Technical Memorandum 30

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ABSTRACT

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An analysis of rainfall records for the Wet-Dry tropics of the far north of Australia is presented. The results of this analysis are used to develop a regulatory mechanism to limit release of waste water from a uranium mine to particularly wet years in accordance with the Australian Government's environmental protection policy.

1 INTRODUCTION

The far north of Australia ('the Top End') has a monsoon-like climate. Virtually the entire rainfall occurs in the Wet season, which varies in length but is generally confined to the November-March period; October and April tend to be transitional months, with the Dry season lasting from about May to September. The area is subject to cyclones during the Wet.

This Wet-Dry climate presents problems in water management for mining operations. These problems are exacerbated for the Ranger uranium mine at Jabiru (Map 1) due to the need to protect the environment of the surrounding Kakadu National Park, particularly the major wetland system downstream of the Ranger mine.

The regulations which control the operation of the Ranger uranium mine include the definition of a Restricted Release Zone. This is a zone where material containing more than 0.02% by weight of uranium is exposed or about to be exposed by excavation, and from which no water may be released to the environment except in accordance with release standards determined by the Supervising Authority. (See Office of the Supervising Scientist Annual Reports, AGPS, Canberra.)

The Australian Federal Government decided as part of the environmental protection of Kakadu National Park that release of waste water from the the Restricted Release Zone at Ranger uranium mine should only be considered when the rainfall is greater than that which occurs, on average, 1-year-in-10. In addition, any water released would have to meet stringent biological and chemical water quality criteria and certain minimum flow conditions must exist in the receiving creek.[1]

Although some of the excess water on the Ranger site is derived from groundwater, the majority of it is clearly accumulated rainfall. Thus volumes of stored water are closely related to rainfall, and that volume which would be expected to occur once in ten years, on average, is closely related to the 1-in-10 exceedence rainfall. The regulatory criterion used to decide whether a particular year meets the Governments '1-in-10' policy decision could thus either be based on the volume of stored water on the Ranger site or on the rainfall.

Although there are conceptual advantages in using a volume criterion, as it is the volume of water that needs to be reduced, there are practical disadvantages from the regulator's standpoint. Firstly, the volume of water held on site depends on water management decisions made by the Company. Thus poor water management decisions could increase the frequency of discharge if discharge were permitted once a certain volume were reached. Secondly, volume measurement is, of necessity, done by the Company within its own site, and thus is not readily monitored by regulatory authorities nor open to public scrutiny. Thirdly the value of the volume criterion would have to be based on a relatively complex model that relates rainfall, evaporation and various runoff factors to the volume accumulated.

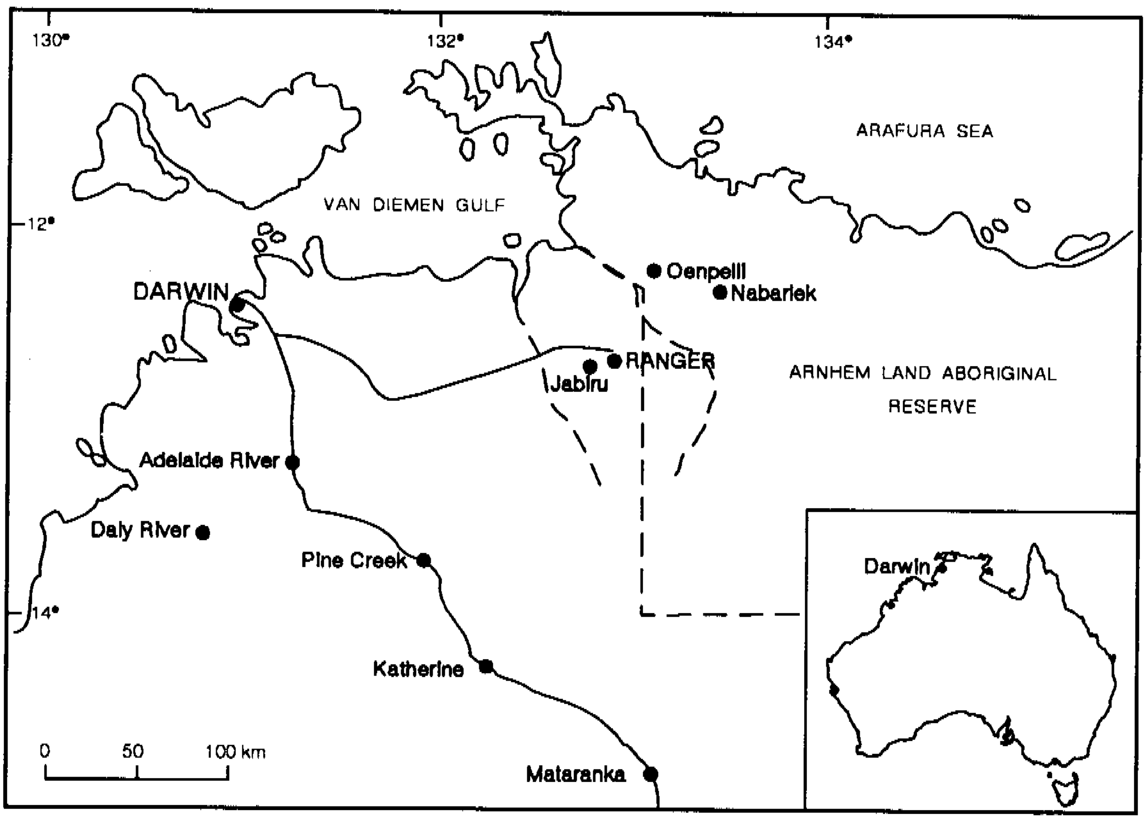
A release criterion based on rainfall does not have these disadvantages; it is therefore, proposed that, at least initially, the criterion used to give effect to the Government's

