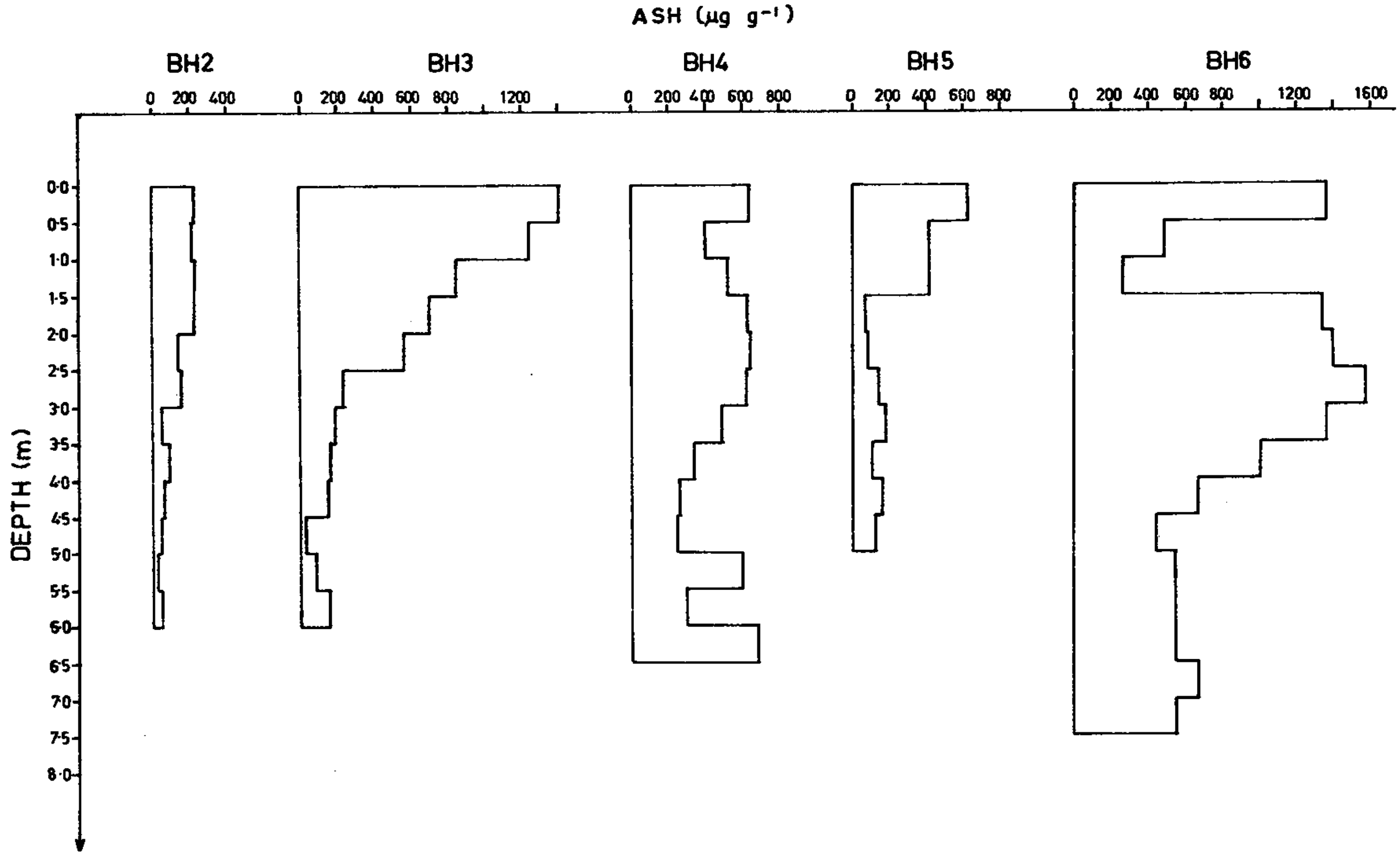
THE DISTRIBUTION OF ^{226}Ra IN THE SOIL PROFILES AT LOCATIONS BH2-BH6

FIGURE 8.2



THE DISTRIBUTION OF ^{210}Pb IN THE SOIL PROFILES AT LOCATIONS BH2-BH6

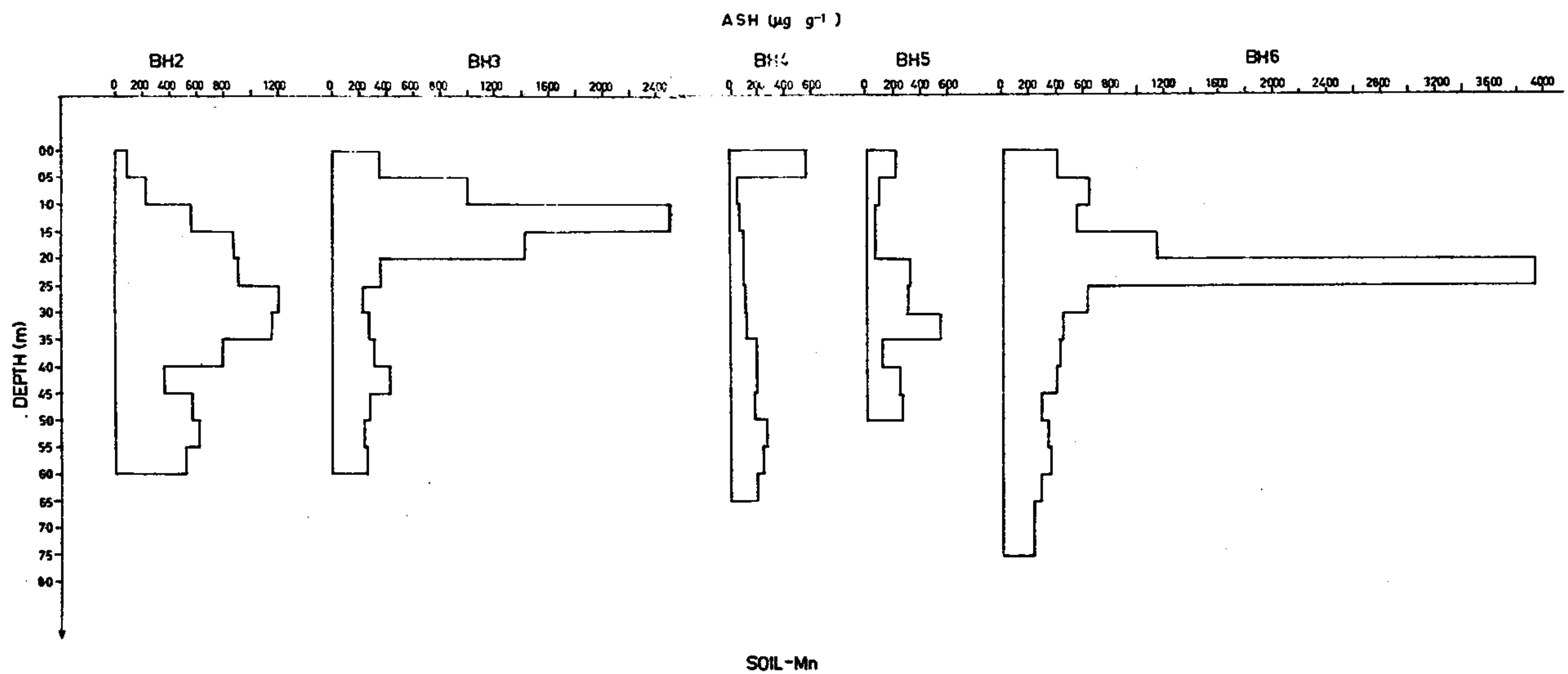
FIGURE 8.3



SOIL-SO_4

THE DISTRIBUTION OF SO_4 IN THE SOIL PROFILES AT LOCATIONS BH2-BH6

FIGURE 8.4



THE DISTRIBUTION OF Mn IN THE SOIL PROFILES AT LOCATIONS BH2-BH6

FIGURE 8.5

RUM JUNGLE ENVIRONMENTAL STUDIES

CHAPTER 9

RADIOLOGICAL ASPECTS

by

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ABSTRACT

A study was conducted of environmental contamination in the Rum Jungle area resulting from the release of radioactive substances.

Radioactivity in the Finniss River system was sampled, exposure routes were identified and dose commitments were estimated.

CONTENTS

9. RADIOLOGICAL ASPECTS

9.1 Introduction

Environmental contamination resulting from radioactivity is treated here separately, not because the release history and subsequent fate of radium differ significantly from those of the other heavy metals, but because different assumptions are used to predict the effects of radioactive pollutants.

Standards for the release of radioactivity are based solely on its possible effect on man and, in contrast with other pollutants, do not involve criteria related to acute effects nor make the assumption that there are thresholds for delayed or long term responses, irrespective of radiation dose or dose rate. Therefore releases of radioactivity at levels acceptable for man will not usually affect biota other than man, since levels will be too low to produce acute effects and any delayed response would be quite undetectable. Exceptions may come from isotopes of low specific activity for which chemical toxicity can be more limiting than radioactivity. Uranium is in this category but radium is not.

Compliance with individual dose limits for man is conveniently assessed by reference to a critical group. A critical group of people is one which, through habits of eating, recreation, occupation, location or any other pertinent factor, is more at risk from released radionuclides than the community at large. Critical groups may be identified by census or defined arbitrarily, as was done here; the characteristics of the group are those used previously for the Alligator Rivers study [Davy & Conway 1974]. The estimated dose to members of such a group will equal or exceed that which could be received by any group of real people.

9.2 Radioactive Releases

Substantial releases of radium occurred during the earlier years of the Rum Jungle (RJ) operation. Estimates of the quantities involved were presented in Section 8.1. During the 1973-74 Wet, the radium-226 and lead-210 content of water samples from the diversion channel, Copper Creek and Old Tailings Creek were frequently determined. In only one case did the concentrations exceed drinking water standards recommended by the International Commission of Radiological Protection (ICRP) (^{226}Ra: 10 pCi ℓ^{-1}; ^{210}Pb: 0.1 nCi ℓ^{-1}; ^{210}Po: 0.7 nCi ℓ^{-1}). Details of the results obtained are available from the computer output related to this report; the ranges of values are indicated below:

Sampling site	^{226}Ra pCi ℓ^{-1}	^{210}Pb pCi ℓ^{-1}
East Branch (upstream mine site)	0.3-0.9	0.1-0.8
Diversion channel (W7)	0.1-2.5	0.1-0.3
Diversion channel (W5)	0.4-1.0	0.1-0.9
Diversion channel (W1)	0.1-2.5	0.1-0.8
Copper Creek	0.9-2.0	0.1-0.5
Old Tailings Creek	0.5-12	0.4-8.5

Over 90% of the radium contained in uranium ore remains in the tails material after milling for the uranium, so it is not unexpected that the runoff water from the tails dump area contained the highest levels of radioactivity.

This effect, the release of radium from tails material is most marked at the end of the Dry when relatively high values occur in those sections of EB where tails material has been sedimented following erosion of the tails dump area. For example pools of water in the EB before the first flow in 1973 contained ^{226}Ra in the range 6-10 pCi ℓ^{-1}. During the first flush of that year, the radium content in the main FR upstream of the junction was 0.8 pCi ℓ^{-1} whereas the value downstream was 12.2 pCi ℓ^{-1}.

At the beginning of the Wet, groundwater from the tails dump area is slightly contaminated with Ra; BH6 registered the highest value (3.4 pCi ℓ^{-1}) but this can be attributed to seepage from White's opencut rather than from leaching of tails material (see Chapter 6).

Springs in the area were monitored only infrequently. Values were generally in the region 3 pCi ℓ^{-1}. Similar or greater values occur elsewhere in the NT (e.g. Oenpelli, Howard Springs, Leichhardt Springs, Mt Brockman) the highest value recorded (100 pCi ℓ^{-1}) being for a spring in the Katherine area.

9.3 Radioactivity in the Finniss River

FR was not sampled during the Wet. During the Dry, levels were quite low. With the exception of two sites, the average value was 0.33 pCi ℓ^{-1} (range 0.17 to 0.7 pCi ℓ^{-1}). The two exceptions corresponded with major bends in the river channel (coordinates 532603 and 483567). The Ra concentrations at these locations were 2.4 and 2.5 pCi ℓ^{-1} respectively. It seems probable that these higher levels are attributable to sediments containing tails material.

Table 9.1 contains results of analyses on sediments from the FR system. Some of the results can be attributed to the influence of the river's velocity on the amount of fine sediments deposited since it is the finer particles that carry a disproportionate amount of radium and other heavy metals. For example the coarse sediments from Old Tailings Creek contained 0.33 pCi g^{-1} whereas the values for the EB-FR junction and its delta were 5.0 and 15.5 pCi g^{-1} respectively. The result for Walker's Ford (7.2 pCi g^{-1}) was unexpected. Some thought has been given to damming FR at Walker's Ford as a future water supply for Darwin. The feasibility study for such a proposal should include a detailed assessment of the radium status in that stretch of river.

Groundwater from the most extensively contaminated sedge meadow of the FR floodplains had a radium content of 0.5 pCi ℓ^{-1} and a ^{210}Pb content of 0.3 pCi ℓ^{-1}. These values are consistent with the soil type and the radioactivity level of the deeper soils (^{226}Ra: 0.44 pCi g^{-1}; ^{210}Pb: 1.0 pCi g^{-1}), providing further evidence that inputs of Ra from the mine site are no longer occurring.

Generally the radioactivity of floodwaters from the plains was of low level (^{226}Ra: ~ 0.3 pCi ℓ^{-1}; ^{210}Pb: < 0.1 pCi ℓ^{-1}). An exception was that general area where the floodwater converged to the FR tidal channel. Here the levels were ^{226}Ra: 3.7 pCi ℓ^{-1}; ^{210}Pb: < 0.1 pCi ℓ^{-1}. Unfortunately it was this area where extensive flooding prevented detailed sampling during 1974.

