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ABSTRACT

Some of the problems expected to arise as a result of contamination of rainfall run-off by the ore and waste rock heaps of the Ranger Uranium Mine, at Jabiru in the Northern Territory of Australia, have been re-examined. A computer program has been written to estimate the quantity of run-off water resulting from any given rainfall pattern. The program was calibrated against measured stream flows in Gulungul Creek; it was then applied to the two major catchment areas surrounding the mine site, and estimates of the quantity and quality of discharge water were made. The effects of the discharge are discussed in relation to the levels tolerable to fish and, in the case of radium, permitted as uptake by humans. A possible modification to the water management plan, which would increase the time for sedimentation before discharge, is suggested.

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RANGER DEPOSIT; URANIUM ORES; URANIUM; MINING; SOLID WASTES; RAIN WATER; POLLUTION; RIVERS; HYDROLOGY; CRUSHING; NORTHERN TERRITORY; RAIN; RADIUM; COMPUTER CODES

PREFACE

During the Ranger Uranium Environmental Inquiry [1975-77] issues were debated as if definitive conclusions were inevitable; there was little scope for qualification, which plays an important part in normal scientific discussion. Hydrological modelling for formulation of water management programs was no exception to this generalisation.

During 1976-77 the Commission undertook the work that is the subject of this report in order to have an independent view on hydrological modelling for the Ranger site before the preparation of final submissions from interested parties at the end of the Ranger Inquiry. Accordingly, the report, in so far as it relies on the nature of specific development proposals, is consistent with plans of that time. In the event, the Commission did not provide a final submission on site specific matters.

On publication of the recommendations of the Ranger Uranium Environmental Inquiry and the Government's acceptance of them, a Supervising Scientist (Designate) was appointed and, initially *de facto*, a group of experts was assembled with the task of mapping out the research program to be undertaken by the Alligator Rivers' Research Institute. A draft version of this report was one of the many working papers put before the group of experts.

In parallel with the deliberations of the group of experts, Commonwealth departments and instrumentalities drafted the environmental conditions to be imposed on Ranger Uranium Mines Pty Ltd. Again, a draft of this report was one of their working documents.

As a result of the conditions laid down by the Commonwealth Government for environmental protection, Ranger Uranium Mines Pty Ltd has substantially changed its water management program. The program is still under discussion but so far the major changes are:

- a substantial reduction in the quantity of seepage waters from the tailings retention scheme that reach surface waters;
- a reduction in the overall volume of water leaving the development site, at least during the early years of mining;

- a rearrangement of the handling of waste rock so that the catchment for retention pond 1 becomes a defined unrestricted catchment (no disturbance involving material with a uranium grade > 0.02 U) - in this way the radium releases will be able to be strictly controlled; and

- rock filters (or gabions) have been installed as sediment traps in the outlet of Retention Pond 1.

Details of the modified water management proposal were published in a series of volumes during mid 1979 by the firm of McMahon, Burgess and Yeates, as consultant to Ranger Uranium Mines Pty Ltd; Volume II of that series indicates that the basic Boughton-Jones model, which is the subject of this report, is still their preferred approach.

Although for the chosen example this report has been superseded, it is believed to contain information useful to others having the task of hydrologically modelling small catchments.

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1. INTRODUCTION

The mining and milling of uranium ore at Jabiru in the Northern Territory of Australia will entail the disposal of large amounts of water which will be contaminated, in varying degrees, as a result of the mining operations. The water, for the most part, arises from rainfall run-off. The contaminants, in the form of suspended solids and dissolved salts of heavy metals, including radium, are picked up as the water flows over, or seeps through, the piles of ore and waste rock. At the Ranger Uranium Mines Pty Ltd (RUM) mine site several dams, or retention ponds, hold back the run-off water until conditions are suitable for its release into Magela Creek. For release to be acceptable, Magela Creek must be in flood to ensure adequate dilution of the contaminated water. Also, releases should not occur early in the wet season (before February 1) when the Magela flood plain is unsaturated. Later release will minimise the uptake of heavy metals by clays and maximise the chance of the contaminated water being carried directly out to sea via the East Alligator River.

To demonstrate, in quantitative terms, the feasibility of this scheme of water management, RUM produced estimates of the run-off based on rainfall data collected over the past few years. As exact calculations obviously cannot be made, a reasonable mathematical model of the catchment is needed. In the work carried out for RUM by Yeates and Walker [1973] the model developed by Boughton [1966] and Jones [1970] for small rural catchments was used. In view of the importance of the question of pollution of the Alligator Rivers system as a result of mining, it was felt that an independent check of calculations of Yeates and Walker would be valuable. The aim of the present work was to provide such a check and, at the same time, to produce a computer program which could be used to examine future questions concerning the hydrology of the area. The water management scheme for the mine which is analysed in this work has been modified by the mine operators.

2. DEVELOPMENT OF HYDROLOGICAL MODEL

In the Boughton and Jones (BJ) model, the catchment is assumed to be composed of a series of water storages which fill in turn from the overflow from the preceding store (Figure 1). The first is the 'interception store' consisting mainly of the surfaces of rocks and vegetation which must be wetted before any rain can reach the soil. Evaporation accounts for some water loss from the interception store. Overflow from the interception store proceeds to the 'upper soil store', which comprises the moisture holding capacity of the soil, known as field capacity or retention. The water in the upper soil store is tightly held by capillary forces and cannot drain under gravity. Water is removed from this store by evaporation and transpiration. Any overflow proceeds into the 'drainage store' which is the additional water absorbing capacity of the same soil between field capacity and saturation, known also as the yield. The water in the drainage store is held in the larger cavities in the soil and is emptied by seepage to the 'subsoil store'; this in turn empties by seepage to groundwater and by transpiration. When the drainage store is filled, the soil is saturated and further rainfall produces run-off. To complete the definition of the model, the rates of evaporation and seepage must be specified, often as functions of time and the contents of the stores; capacities also have to be assigned to the stores.

From this brief description, it will be apparent that it is difficult to estimate the reliability of the model, and to find values for the parameters. For these reasons, it is highly desirable to have measurements for comparison with the calculated results. Initially, the only gauged catchment data in the monsoonal areas of the Northern Territory were some flow rate measurements for Gulungul Creek for 10 months of the 1974-75 water year* [Department of the Northern Territory, Water Resources Branch (WRB) - private communication]. More recent data are discussed in Appendix A. Although the catchment area for Gulungul Creek is considerably larger than those associated with the retention ponds (7000 ha compared with 200 ha) and although some of this larger catchment includes areas of Mt Brockman which are not typical of the mine site, the overall advantages of using the measurements as a guide to the model were thought to be great.

Further objections can also be raised against applying results for the undisturbed catchment of the creek to the very much disturbed catchment of a mine compound. These arguments have some justification, but the following points indicate that the difference in catchment behaviour will probably not be great:

(a) The mining company intends to regrass all disturbed areas as soon as the disturbances to the areas are completed.

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* The water year commences on 1st September.

(b) The annual burning of the vegetation in the natural catchment in bushfires tends to reduce the difference between the two catchments.

The model was therefore tested using the observed behaviour of Gulungul Creek, modified to some extent, and then used to predict the flows in the mine catchment areas. Initial calculations using the BJ model would not fit the measurements. Small modifications to it were necessary to obtain close simulation of the flow in Gulungul Creek. The modified scheme is shown in Figure 2.

From Figures 3 and 4, it can be seen that small flows occur early in the season (November), when the ground could hardly be saturated and, according to the BJ model, saturation is necessary for flow to occur; this early flow is probably due to the finite rate of infiltration. Clearly, if heavy rain falls on ground that is completely dry, there may be some run-off simply because the soil cannot absorb the water as fast as it falls. The BJ model makes a rough attempt to include this phenomenon by assuming that any daily rainfall over and above a certain critical value will produce run-off regardless of the soil moisture. This critical value, which defines the maximum quantity of rain which can infiltrate the ground in one day, is a parameter of the calculation. In the early work on Gulungul Creek, no value of the parameter could be found which gave the early flows and also reasonable mid-season flows. Yeates effectively nullified this part of the model by setting the parameter at a high value, which was greater than almost all the recorded daily rainfall figures.

A feature of the early stream flow is its exponential fall-off over a period of a few days following a rainstorm. Possibly this behaviour could be attributed to the size of the catchment, where rain falling on the outermost edge could take some time to reach the stream gauging station. However, to account for both the existence and persistence of the early season flows, a 'run-off store' was postulated. Because of the limited infiltration rate, some rainfall always enters the run-off store. The water is then released from this store at an exponentially decreasing rate, with a time constant of two to three days. The fraction of the rainfall absorbed and released in this way increases as the infiltration rate decreases as a consequence of the increasing level of soil moisture as the wet season advances. In other words, the run-off coefficient increases with increasing soil moisture. With suitable parameters, this modification to the model enabled the early run-off to be reproduced, as well as the time delay in the run-off.

The second major feature which is not explained by the BJ model is the small but sustained flow at the end of the wet season. This was reproduced in the modified model by assuming that the drainage store seeps slowly into the creek. Such an effect was not included in the BJ model, which was concerned with small farm dams that would not necessarily intercept such a source of water. Also, since long-term seepage contributes only 2 to 3 per cent to the total annual creek flow, it could well be ignored.

As the rainfall at Jabiru occurs largely in violent storms, and as the foliage cover at the mine site is likely to be minimised, the interception store was omitted from the model. Also, as it was assumed that all water that was not lost by evaporation eventually reached the ponds, it was not necessary to make explicit references to the subsoil and groundwater stores. In the modified model, the drainage store was emptied primarily by evaporation and, to a small extent, by seepage.