[1]Extract from a press release (January 1989) by Senator Graham Richardson, Minister for the Arts, Sport, the Environment Tourism and Territories: The Government has decided to re-affirm its previous decision that water release from the Restricted Release Zone (RRZ) at the Ranger mine should only be considered in particularly wet years when the rainfall exceeds that expected in about 1 year in 10. The Government's decision is based on a re-examination of the issue requested by the Government in March 1987 and conducted by the Supervising Scientist in consultation with members of the Coordinating Committee for the Alligator Rivers Region........An important component of this control regime will be the requirement that release will only occur when there is high flow in Magela Creek and large dilution of the discharged water is available. The minimum dilution of discharged water in Magela Creek will be determined on the basis of pre-release biological tests carried out according to protocols developed by the Supervising Scientist, and with a number of other requirements set down in the Ranger Environmental Requirements.

decision be based on rainfall. This note discusses the development of a suitable criterion, based on rainfall, to decide in which years water could be released providing that the other criteria on water quality and creek flow were also met. The development of this criterion should not stop development of appropriate models that would be of operational use to the Company and might be used in future to set a criterion based on water volume.

There are few studies available of rainfall patterns in the Top End and even those that do exist may not be appropriate for the present study. Taylor & Tulloch (1985) for example studied the variations in the monthly rainfall from one year to another and the significance of these variations for agriculture. They found that 'much of the variation between years or groups of years lies in the dry and dry-wet transition periods'. When considering releases of waste water from the Ranger mine site, it is the rain which falls in the months within the Wet season that is of interest. This is because it is the cumulative effect of the Wet season rainfall which contributes to the volume of water stored within the RRZ. The present report shows that if cumulative rainfall is considered, the variations between years are reduced and the application of statistics to the prediction of the total rainfall is valid.

The available rainfall data for Jabiru, however, cover too short a period for satisfactory statistical analysis on which to base a release criterion. Therefore ways in which the Jabiru data may be extended in order to improve the statistical analysis are also examined, and values of release criteria based on such an analysis are recommended.



Map 1. Map showing the location of sites from which rainfall data were examined

To be of practical value, the release criterion must be able to be applied before the end of the Wet season, since there is also a requirement that any release must be into the local creek when running at high flow and likely to continue at high flow for at least some days. Thus the release criterion must anticipate the total Wet season rainfall by some weeks. Because of the anticipatory nature of this regulatory mechanism it is described as a 'trigger'; that is a condition which when reached will initiate other activities.

2 OBJECTIVES

The aims of the study reported here were to:

- Investigate regional rainfall data from the Top End to determine whether there are common patterns within years and trends over many years.
- Investigate rainfall data from individual weather stations with longer records to determine which is most similar to Jabiru.
- Using the above, to extend the limited Jabiru rainfall data and thus give improved confidence in the prediction of Jabiru rainfall patterns.
- Determine an appropriate value of the 1-in-10 exceedance rainfall for Jabiru to be used as the design basis for a water release trigger mechanism.
- Develop a value or values of rainfall that would permit prediction of total Wet season rainfall (with some specified degree confidence), to be used as an anticipatory trigger mechanism for release of waste water.