9.4 Exposure Routes

The following exposure routes can be identified for the FR area:

- consumption of vegetables grown in the area,
- consumption of aquatic food caught in the river,

- consumption of beef and buffalo reared on the floodplains,
- drinking water drawn from FR.

(Note that the levels for chemical contaminants in waters from EB make it unpotable.)

9.4.1 Vegetables

Table 9.2 contains results for vegetables obtained from a commercial market garden a few km downstream from the RJ area (lat. 12°58.4', long. 130°57.5'). These gardens are irrigated with spring water. For comparison, analyses of vegetables from other unpolluted areas of the NT are included. The results indicate that consumers of vegetables from the RJ area are not exposed any more than they would be by consuming vegetables from elsewhere.

9.4.2 Aquatic food

Mussels Insufficient mussels were collected from the FR to generate a worthwhile average for their radium content. Instead the radium content of FR waters has been averaged and the related content for mussels estimated from the well defined concentration factor - Ra content of water curve obtained from work in the Alligator Rivers area [Davy & Conway 1974]. The respective values were 0.63 pCi ℓ^{-1} and 0.13 pCi g^{-1}.

Barramundi Table 9.3 summarises results for barramundi and some other fish from FR. This table also shows the Zn, Mn and Cu concentrations in barramundi flesh and the related concentration factors (CF). For all four contaminants, concentration factors appear to decrease with increasing concentration of the contaminant in water. Figure 9.1, which is a plot of CF for Ra against the Ra content of water, pools results from the FR and the Alligator Rivers. No doubt some of the scatter indicated in this figure is due to fish mobility but fish age also seems to be important since juveniles (< 1 kg body weight) show a lower Ra content in the flesh (and therefore a lower CF) than more mature fish (> 2 kg body weight). For the mature fish the Ra content of bone is about 4 times that of flesh when both are expressed on a fresh weight basis.

The usual way to derive an acceptable level for Ra concentration in food which supplies protein is to assume that all protein intake is derived from that source alone; in this case the daily consumption of fish is taken as 350 g. Under these conditions the derived level is 0.06 pCi g^{-1}; this concentration will lead to an annual intake of 8 nCi ^{226}Ra. Continued exposure at this level will eventually produce the maximum allowable body burden of ^{226}Ra. Barramundi from four of the nine sampling sites equalled or exceeded this limit. In assessing the radium ingested by members of the critical group by consuming barramundi, the results for all nine sites were averaged.

Crocodile (Johnston's) Only one crocodile was taken. The Ra content of its flesh was the same as the one taken from the South Alligator River. However as both were from sections of the respective rivers where tails material polluted the bottom sediments, the Ra content of the former (0.04 pCi g^{-1}) was attributable to RJ operations.

9.4.3 Buffalo-Beef

Up to the time of writing it had been impossible to obtain buffalo and beef samples from the FR station. To arrive at an estimate it was assumed that the Ra content of meat from the Finniss plains is a multiple of the Ra content of meat from the Magela plains, the multiplying factor being the ratio of the Ra content of the respective pasture grasses. This approach makes the reasonable assumption that the Ra content of the grazing animal is linearly related to the Ra content of its food. The uncertainty in the method stems from the minimal amount of pasture sampling carried out for the Magela plains.

The average Ra content of pasture grass from the Finniss plains was 0.95 pCi g^{-1}; and that for the Magela plains, 0.31 pCi g^{-1} both dry weight. The average Ra content of buffalo flesh from the Magela plains was 0.024 pCi g^{-1} with a range of 0.005 to 0.05 pCi g^{-1} both fresh weight. (Note that dry weight is 20% of fresh weight.)

If the acceptability of Ra in meat is based on a daily consumption of 350 g, the derived limit would be 0.063 pCi g^{-1} (fresh weight). The estimate for meat from the Finniss plains based on the assumptions given above is 0.015 pCi g^{-1} (fresh weight).

9.4.4 Water

It is unusual for non-aborigines to draw their drinking water from the FR when fishing etc., but aborigines undoubtedly do. The local aborigines maintain at least two camps on the FR south bank - one at Sweet's lookout and the other at a stockman's shed ~ 3 km further south.

In arriving at an estimate for the Ra intake with water, the 6 sampling sites on this stretch of FR were averaged to give 0.63 pCi ℓ^{-1}. The concentration recorded at the Sweet's lookout site was 2.4 pCi ℓ^{-1}.

9.5 Radium Intake

Table 9.4 provides an estimate of the yearly intake of ^{226}Ra resulting from a rather extreme hypothetical diet. The total intake of just over 8 nCi y^{-1} is slightly in excess of the annual limit of 8 nCi y^{-1} derived from the recommendations of the International Commission on Radiological Protection for dose limits for members of the general public, meat and fish contributing most to the estimate. It should be noted that the radium concentration in meat is an estimated value and not an average over many samples.

From the data available it is not possible to say how much of this estimated intake is due to naturally occurring radium and how much arises due to past releases of radium from the Rum Jungle area. As a comparison the estimated radium intake arising naturally in the Magela plains of the Alligator Rivers area is also about 8 nCi y^{-1} for a similar critical group.

In principle, tables similar to Table 9.4 could be drawn up for other daughters of the uranium chain e.g. ^{210}Po and ^{210}Pb. In practice the ^{210}Pb concentrations are measured by measuring the α activity of ^{210}Po and assuming the ^{210}Pb is in equilibrium with it. The ^{210}Pb level in many of the foodstuffs was below the limit of detection; see for example Table 9.2 for vegetables where all ^{210}Pb values are less than 0.01 pCi g^{-1}. Similarly for barramundi almost all samples had a ^{210}Pb concentration of less than 0.03 pCi g^{-1} (fresh weight), the exceptions being 0.09 and 0.07 pCi g^{-1}. If barramundi were eaten at the rate of 350 g d^{-1} intake of ^{210}Pb-^{210}Po would be less than one tenth the recommended ICRP limit for members of the public.

It must be remembered that in framing recommendations for radioactive isotopes that have long biological and radio-active half-lives, the ICRP assumes that ingestion continues throughout the life of the exposed person and, in the case of ^{226}Ra, the maximum permissible body burden will be reached only after 50 years' exposure at the recommended limits of exposure.

TABLE 9.1

HEAVY METAL CONTENT OF SEDIMENTS

FROM THE FINNISS SYSTEM

(GRAB SAMPLING)

Location*		Concentration (dry weight)				
		Cu	Mn	Zn	^{226}Ra	^{210}Pb
		μg g^{-1}			pCi g^{-1}	
Tailings Creek	(0)	450	58		0.33	14
EB-FR junction	(9.4)	140	12		5.0	220
EB delta	(9.6)	240	40	11	15.4	51
Point D	(26)	25	11	8	1.0	1.5
Bad Crossing	(39)	650	375	56	1.1	13
Walker's Ford	(50)	320	90	36	7.2	8.3
Boyne's Point	(82)	15	95	8	1.2	2.5
Ironstone †	(100)	0.4	75	1	0.06	0.4

* *Bracketed figures: km distance downstream from mine area.*

† *Tidal stretch*

TABLE 9.2

ELEMENTAL COMPOSITION OF VEGETABLES

(FRESH WEIGHT BASIS)

Vegetable	Source	Composition								
		Cu	Mn	Zn	Pb	Mg	Ca	^{226}Ra	^{210}Pb	U
		$\mu g\ g^{-1}$	$\mu g\ g^{-1}$	$\mu g\ g^{-1}$	$\mu g\ g^{-1}$	$\mu g\ g^{-1}$	$\mu g\ g^{-1}$	$pCi\ g^{-1}$	$pCi\ g^{-1}$	$pCi\ g^{-1}$
Tomatoes	Jabiru	0.66		5.1	< 0.33			0.005		0.001
	Adelaide R.	0.33	3.7	1.6	0.04	68	28	0.002	< 0.01	0.0007
	Rum Jungle	0.03	0.9	1.4	< 0.02	76	42	0.002	< 0.01	< 0.0007
Tomatoes (tree)	Adelaide R.	0.53	1.0	2.0	0.06	96	42	0.002	< 0.01	< 0.0006
Cucumber	Jabiru	0.25		2.4	0.2			0.007		0.0014
	Adelaide R.	0.34	0.7	2.7	0.05	130	90	0.01	< 0.01	< 0.0002
	Rum Jungle	0.4	2.3	2.2	0.1	190	200	0.004	< 0.01	0.002
Cucumber (apple)	Adelaide R.	0.6	1.2	3.6	0.1	170	160	0.01	< 0.01	< 0.0003
Cucumber (gherkin)	Rum Jungle	0.3	1.6	1.8	0.08	130	140	0.004	< 0.01	< 0.0003
Potato (sweet)	Rum Jungle	2.1	4.1	2.7	0.2	210	170	0.03	< 0.01	0.003
Marrow	Rum Jungle	0.5	1.1	1.5	0.02	120	64	0.003	< 0.01	0.017
Egg plant	Adelaide R.	0.7	5.4	1.9	0.03	170	90	0.008	< 0.01	0.0004
Zucchini	Adelaide R.	0.6	7.5	5.7	0.02	190	80	0.003	< 0.01	< 0.0004
Capsicum	Adelaide R.	0.4	7.2	2.2	0.03	100	65	0.001	< 0.01	< 0.0004
Cabbage (red)	Jabiru	0.19		7.2	0.76			0.059		0.009
Cabbage (chinese)	Jabiru	0.14		29.0	3.4			0.06		0.012
Radish	Jabiru	0.2		5.7	< 0.3			0.05		0.003
Sweet corn	Jabiru	2.1		36.0	< 0.5			0.001		0.007
Beans (string)	Jabiru	0.9		6.5	0.3			0.07		0.01
Beetroot	Jabiru	0.6		12.6	< 0.5			0.05		0.03

TABLE 9.3

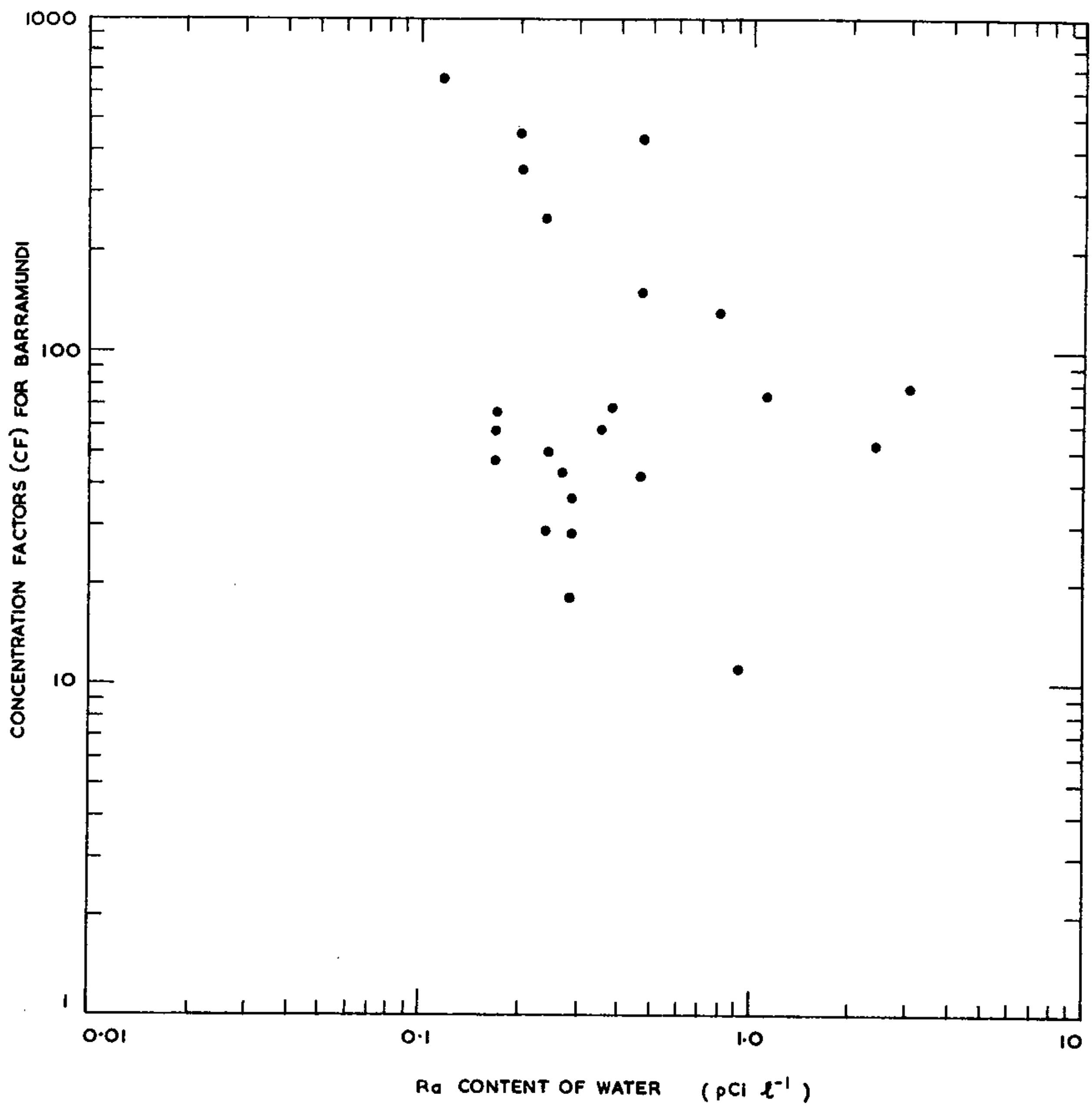
CONCENTRATION FACTORS (CF) FOR SOME HEAVY METALS IN SOME AQUATIC FOODS

	Concentration in water				Concentration in flesh				Concentration Factor			
	Cu	Zn	Mn	Ra	Cu	Zn	Mn	Ra	Cu	Zn	Mn	Ra
	$\mu g\ \ell^{-1}$			$pCi\ \ell^{-1}$	$\mu g\ g^{-1}$			$pCi\ g^{-1}$				
Barramundi	30	30	40	2.4	1.7	8.8	1.2	0.12	57	290	29	50
"	30	< 5	< 5	0.17	1.0	7.3	1.5	0.11	33	> 1500	> 300	650
"	30	< 5	< 5	0.28	0.5	5.2	0.7	0.01	17	> 1100	> 140	36
"	20	10	20	0.17	0.18	2.7	0.31	0.01	9	270	16	59
"	50	< 5	< 5		0.35	2.2	0.29		7	> 440	> 57	
"	20	20	< 5	0.24	0.23	3.1	0.23	0.06	12	160	> 47	250
"	20	20	< 5	0.24	0.45	4.5	0.43		22	220	> 87	
Tarpon	20	20	< 5	0.24	0.21	3.5	0.86	0.007	11	170	> 170	29
Barramundi	30	20	60	0.17	0.35	2.2	0.29	0.01	12	110	5	59
"	30	20	60	0.46	0.27	2.6	0.35	0.02	9	130	6	43
Black Bream	< 10	< 10	< 10	0.2	1.1	15	3.2	0.09	> 110	> 1500	> 320	450
"	< 30	< 30		1.1	0.48	11.5		0.08	> 16	> 380		73
"	< 30	< 30		0.8	0.2	11.3		0.1	> 7	> 380		125
Barramundi	< 30	< 30		0.8	2.6	10.5		0.35	> 90	> 350		440
Crocodile	< 10	< 10	< 10		2.2	14	7.3	0.04	> 220	> 1400	> 730	