Definitions and values of parameters used in the calculations are given in Table 1; the agreement between calculated and measured values was reasonably good. In fact, the discrepancies between the rainfall data published by the WRB and those of RUM make the search for improvement pointless, as can be seen by comparing Figures 3 and 4.

It is worthwhile considering the extent to which the parameters derived in this way are supported by other available data. Measurements have been made of the specific yield and the specific retention of the soils in the tailings dam area [Coffey and Hollingsworth 1973, 5:65]. The specific retention or field capacity, expressed as a volume percentage, has an average value of about 30 per cent. This value, when combined with a reasonable value for the depth of the upper soil (500 mm), gives the bound water volume (per unit area) of 150 mm which is the value used for the parameter VSS. The specific yield or free draining capacity of the soil varies considerably for the various types of soil, but has an average value of 5 to 6 per cent. To obtain a measure of the depth of soil involved in free drainage, the groundwater levels measured in boreholes in the anomaly 1 area have been examined [Coffey and Hollingsworth 1973, 5:52]. In Figure 5, the seasonal variation of the water levels is compared with the calculated volume of water in the drainage store during 1972-73. It can be seen that the groundwater rises and falls through about 6000 mm which, if taken with the 5 to 6 per cent specific yield, gives a drainage volume (per unit area) of 300 to 360 mm and compares well with the value used for the parameter VDS (350 mm). The other parameters in the program do not lend themselves to comparison with existing data.

This simple model of the Gulungul catchment gave a reasonable correspondence with the measured creek flow, taking into account the limited data available. The computer program was then extended to account for the storage of water in a dam and for evaporation from the direct rainfall onto its variable surface area. Various subsystems of the Ranger water management circuit were then examined using this program.

3. THE HYDROLOGY OF THE RETENTION PONDS

The layout of the mine site considered in this report is shown in Figure 6. This scheme was proposed in 1974 and modified in 1979.

3.1 Retention Pond No. 1

The No. 1 retention pond (RP1) is designed to hold back the water which runs off from the waste rock dump. The pond covers an area of approximately 40 ha and can hold up to 8 x 10^5 m^3 of water. The area of its catchment is 255 ha.

The release of water from No. 1 pond can be controlled to a limited degree by opening a sluice gate to Coonjimba Creek during times of heavy rainfall. Computer simulation of the behaviour of this pond has been carried out for the 1972-73 and 1975-76 water years. The first year was considered to be an average year and the second was a 1 in 100 year flood. The following conditions were applied to the pond for the calculations:

(a) The pond was initially empty.

(b) No water was discharged until the pond had filled to its normal capacity.

(c) Discharges occurred in an uncontrolled manner when the water reached the sluice gate level.

The discharge pattern is shown in Figures 7 and 8 and is summarised in Table 2.

3.2 Retention Pond No. 2

The No. 2 retention pond (RP2) is intended to retain the water derived from the ore stockpile heaps. The pond has an area of approximately 19 ha and will hold approximately 6×10^5 m^3 of water. It has a catchment area of 141 ha. The proposal to release water from RP2 has been governed by the belief that it would be considerably more contaminated by heavy metals than RP1. Therefore, it was intended that this water would not be discharged down the creek which originally drained the catchment but would be pumped directly into Magela Creek at suitable times. As pointed out in Section 1, discharges should not occur before the 1st February. Also, Magela Creek must be in flood to ensure adequate dilution of the discharge water. A 100-fold dilution, the value used by Yeates and Walker, was considered adequate; what this dilution achieves is discussed in the next section.

The behaviour of RP2 was simulated using the computer program and with the following assumptions:

(a) The dam was originally empty.

(b) For the 1972-73 year, pumping did not start before 1st February; for the 1975-76 year, pumping started when the pond was full.

(c) Pumping was related to the flow in Magela Creek as follows (where 1 cumec = 1 m^3 s^{-1}):

Daily Average Flow (Magela Creek) (cumecs)	Pump Rate (cumecs)
0-50	0
50-100	0.5
100-150	1
150-200	1.5
> 200	2

The pump rates in the above table could be achieved by using combinations of one 1 cumec and two 0.5 cumec pumpings.

The results of these calculations are shown in Table 2 and Figures 9 and 10. It is interesting to note that, in the 1975-76 case, there was no need to pump the pond until mid-February. The opportunities for discharges were far fewer in 1972-73, but the 7 x 10^4 m^3 remaining in the dam would have been disposed of easily as make-up water in the mill-tailings dam circuit. These results confirm that no discharges need take place before the 1st February and generally confirm the feasibility of this aspect of the proposed water management scheme.

3.3 Comparison with Yeates and Walker's Results

To compare the above results with those of Yeates and Walker [1973] and Yeates [1976], it is necessary to allow for the different points of view between the two studies. Yeates and Walker considered the combined mining and milling operations to a greater degree than was done in the present work where primary concern is with the effects of the operation upon the water quality of the surrounding area. Hence, Yeates and Walker allowed for volumes of water to be taken from RP2 to replace evaporation losses from the mill-tailings dam circuit. They also ensured that there is no net gain in water storage over the year. Taking these points into account, the following comparative comments can be made:

(a) There is a discrepancy when comparing the RP1 and RP2 results for the 'average' year 1972-73. Yeates and Walker's calculated yield from the RP1 catchment is 44 per cent greater than the present estimates, whereas for RP2, it is 44 per cent less. It is not easy to see why these two disturbed catchments should behave so differently when compared with the natural catchment model.

(b) In the present work, the 1975-76 rainfall data were used for the 'wet year' calculations, whereas Yeates and Walker used a generated rainfall function. Yeates and Walker's RP1 result is 25 per cent higher, and their RP2 result is 45 per cent lower than the present calculations.

(c) Yeates and Walker calculated that the water impounded by the ponds will increase as mining proceeds. This effect arises from the changing nature of the catchment area. For example, between year 2 and year 10, the water input rises by 40 per cent for a dry year and 24 per cent for a wet year [Yeates and Walker 1973, II:Table XX]. The present work does not take into account the changing nature of the catchment, as it is believed that the effect of the altered catchment is too uncertain. The changes are more likely to alter the time of arrival of the run-off water than to make any significant difference to its total quantity.

4. CONTAMINATION LEVELS

4.1 Heavy Metal Concentrations in Retention Ponds

The general behaviour of contamination levels in the retention ponds has been investigated using the computer program. The calculations show that the concentration of contaminants in the ponds is virtually the same as that of the water entering the ponds. There are seasonal variations of ± 20 per cent, depending on the balance between evaporation and dilution by rain falling directly into the ponds. There are some measurements showing that the early wet season rains will carry a higher concentration of heavy metals than the later rains [Davy 1976], as shown in Figure 11. This effect is presumably due to bacterial or chemical action which frees the metallic ions during the dry season. However, computer calculations show that the quantity of water in the early, more contaminated, flow is so small that the concentration of heavy metals in the pond water is very soon dominated by the large quantities of purer water that enter later.

As it has been shown that the contamination levels of the pond water are equal to that of the run-off water, the contamination levels of the pond water can be readily deduced from the following information:

(a) The nature of the catchment areas of the ponds; this is set out in Table 3.

(b) The contamination load imparted to the rain water as it seeps from, or runs off, the various types of catchment; this is shown in Table 4.

The contamination levels derived from these data are shown in Table 5.

The second point, which is clarified by the computer calculations, is that the increased heavy metal concentrations expected in the early wet season run-off are of no great significance owing to the small volumes of water involved. Therefore, on the basis of heavy metal contamination, there are no grounds at present for requiring the early run-off to be treated differently from the later flows. The situation, however, could be reversed when the sulphate question is considered. Seepage of water from the tailings dam throughout the dry season, combined with evaporation from the foot of the embankment, could leave a deposit of sulphate ready to be redissolved and washed into the retention ponds. The concentration of the sulphate in this water could well be sufficiently high to justify returning it to the tailings dam before the volume of water becomes too large as a result of the further rains. The Ranger Inquiry Commission recommended that the tailings dam seepage be intercepted either by an impermeable membrane over the floor of the dam or by a toe drain around its perimeter [Ranger Inquiry 1977:159]. If this recommendation is adopted, the sulphate problem should not involve RP1.

4.2 Comparison with Yeates and Walker's Results

The calculated contamination levels of the two retention ponds are compared with Yeates and Walker's values (Table 5). The greatest disagreement between the two sets of estimates is in the relative contamination levels between RP1 and RP2. In the case of RP1, Yeates and Walker estimated the contamination levels to be considerably lower than the present values. The present values are based on the ultimate size of the waste rock heap (100 ha), but this does not seem to be the case in Yeates and Walker's work. On the other hand, the new values for the contamination of RP2 are lower than those of Yeates and Walker. A possible explanation for this discrepancy could be the addition of mine pit seepage water to RP2, after some years of mining, when there may be too much water from this source to be absorbed in the mill-tailings dam circuit. No account of this source of water has been taken in the present work because of the large uncertainty in the expected volume of water. Any action to be taken with respect to the mine pit water will probably have to be decided during the course of mining, depending on the volume and purity of the water. The possibilities are:

(a) If the volume is small, the pit water will be used as make-up water for the mill.

(b) If there is an excess after replenishing the mill supply, the surplus water will be discharged *via* RP2, with the possibility that it may be necessary to precipitate radium, with barium chloride, if the radium levels become too high after dilution in RP2 and Magela Creek.