3 EXAMINATION OF REGIONAL RAINFALL DATA

The following databases were used:

1. Data for Jabiru Airstrip from 1971-72 to 1986-87.
2. Two series of rainfall data for Darwin Post Office: from April 1869 to January 1942 and from November 1947 to March 1962; and data for Darwin Airport from January 1941 to December 1986.
3. Data for Katherine (1873-1985), Pine Creek (1875-1986), Daly River (1885-1899, 1963-1983), Oenpelli (1911-1987) and Nabarlek (1980-1987).

In all cases the raw data have been changed from calendar year to Wet season year - 1 September to 31 August.

Modification of the data sets

Darwin

The rainfall record from the Darwin Post Office is the longest data set for the Region, but has a gap of 5 years from February 1942 following the bombing of the Post Office on

19 February 1942; there is also a gap from 1962 to the present. Rainfall data are available from Darwin Airport (6.3 km NE of the Post Office) for the missing years, so the possibility of generating the missing Post Office data from the Airport data was investigated.

For the years 1948-49 to 1961-62 the mean ratio of the Wet season rainfall recorded at Darwin Post Office to that at Darwin Airport is 0.97 ± 0.10 and the Spearman rank coefficient is 0.83, suggesting good correlation between these data; there is no obvious trend nor any step change (Fig. 1). Therefore, the Airport data for 1941-42 to 1947-48 and for 1962-63 to 1985-86 were multiplied by 0.97 to give 'synthetic' Darwin Post Office data for these periods. These synthetic data were then combined with the existing data for Darwin Post Office, to give a data set covering 117 Wet seasons - with no gaps. This synthetic set (Fig. 2) has a long-term arithmetic mean of 1566 mm and a standard deviation of 292 mm and appears closer to a normal distribution than a log-normal distribution (see Fig. 3). A test of these data using the Filliben probability plot correlation coefficient (Filliben 1975) confirms that the distribution is slightly closer to normal than log-normal. The Filliben correlation coefficient for a normal distribution is 0.974 whereas for log-normal it is 0.957. As this synthetic Darwin data set is the largest available, it has been used for most of the statistical analysis which follows.

Oenpelli

The data set for Oenpelli has a number of missing values. Many of these are for months with a low expectation of rainfall and thus they have only a small influence on the Wet season totals. Nevertheless the missing data points have been estimated and a modified data set, 'Oenpelli interpolated', has been created. The values interpolated have been agreed with Ranger's hydrologist, to ensure that in any discussions with the Company the same Oenpelli database is used.

Pine Creek

The Pine Creek data have been extended by interpolating missing data points as had been done for the Oenpelli data.

Table 1 gives the mean, standard deviation and standard error for the various data sets.

Long-term cycles

All data have been plotted as cusum graphs against their individual long-term means so that changes in mean rainfall can be more easily seen than they would be on plots of the raw data (Fig. 4). (On a cusum graph a constant slope indicates an unchanging mean value. Where the long-term mean is used as the basis of the cusum graph, sections with a negative slope indicate periods with means less than the long-term mean and sections with a positive slope indicate periods with means more than the long-term mean.) For clarity only the Darwin, Oenpelli, Katherine and Pine Creek have been plotted; the other data sets however show the same general trends. From Fig. 4 it can be seen that from about 1920 to 1960 the rainfall throughout the Region was below the long-term average, and that from 1960 to the present (say 1985) all sites have had rainfall above the long-term average. It appears that there may now be a change to a lower average. Certainly the rainfall at Jabiru over the past few years has been lower. Short-term patterns are also discernible, superimposed on the long-term pattern of rainfall. Plotting the Darwin and Oenpelli data as correlograms (Brooks & Carruthers 1953) suggests short-term cycles of about 6 years and, possibly, long-term cycles of 15 to 20 years (Fig. 5). (A correlogram is a plot of serial correlation with lagged data. Thus if there is a regular cycle in the data, the correlation will be higher between data points separated by the length of one cycle.)