TABLE 9.4

THE INGESTION OF RADIUM BY A HYPOTHETICAL GROUP

Exposure route	Assumed consumption ($kg\ y^{-1}$)	Radium concentration $pCi\ g^{-1}$ (fresh weight)	Yearly intake (nCi)
Water	730	0.000 63	0.46
Meat	200	0.015	3.0
Fish	40	0.086	3.4
Cultivated vegetables	70	0.0086	0.6
Cultivated fruit	20	0.007	0.14
Crocodile	15	0.04	0.6
Goose	5	0.0043	0.02
Mussels	2	0.13	0.26



CONCENTRATION FACTOR FOR RADIUM BY BARRAMUNDI AS A FUNCTION OF RADIUM CONCENTRATION IN THE SUPPORTING WATER

FIGURE 9.1

RUM JUNGLE ENVIRONMENTAL STUDIES

CHAPTER 10

MODELLING OF HEAP BEHAVIOUR

by

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ABSTRACT

Modelling studies were conducted on the processes responsible for the bacterial oxidation of iron sulphides arising from mining wastes. It was concluded that the oxygen supply was the most likely rate limiting process. Hence any modelling of the oxidation process must conceive of a mechanism that can supply the comparatively large quantities of oxygen required to explain the ion concentrations.

CONTENTS

10. MODELLING OF HEAP BEHAVIOUR

10.1 Introduction

High heavy metal concentrations in the water flowing from coal mines, mine wastes, overburden heaps and old tailing dams are a common occurrence [Smith & Bradshaw 1972; Dugan 1972; Weatherley & Dawson 1973]. The metal ions result from the oxidation of metal ores, a process frequently catalysed by bacteria. The most widely reported oxidation occurs in waste and overburden heaps containing pyritic ores where the oxidation is catalysed by the autotrophic bacteria, ferrobacilli and thiobacilli [Dugan 1972; Miller et al. 1963]. This process is characterised by acid water (pH 2-4) as well as the presence of heavy metal ions.

The Intermediate and White's overburden heaps contain significant quantities of pyrites while Dyson's heap contains somewhat less (see Table 10.1). Analysis of both spring and runoff water shows them to be quite acid (pH 2-4) and to contain significant quantities of sulphate ions as well as Cu, Co, Mn, Fe, etc. Hence it seems likely that bacterial oxidation of sulphides in the heap is taking place.

Modelling of the bacterial oxidation is a difficult problem since the actual oxidation process is not well understood and a considerable amount of data on the water transport properties of the overburden heaps is still lacking. Hence modelling studies at this stage have been confined to understanding what processes may take place and which processes must be precluded because they do not fit the data available. Attention has also largely been confined to White's overburden heap for the following reasons:

(i) Intermediate heap has no significant spring flow except after heavy rain. This makes comparison with water transport calculations of doubtful value.

(ii) Spring flow from Dyson's heap indicates that this heap has markedly nonhomogeneous structure.

(iii) White's heap is the largest and contributes a greater mass of heavy metals to the East Finniss system than the other two heaps (see Table 6.10).

This section discusses the chemical equations thought to describe the oxidation, the various rate limiting processes and the implications of some of the measurements carried out to date.

10.2 Oxidation Process

There is still some uncertainty in the literature [Dugan 1972] as to the exact process by which the ferrobacilli and thiobacilli oxidise the sulphides to extract energy for their own growth. However, it will be sufficient for some of our needs to obtain the stoichiometric chemical equations which describe the oxidation and estimate under what conditions the oxidation may proceed.

As well as sulphide and oxygen, the bacteria need elements such as potassium and carbon for their growth. However, it would appear that under most conditions the supply of these is adequate and the main rate-limiting process is the supply of oxygen. Similarly, the rate of oxidation will depend on the acidity of the environment and the concentration of some metals such as Mn. However, the bacteria tend to modify their environment to suit themselves and produce strains which can cope with the presence of metals normally noxious to them. Hence we assume that any of the reactions required in oxidation will proceed, and use the stoichiometric equations as a basis for estimating oxygen and sulphide usage.

Oxidation of the iron pyrites can be described by either of

$$FeS_2 + \frac{7}{2}O_2 + H_2O \rightarrow FeSO_4 + H_2SO_4 \text{ — low oxygen requirement} \qquad \text{...(10.1)}$$

or

$$FeS_2 + \frac{15}{4}O_2 + \frac{1}{2}H_2O \rightarrow \frac{1}{2}H_2SO_4 + \frac{1}{2}Fe_2(SO_4)_3 \text{ — high oxygen requirement} \qquad \text{...(10.2)}$$

Similarly, oxidation of chalcopyrites can be described by either

$$CuFeS_2 + 4O_2 \rightarrow CuSO_4 + FeSO_4 \text{ — low oxygen requirement} \qquad \text{...(10.3)}$$

or

$$CuFeS_2 + FeS_2 + 8O_2 \rightarrow Fe_2(SO_4)_3 + CuSO_4 \text{ — high oxygen requirement;} \qquad \text{...(10.4)}$$

and zinc and similar sulphides by

$$ZnS + 2O_2 \rightarrow ZnSO_4 \qquad \ldots(10.5)$$

Clearly the equations 10.1 to 10.5 are a simplification of the processes involved, but these equations can be used to give estimates of the quantity of oxygen required to explain the measured reaction products, and of sulphate ore that must be consumed to explain these reaction products.

10.3 Estimates of Oxygen Required and Sulphides Consumed

Equations 10.1 to 10.5 indicate that O_2 requirement and sulphide usage can be estimated from either metal ion or sulphate concentrations. Examination of the analysis of water flowing from the heaps shows, however, that the iron concentration is well below that expected from the measured sulphate ion concentration. This is not unexpected since iron sulphate forms ferric hydroxide which precipitates out. Two methods were used to estimate the oxygen consumption:

(i) The O_2 usage was estimated from the measured SO_4 concentration, on the assumption that all the O_2 was used in oxidising iron sulphide (equations 10.1 and 10.2).

(ii) The Cu, Zn, Mn, etc. concentrations were used to estimate the O_2 needed and the SO_4 produced in the oxidation of these sulphides. The balance of the SO_4 concentration was then assumed to be due to iron sulphate oxidation and the O_2 usage estimated as in (i).

In practice, the nonferrous metal ion concentrations were low and the two estimates differed by less than 1%. The results for the simpler approach described in (i) above are quoted here. Naturally equations 10.1 and 10.2 will each give a different result for oxygen usage. It was assumed that either process was equally likely and that the O_2 usage was estimated from averaging the requirement of the two processes.

As indicated in Chapter 6, the metal ion and sulphate concentrations measured in the runoff water vary considerably. The SO_4 concentration in the runoff is also usually significantly below that measured in spring water, so any estimate of the total amount of oxygen required will depend on the runoff fractions assumed, as well as the concentration of SO_4 in the runoff. As was done in Chapter 6 the runoff fraction is assumed to be either 25 or 50%. As in that chapter also a high and a low estimate of the SO_4 concentrations are used; the former from the 1969-70 measurement on the central runoff and the latter from the 'typical' storm measured on March 3, 1974. Ion concentrations in the various springs from White's heap do not vary greatly and a simple average of the values has been assumed.

These data are summarised in Table 10.2 which also gives estimates of the oxygen and sulphide used in an average season.

10.4 Implications of Oxygen and Sulphide Consumption

There are a number of inferences that can be drawn from the oxygen and sulphide consumption about the oxidation mechanism and where in the heap it may take place.

The first and major point is that the solubility of oxygen in water is 8 mg ℓ^{-1} which is about three orders of magnitude too low to allow rainwater to act as a significant source of the oxygen required. Similarly, the low solubility of oxygen in water implies that little of the oxidation takes place in the region of the stack below the water table. This means that the processes of interest take place in that region of the heap which is unsaturated with water and, if water transport is required to explain the movement of oxygen, bacteria or metal ions, it means also that the water transport equations applicable to an unsaturated medium have to be solved. These are mathematically less tractable than the equations for a saturated medium and require more data for their solution.

The second point is the large volume of air required to supply the oxygen. For White's heap this is between 1.0×10^7 and 1.8×10^7 m^3 for a typical year, depending on the assumptions made about runoff fractions and ion concentrations in runoff. If the stacks are assumed to have ~ 20% pore volume, the volume of air required implies that the air in the pores must be changed between 13 and 20 times a year. This tacitly assumes that the oxidation takes place in the stack as a whole. If, however, the oxidation is assumed to be confined to the first 30 cm or so of the surface [Burgess & Richmond 1970], then the pore volume in that region of the heap must change about 1000 times a year. This means about 3 times a day if it is assumed the process goes on all the year round, or about 10 times a day if the oxidation is confined to the Wet.

The total mass of sulphur from sulphide ore consumed in a typical year is between 1.6×10^3 and 2.6×10^3 tonnes. Again, assuming that the oxidation process goes on in the heap as a whole, then the sulphide content would be exhausted in about 100 years and in about 2 years if it were confined to the top 30 cm surface layer. If we were to assume that the sulphide comes from a layer on the surface that was exhausted each year, then this layer would have to be ~ 14 cm thick. If we ignore for the moment the problem of how oxygen is supplied to this layer and assume that the oxidised layers are rather like the layers of an onion skin, then in the 17 years since White's overburden heap was completed, we would expect the total oxidised layer to be some 2.48 m deep.

10.5 Ion Concentration in Stack near Heap Surface

In October 1974, at the end of the Dry, a number of samples were taken of the soil from just below the surface of White's and Intermediate heaps. Trenches some 1.8 m deep were dug in the surface of these heaps and samples taken from the sides and bottom of the trench at well defined intervals. Half the trench sites were chosen to coincide with areas where pyrites outcropped on the surface and the other half from areas where there was no evidence of pyrites. The details of this sampling are given in Table 10.3.

Regression analysis on the sulphide, iron, copper and water concentrations from the pyritic areas showed no significant trend with increasing depth from the surface. Independent sets of measurements, say, on one face of a trench did at times show a definite trend but averaged over all sets any such trends were masked by the variability of the concentrations in the samples.

A similar analysis of the non-pyritic areas of White's that had 100% grass coverage and those with 10% grass coverage, showed no significant trend with increasing depth. There was also no significant difference between the average SO_4 concentration for the two areas (82 ± 73 and 60 ± 60 respectively).

The average value of the sulphide content of this first 1.8 m in the pyritic areas of White's was (0.83 ± 0.27)%. This is low compared to the (1.94 ± 0.73)% for similar areas on the Intermediate heap, which has been in existence for a shorter time. It should be noted that these are both lower than the values of 3.27 and 3.06% found for the average sulphide content of these heaps from auger-drill samples (Table 10.1).

10.6 Conclusions

The annual consumption of pyrites in White's heap due to oxidation is small compared to the quantity in the heap and there is no evidence from samples of spring water in 1969-70 and 1974 that ion concentrations are dropping. It seems, therefore, that oxygen supply is the most likely rate limiting process in the oxidation of the sulphides in the overburden heaps. Hence any modelling of the oxidation process must conceive of a mechanism that can supply the comparatively large quantities of oxygen required to explain the ion concentrations. If this supply comes from air in the heaps, then the pore volume must change about 15 times a year and even more often if the oxidation process is confined to a volume significantly less than the whole volume of the heap.

The flow of water through the heap provides one possible mechanism for air change in the pore volume. Since water flowing over and through the heaps also carries the metal and SO_4 ions into the river system, modelling of the water flow in the heap appears to be a necessary part of the complete model. This problem is under study.

It is not clear at this stage how important it is to know the details of the actual oxidation process. This may become clearer when the timescale for oxygen transport is better known. For example, if the actual oxidation process is faster than the rate at which oxygen can be supplied, then clearly the details of the oxidation process are not important.