4.3 Dilution by Magela Creek During Discharge

The next problem is to determine the dilution of the water from RP2, for example, by Magela Creek during discharge. The problem is complicated by the high concentrations of copper, lead and especially zinc in the undisturbed Magela Creek. The average values of these natural contamination levels are shown in Table 6, but the actual values vary considerably, a factor of ten being quite normal. The natural concentrations of copper and lead are equal or close to the "maximum safe level (for no effect on fish life)" and for zinc the concentration is five times the "safe level" [Ranger Inquiry 1977:103]. These comparisons would be valid only if the natural contaminants are in the most toxic (ionic) form whereas, in reality, they are probably bound in to a relatively inactive complex form. In this case, the "safe levels" can be used as permissible increments and a dilution of 26 times would be sufficient to make the water from either pond safe, zinc being the most critical pollutant.

Another approach is needed if the natural contamination of Magela Creek is not to be ignored. As it has been shown in Section 3.2 that the water in RP2 can be disposed of without ever adding more than one per cent to the flow in Magela Creek, one way would be to look at the state of the Magela Creek water when the RP2 water is added to it in this proportion (Table 6). At the times of discharge (about 20 days per year), the copper, lead and zinc concentrations are raised respectively by 10, 20 and 4 per cent; all of these percentages are much less than the natural variation in the original Magela Creek concentrations.

Although the predicted concentrations of uranium and radium are increased by three and two times, respectively, their concentrations would still be much lower than the safe levels, as these metals are relatively non-toxic to fish. In conclusion, therefore, although one must agree with the view [Ranger Inquiry 1977:113] that much more work should be done to increase the understanding of the effects of heavy metals on fish, a 100-fold dilution would seem a reasonable criterion to set at present.

4.4 Radium

Radium is a special case; the limit to the quantity that may be safely discharged arises from radiological hazards to local inhabitants who may ingest an increased quantity of radium in locally collected food (for example, Aboriginals at present eat many fresh water mussels). In considering this question it is the total quantity of radium transported that is relevant and not its dilution.

The total average annual load of radium carried by Magela Creek is 1850 MBq (0.05 Ci) [Ranger Inquiry 1977:101]. The additional load, arising from the discharge of the two retention ponds, should, according to the present calculations, be 740 MBq (0.02 Ci); this would raise the average radium content by almost 50 per cent. An earlier estimation of the additional radium load was double this value, and led to a total ingestion of 300 Bq (8000 pCi) per year by each member of a hypothetical critical group of people; 300 Bq is the International Commission on Radiological Protection (ICRP) recommendation for the maximum permissible annual radium intake brought about by human activities [Ranger Inquiry 1977:123]. On these grounds, the discharge of the radium would be justified. However, there are several arguments against this conclusion [Ranger Inquiry 1977:124]:

(a) The possible natural radium uptake is anomalously high in the area (also 300 Bq per year).

(b) The ICRP recommendations are based on a cost benefit argument and, in the present case, it could be argued that the group most likely to be subjected to additional radium would be local Aboriginals who may not gain substantial benefits from mining.

(c) The ICRP recommends that all reasonable economic efforts should be made to reduce the radiological load to the lowest practicable value.

Another argument implies that mining may not increase the radium output to the waterways by as much as was calculated above [D.R. Davy, AAEC private communication]. There is evidence that the orebody is responsible for producing high radium concentrations in Georgetown Billabong and in Gulungul Creek, by way of groundwater movement along geological faults. If this is so, then removal of the ore and waste rock would simply change the route by which the total radium load entered the river system (see Preface for outline of present scheme).

4.5 A Possible Variation to the Water Management Scheme

Throughout the Ranger Water Management Study [Yeates and Walker 1973] there is the understanding that the water in RP1 is far less contaminated by heavy metals than the water in RP2. The present study does not support this view. Because of the conclusion reached by Yeates and Walker regarding the water qualities, the water from the two ponds is treated in vastly different ways; RP1 is used to dilute RP2, or is released as an uncontrolled discharge down a natural creek bed, whereas RP2 is pumped to Magela Creek only when a 100-fold dilution can be ensured. Although the operation of RP2 appears to be a reasonably effective way of disposing of dissolved heavy metals, neither pond would permit much sedimentation to occur before discharge. It has been claimed [Yeates and Walker 1976:8] that the main source of suspended solids will be in the waste rock piles and that the water derived from this source will be held in RP1 for three days before discharge. This three-day holding period is clearly impossible, as large quantities of water are continually entering the pond in February and March when the discharges must occur. In fact it seems that RP1 achieves very little; it does not protect Coonjimba Billabong from the possibly heavy loads of manganese and sulphate leached from the tailings dam; it is also ineffective as a sedimentation pond. The manner of discharge from the two retention ponds with similar water quality is inconsistent.

As the pumping capacity between RP2 and Magela Creek could handle more water than is collected in the RP2 catchment alone, it would be possible to reorganise the pond system to include the run-off from the waste rock catchment in the water pumped to the creek, after storing it for a few days to allow sedimentation. To achieve this result, the best arrangement would be to have three ponds. The first pond, the receiving pond, would collect the run-off water from both catchments. When this pond is filled it would be discharged to two other ponds alternately. The water in these two discharge ponds would be pumped to Magela Creek, subject to the criteria applied to RP2. The feasibility of this scheme from a water balance point of view was tested with the computer program. The receiving pond was assumed to have the same area-volume relationship as RP1 and the discharge ponds to be like RP2. Rainfall data for the wet year 1975-76 were used.

The receiving pond was discharged six times. In one case, a relatively small overflow occurred, which would not be necessary in practice, as it arose from the strict 24-hour time increment of the computer calculations. Each discharge pond was pumped to Magela Creek after the water had remained in it for three days. The behaviour of the system is illustrated in Figure 12.

This description is very brief, and is only meant to indicate the feasibility of building a system that would safeguard Coonjimba Billabong. The actual effect that three days of sedimentation would have on the silt load is unknown, but presumably some advantage must accrue. Obviously more work is necessary to optimise the sizes of the ponds and to find suitable locations for them.

5. CONCLUSIONS

A computer program was developed from the Boughton and Jones model, using stream flow data for Gulungul Creek to suggest minor modifications to the model and to determine the model parameters. The program relates run-off to rainfall and has been applied to the proposed retention ponds at Ranger Uranium Mine. The contamination levels of the water in the retention ponds were the same as the average levels in the water entering the ponds. The water qualities in the two retention ponds were also substantially the same, and hence the disposal methods originally proposed by Ranger Uranium Mines Pty Ltd for the two lots of water are anomalous.

It was shown that generally all the water from both ponds could be disposed of by pumping to Magela Creek, while ensuring a 100-fold dilution in the creek water. This 100-fold dilution will cause rises in the levels of copper, lead, zinc and uranium in the creek, but the resulting levels should, on the basis of rather scant data, be tolerable to fish life. The discharge of radium will not exceed the maximum permissible limit set out by the ICRP, but attention should be paid to the ICRP recommendation that "all exposures be kept as low as is reasonably achievable, economic and social considerations being taken into account" [ICRP 1977].

Because of the scarcity of reliable data, constant monitoring of pollution levels, discharge quantities and effects on biota should be carried out in conjunction with the mining, and corrective action taken if necessary. Finally, an indication is given of how a pond scheme could be organised to permit more effective sedimentation of the run-off water before discharge.

6. ACKNOWLEDGEMENTS

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TABLE 1
DEFINITIONS AND VALUES OF PARAMETERS USED IN CALCULATIONS

Parameter		Value
VSS	Capacity of soil store	150 mm
VDS	Capacity of drainage store	350 mm
A	Factor relating fraction of rainfall entering runoff store to soil store moisture content	0.05
B	Factor relating fraction of rainfall entering runoff store to drainage store moisture content	0.5
C	Fraction of contents of runoff store running off per day	0.5
D	Maximum daily seepage loss from drainage store	0.4 mm
E	Ratio between evapo-transpiration rate and pan evaporation rate	0.7

TABLE 2
RESULTS OF CALCULATIONS OF WATER BALANCE FOR RP1 AND RP2

Present Calculations	Retention Pond 1		Retention Pond 2	
	Average	Wet	Average	Wet
	%*	%	%	%
Runoff to dam	24	40	24	43
Evaporation from soil	62	47	63	50
Evaporation from dam	10	7	9	3
Seepage to dam	2	2	2	2
Rainfall direct to dam	7	9	6	5
Discharge from dam	12	36	0	47
Increased dam storage	12	8	24	0
	10^3m^3	10^3m^3	10^3m^3	10^3m^3
Discharge from dam	440	1950	500	1430
Increased storage	460	420	50	0
Net discharge possible	900	2370	570	1430
Calculations by Yeates† (year 2)				
Discharge to Coonjimba Creek	938	2570		
Discharge to RP2	361	408	361 (transferred)	408 (transferred)
Discharge to Magela Ck			524	1082
Discharge to mill circuit			159	114
Net discharge	1299	2978	322	788

* Percentage of total rain for year

† Yeates & Walker [1978] Vol.I, Tables I,II,III,VI,XV
Vol.II, Table XX

TABLE 3
COMPOSITION OF CATCHMENT AREAS OF RETENTION PONDS

Retention Pond 1

	ha
Natural inside mine area	155
Waste rock heap (ultimate size)	100
Total	255

Retention Pond 2

Mine plant compound	130
Surge ore pile*	0.5
Low grade ore+	6.0
Lateritic ore+	4.5
Total	141