Plotting the Darwin rainfall data on a cusum graph and fitting slopes by eye (Fig. 6) reveals a series of cycles consisting of a group of years of fairly constant annual rainfall, followed by another group of years with a fairly constant but different annual rainfall. Changes in means occurred about 1898, 1915, 1923, 1957 and 1966 (and possibly 1984). The periods of fairly constant annual rainfall range in duration from about 5 years to 30 years. It appears from the cusum graph that, since all the positive slopes are similar and the negative slopes are also similar, the annual rainfall pattern is bi-modal - alternating periods of low rainfall and high rainfall with all the low periods having roughly the same average and all the high periods also having a common average. The drier periods have average annual rainfalls of around 1380 mm and the wetter periods have average annual rainfalls of about 1660 mm; most of these periods have annual rainfall significantly different from the long-term average (see Table 2).

If these patterns are typical of the NT monsoonal climate, it illustrates the difficulty in making predictions for the next 20 or 30 years at Jabiru. The long-term average may not be useful and the shorter term high or low averages would only be useful if the pattern were sufficiently regular to be predictable. All that can be said is that up to about 1984 Darwin has had about 20 years at the higher average (1681 mm, S.D. 289 mm) and since that date appears to be changing to a lower average and that there is evidence of both short-term and longer term cycles. As these patterns appear to be common through the Region we could expect a lower average for the next few years and this may also be seen at Jabiru.

Distribution of annual rainfall

As indicated above, the Darwin data appear to be normally distributed. Examination of other regional data sets suggests that they are also as close to normal as to log-normal distribution (Vardavas 1990). This is in agreement with the finding of Pittock (Pittock 1975) that, except for the more arid region, variation in Australian annual rainfall generally conforms to approximately normal distribution; the statement by Gani (1975) that '.. there is evidence to indicate that for high precipitation, monthly rainfall observations follow the normal distribution, while for low precipitation the distribution is log-normal'; and the World Meteorological Organisation (1983) who state that annual rainfall frequency distributions approach normal as the period of observations increases.

Using a normal distribution, the 10% probability of exceedance rainfall for the Darwin data is 1940 mm. Although the evidence is in favour of a normal distribution, the Log Pearson distribution is so widely used in meteorological analysis that it was decided to check whether the assumption of a Log Pearson distribution would give a significantly different prediction of the 10% probability of exceedance rainfall. Using a Log Pearson type III distribution the mean is 1568 mm and the 10% probability of exceedance rainfall becomes 1938 mm (Table 3). It can be seen that they are almost identical.

As the Darwin data are the longest reliable data set that we have, based on this analysis and the publications quoted above it is recommended that predictions of annual exceedance rainfall for Jabiru are calculated assuming a normal distribution. It may however be necessary to take account of the small number of data points when making these calculations.

Rainfall pattern by month

If, as the total annual rainfall increases, the normalised curve of cumulative rainfall by month had less scatter between years, then it would be appropriate to use normalised data based only on the wetter years to model the rainfall within a 1-in-10 rainfall year. In order to test this hypothesis, normalised cumulative data were generated for the 10 wettest and 10 driest years in Darwin (Table 4) (Fig. 7). The hypothesis is not supported by these data, the shape of the curve being substantially independent of the total rainfall. In fact there is somewhat greater scatter between years for the 10 wettest years due to the influence of cyclones in these years. Average normalised data were also generated from the Darwin, Oenpelli and Jabiru data (Table 4) and the shape of the normalised curve is essentially the same for all three sites (Fig. 8).

It has also been suggested that years with very high total rainfall could have (almost) all of that rainfall in one month, and that planning and regulation should take account of this. Neither the normalised data, nor the data presented on Fig. 9 - showing the relationship between the number of months having a rainfall greater than 100 mm and the total rainfall for the year - support this suggestion. High rainfall years result from rain spread over several months, not from one extremely wet month.

Predictions within the year

As indicated in the Introduction, an essential feature of the trigger mechanism is that it should be capable of predicting before the end of the Wet whether it will in fact be a 1-in-10 Wet. This is because from an environmental viewpoint the best time to release water is fairly early in the Wet when the maximum dilution and dispersion of contaminants can be expected. Clearly any such prediction will be subject to error and it is desirable to calculate the probability of predicting a 1-in-10 Wet in a year which eventually has a less than 1-in-10 rainfall. To improve the statistics of this calculation the largest available rainfall data base, i.e. Darwin, was used.