TABLE 10.1

ANALYSIS OF BULKED

AUGER-DRILL SAMPLES

	% by Weight	
	White's	Intermediate
Cu	0.086	0.2
Zn	0.011	0.025
Ni	0.026	0.2
Co	0.013	0.03
Mn	0.099	0.027
S	3.27	3.06
Pb	0.048	0.5

TABLE 10.2

ESTIMATES OF ANNUAL USAGE OF OXYGEN AND SULPHUR

IN WHITE'S OVERBURDEN HEAP

Source	SO_4 concentration mg ℓ^{-1}	Implied O_2 usage mg ℓ^{-1}	Water discharge m^3		Annual oxygen usage g (x 10^{-4})	
			25% Runoff	50% Runoff	25% Runoff	50% Runoff
Spring and ground water	21 400	12 840	318 000	211 000	4.08	2.71
Runoff water	Low 142 High 7551	Low 85 High 4539	Low 106 000	High 212 000	Low 0.009 High 0.480	Low 0.018 High 0.96
					4.09 4.56	2.73 3.67

Annual sulphur usage lies between 1.56 and 2.61 x 10^9 g y^{-1}

Annual air usage lies between 1.05 and 1.76 x 10^{13} cm^3 y^{-1}

Stack volume 3.95 x 10^{12} cm^3

Pore volume at 20% 7.95 x 10^{11} cm^3

TABLE 10.3

ANALYTICAL RESULTS FOR THE TRENCHES IN WHITE'S AND INTERMEDIATE OVERBURDEN HEAPS

Site	Interval cm	Temperature °C Sun	Temperature °C Shade	Temperature °C Sample	pH	Wet weight Water %	Conductivity µS cm^{-1}	SO_4 µg g^{-1} dry wt.	S % dry weight	Dry weight µg g^{-1} Cu	µg g^{-1} Mn	µg g^{-1} Pb	% Fe	µg g^{-1} Zn	µg g^{-1} Co	µg g^{-1} Ni	Remarks
WP1	WO-6	47	31.5	32	3.5	8.1	2738	2765	2.05	146	72	100	9.8	21	25	78	Black shale. No obvious Cu mineralisation
	W6-12			32	3.5	7.7	2283	2506	2.10	85	42	97	9.2	4	20	49	
	W12-18			32	3.5	9.5	2651	2731	1.83	136	54	179	8.1	4	17	61	
	W18-30			32	3.5	6.5	2477	2570	1.28	81	61	109	8.6	4	11	46	
Coordinates 085370	E0-6			32	3.5	6.7	3816	3410	2.27	6000	89	159	11.5	5	26	123	
	E6-12			32	3.5	9.8	2289	2438	1.85	812	73	173	10.0	4	17	138	
	E12-18			32	3.5	10.1	1180	1598	1.63	557	72	218	9.7	4	22	154	
	E18-30			32	3.5	8.5	1162	1558	1.34	360	44	95	8.1	4	11	51	
	S0-6			32	3.5	20.7	432	183	0.88	84	48	118	8.6	4	37	90	
	S6-12			32	3.5	9.3	328	174	1.43	71	31	121	9.2	< 4	< 4	6	
	S12-18			32	3.5	9.2	268	167	1.34	77	46	131	7.8	< 4	5	22	
	S18-30			32	3.5	10.2	406	240	1.31	148	42	104	6.4	4	19	71	
	30-60			32	3.0	8.2	1007	1498	1.19	92	47	90	9.0	3	9	24	
	60-90			32.5	3.5	5.7	830	874	1.06	70	76	68	9.6	4	9	31	Black shale + brown ferruginous rock
	90-120			37.7	3.0	5.0	1079	1630	1.23	98	79	62	9.7	4	15	43	
	120-180			40.7	3.5	9.1	1325	1930	0.59	256	85	183	11.4	27	98	147	
WP2	W0-6	47	35	39	3.5	3.0	280	92	0.70	294	51	318	7.9	72	126	161	Black shale + brown ferruginous rock. No obvious Cu mineralisation.
	W6-12			39	3.5	6.1	145	135	0.31	505	48	427	11.7	24	141	195	
	W12-18			39	3.5	4.6	145	174	0.20	680	252	464	10.2	15	153	136	
	W18-30			39	3.5	2.8	114	152	0.42	574	77	63	9.7	4	156	141	
Coordinates 098388	N0-6			39	3.5	6.7	143	30	0.48	589	432	357	14.1	83	205	223	
	N6-12			39	3.5	7.7	151	134	0.40	363	83	298	9.1	39	120	166	
	N12-18			39	3.5	7.2	199	80	0.37	377	57	219	9.4	32	107	134	
	N18-30			39	3.5	6.9	270	195	0.55	369	67	527	12.6	82	100	158	
	E0-6			39	3.5	4.7	216	164	0.68	461	62	621	11.2	91	127	153	
	E6-12			39	3.5	4.7	260	93	0.31	280	69	1400	9.7	74	122	164	
	E12-18			39	3.5	4.4	199	157	0.38	245	59	157	8.3	22	262	220	
	E18-30			39	3.5	3.4	204	76	0.18	2890	76	81	14.1	35	323	364	
	30-60			36	3.5	3.3	94	134	0.44	807	123	49	11.2	24	161	193	
	60-90			36	3.5	4.7	126	140	0.64	954	75	315	11.2	33	291	273	
	90-120			36	3.5	6.9	255	186	0.40	675	176	266	13.1	32	166	178	
	120-180			36	3.5	7.5	444	259	0.75	1320	125	2400	11.0	400	319	300	

TABLE 10.3 (continued)

Site	Interval cm	Temperature °C Sun	Temperature °C Shade	Temperature °C Sample	pH	Wet weight Water %	Conductivity μS cm^{-1}	SO_4 μg g^{-1} dry wt.	S % dry weight	Dry weight Cu μg g^{-1}	Mn μg g^{-1}	Pb μg g^{-1}	Fe %	Zn μg g^{-1}	Co μg g^{-1}	Ni μg g^{-1}	Remarks
WP3 (Coordinates 060390)	W0-6	47	36	36	3.5	2.1	222	64	0.37	228	71	94	9.2	< 4	50	85	Black shale + brown ferruginous rock. Obvious Cu mineralisation.
	W6-12			36	3.5	3.0	130	43	0.15	1720	144	58	12.0	4	270	308	
	W12-18			36	3.5	2.7	180	151	0.20	1530	100	62	10.0	< 4	253	270	
	W18-30			36	3.5	4.5	540	203	0.31	219	90	178	10.3	< 4	199	509	
	N0-6			36	3.5	2.8	151	30	0.35	395	65	132	11.9	< 4	151	279	
	N6-12			36	3.5	3.4	216	46	0.26	490	24	99	27.2	< 4	213	313	
	N12-18			36	3.5	4.6	280	72	0.20	493	26	182	10.7	< 4	135	248	
	N18-30			36	3.5	4.4	315	84	0.29	238	21	181	8.4	< 4	136	233	
	E0-6			36	3.5	1.7	94	197	0.33	282	80	95	11.5	4	83	87	
	E6-12			36	3.5	3.5	245	185	0.13	427	872	30	16.2	5	426	281	
	E12-18			36	3.5	3.6	180	120	0.15	885	800	52	15.4	4	280	266	
	E18-30			36	3.5	3.4	260	117	0.29	672	107	115	8.8	4	224	832	
	30-60			36	3.5	5.4	795	94	3.37	1480	178	221	16.1	25	181	836	
	60-90			36	3.5	6.0	406	2530	1.03	620	71	137	9.9	4	65	214	
	90-120			36	3.5	4.9	378	205	0.95	245	69	79	8.6	4	37	90	
	120-180			36.5	5.0	6.6	540	806	0.66	728	267	109	9.3	42	160	298	
WNP1 (Coordinates 075423)	N0-12	45	30.5	31	10.0	5.8	47	35	0.09	40	56	24	12.0	< 4	7	< 4	Appeared homogeneous. Level light grey clay + soft grey, broken rocks. 100% grass cover.
	N12-30			31	10.0	4.2	52	37	0.02	12	25	< 4	5.8	< 4	< 4	27	
	E0-12			31	10.0	4.5	89	39	0.09	49	62	41	4.8	4	21	25	
	E12-30			31	10.0	3.9	72	23	0.02	19	38	35	8.7	< 4	7	11	
	S0-12			31	10.0	4.1	97	52	0.04	44	188	9	3.9	< 4	21	44	
	S12-30			31	10.0	4.3	105	52	0.02	13	28	< 4	2.6	< 4	4	4	
	30-60			31	8.0	7.8	42	20	0.04	10	46	9	6.8	< 4	< 4	< 4	Reddish brown clay + reddish purple soft rocks.
	60-90			31	6.5	10.5	328	192	0.22	15 500	356	71	11.5	65	536	562	
	90-120			31	6.0	15.0	444	192	0.68	38 700	1707	145	23.0	257	1200	1280	Brownish grey clay + harder black shales. Very little Cu mineralisation apparent.
	120-180			31	6.0	13.5	378	175	0.64	40 200	736	3360	12.5	93	1350	1640	
WNP2 (Coordinates 071415)	W0-12	49	36	34	6.0	3.2	87	48	0.09	290	124	119	6.9	62	103	121	
	W12-30			34	6.0	4.6	95	33	0.48	1850	146	153	8.6	123	269	302	Soft brown soil + small 5 mm brown pebbles. Sloping and compacted. Very little void space. ~ 10% grass coverage.
	N0-12			34	6.0	6.8	92	27	0.04	401	143	77	7.4	416	86	97	
	N12-30			34	6.0	6.5	64	22	0.09	1290	35	789	5.2	416	495	493	
	S0-12			34	6.0	5.7	94	31	0.15	533	132	114	5.4	65	74	89	
	S12-18			34	6.0	6.9	75	25	0.09	1120	89	194	4.9	84	260	248	
	30-60			34	5.0	6.1	88	148	0.07	1390	132	412	10.7	257	383	405	Black shale + obvious Cu mineralisation.
	60-90			34	5.0	4.9	75	26	0.24	1860	173	333	8.8	35	528	511	
	90-120			34	7.0	3.8	420	179	0.55	648	682	67	9.6	450	303	327	Ditto, and abandoned because in shale.

TABLE 10.3 (continued)

Site	Interval cm	Temperature °C Sun	Shade	Sample	pH	Wet weight Water %	Conductivity µS cm^{-1}	SO_4 µg g^{-1} dry wt.	S % dry weight	Dry weight: µg g^{-1} Cu	µg g^{-1} Mn	µg g^{-1} Pb	% Fe	µg g^{-1} Zn	µg g^{-1} Co	µg g^{-1} Ni	Remarks
IP1	N0-9	53+	36	46.5	3.0	10.3	2227	2330	1.72	961	183	77	10.6	46	149	375	0-180 cm black shale. No obvious Cu mineralisation. Interval increased due to time running out.
	N9-18			46.5	3.0	11.0	2017	2145	0.95	415	105	123	10.6	5	55	124	
	N18-30			46.5	3.0	7.7	645	705	1.06	155	63	56	7.7	< 4	22	50	
Coordinates 031428	E0-9			46.5	3.0	7.2	2130	2230	2.29	483	105	116	9.9	32	75	145	
	E9-18			46.5	3.0	15.3	1957	2122	1.12	357	87	86	9.8	5	44	83	
	E18-30			46.5	3.0	6.1	2361	1881	2.71	232	53	124	7.5	< 4	34	79	
	S0-9			46.5	3.0	12.8	2698	2126	1.87	535	193	77	11.6	6	141	399	
	S9-18			46.5	3.0	11.8	1921	1827	1.34	365	115	116	9.6	< 4	47	131	
	S18-30			46.5	3.0	9.9	415	405	0.75	342	70	2220	8.3	< 4	37	75	
	30-60			37.5	3.5	4.8	398	156	2.77	1390	74	331	10.0	54	217	294	
	60-90			36.5	3.5	5.3	756	338	3.30	2210	68	704	10.2	56	342	387	
	90-120			36.5	3.5	6.7	944	450	2.60	984	81	307	7.6	138	186	224	
	120-180			33.2	3.5	7.2	821	526	2.16	519	134	180	8.4	67	121	208	
IP2	W0-15	53+			2.5	9.4	5397	3766	2.64	2830	89	52	8.4	40	539	584	Black shale. Interval increased due to time. Black shale + brown ferruginous rock.
	W15-30				2.5	6.5	3008	2396	1.83	2200	9	70	6.6	4	1250	1720	
Coordinates 015411	N0-15				2.5	13.1	4197	4864	1.96	1490	62	63	10.2	< 4	238	312	
	N15-30				2.5	10.4	3148	2486	1.25	694	12	66	6.2	< 4	220	276	
	S0-15				2.5	12.9	5397	3595	2.31	1850	49	85	10.9	< 4	291	359	
	S15-30				2.5	8.1	3148	2454	1.34	1270	24	43	6.7	< 4	377	432	
	30-60				3.0	9.0	3148	2447	3.06	2700	43	210	9.8	4	245	322	Black shale + brown ferruginous rock. No obvious Cu mineralisation. Thermometer burst.
	60-90				3.0	9.4	3107	2412	1.01	2500	68	61	11.5	< 4	518	1140	
	90-120				3.0	12.2	3148	2383	2.24	2110	12	90	8.8	< 4	394	830	
	120-180				3.0	11.6	4722	3350	2.40	3840	16	65	8.9	< 4	509	905	
INP1	W0-30	53+	36.5	36	10.0	0.5	581	247	0.24	3520	1813	60	4.3	23	1180	770	0-120 cm grey soil + hard quartzite rocks. Cu stains on surface + obvious Cu minerals amongst soil.
Coordinates 006425	N0-30				10.0	1.0	225	145	1.41	3680	306	37	7.5	52	1040	950	
	E0-30				10.0	1.0	328	137	1.03	4430	1591	77	5.1	54	883	1040	
	30-60				6.0	3.5	387	145	1.52	7510	818	43	7.0	34	847	1260	Abandoned at 120 cm due to time and submerged boulder.
	60-90				6.0	4.0	472	182	3.74	29 000	778	31	9.3	4	950	1250	
	90-120				7.5	3.0	472	202	1.54	6060	869	62	5.4	4	803	863	

W = White's *I = Intermediate* *1, 2, 3 = pit number*
P = pyritic *NP = nonpyritic* *E0-6 = East wall 0-6 cm, etc.*
30-60 = Single bulk sample as taken out by back hoè between 30-60 cm.