* Stockpile for one month at 4000 tonne per day, assuming 25×10^4 tonnes covers 1 ha

\+ Estimates by Davy [1976]

TABLE 4
ESTIMATED CONTAMINATION LEVELS OF WATER ENTERING RETENTION PONDS FROM VARIOUS SOURCES
[After Yeates 1976:5]

	Cu µg/L	Pb µg/L	Zn µg/L	U µg/L	Ra pCi/L
Natural area inside mine area	20	20	15	5	5
Mine plant compound	20	30	25	30	10
Waste rock heaps	50	50	40	100	25
Surge ore	50	50	40	320	170
Low grade ore	50	50	40	250	75
Lateritic ore	50	50	40	210	120

TABLE 5
ESTIMATED CONTAMINATION LEVELS OF WATER IN RETENTION PONDS

	RP1	RP2
Cu µg/L	32 (12)	22 (52)
Pb µg/L	32 (17)	32 (27)
Zn µg/L	25 (16)	26 (26)
U µg/L	42 (26)	46 (180)
Ra Bq/L	0.48 (0.28)	0.63 (1.4)

Values in parentheses are derived from Yeates [1976:96]

TABLE 6
CONCENTRATIONS OF HEAVY METALS IN MAGELA CREEK COMPARED WITH 'SAFE LEVELS'

	Magela Creek (Average Natural) (1)	Magela Creek (During discharges) (2)	Ratio (3)	"Safe levels" (4)
Cu (μg/L)	2	2.2	1.1	2
Pb (μg/L)	1.6	1.9	1.2	2
Zn (μg/L)	5	5.2	1.04	1
U (μg/L)	0.2	0.65	3.25	130
Ra (mBq/L)	7.4	13.7	68.5	

Column (1)	Yeates [1976:96]: these data cannot be taken as definite
Column (2)	Calculated from (1) and RP2 concentrations given in Table 5, assuming 100 parts of Magela Creek water to 1 part of RP2 water.
Column (3)	Ratio of concentrations 'after discharge' to 'before discharge'.
Column (4)	Yeates [1976:103]: fish are supposedly unaffected by contaminants at these concentrations: these data are of very doubtful validity in their applicability to the Magela Creek situation.