In order to produce a model to predict the Wet-year rainfall before the end of the Wet, the monthly data for Darwin were normalised, in turn, to the rainfall at the end of January, February, March and April. The ratio between the year-end total and the normalisation month was then plotted as a cumulative frequency graph (Fig. 10) (equivalent to a probability plot). These ratios are not normally distributed (as there is a defined lower value of 1). Consequently, the ratios corresponding to particular confidence levels (probability) must be read from the figure rather than calculated from an assumed data distribution. For convenience, interpolated ratios corresponding to selected levels of confidence are given in Table 5. Although these ratios are based on Darwin data, because of the common rainfall pattern in the Region, they can be used to predict the minimum expected total rainfall, from the actual rainfall to a particular date, for other weather stations in the Region. For example, from Table 5, one can have 90% confidence that the total rainfall will be at least 1.5 times the rainfall to the end of January, and there is a 35% chance that it could be more than twice the rainfall to the end of January.

4 EXTENDING THE JABIRU DATA

The rainfall data for Jabiru cover too short a period for satisfactory statistical analysis. If it were possible to extend the actual Jabiru data by using data from other weather stations with longer records, thus creating a synthetic set of Jabiru rainfall data, then a better statistical analysis would be possible. The examination of the regional data above indicates general similarities in the rainfall patterns throughout the region, suggesting that it may be reasonable to create a synthetic Jabiru data set by comparison with another regional weather station. The question is, which would be the best station to use.

It is common meteorological practice to calculate missing daily or monthly rainfall data by interpolation between the results from rain gauges that are similarly situated and fairly closely spaced. The problem here is to generate annual synthetic rainfall data using data from rain gauges that are many kilometers apart. For this to be valid the compared stations should have similar topography and be similar distances from the sea. One might expect that there would be similarities between Darwin, Jabiru and Oenpelli as they all experience a monsoonal climate, however, while the topography of Jabiru and Oenpelli are similar, that of Darwin is different to Jabiru. Katherine and Pine Creek being further inland will be slightly less affected by monsoons. The topography and distance from the sea at Daly River are similar to those at Jabiru. Thus one might expect either Oenpelli or Daly River to be the best comparative station.

Methods of comparison that are available include comparing the short-term Jabiru mean values with both the long-term and the coincident means for the other sites; comparing the pattern of the Jabiru data with the pattern at the other sites by ranking and by cusum methods; plotting the Jabiru data against the coincident data from other sites (simple regression); the methods of annual ratios and cumulative deviations (Craddock 1979); and the use of the two-station comparison method recommended by USGS (1982) for annual series discharge data. If any of these comparisons appear promising then they could be used as the basis from which to choose the best comparison station and generate a synthetic long-term data set for Jabiru.

There are three problems: the choice of the best comparison station, the choice of the best method of calculating synthetic Jabiru data and the choice of the best length of record to use for the calculations.

Comparison of Jabiru data with data from other stations

USGS Method

The USGS two-station comparison was recommended by the Bureau of Meteorology (private comm. 1988) but with the following caveat: 'However, it should be remembered that this method assumes a non-serially correlated data set and thus the serial correlation of annual rainfall should be examined before the method is applied (before any frequency distribution is fitted for that matter)'. Another reservation about this method is that it was developed for flood prediction and may not be appropriate for rainfall prediction. As can be seen from the cusum plots and correlograms (Figs 4 & 5) the data sets do appear to be serially related, as would be expected.

Using the USGS two-station comparison for Jabiru and Oenpelli, the correlation coefficient meets the criteria that indicate that improved values of the mean and standard deviation can be achieved by this method. Using this method the adjusted Jabiru mean, based on Oenpelli, becomes 1388 mm and the equivalent years of record for the adjusted mean is 22.6 years. This means that, although the data set covers 77 years, the degree of reliability of statistical calculations based on it is only that attainable from a random data set covering 23 years.

The correlation coefficient between Jabiru and Darwin does not meet the criteria for using the USGS method.

Comparison of means

Table 1 shows the mean rainfall with its standard deviation and standard error of the various data sets available. It can be seen that the Jabiru mean and standard deviation are closest to the long-term Darwin PO data. Unfortunately, however, there are no Darwin PO data for the years for which the Jabiru data are available. For the years for which Jabiru data are available, the mean of the Darwin Airport data is considerably higher than that for Jabiru while the mean of the Oenpelli data is slightly higher.