RUM JUNGLE ENVIRONMENTAL STUDIES

CHAPTER 11

REMEDIAL PROPOSALS

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R. RICHARDS†

ABSTRACT

A description is given of a method which may help alleviate the pollution in the Rum Jungle area caused by mining operations. It is proposed that revegetation methods may counteract the main problems of erosion and oxidation of material.

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11. REMEDIAL PROPOSALS

11.1 Introduction

Work in the Rum Jungle (RJ) area has documented the causes and effects of the pollution (see previous chapters). Now it is most important to prevent or alleviate this pollution.

Although physical methods such as contour banks and earth moving will play a large part in decreasing the release of pollutants, particularly from the most intractable areas such as the Tailings Dam, a search through the literature indicates that in many different situations the most effective long term solution is the estblishment of a vegetative cover, up to pre-mining or better standards.

The annotated bibliography compiled by Coaldrake et al. [1973] is the source for the origin of many papers on this subject.

The establishment of vegetative cover has beneficial effects as follows:

(i) Reduces erosion of the source material and its consequent flow into drainage lines.

(ii) Establishes a soil-plant layer which decreases the effects of environmental factors such as temperature, rainfall and infusion of oxygen, and their interactions on the bulk of underlying source material. The mechanisms by which these factors affect the source material have been described elsewhere in this report.

(iii) Provides the basis for the invasion of less tolerant plants and subsequently animal species into a less hostile environment.

(iv) Improves the area aesthetically.

The Animal Industry and Agriculture, and Forestry Branches of the Department of the Northern Territory (DNT) were approached by the AAEC to develop methods of revegetating the heaps of low grade ore and overburden of RJ.

11.2 Method

11.2.1 Preliminary investigations

Site selection

During the RJ mining operation heaps of low grade ore and overburden were constructed. The rocks in these heaps contain sulphides which undergo oxidation to form sulphates when exposed to air. These sulphate ions reduce the pH of the soil solution on the heaps and bring toxic heavy metals into solution. The apparent toxic nature of the soil on the heaps has kept plant growth at a very low level.

It was felt that low pH and/or heavy metal toxicities would be the factors most likely to inhibit plant growth apart from low or unbalanced levels of plant nutrients.

Electrical conductivity (Ec) was chosen as an indicator of these inhibiting factors because it is a fast and simple test and, since it provides an indication of the concentration of ionised salts in the solution, we felt that it might in turn indicate the concentration of heavy metals in solution.

White's overburden heap was chosen because it was representative of the waste rock as well as being easily accessible.

A broad survey of the heap was made with respect to pH and soluble salts (Ec). On this basis an area 60 m x 18 m suitable as a trial site was chosen to represent the more hostile end of the environment.

Chemical testing of the site pre-treatment

The trial site was intensively sampled (surface samples from 60 points) for pH and electrical conductivity, to indicate the variations in the local soil conditions and to relate these to post-treatment analyses.

The chemical tests in this trial were performed by the Scientific Services Section of the AI&AB except where otherwise indicated.

11.2.2 Trial design

Iso-pH and iso-Ec maps were drawn, showing the systematic variation over the trial site. The trial was set up on this basis. The area was divided into 18 equal treatment areas (10 m x 6 m), ranked according to their average Ec values. The equal areas were then divided into 3 blocks of 6 on the basis of this ranking. Treatments were then allocated at random within each block (see Figure 11.1).

Treatments

In accordance with established agricultural practice, agricultural lime ($CaCO_3$) was used to increase the pH of the soil. A factorial arrangement of three lime rates and two fertiliser rates (ACF 12:1) was used.

ACF 12:1 is an N-P-K mix of the approximate analysis 12-14.8-10.

Treatment number	Lime ($CaCO_3$) t ha^{-1}	Fertiliser (ACF 12:1) kg ha^{-1}
1	5	
2	10	
3	20	
4	5	100
5	10	100
6	20	100

A nil treatment was not included since this in fact already existed over most of the area.

Species

A shotgun mixture of species was surface sown over the whole trial area after the lime and fertiliser had been disced into the top 10-15 cm. Species were necessarily chosen for their availability rather than suitability. The trial commenced on February 26, 1973.

Species sown were

(i) Natives - collected on White's dump and sown at a rate of $\sim$ 0.5 kg ha^{-1}. *Tridax* sp., *Phaseolus radiatus, Aristida hygrometrica, Alysicarpus vaginalis, Pennisetum pedicellatum, Cyperus* sp. *Heteropogon contortus, Schizachrium* sp., and *Rhynchelytrum* sp. *Pennisetum* sp. is not a native but has spread widely and occurs throughout most of the northern part of NT.

(ii) Introduced - sown at a rate of 4 kg $species^{-1}$ ha^{-1}. Grasses: *panicum maximum* (Common Guinea, Hamil, Coloniao, *Cenchrus ciliaris* (Gayndah), *Paspalum plicatulum* (Rodd's Bay), and *Brachiara decumbens* (Signal grass). Legumes: *Calopogonium mucunoides* (Calopo), *Stylosanthes humilis* (Commercial Townsville stylo (NT)), *Stylosanthes hamata* (Verano), *Stylosanthes guyanensis* (Schofield), and *Lablab purpureus* (Dolichos Lablab).

11.2.3 Post-treatment chemical testing of site

Ten random samples from the top 8 cm of each plot were bulked and tested for pH and Ec in March 1973, and January and May 1974. In addition, the samples taken in May 1974 were analysed for water solubles, minerals, exchangeable cations and available phosphorus. Further information was supplied by the AAEC on pH, Ec and mineral assay from samples taken from untreated areas in October 1974.

11.2.4 Plant performance measurements

Plant population counts were taken in March, April and May 1973 and an estimate of population was made in January 1974. The percentage groundcover was estimated in March, April and May 1973, January 1974 and March 1975. The dry matter production of each plot was measured in January and February 1974 and March 1975. The material cut in January and February 1974 was analysed for N, P, K, Zn, Cu, Pb, and Mn.

The botanical composition of each plot was noted in March, April and May 1973, January 1974 and March 1975 by scoring each species as present or absent in each plot. Four profiles were dug to a depth of 30 cm in January 1974 on the following selected sites: a bare area, two areas of vigorous growth, and an area of sparse, stunted plant growth. Root density, pH and Ec were measured in horizontal soil layers.

11.3 Results

11.3.1 Soil chemistry changes

pH and Ec (see Table 11.1)

Before treatment the mean pH over the trial site was 3.6 and the mean Ec, 0.59 mmho cm^{-1}. There was a far greater range of Ec values than pH values and they were negatively correlated at the 5% probability level.

One month after treatment the pH had increased to a mean of 5.4 while after fourteen months it had decreased to a mean of 4.8, the average increase being 1.8 units. A 't' test showed that liming increased the pH significantly in proportion to the lime rate used except at the 20 tonne level where the increase was too variable.

The Ec of all treatments decreased initially, with a slight rise evident after fourteen months. The decrease in Ec was inversely proportional to the lime rate used. Group III with high Ec behaves rather differently from the others, with a sharp drop in Ec initially, followed by an increase up to, and in one case, exceeding, pre-treatment values. The post-treatment mean of Ec values was 0.45 mmho cm^{-1}.

Water solubles and mineral assay

Figure 11.2 shows the very strong relationship obtained between Ec and SO_4 concentration. Supplementary sampling and analysis for heavy metals performed by the AAEC (Chapter 10) indicated that concentrations varied widely with location and depth. However there were sufficient local concentrations of metals to suggest that copper, lead and possibly zinc but not manganese might be present at toxic levels in the untreated soil although solubilities and availabilities would change with pH changes.

There was no association apparent between the distribution of heavy metals and the pH and Ec distributions. The levels of phosphorus and potassium were generally considered adequate although it was possible that a proportion of phosphorus may have been fixed by exchange with aluminium in the sesquioxides (see Table 11.2).

Exchangeable cations (see Table 11.3)

The levels of H, Al, Ca, Mg, Na and Fe were measured. It was apparent that the levels of Fe and particularly Al were quite high enough to be toxic and to be a severe problem with regard to P fixation. Calcium levels of about 3000 $\mu g\ g^{-1}$ are not low for a soil of this pH. Magnesium levels of about 7.8% of the total exchangeable cations are probably low enough to be regarded as deficient.

Available phosphorus (see Table 11.3)

The available phosphorus (obtained by acid extraction) was low. Untreated soil contained about 2-3 $\mu g\ g^{-1}$ while soil treated with lime only contained about 5 $\mu g\ g^{-1}$. This is probably a pH effect. Samples from lime plus fertiliser treatments had about 4 $\mu g\ g^{-1}$ although two seasons' growth had occurred before sampling in all cases. The aluminium and available phosphorus levels were negatively correlated. These phosphorus levels are 3 or 4 times lower than adequate for reasonable plant growth.

11.3.2 Dry matter production (see Table 11.4)

It is obvious that there is a significant response to fertiliser. The total production with fertiliser (20 670 kg ha^{-1}) is nearly three times that without fertiliser (7620 kg ha^{-1}).

The difference between the lime levels is not so marked although the yield does increase with lime rate; 7415 kg ha^{-1} with 5 t ha^{-1} to 10 895 kg ha^{-1} with 20 t ha^{-1}. The yield at the 20 t rate without fertiliser (1115 kg ha^{-1}) is less than half that at the same rate with fertiliser (2517 kg ha^{-1}).

11.3.3 Botanical composition

The initial plant counts taken in March, April and May 1973 showed that the germination rate was excellent but the establishment was much lower (see Table 11.4). It was difficult initially to distinguish between the various grasses since they were generally stunted and discoloured. They were included under a general heading until it was possible to identify them specifically. The legumes were fewer and easier to identify; data are presented in Table 11.5.

11.3.4 Root density (see Table 11.6)

The root density profiles which were taken after approximately one year's growth indicate that even where there was quite reasonable plant top growth there was poor root development. The top 10 cm of soil contains over two thirds of the roots, with the greatest density being in the top 3 cm.

11.4 Discussion

11.4.1 Cumulative production

The cumulative production from three years' growth is low at best when compared to a commercial pasture situation using the same species as sown here. The best yield achieved (3379 kg ha^{-1} with fertiliser and 10 t ha^{-1} of lime) would be about 30% of a *Paspalum plicatulum* pasture, for example.

However, when compared to a native annual grass pasture (900 to 1200 kg dry matter ha^{-1} y^{-1}) it assumes quite reasonable proportions, particularly since the material produced is not being removed by grazing or (as yet) fire. This helps to form a mulch, one of the properties of which is to fix copper and lead so that they become less toxic to the growing plant. In addition 1000 kg ha^{-1} is considered sufficient to control erosion.

11.4.2 Botanical composition

The frequency of occurrence of species as indicated in Table 11.5 is not the only factor of importance. Contribution to the dry matter produced, ability to spread and longevity are also important. *Rhynchelytrum* sp. (Red Top) has occurred in almost all plots throughout the period of the trial. It forms a low percentage of the total dry matter due to its low production per plant. However it seeds prolifically which indicates that it will spread quickly. Townsville stylo also seeds prolifically and individual plants may produce a moderate growth on these heaps. Townsville stylo seed is not as mobile as Red Top which may be an advantage on exposed sites such as these heaps, if a species is to become a useful coloniser.

Pennisetum pedicellatum established well in the first year and then became by far the largest producer in the second Wet. However its production and survival in the third Wet decreased by at least half. *Pennisetum* sp. is well known in NT as a coloniser of disturbed sites. The fact that there was no further surface disturbance at or near the trial site would have contributed to reduced seedling establishment. In addition, the high mobility of the seed would not have helped to increase the trial site population despite the large amount of seed produced.

Species such as the *Panicum* species and *Paspalum plicatulum* have made small but consistent contributions to the dry matter, the latter in some cases appearing to have perennated. The low mobility of *Paspalum* seed would also have helped in the yearly regeneration of the population.

Buffel grass has been disappointing although it may suffer some of the disadvantages of *Pennisetum* sp.

Stylosanthes hamata, or Verano, was not recorded in the first two years (it was in fact confused with Townsville stylo) and in the third year is by far the major contributor to dry matter production. Verano is a facultative perennial species suited to dry monsoonal climates such as at Katherine or Daly Waters.

11.4.3 Species selection

The selection or evolution of a tolerant plant population has received much attention in other attempts to revegetate heavy metal wastes in Australia and overseas. The general approach has been to collect seeds of species growing on, or very close to, the area to be revegetated and to sow them on that area.

Of the nine different species that had sufficient seed to be collected here, only two, *Alysicarpus vaginalis* (a short-lived legume) and *Rhynchelytrum* sp. (Red Top), could be considered as having adapted. *Pennisetum* sp. made good growth but its ability to regenerate under these conditions is suspect at this stage. Survival and growth of the other species is minimal.

Of the introduced species, Townsville stylo, Verano and *Paspalum plicatulum* rank about the same as *Alysicarpus* sp. and *Rhynchelytrum* sp.

As the three main native species occur widely, the making or purchase of local mature hay which would contain their seeds is a method of planting which is preferable to the collection of seeds on site.

There is further scope for the trial of introduced species under improved soil and fertility conditions.

11.4.4 Water relations and heavy metal toxicity

From the root profile investigations, the root density was found to decrease sharply below 10 cm (see Table 11.6). The analyses indicated that Al and possibly Cu were at toxic levels thus causing this decrease below (approximately) the treatment depth.