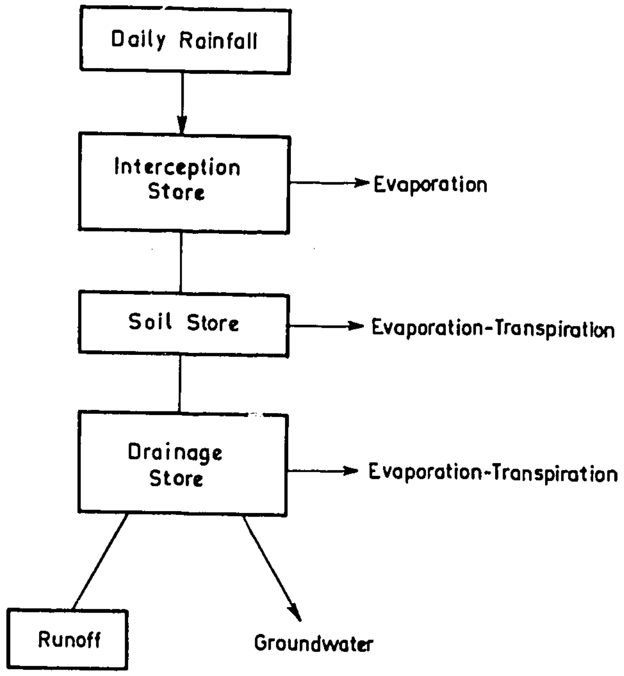

FIGURE 1. BOUGHTON & JONES MODEL FOR SMALL CATCHMENTS

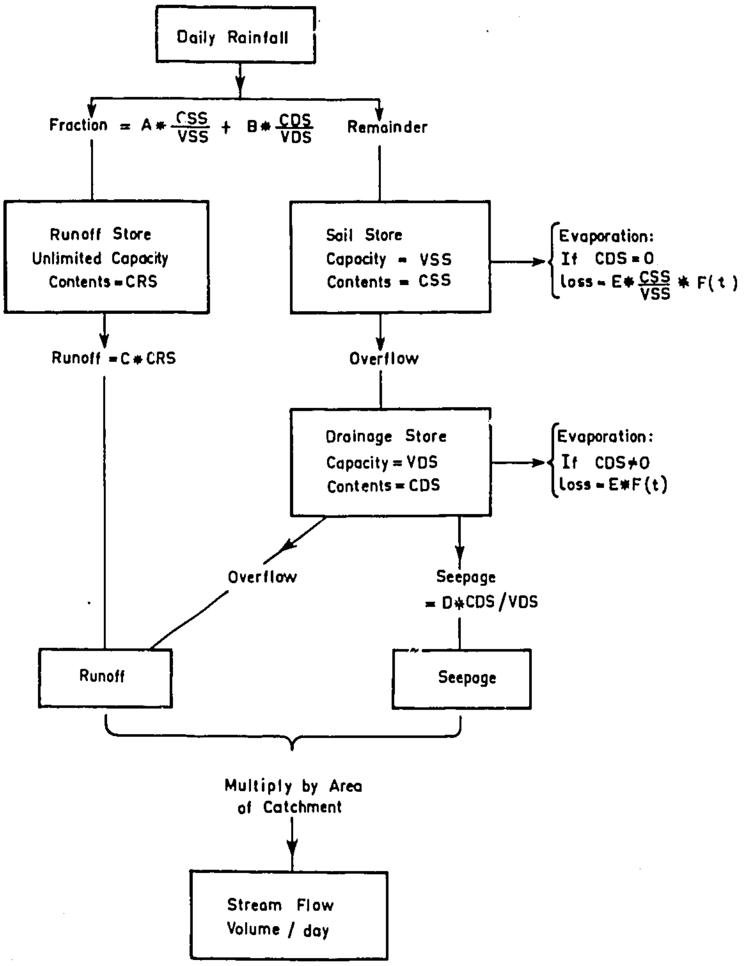

FIGURE 2. MODIFIED BOUGHTON & JONES MODEL

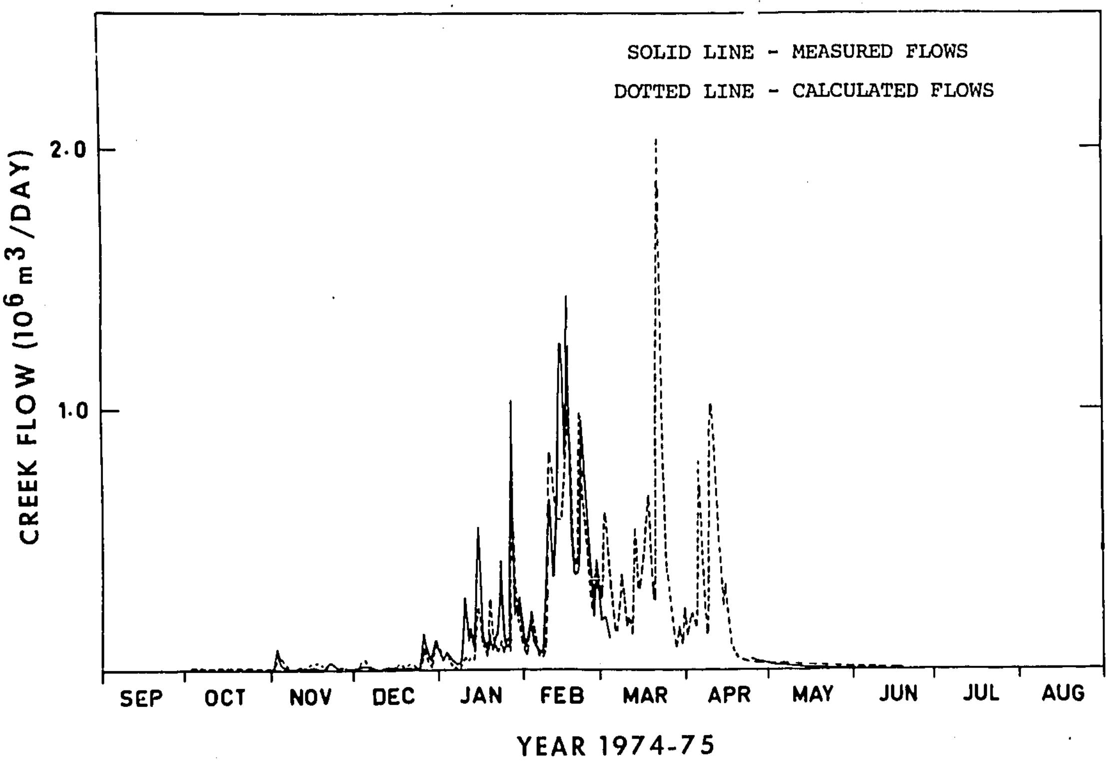

FIGURE 3. COMPARISON OF MEASURED AND CALCULATED FLOWS IN GULUNGUL CREEK USING WRB RAINFALL DATA

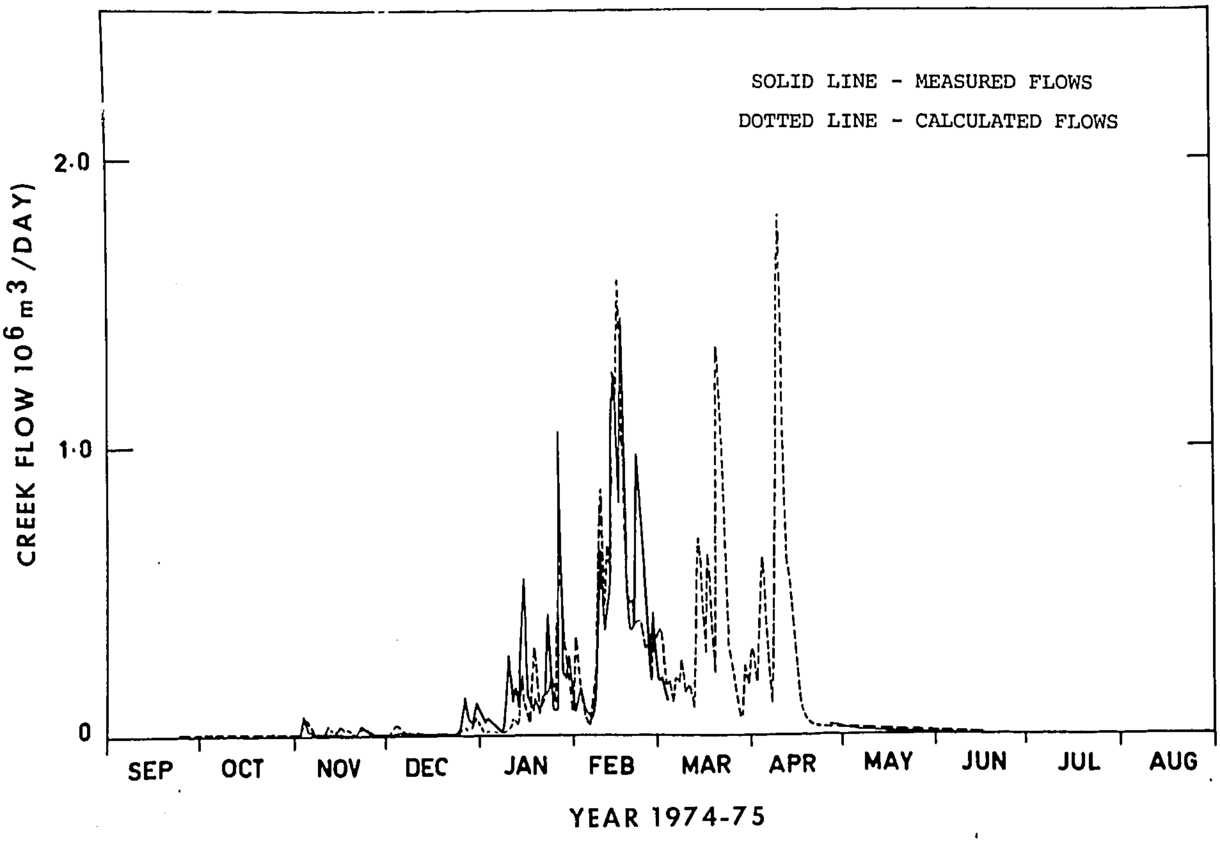

FIGURE 4. COMPARISON OF MEASURED AND CALCULATED FLOWS IN GULUNGUL CREEK USING RANGER RAINFALL DATA

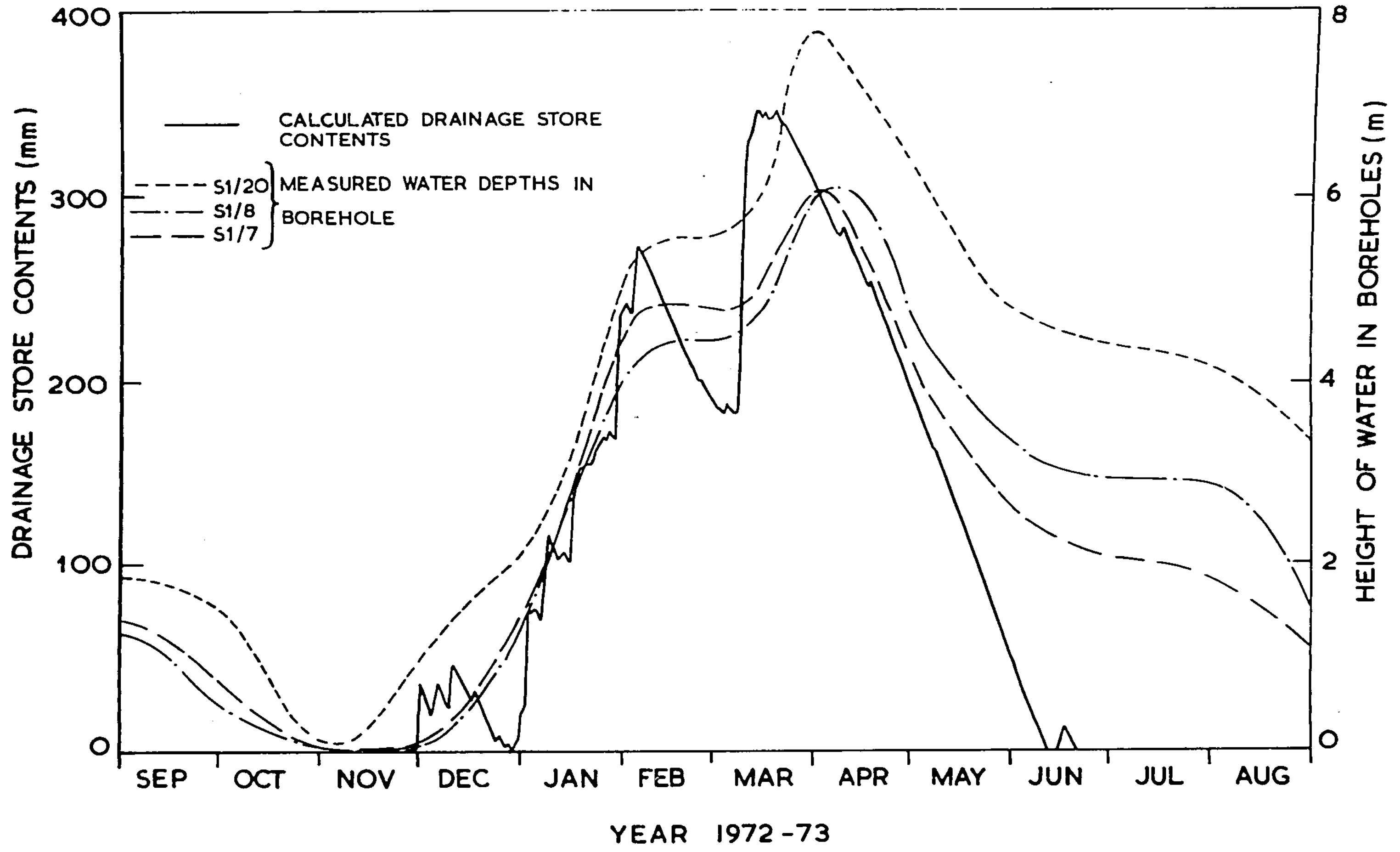

FIGURE 5. COMPARISON OF MEASURED RISE OF WATER LEVEL IN BOREHOLES WITH CALCULATED DRAINAGE STORE CONTENTS (Coffey & Hollingsworth, 1973, 5 :52)