Simple regression

Table 6 shows the linear correlation coefficients between Jabiru rainfall data and that from other sites. Figure 11 shows the correlation between the Jabiru data and the coincident Oenpelli and Darwin data respectively. It can be seen that the correlation with Darwin is poor and that while the correlation with Oenpelli is better it is not particularly good.

Ranking methods

Table 6 shows the Spearman rank coefficients between Jabiru data and the other data. The Spearman rank coefficient between Jabiru and both Nabarlek and Oenpelli is 0.67, suggesting that the Jabiru data may fit the Nabarlek and Oenpelli data better than any of the other data.

Cusum methods

Figure 12 shows cusum comparisons between Jabiru data and the other data. The number of data points for Jabiru are perhaps too few for this method to be really useful. Changes in the slope of a cusum graph indicate changes in the mean value. Where for two stations, such changes occur in synchronism, the changes can be assumed to be due to general climate changes. Any changes of mean occurring in only one of the two stations indicate that that station should not be used as a comparison station, as such changes in the mean imply a change in the station conditions such as, for example, relocation of the rain gauge. In general however it can be seen that changes of mean do occur at the same time for all stations except Pine Creek.

Cumulative deviations and annual ratios

Figure 13 shows comparison between Jabiru data and the other data using the method of cumulative deviations (a form of the widely-used double mass graph in which cumulative rainfall for one station is compared with the cumulative rainfall for surrounding stations) as proposed by Craddock (1979). Figure 14 compares the same data using the method of annual ratios. The value of these methods is that they show step changes due, for example, to changing the position of one rain gauge, or steady changes due, for example, to the growth of trees around one of the stations. If either of these effects are visible then the stations concerned are not suitable comparison stations. For the cumulative deviation graphs, there is a suggestion of a discontinuity between Jabiru and all other stations, except Nabarlek, occurring about 1978. This suggests that the rain gauge may have been moved or a new building put up at about this time. On the basis of the annual ratio graphs, Daly River would be rejected as a comparison station. On the basis of the cumulative deviation graphs, Katherine should probably be rejected as a comparative station.

Synthetic Jabiru data

Table 7 summarises the comparisons between Jabiru and the other stations. For each numerical comparison method the other stations are ranked from 1 to 6 according to their closeness of fit to the Jabiru data; and for tests for suitability as comparison stations classified as 'Yes' or 'No'. It can be seen from this table that Oenpelli is the station most similar to Jabiru and Nabarlek is the next most similar. Since the record for Nabarlek is so short it cannot be used to modify the Jabiru data (however, if in future an extended data set were needed for Nabarlek, this analysis indicates that it could be obtained from the Jabiru and Oenpelli data).

Thus, as might have been expected Oenpelli is the best available comparative station for Jabiru.

The choice of a method of calculating synthetic Jabiru data is between the USGS method and simple ratio correction. The USGS method is the more complex, and may not apply since the data do appear to be serially related, thus simple ratio correction seems appropriate.

Synthetic Jabiru data sets have been created by using simple ratios to combine the actual Jabiru data with each of the regional data sets in turn. The resultant means, standard deviations and standard errors are given in Table 8.

Since, as indicated above, the Jabiru and Oenpelli data are the most similar, it is the synthetic Jabiru data set based on the Oenpelli data by simple ratio that has been used for further analysis.

Design basis value of 1-in-10 exceedance value for Jabiru

Many authors have demonstrated cyclic patterns in annual rainfall statistics (Lamb 1982, Pittock 1975, Mandelbrot & Wallis 1968, Cornish 1977, Graham & White 1988, Stahle et al. 1988, Doran & McGilchrist 1983) and this report confirms the presence of such patterns in the regional rainfall. The cyclic pattern means that there does not appear to be any evidence that very long-term data sets will provide better predictions for near future rainfall patterns than will relatively short-term data sets. The World Meteorological Organisation (1967) supports the use of 30-year means ('normals'), updated each decade for the study of climate. Lamb & Changnon (1981) have suggested that 5-year normals may be the best predictors for rainfall in the short-term future and Sabin & Shulman (1985) found the 'most efficient' normal to be between 35 and 40 years. On this basis it seems reasonable to use a period of 30 years for analysing the Jabiru data.