Although it is true that most of the added fertiliser would be in the top 10-15 cm, plants normally put down roots deeper than this to obtain water. That they are unable to do so because of the described toxicities has important implications for the type of plant species suitable for revegetation. It is apparent that under rain fed conditions this environment may be more suited to annuals or facultative perennials such as Verano even though the adjacent native pastures contain a number of perennial grasses. Species such as *Chrysopogon* may be suitable since their mechanism for survival is to draw water from reserves contained in thick butts.

The physical profile of the top layers of the heap is mainly influenced by the chemical breakdown of the rock. The top centimetres contain a proportion of fine material, high enough to cause surface crusting. This layer is very dry and powdery when broken up during the Dry. Below about 15-20 cm the material is not so highly weathered and consists of small and large rocks and rock flakes. These quite often contain moisture throughout the year. The situation is one of moisture being physically within reach of the plants but not available to them because of root toxicities caused probably by Al and possibly Cu. Deep ripping and incorporation of lime at depth (> 1 m) could reduce the toxicities but would also expose fresh material for weathering in the short term.

11.4.5 Fire

A further factor which has not as yet been an influence in this trial is fire. There are yearly wild fires around Rum Jungle and these will most certainly be an influence on selection towards annuals and towards a decrease in the range and population density of species by:

- physical destruction of the plants and the seeds, and
- destruction of the organic mulch layer.

11.4.6 Heavy metal toxicity (see Table 11.7)

One of the major aspects relating to the revegetation was the effect on plant growth of the heavy metals. These are rated in descending order of toxicity; nickel, copper, cobalt, zinc, manganese, lead [Chapman 1966].

From data collected by the AAEC (see Chapter 10) the average levels of elements in the soil are compared to toxic levels. Similarly plant tissue levels are compared to toxic levels in Table 11.8.

In consideration of the data in Table 11.8 it is important to realise these are total, not exchangeable levels in the soil and that the tissue analysis is from bulked material cut at ground level. Also, many of the elements such as lead and nickel are inextricably bound in their soil chemistry with arsenic and iron for example. Finally, although soil averages are given, local concentrations of elements occur to such an extent that patches of plants are affected by toxic levels of one or more elements.

Aluminium, as discussed previously, is primarily a root toxin. Consideration of the data presented in Table 11.2 shows that pretreatment levels of Al were very high at pH 3.6. Plants have different sensitivities to Al but there would be little doubt that greater than 20 $\mu g\ g^{-1}$ in the soil would be toxic or nearly so. Table 11.3 shows that Al levels can be readily controlled by pH control. At the highest lime rate (20 t ha^{-1}), the concentration is below toxic levels. A combination of lime and organic mulch treatments could be used to lower the Al levels.

Overall, however, it appears that the element which causes the greatest concern is copper. The solubility of Cu can be decreased by liming, but it is apparent that the soil level is too high for this treatment to be solely sufficient. The use of a mulch of organic material to fix Cu (and Pb and Al) is necessary. Low quality hay would be best, although there are other types of organic mulch which have proved suitable, e.g. sewage.

11.5 Supplementary Trials

11.5.1 1974 trial

Following the results obtained from the trial sown in 1973 it was decided to investigate several factors more fully. To this end a trial of randomised block design with twelve treatments and two replications was set up in January 1974 and the first cut was made in May 1974.

TREATMENTS

Lime rates (L)	0, 1, 2, 4 t lime ha^{-1} + 400 kg ACF 12:1 ha^{-1}
Fertiliser rates (F)	100, 200, 400, 800 kg ACF 12:1 ha^{-1} + 10 t lime ha^{-1}
Mulch treatment	4 t hay ha^{-1} + 400 kg ACF 12:1 ha^{-1} + 10 t lime ha^{-1}
Trace element treatment	400 kg ACF 12:1 ha^{-1} and Fertica Blue Trace Element Mix + 10 t lime ha^{-1}
Slow release phosphate	Blood and Bone + ACF 12:1 + 10 t lime ha^{-1}

The trial area was sown at a total rate of 25 kg ha^{-1} with the following species: Buffel grass (US and Gayndah), Rhodes grass (Pioneer), Hamil grass, Green Panic, *Paspalum plicatulum*, Blue Panic, Cook stylo, Endeavour stylo Calopo, Centro, Siratro, and native species collected on site as for 1973 trial. Several species were not available, and notable and unfortunate omissions are Molasses grass, Birdwood grass, other Rhodes and Buffel cultivars, Townsville stylo, Verano, *Andropogon gayanus* and *Chrysopogon* sp. (native). As for the previous trial a pH and Ec survey was made before and after treatment.

Results and discussion

The data collected to date are presented in Table 11.9. There is a significant response to both lime and fertiliser at all levels. It is obvious that the criterion of 1000 kg ha^{-1} of plant dry matter necessary for runoff control is met only by the highest fertiliser rate and the mulch treatment.

Yield figures for the second season's growth have not yet been taken although observations indicate that the yield has decreased, with the relativities between the treatments remaining the same. A botanical survey is being carried out which indicates the survival of *Pennisetum* sp., Red Top, *Paspalum plicatulum*, and a scattering of other grass species. The collated results are not yet available.

As with the 1973 trial an attempt was made to investigate the nutrient relations in the soil, with particular emphasis on P. It was supposed that if the solubility of the Al could be decreased by increasing the pH with lime, then there might be a consequent release of fixed P which would then become available to the plant. Although the Al decreased drastically, the available P did not increase in a manner which could be attributed to this.

11.5.2 Forestry trials

The early planting of tree species is an accepted method of revegetation for both stability and aesthetic reasons. A trial was set up on similar lines, and adjacent to, the trial by the Animal Industry and Agriculture Branch.

Trial design

Four rates of lime 0, 2.5, 5, 7.5 t ha^{-1}, each applied to five seedlings of six species with no replication. The lime was evenly applied to the surface and scarified in to a depth of 15 cm. The trees were planted at 3 m centres along ripper lines 20 cm deep. Two pockets of 150 g of ACF 12:1 were placed about 25 cm from the base of each seedling.

Species used were: *Eucalyptus polycarpa, Pinus carribaea, Eucalyptus bleeseri, Callitris intratropica, Acacia auriculoformis,* and *Khaya senegalensis.*

Survival was measured at the end of each growing season as well as growth measurements where appropriate. The results are given in Table 11.10.

11.6 Discussion

E. Polycarpa is outstanding in its survival in the trial although its growth is not particularly good. The best growth has been made by the surviving *A. auriculoformis,* followed by *K. senegalensis.* None of the others appear worthy of persisting with in this context.

Perhaps the most surprising result is the low survival at the highest lime rate when it might have been expected that the survival would have been proportional to the amount of lime applied, over this range. An ancillary observation of some interest and importance is that each hole where trees are or were growing contains a varying population of grass species, basically *Pennisetum.* It is believed that this is a local colonisation by seeds moving from the adjacent AI&AB trial and taking root in the soil originally brought in with the trees seedlings.

There is little evidence of this occurring on the untreated heap, although it is possible that the trees provide a trap for the seeds. There is no colonisation around the many rocks which could presumably perform a similar function.

11.7 Conclusion

To suggest treatment proposals for revegetation methods to counteract the main problems of erosion and oxidation of material, one must know the methods by which plants may be established and the protection levels at which they must exist to be effective.

The first step must be to lower the levels of toxic elements, which can be done primarily by pH control using agricultural lime. This will lower the solubility of some elements and consequently their concentration in the soil solution. It will at the same time increase the availability of major plant nutrients. For Cu, Al and Pb whose levels are too high to be completely neutralised by pH, an additional method of control is necessary. These elements are readily fixed by an organic mulch such as hay or sewage. It is also necessary to raise the levels of major plant nutrients and this can be best achieved with the application of an N-P or N-P-K fertiliser mix.

The choice of species is not as yet easily defined. The three main native species can be readily obtained in mature hay. Of the improved species, Townsville stylo and Verano have grown well enough. One or more of the characteristics of a climatically adapted grass species would prove useful:

- spreading or stoloniferous habit,
- shallow rooting,
- sets seed heavily, and
- seed is not readily transported away from plant. All species would be sown at a higher than commercial rate.

Runoff and, therefore, a large proportion of erosion can be satisfactorily controlled with 1000 kg of dry matter on the surface per hectare. This is not a particularly difficult level to attain with sown species, and if the layer of mature native hay is added it should be readily achieved in one Wet if the methods suggested in Section 11.7 are followed.

11.8 Suggested Methods and Estimated Costs of Regeneration

The principle underlying the establishment of vegetation in this situation is to improve the conditions for plant growth in the root zone. The limit that must be applied to this is that the increased aeration that would accompany it must not extend too deeply into the as yet unoxidised material.

It is proposed that an arbitrary figure for the root zone, say less than 30 cm could be appropriate.

11.8.1 Material costs

Lime

The work shows that a lime rate of 10 t ha^{-1} is sufficient to bring the pH of the soil from below to above 5, which acidity is acceptable to most native and pasture species.

Cost - Lime $3.00 per 50 kg bag. Approximate cost per hectare at 10 t ha^{-1} = $600.00 plus freight.

Fertiliser

To obtain a yield in excess of 1000 kg ha^{-1} it will be necessary to apply an N-P or N-P-K fertiliser at a rate between 600 and 800 kg ha^{-1}. Soil K levels are adequate.

There are a number of alternatives:

	N	P	K	$ t^{-1}
Monammonium phosphate*	12.5	21.0		200
Diammonium phosphate*	19.4	20.0		211
Crop King 55*	12.0	13.8	10.0	182
Crop King 66*	12.0	12.3	18.1	192
Rum Jungle Rock Phosphate				

* Prices ex Brisbane plus freight of $85.00 t^{-1}.

Cost - assume use of monammonium phosphate at 600 kg ha^{-1}, cost ha^{-1} of fertiliser $120.00 (add to this freight of about $50.00 = $170.00).

Mulch

Assume the use of mature *Pennisetum* sp. hay, locally quoted at $0.50 to $1.00 per bale. It would be a distinct advantage in ease of spreading and in performance of its function if it were cut with a double chop forage harvester to give pieces 8-12 cm long. A bale of hay gives reasonable ground cover over approximately 50 square metres i.e. ~ 2000 kg ha^{-1} dry matter.

Cost - 200 bales at $0.60 per bale = $120.00 (add freight to this).

Seed

The most suitable species are by no means clear so it is possibly best to give a list in order of decreasing confidence in their ability to succeed.

SPECIES

	Approx. Cost kg^{-1}
Natives (included in hay)	$0.60 per bale
Townsville stylo	$2-4.00
Verano	$6-8.00
Paspalum plicatulum	$3.00
Hamil Panic	$2.00
Buffel grass cultivars (as available)	$3-4.00
Rhodes grass cultivars (as available)	$3-5.00
Molasses grass cultivars (as available)	$3.00
Birdwood grass	$3-4.00
Sorghum almum or other grass/hay crop	$0.40

Assume total seeding rate of 25 kg ha^{-1} and multiple Buffel and Rhodes grass cultivars. Cost ha^{-1} $70.00.

11.8.2 Operational Costs

Ground preparation

Machinery costs may be high since there will be a need to work in fairly hard and rocky soil. It is proposed that the lime, fertiliser and hay be incorporated into the top layers. It may well prove impossible to incorporate the hay, in which case it will have to be surface spread.

It is anticipated that a crawler tractor would have to be used to perform the initial ripping to open up the soil. Standard agricultural machinery such as bulk super spreaders, tractors and disc ploughs could be used to carry out the other operations or they could be applied from the air. The operations proposed are as follows:

- ripping of the surface layers with the crawler;
- surface spreading of lime and fertiliser, and surface spreading of hay;
- incorporation of treatments into soil using a disc plough or similar; and
- surface spreading of seed and harrowing of seed bed.

Physical methods to control the rate of runoff will be a useful method of enhancing plant growth by making moisture available for a longer period. It is proposed that these would include doing the above work on the contour and also some flattening or shaping.

The operational costs are the most difficult to compute as they depend on whether the work is done on a contract or plant purchase basis. There are very limited sources for figures for the former, and it is not practicable to use them as a source for these estimates.

The figures that follow then, are operating costs of machinery. Figures are supplied after consultation with our Branch economist.

RIPPING

D6 Bulldozer at \$27.00 h^{-1} (NB hire rate)

width of 5 tyne rippers 3 m, at a speed of 1.6 km h^{-1}

covers an area of 1 ha in 1 hour.

Cost ha^{-1} = \$27.00.

LIME, FERTILISER AND SEED SPREADING

Conventional Method

Labour	\$3.50 h^{-1}
Fuels, etc.	\$0.50 h^{-1}
Tractor MF165	\$3.00 h^{-1}
Fertiliser spreader	\$1.30 h^{-1}

Assume that for spreading lime and fertiliser the tractor works at 6.5 km h^{-1} spreading the material over a 10 m swath. It is likely that each will require a separate operation.

Tractor cost ha^{-1} at 6.5 km h^{-1}	\$0.45
Spreader cost ha^{-1} at 6.5 km h^{-1}	\$0.20
Operation cost (labour and fuels, etc) ha^{-1}	\$0.60

Total \$1.25 per operation.

Total cost for spreading lime and fertiliser \$2.50 ha^{-1}.

Much of the seed can be spread in a similar fashion using the fertiliser spreader but probably over only half the width of the lime and fertiliser, i.e. 5 m.

Some of the more bulky seeds such as Buffel may have to be hand or otherwise sown.

Tractor cost ha^{-1} at 6.5 km h^{-1} and 5 m width	=	\$0.90
Spreader cost ha^{-1} at 6.5 km h^{-1} and 5 m width	=	\$0.40
Operation cost (labour and fuels, etc) ha^{-1}	=	\$1.20
Cost of sowing seed	=	\$2.50
Cost of lime, fertiliser and seed application by conventional methods	=	\$5.00 ha^{-1}.