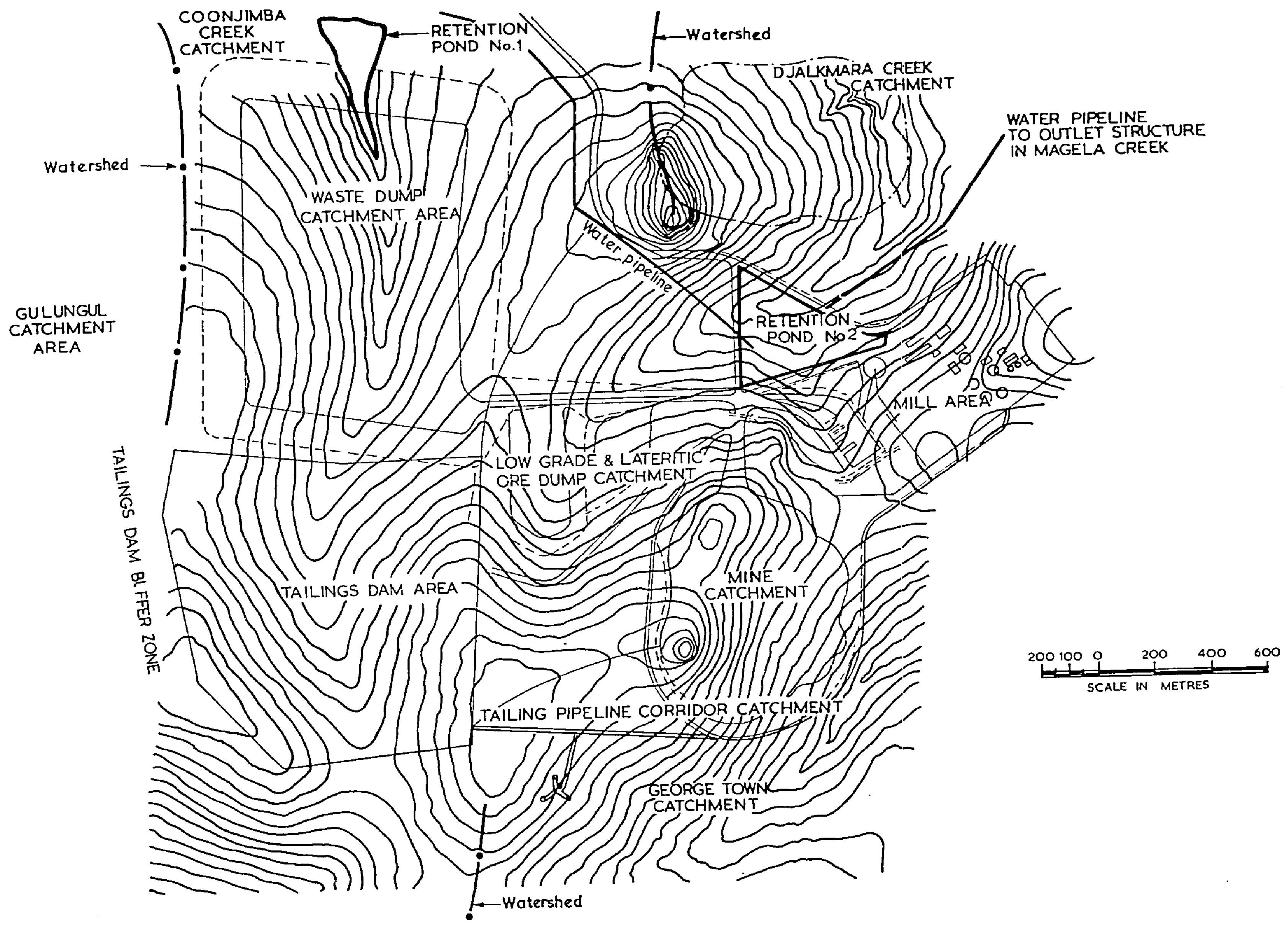

FIGURE 6. GENERAL LAYOUT PLAN OF MINE AND MILL WATER CATCHMENTS

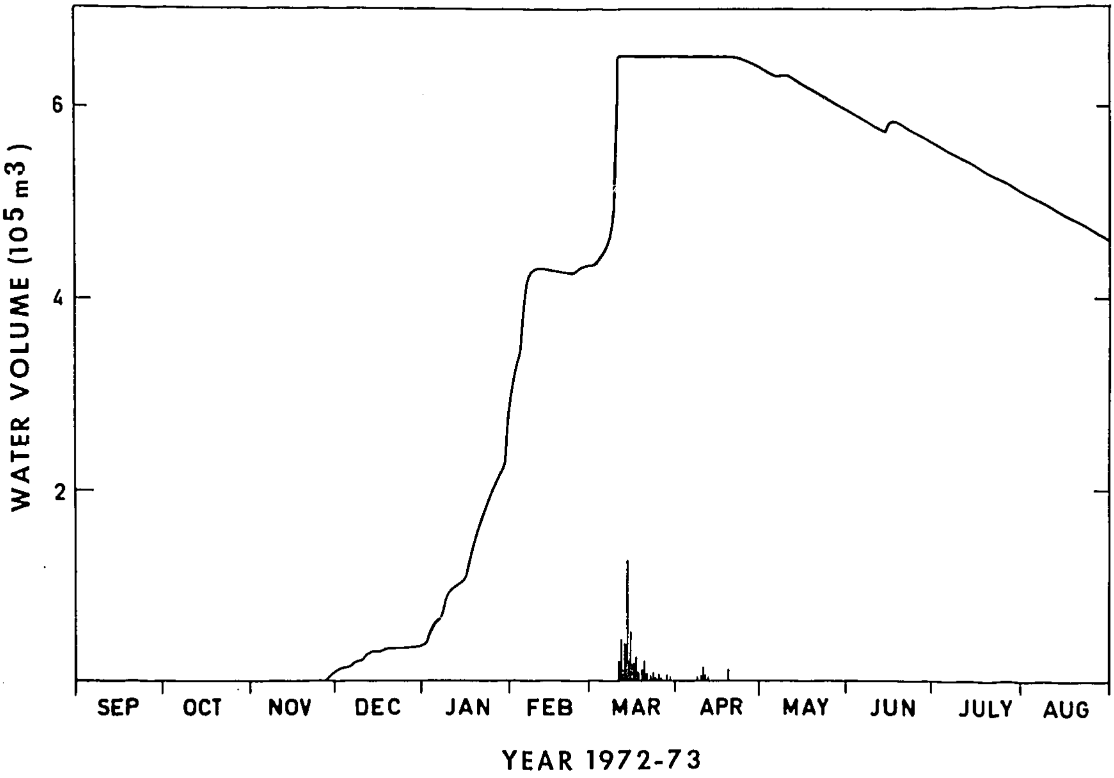

FIGURE 7. ESTIMATED BEHAVIOUR OF RP1 (AVERAGE YEAR) SHOWING CONTENTS OF DAM AND QUANTITIES DISCHARGED (VERTICAL STROKES)

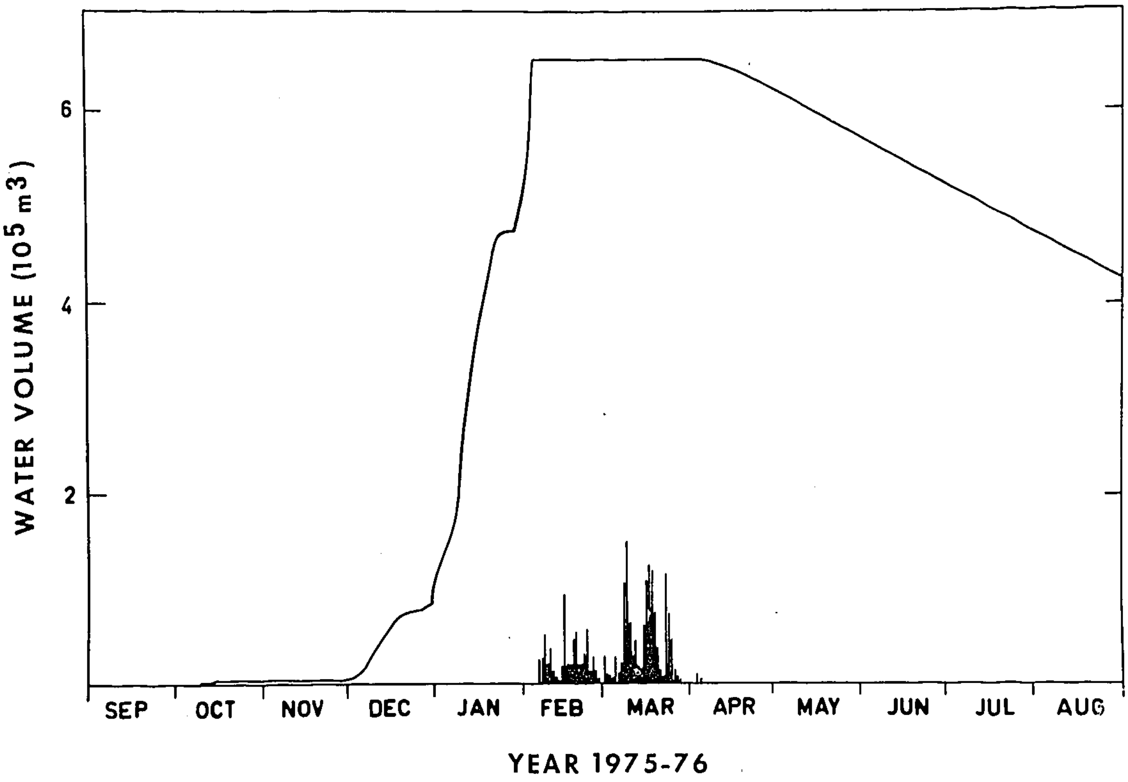

FIGURE 8. ESTIMATED BEHAVIOUR OF RP1 (WET YEAR) SHOWING CONTENTS OF DAM AND QUANTITIES DISCHARGED (VERTICAL STROKES)