On top of this there will also be the cost of cartage and of the labour of one or more extra men to assist in the operations. These could bring the cost up to around \$10.00 ha^{-1}.

Aerial applications

Cost of applications of fertiliser at 600 kg monammonium phosphate ha^{-1}	= \$9.00 ha^{-1}
Cost of application of lime at 10 t ha^{-1}	= \$9.00 ha^{-1}
Cost of application of seed at 25 kg ha^{-1}	= \$1.20 ha^{-1}
Total cost	= \$19.20 ha^{-1}

Spreading of hay mulch

The spreading of the mulch may prove to be the least efficient step with respect to time, although if it is dry it might flow from the back of a tip truck. No estimate of spreading is given since there are many alternatives and variables.

Incorporation of treatments

Following the application of fertiliser lime and the mulch, it is proposed that these be turned in using a disc plough.

Labour	\$3.50 h^{-1}
Fuels, etc.	\$0.50 h^{-1}
Tractor MF165	\$3.00 h^{-1}
18 disc plough	\$3.80 h^{-1}

Assume that the tractor operates at 5 km h^{-1} with the discs cutting approximately 3.5 m. This gives a rate of 1.75 ha^{-1}.

Cost of ploughing operation \$7.00 ha^{-1}.

After this operation the seed would be sown and possibly harrowed in, although the cost of the latter is not considered here.

11.8.3 Summary

	Total Costs
Materials	
Lime	\$600.00
Fertiliser	\$120.00
Seed	\$ 70.00
Hay	\$120.00
Operational	
Ripping	\$ 27.00
Spreading lime, fertiliser, seed	\$ 10.00
Hay mulch	?
Ploughing	\$ 7.00
Estimated rehabilitation cost	\$854.00 ha^{-1}.

TABLE 11.1

pH AND ELECTRICAL CONDUCTIVITY CHANGES

	Ec group	pH										Ec									
		Treatments						$\bar{x}$ Ec group	$\bar{x}$ lime rate			Treatments						$\bar{x}$ Ec group	$\bar{x}$ lime rate		
		1	2	3	4	5	6		5	10	20	1	2	3	4	5	6		5	10	20
16.2.73	I	3.7	3.7	3.6	3.7	3.6	3.7	3.7				0.24	0.20	0.25	0.24	0.10	0.19	0.22			
	II	3.6	3.7	3.4	3.5	3.7	3.5	3.6	3.6	3.6	3.5	0.64	0.30	0.39	0.29	0.27	0.49	0.40	0.20	0.16	0.23
	III	3.6	3.4	3.3	3.3	3.6	3.3	3.4				1.16	1.07	1.72	1.03	0.87	1.05	1.15			
	$\bar{x}$ treat	3.6	3.6	3.4	3.5	3.6	3.5	$\bar{\bar{x}}$ = 3.55				0.66	0.52	0.79	0.52	0.44	0.64	$\bar{\bar{x}}$ = 0.59			
26.3.73	I	5.0	4.9	6.6	4.6	5.6	5.2	5.3				0.24	0.23	0.43	0.20	0.22	0.23	0.26			
	II	5.3	5.6	6.9	4.1	5.3	4.4	5.3	4.8	5.4	6.0	0.26	0.32	0.58	0.28	0.29	0.25	0.33	0.11	0.10	0.13
	III	4.9	5.0	5.1	4.6	5.9	7.6	5.5				0.33	0.41	0.34	0.60	0.31	0.46	0.41			
	$\bar{x}$ treat	5.1	5.2	6.2	4.4	5.6	5.7	$\bar{\bar{x}}$ = 5.4				0.26	0.32	0.45	0.36	0.27	0.31	$\bar{\bar{x}}$ = 0.33			
25.1.74	I	4.4	5.0	6.9	5.7	5.2	6.9	5.7				0.10	0.10	0.27	0.12	0.10	0.30	0.17			
	II	4.6	7.8	6.1	5.1	5.9	6.3	6.0	4.6	5.5	6.1	0.29	0.14	0.19	0.12	0.13	0.69	0.26	0.15	0.09	0.20
	III	4.1	4.4	5.2	3.9	4.8	5.2	4.6				0.78	0.79	1.28	1.30	0.31	0.89	0.89			
	$\bar{x}$ treat	4.4	5.7	6.1	4.9	5.3	6.1	$\bar{\bar{x}}$ = 5.4				0.39	0.34	0.56	0.51	0.16	0.62	$\bar{\bar{x}}$ = 0.44			
30.5.74	I	4.4	5.1	5.5	4.8	4.9	5.4	5.0				0.12	0.12	0.15	0.14	0.11	0.22	0.14			
	II	4.6	5.5	5.6	4.6	5.2	5.3	5.1	4.2	4.9	5.3	0.45	0.11	0.24	0.12	0.15	0.48	0.26	0.23	0.11	0.16
	III	3.7	4.2	4.9	3.6	4.7	5.1	4.4				1.08	0.87	1.28	2.20	0.65	0.42	1.08			
	$\bar{x}$ treat	4.2	4.9	5.3	4.3	4.9	5.3	$\bar{\bar{x}}$ = 4.8				0.55	0.37	0.56	0.82	0.30	0.37	$\bar{\bar{x}}$ = 0.50			

<u>TABLE 11.2</u>

<u>SOIL ANALYSIS, PRE-TREATMENT</u>

Ec group	Treatment no.	Total amounts of elements in soil			
		pH	Al%	P%	K%
I	1	3.7	8.9	0.19	3.1
	2	3.7	10.5	0.08	4.1
	3	3.6	8.4	0.16	2.8
	4	3.7	9.3	0.20	3.0
	5	3.6	10.5	0.11	4.0
	6	3.7	8.3	0.18	3.4
II	1	3.6	9.6	0.19	3.5
	2	3.7	9.3	0.33	3.5
	3	3.4	9.0	0.20	3.3
	4	3.5	8.7	0.21	3.2
	5	3.7	9.3	0.13	3.3
	6	3.5	9.1	0.39	3.9
III	1	3.6	9.0	0.06	3.6
	2	3.4	9.3	0.22	4.0
	3	3.3	9.4	0.33	4.0
	4	3.3	9.8	0.17	3.6
	5	3.6	9.1	0.10	2.9
	6	3.3	8.9	0.08	3.6

TABLE 11.3

SOIL ANALYSIS - (POST-TREATMENT)

Ec. group	Treatment number	Cumulative yield kg ha^{-1}	pH	Ec	SO_4	Al µg g^{-1}	Ca µg g^{-1}	Mg µg g^{-1}	Cu µg g^{-1}	Pb µg g^{-1}	Zn µg g^{-1}	Mn µg g^{-1}	Avail. P µg g^{-1}
I	1	1190	4.7	0.13	50	894	1700	120	0.02	0.02	*	0.02	7
	2	470	5.6	0.13	50	164	2900	110	0.03	0.10	0.02	0.02	< 1
	3	1745	6.3	0.17	60	5.9	4100	160	0.03	0.02	*	0.01	4
	4	3165	5.4	0.14	55	330	3300	130	0.01	0.03	*	0.01	2
	5	3005	5.2	0.13	50	464	2700	190	0.03	0.02	*	0.01	1
	6	2665	6.4	0.19	65	16.7	4100	160	0.01	0.02	*	0.01	3
II	1	710	5.0	0.36	150	539	3300	190	0.03	0.02	*	0.01	4
	2	1565	6.2	0.13	40	23.9	4300	130	0.02	0.03	*	0.01	6
	3	1130	6.5	0.26	95	7.0	4200	140	0.02	0.03	*	0.01	4
	4	2230	4.9	0.13	45	737	1900	110	0.02	0.02	0.01	0.02	5
	5	3370	5.7	0.15	50	120	3500	150	0.03	0.03	*	0.01	2
	6	3045	6.1	0.46	200	18	5300	120	*	0.03	*	0.01	6
III	1	20	3.9	0.92	465	1270	2300	160	0.03	0.03	*	0.01	4
	2	320	4.5	0.82	420	536	2700	190	0.01	0.03	*	0.01	5
	3	470	5.3	1.05	595	148	4600	190	*	0.02	*	0.01	6
	4	100	3.7	1.94	1340	1530	2500	610	0.04	0.03	*	0.01	7
	5	1250	5.2	0.65	320	214	3400	210	0.10	0.03	*	0.02	6
	6	1840	5.9	0.27	180	5.9	4700	200	0.02	0.03	*	0.01	4

* *denotes < 0.01*

TABLE 11.4

OBSERVED PLANT COMMUNITY AND YIELD FOR THE RANGE OF EXPERIMENTAL TREATMENTS

		Plant population plants m^{-2}				Yield dry matter kg ha^{-1}			
	Date	22.3.73	4.4.73	29.5.73	24.1.74 (estimate)	24.1.74	13.2.74	5.3.75	Cumulative Yield
Ec. Group	Treatment No.								
1	1	28	22	30	20	420	610	160	1190
	2	146	69	8	20	160	230	80	470
	3	53	42	39	30	460	585	700	1745
	4	82	62	26	70	1100	1885	180	3165
	5	52	42	31	40	1360	1225	420	3005
	6	76	125	34	40	180	585	1900	2665
2	1	9	4	11	20	100	530	80	710
	2	21	15	13	40	450	745	370	1565
	3	41	14	9	10	470	450	210	1130
	4	112	45	34	50	970	750	510	2230
	5	13	40	21	60	980	2340	50	3370
	6	62	48	28	20	450	1475	1120	3045
3	1	13	14	< 10		10	10		20
	2	13	10	< 10	< 10	10	70	240	320
	3	14	13	< 10	10	80	50	340	470
	4	< 10	23	11	< 10	10	10	80	100
	5	12	34	24	30	660	450	140	1250
	6	47	53	34	30	350	1150	340	1840

TABLE 11.5

BOTANICAL COMPOSITION

Species	Ec group I						Ec group II						Ec group III					
	Treatments						Treatments						Treatments					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Stylosanthes humilis	abc	ac	abc	abc	abc	abc	abc	abc	abc	abc	ac	abc	abc	abc	abc	ab	abc	abc
Rhynchelytrum sp.	abc	abc	abc	abc	abc	abc	abc	abc	ac	ab	abc	abc	c	abc	abc	abc	bc	ac
Pennisetum pedicellatum	abc	ab	ab	abc	ab	ab	ac	a	ab	ab	ab	ab	a	ac	bc	bc	a	ac
Paspalum plicatulum	ab	abc	ab	abc	abc	abc	bc	abc	a	abc	abc	ac	ac		abc		bc	a
Grass species mainly *Panicum* spp.	ac	abc	abc	abc	abc	abc	ac	ac	abc	abc	bc	abc		a	a	b	b	bc
Alysicarpus vaginalis	bc	c	bc	bc	abc	bc		bc	bc	bc	bc	b		c			bc	b
Stylosanthes guyanensis	b	c	ab	ab	a	a		b		bc		a			ac	b	b	abc
Brachiaria decumbens	bc	c		ac		abc		b	b		ab		bc	bc				c
Calopogonium mucunoides	a	a	a	a	a		a			a	a		a	a	a	a		ac
Cenchrus spp.	ab	a	a	a		ab		a	a	ab		a				a	a	
Stylosanthes hamata	c		c	c	c	c		c		c	c	c					c	c
Heteropogan-triticeus										a		a						

a = *species present in March 1973*
b = *species present in January 1974*
c = *species present in March 1975.*

TABLE 11.6

DISTRIBUTION OF ROOT DENSITY, AND pH AND Ec VALUES ON FOUR SELECTED SOIL PROFILES

Ec Group	Treatment Number	Plot	Profile cm	pH	Ec	Root density	Comments
I	5	Bc	0-4	5.0	1.6		Bare area with no plant growth.
			4-10	4.8	2.2		
			10-15	4.2	0.86		
			15-30	4.0	0.62		
II	5	Ca	10-4	6.0	0.31	2.10	An area of vigorous plant growth and dense root matting on the soil surface.
			4-10	4.8	0.24	1.81	
			10-15	5.1	0.26	1.05	
			15-30	4.8	0.27	0.71	
I	4	Da	0-4	5.9	0.10	2.27	As for Ca.
			4-10	5.6	0.13	1.79	
			10-15	4.7	0.25	0.79	
			15-30	4.5	0.28	0.18	
III	3	Dc	0-4	5.7	0.32	0.56	Profile taken from an area of sparse, stunted plant growth.
			4.10	4.6	0.32		
			10-15	4.4	0.31		
			15-30	4.8	0.43		

Note

(i) *pH and electrical conductivity measured in 1:5 water suspension.*

(ii) *Electrical conductivity units (Ec) are mmho cm^{-1}.*

(iii) *The units of root density are obtained by log*

$$\frac{(10^5 \times \text{wt of washed and dried roots})}{\text{initial wt. of dried soil sample}}$$

TABLE 11.7

PLANT TISSUE LEVELS OF HEAVY METALS

Ec. group	Treatment number	Cumulative yield*	Tissue analysis µg g^{-1}			
		kg ha^{-1}	Cu	Zn	Pb	Mn
I	1	1190	8.1	9.8	3.0	65
	2	470	11.1	16	6.2	19
	3	1745	9.7	8.2	3.1	25
	4	3165	4.7	8.5	3.3	25
	5	3005	8.7	8.1	2.4	26
	6	2665	6.8	7.2	3.4	23
II	1	710	11.6	15.1	10.1	34
	2	1565	3.0	11.5	1.8	17
	3	1130	14.4	11.0	5.2	15
	4	2230	6.3	10.5	3.0	31
	5	3370	6.2	8.7	2.4	26
	6	3045	7.6	7.3	5.2	22
III	1	20				
	2	320	12.0	28.0	15.5	23
	3	470	11.9	12.0	9.5	35
	4	100				
	5	1250	26.0	13.5	5.8	33
	6	1840	7.3	7.0	2.8	27

* *Dry matter*

TABLE 11.8

COMPARISON OF PLANT TISSUE LEVELS WITH TOXIC LEVELS

Element	Soil level* $\mu g\ g^{-1}$	Toxic level $\mu g\ g^{-1}$	Tissue level	Toxic level
Ni	137	20**		40
Cu	607	250	3-26	20
Co	81	Data not available		
Zn	42	100	7-28	400
Mn	127	600	15-65	1000
Pb	211	200	2-10	50

* *0.10 cm*

** *Exchangeable nickel*

TABLE 11.9

1974 TRIAL

Treatment	Mean Yield kg ha^{-1}	Mean pH	Mean Ec mmho cm^{-1}
L0	143	3.9	0.36
L1	90	3.7	0.93
L2	208	3.9	0.42
L4	592	5.1	0.45
F0	30		
F1	215		
F2	217		
F4	555		
F8	1435	6.0	0.75
Mulch	1099	5.5	0.49
Trace	461		
Slow Release P	304		

TABLE 11.10

SURVIVAL OF TREES (No.)

Species	Lime rate (t ha^{-1}												
	0			2.5			5			7.5			
	i	ii	iii	i	ii	iii	i	ii	iii	i	ii	iii	Total at iii
K. senegalensis	5	5		5	4	3	5	5	3	5	4	1	7
A. auriculoformis	5	4		5	4	3	5	5	1	5	3	2	6
C. intratropica	5	1	1	5	1		5	3		5	2	1	2
E. bleeseri	5	3	1	5	4	4	5	4	2	5	4		7
P. carribaea	5	5		5	5	1	5	3	2	5	5		3
E. polycarpa	5	5	5	5	5	4	5	5	4	5	5	5	18
	30	23	7	30	23	15	30	25	12	30	23	9	

Date of observation key

i February 73
ii May 73
iii March 75

CORRIGENDA

Plate 11.1

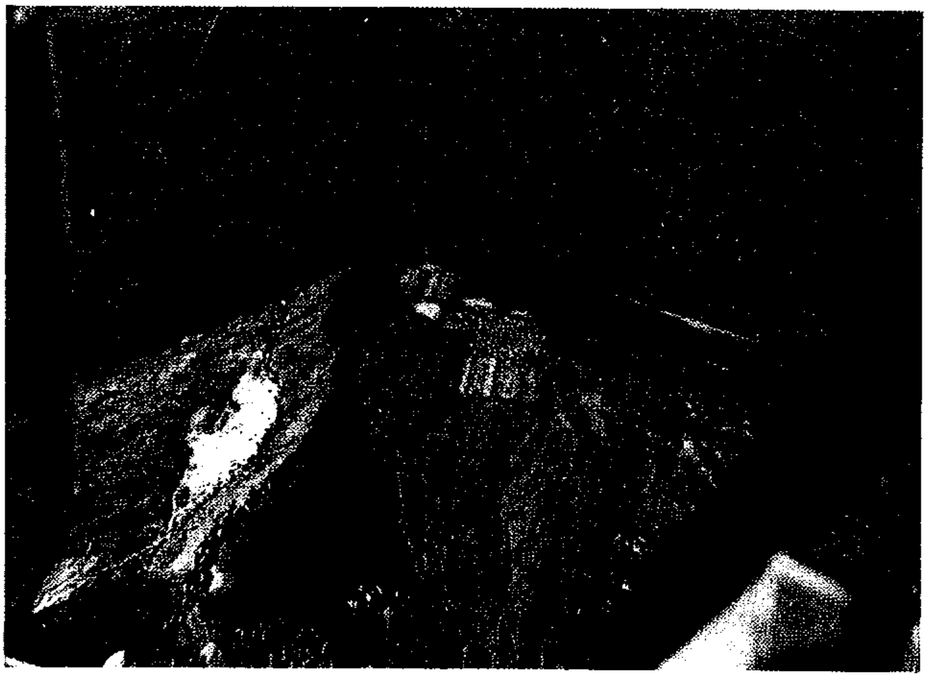
'1972' should read '1973'

Plate 11.2

'1973' should read '1974'
'1972' should read '1973'
'1972' should read '1973'
'1973' should read '1974'

White's Heap - composite photograph showing growth pattern for 1972 trial

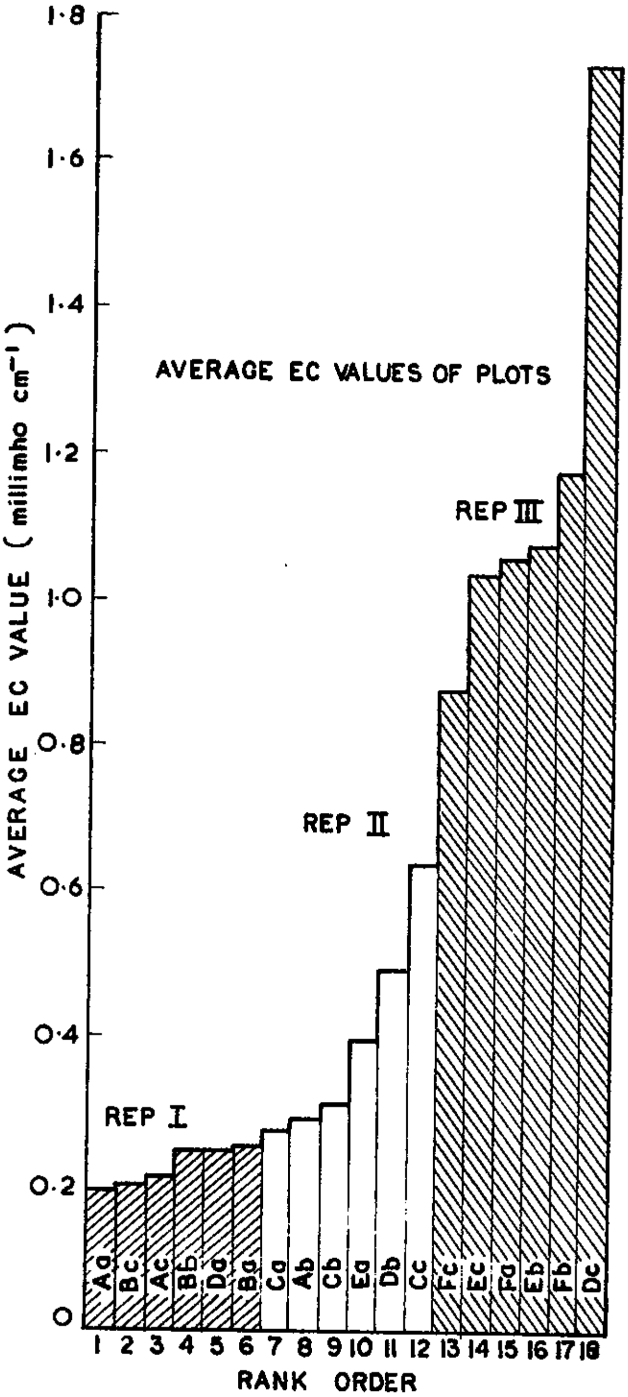
PLATE 11.1

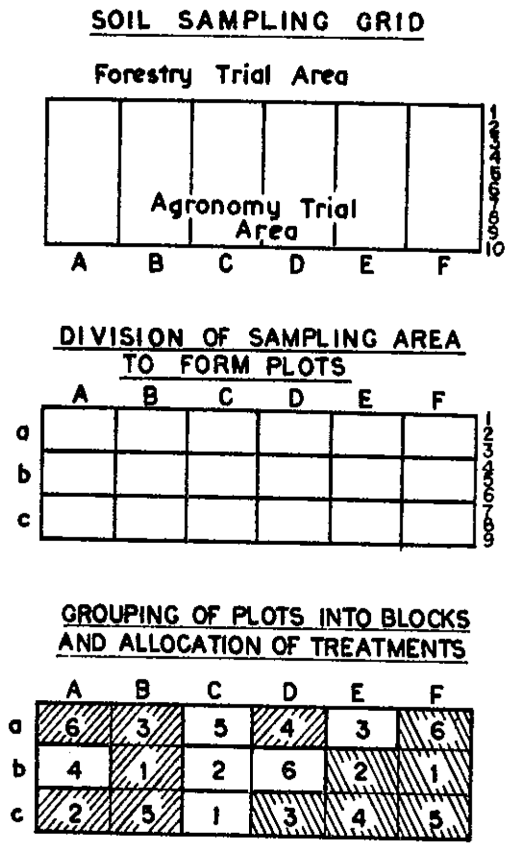


Aerial view of White's Heap. Four sites are clearly seen. Reading from the tip of the heap these are

a) The 1973 trial, replication 1
b) The complete 1972 trial
c) The 1972 forestry trial
d) The 1973 trial, replication 2

PLATE 11.2

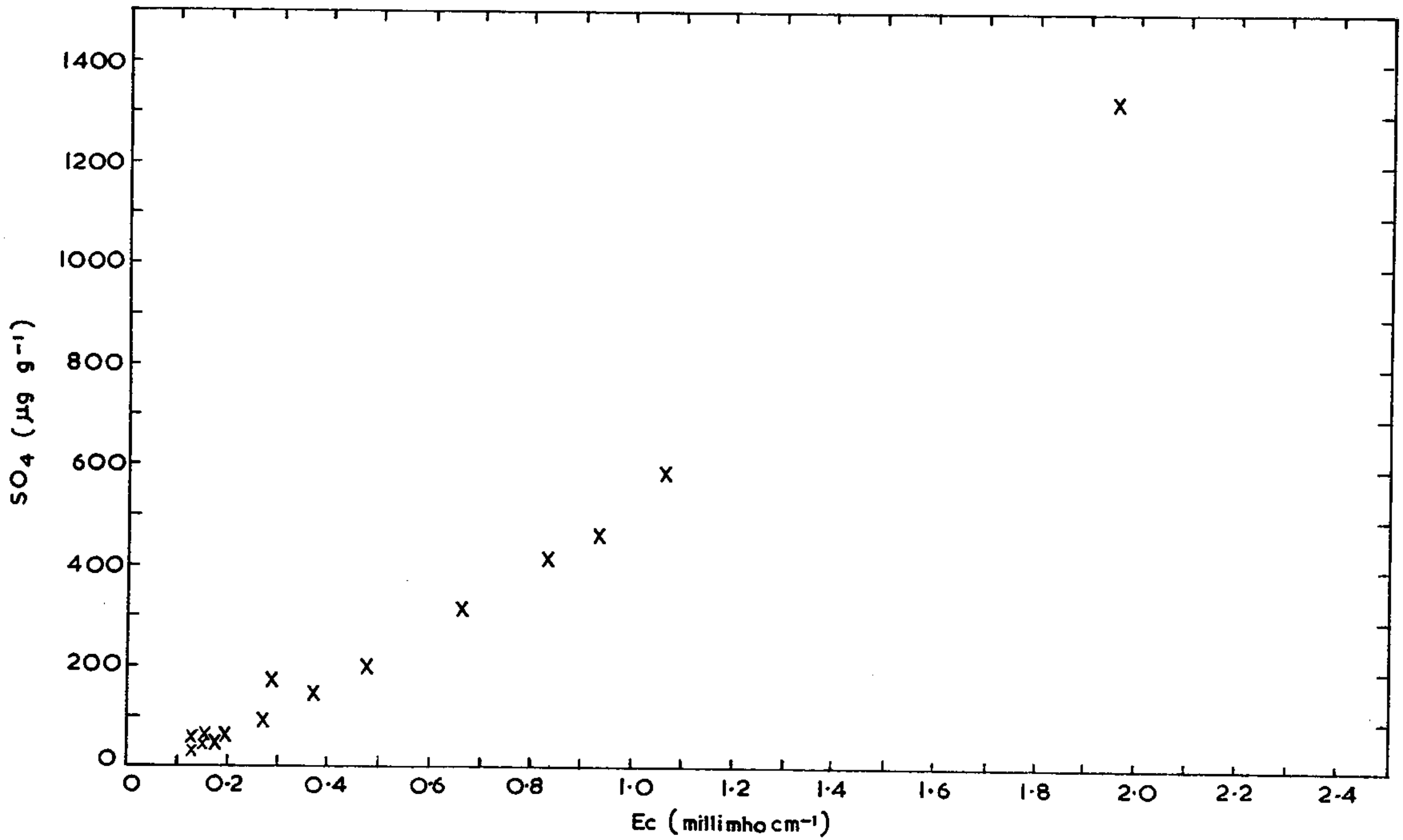




No	LIME	FERT	No	LIME	FERT
1	5 Tonnes ha^{-1}	0 Kg ha^{-1}	4	5 Tonnes ha^{-1}	100 Kg ha^{-1}
2	10 Tonnes ha^{-1}	0 Kg ha^{-1}	5	10 Tonnes ha^{-1}	100 Kg ha^{-1}
3	20 Tonnes ha^{-1}	0 Kg ha^{-1}	6	20 Tonnes ha^{-1}	100 Kg ha^{-1}

LAYOUT OF THE EXPERIMENT

FIGURE 11.1



SOLUBLE SULPHATE LEVEL IN SOIL AS A FUNCTION OF ITS CONDUCTIVITY

FIGURE 11.2

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ABBREVIATIONS

AAEC	The Australian Atomic Energy Commission
AM & S	Australian Mining and Smelting Co. Ltd.
BMR	The Bureau of Mineral Resources
Bogum	Below ore grade uranium
CRA	Conzinc Riotinto of Australia Ltd.
DNT	The Department of the Northern Territory (now called The Department of Northern Australia (DNA)
EB	The East Branch (of the Finniss River)
FC	Florence Creek
FR	The Finniss River
ICRP	International Commission on Radiological Protection
NT	The Northern Territory
RJ	Rum Jungle
RJCS	Rum Jungle Creek South
TEP	Territory Enterprises Pty. Ltd.
WRB	Water Resources Branch