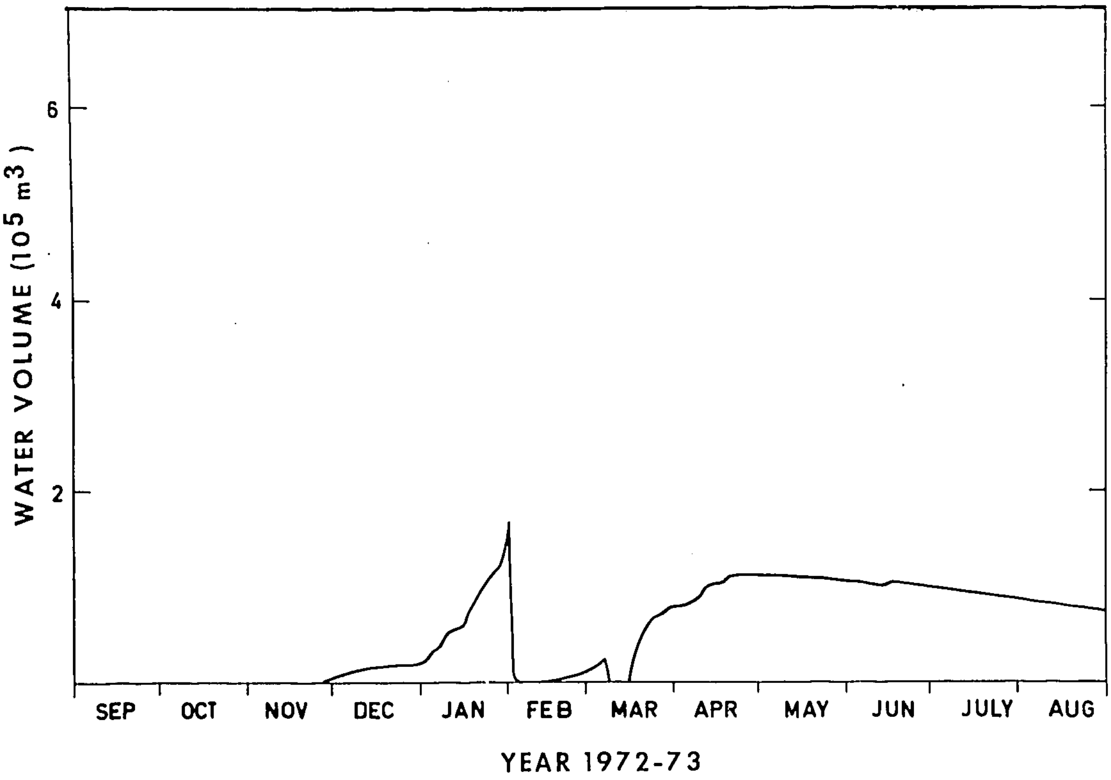

FIGURE 9. ESTIMATED BEHAVIOUR OF RP2 (AVERAGE YEAR) WITH WATER BEING PUMPED TO MAGELA CREEK DURING FEBRUARY AND MARCH

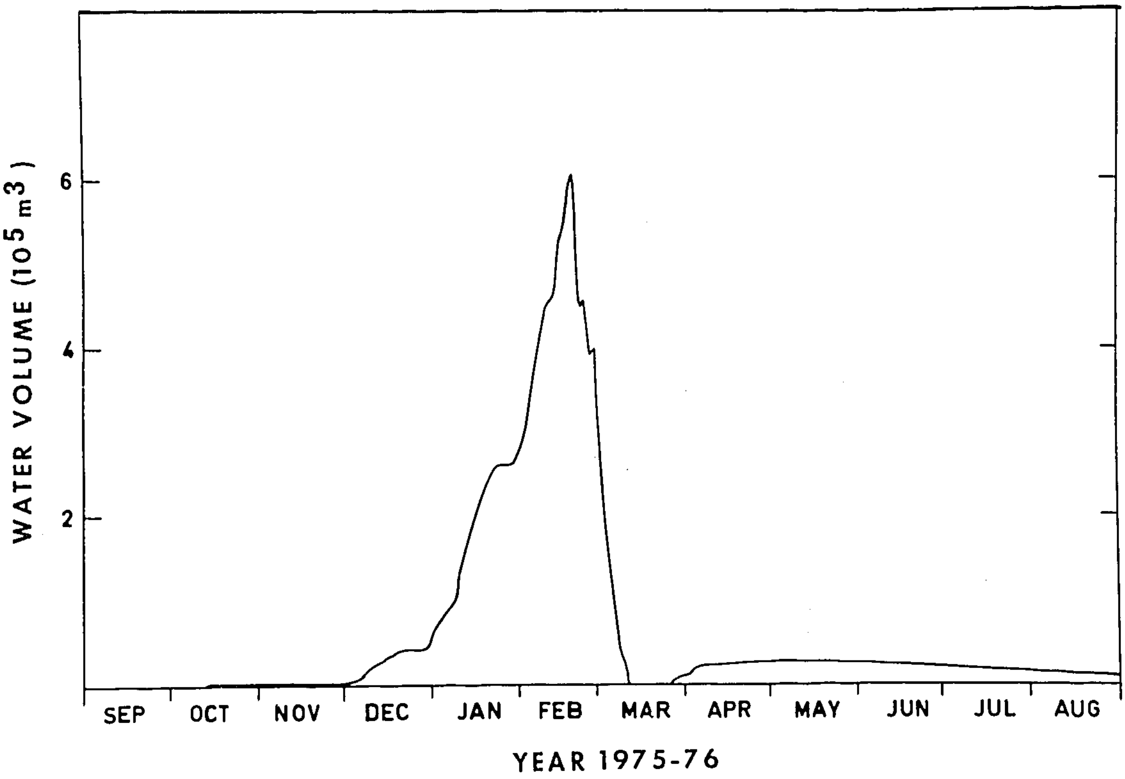

FIGURE 10. ESTIMATED BEHAVIOUR OF RP2 (WET YEAR) WITH WATER BEING PUMPED TO MAGELA CREEK DURING FEBRUARY AND MARCH

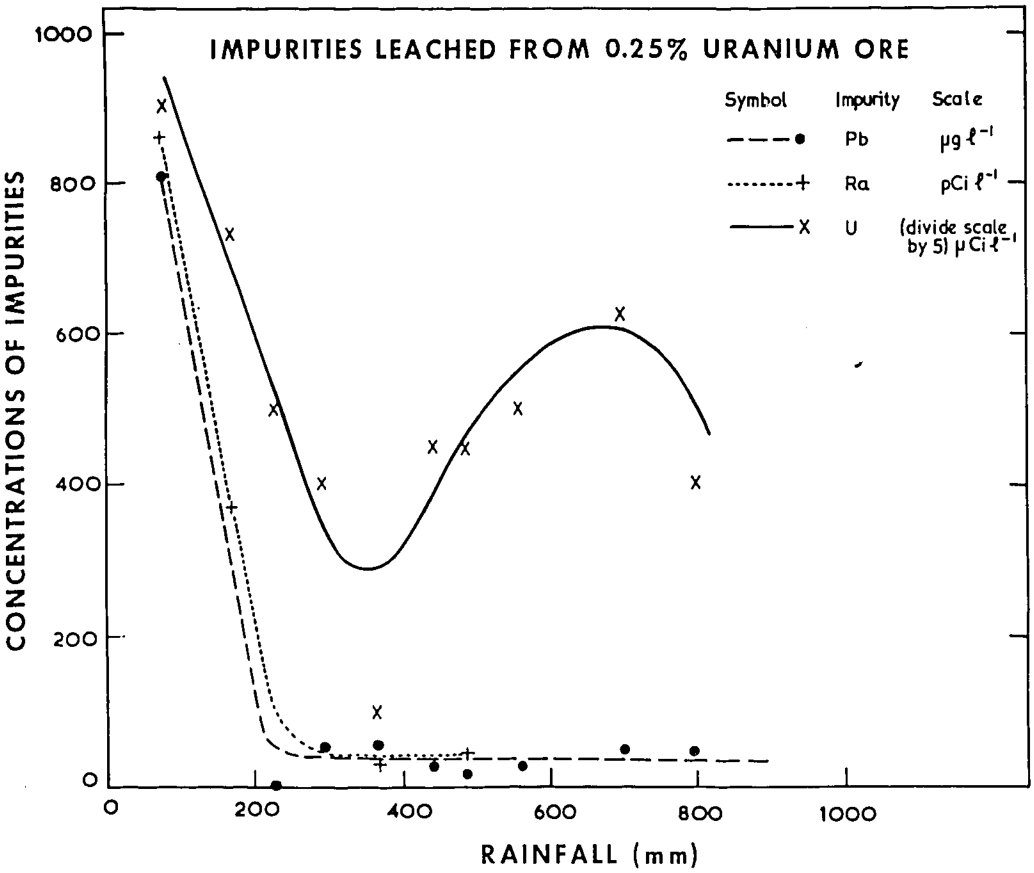

FIGURE 11. THE CONCENTRATION OF THREE HEAVY METALS IN RUNOFF FROM A URANIUM ORE HEAP AS A FUNCTION OF THE AMOUNT OF RAIN FALLEN, STARTING FROM THE BEGINNING OF A WET SEASON (Davy 1976)

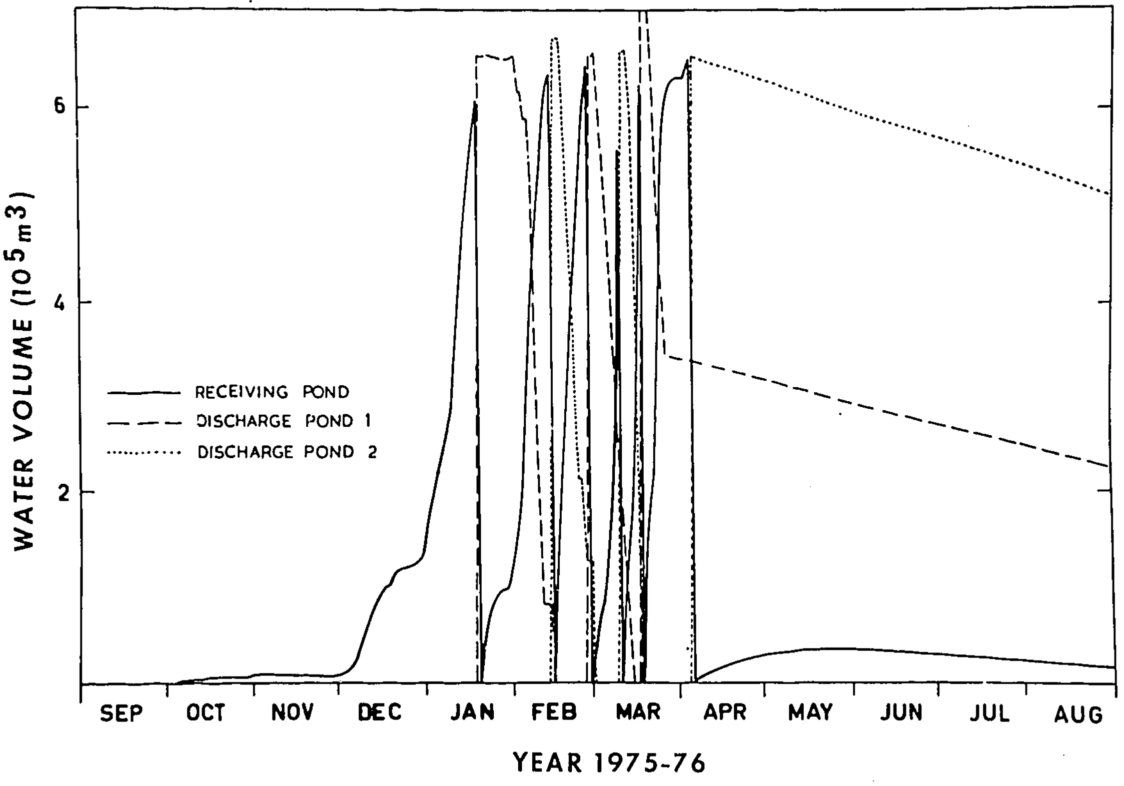

FIGURE 12. WATER STORAGE IN THREE PONDS OPERATED IN A MANNER SO AS TO MAXIMISE SEDIMENTATION TIME

APPENDIX A
TEST OF MODEL WITH ADDITIONAL DATA

Since the preparation of this report, further data on gauged catchments have been produced. From these data, two sets have been chosen as relevant to the conditions expected at Oenpelli. These are as follows:

Gauging Station	Area (ha)	Years	Rainfall Station	Years
Acacia Creek No.817085	1080	1962-74 (incomplete)	Manton Dam No.014135	1962-74
Coomalie Creek No.817066	7692	1958-74	Batchelor (Huendot Farm) No. 014146	1963-71
			Batchelor (Triangle B Ranch) No. 014190	1970-74

The daily run-off was calculated for these two catchments using the parameters derived from the Gulungul Creek data. The results are shown in Table A1. The quality of the data does not appear to be good enough to warrant changes to the model or to the parameters. This is evidenced in the systematic differences between the two catchment areas in correlation and run-off coefficients. There are other points which do not support the use of the data for extensive refinement of the calculations. For example, in the Acacia Creek/Manton Dam data there are several instances where a flood peak precedes the storm which should have caused it. Also the correlation coefficient between the two sets of daily rainfall figures for 1970-71 which apply to the Coomalie Creek catchment is only 0.51. The two weather stations are about 17 km apart. The distances between the catchment areas and the rainfall gauges, and the fact that one rainfall measurement is taken to apply to the whole catchment, together with the often local nature of storms in the Northern Territory, could provide the reason for the erratic correlations between rainfall and river flow.

On the positive side, it is worth noting that, except for the dry season 1969-70 which gave an extremely low run-off (2 per cent) in the Acacia Creek catchment, the calculated annual run-off varied between 0.8 and 2.6 times the measured values, with a mean of 1.5. If these figures mean that the model tends to overestimate the run-off, the fault is in the right direction as far as the design of retention ponds is concerned.

TABLE A1

COMPARISON OF CALCULATED AND MEASURED RUN-OFFS FOR TWO SMALL CATCHMENTS

Gauging Station/ Rainfall Station	Year	Annual Rainfall (mm)	Percentage Calculated	Annual Run-off Measured	Run-off Ratio Calc./Meas.	Correlation Coefficient
Acacia Creek/ Manton Dam	1962-63	1443	28.2	19.2	1.47	0.70
	1963-64	1416	27.2	11.8	2.30	0.69
	1965-66	1582	35.2	32.4	1.08	0.75
	1967-68	2006	40.5	47.9	0.84	0.59
	1968-69	1679	40.5	46.2	0.88	0.59
	1969-70	1001	14.1	2.1	6.70	0.57
	1971-72	1597	26.3	33.8	0.78	0.68
	1972-73	1793	39.7	36.3	1.09	0.76
Coomalie Creek/ Batchelor (Huendot Farm)	1963-64	1220	22.3	10.2	2.18	0.86
	1964-65	1566	30.0	14.3	2.10	0.68
	1965-66	1263	30.4	18.0	1.68	0.83
	1966-67	1457	27.8	23.6	1.18	0.88
	1967-68	1911	41.3	25.4	1.63	0.89
	1968-69	1406	28.1	33.6	0.84	0.77
	1969-70	1000	16.6	7.4	2.24	0.74
	1970-71	1452	25.9	13.8	1.88	0.84
Coomalie Creek/ Batchelor (Triangle B Ranch)	1970-71	1651	31.5	12.1	2.60	0.76
	1971-72	1570	27.7	15.6	1.77	0.78
	1972-73	1386	24.5	20.4	1.20	0.64
	1973-74	2102	44.0	38.7	1.13	0.87

APPENDIX B
SENSITIVITY ANALYSIS

An analysis of the sensitivity to variations of the various parameters was made in the following way. The 1973-74 rainfall data from Batchelor Triangle B Ranch (Station 014190) and the 7700 ha Coomalie Creek catchment were chosen as a typical year and catchment. The run-off was calculated with the standard parameters. These run-off figures were stored and used for comparison with the results of subsequent calculations, in place of the measured run-off data usually used for comparison. In the subsequent calculations, one parameter at a time was varied over a range sufficient to produce reasonable deviations in the predicted run-off. The results for five parameters are presented in Figure B1. Ratios between the annual run-offs calculated with the perturbed parameters and the annual run-offs calculated with the standard set are shown. Also shown are the correlation coefficients between the daily run-off tables produced by the two calculations. Two of the seven parameters (Table 1) were too insensitive to warrant inclusion in the figure; these are factor A, the fraction of rainfall (depending on the contents of the soil store) proceeding to the run-off store, and factor D, the maximum daily seepage loss from the drainage store.

It is reassuring to see from these results that no single parameter is extremely critical; that is, a small change in one of the parameters does not precipitate large changes in the predicted run-off.

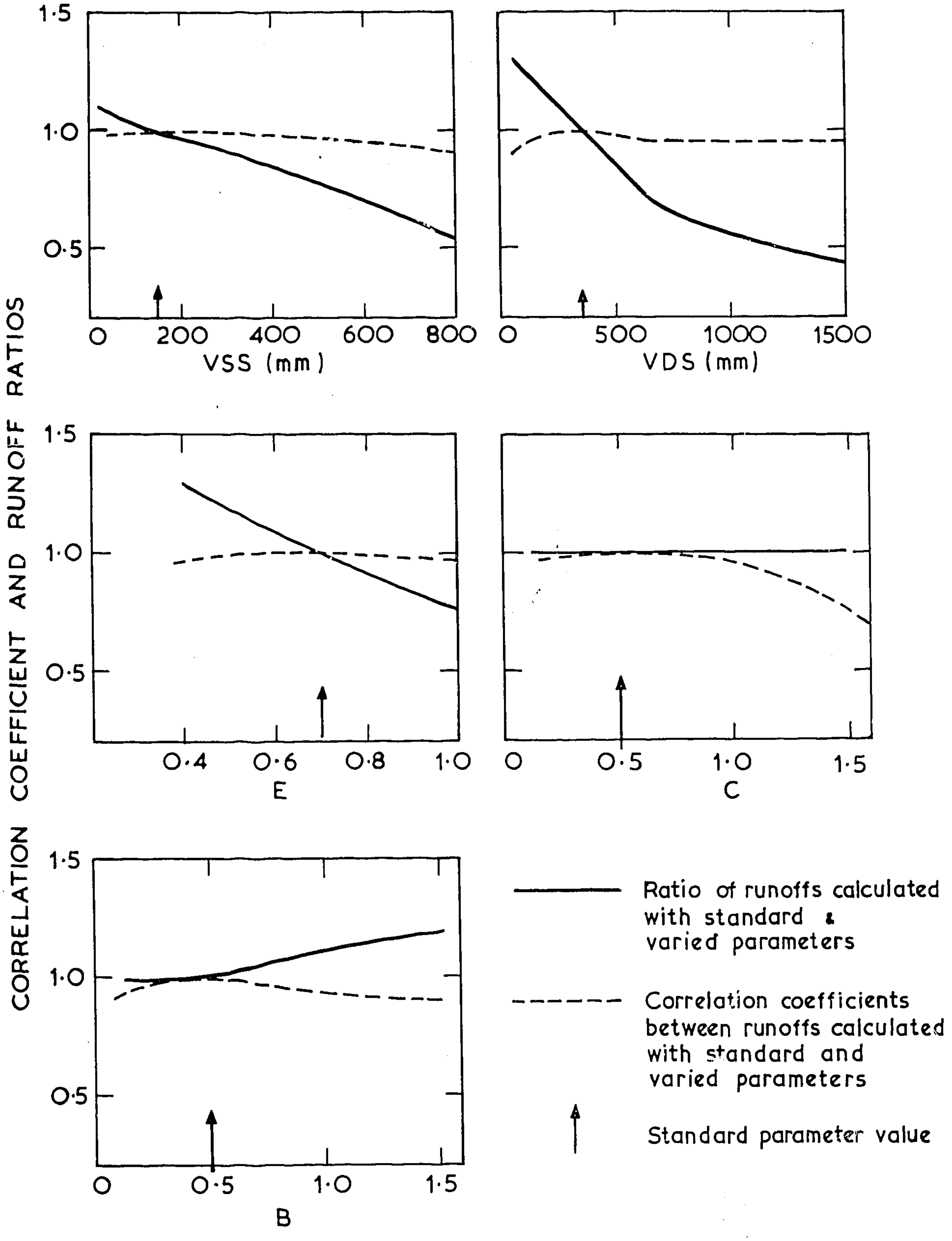

FIGURE B1. PARAMETER SENSITIVITIES