Table 9 and Fig. 15 show the result of analysing the synthetic Jabiru data for both 30 years and the full 77 years and assuming normal or Log-Pearson distributions. It can be seen that up to the 10-year return frequency the results are very similar, whether normal or Log-Pearson distribution is assumed, as was found for the Darwin data. There is a difference between the 30-year Log-Pearson calculation and the other values for the longer return periods because this calculation is strongly influenced by the skew of the data and is thus less reliable for small data sets.

If the whole of this synthetic Jabiru set is used, the mean annual rainfall is 1350 mm and (assuming a normal distribution) the 1-in-10 exceedance rainfall is 1750 mm. However, even this data set is not large enough to justify using the normal distribution's probability values. The set should be regarded as a sample from a normal distribution and probability calculated using the Student's t-statistic: in that case the 1-in-10 exceedence rainfall becomes 1800 mm.

If, on the other hand, only the more recent 30 years of synthetic data are used then the mean annual rainfall becomes 1500 mm and the 1-in-10 exceedance rainfall becomes 1850 mm or 1900 if the Student's t-statistic is used. (Note: in order not to suggest that such analyses as these produce results of great precision these values are rounded to 50 mm.)

From this analysis of the synthetic Jabiru data it is recommended that for trigger mechanism design purposes a 1-in-10 exceedance rainfall of 1850 mm be used.

5 TRIGGER MECHANISM

Selection of trigger values

Trigger values need to be chosen for any date in the Wet such that cumulative rainfall in excess of the trigger value indicates with some level of confidence that the year will be a 1-in-10 rainfall year.

Using the chosen design value for Jabiru of 1850 mm for the '1-in-10' total rainfall for the Wet year, and the normalised average cumulative rain distribution based on Darwin data (Table 4), cumulative rainfall values can be calculated for any date in the design basis '1-in-10' wet year. These values, being averages, represent a 50% probability that the rainfall by the end of the Wet season will reach or exceed the '1-in-10' rainfall of 1850 mm. The uncertainties associated with these values, particularly early in the Wet season, are such that there is also a reasonably high probability that a much lower end-of-season rainfall will occur. In order to reduce the chance of releasing water in a year which eventually turns out to have much less than a '1-in-10' rainfall, these calculated design values need to be increased, using values from Table 5, for the earlier dates in the Wet season to give increased confidence that a '1-in-10' rainfall will actually occur. Trigger values calculated in this way are given in Table 10. The confidence level for the selected 1 February value is approximately 85% - that is, if 1220 mm of rain has fallen by 1 February then for 85 out of 100 such years the total rainfall by the end of the Wet season would exceed 1850 mm. Towards the end of the Wet season, when the cumulative rainfall is approaching more and more closely the year's final rainfall, a relaxation in the level of confidence for predicting the rainfall yet to come is acceptable, since in any year considered suitable for release, the actual accumulated rainfall will by then be sufficiently high that a high rainfall year is guaranteed. For example, the 15 March trigger level is 1580 mm which gives a 60% confidence that the rainfall will be equal or greater than the '1-in-10' rainfall and an 80% confidence that the rainfall will be between 1750 mm and 2070 mm (see Table 11). This is illustrated in Fig. 16.

Test of trigger mechanism

Applying the trigger values in Table 10 to the actual Jabiru daily record for the available 16 years (71-72 to 86-87), the trigger values were reached in 3 of these years. Two of these 3 years were the only two whose annual rainfall was above the '1-in-10' value of 1850 mm (2223 mm and 1895 mm). In the third, year the trigger level was reached on only two successive days in March and the eventual total rainfall was 1627 mm (which represents a return frequency of about 1-in-4 years). A definition of the minimum period for which the cumulative rainfall must exceed the trigger value might need to be considered in drafting any release authorisation to avoid releases being approved as a result of such short-term excursions.

6 CONCLUSIONS

1. There is a similarity in the pattern of annual rainfall throughout the Region, with the 20 years up to 1985 being above the long-term average for all sites.

2. All the regional rainfall data fit a normal distribution quite well and marginally better than they fit a log-normal distribution, thus a normal distribution has been assumed for predicting the 1-in-10 rainfall exceedance.

3. The pattern of normalised annual rainfall does not depend significantly on the total rainfall for the year, and there is no evidence that single events have in the past represented a major portion of the annual rainfall. Thus, at any time during a year, a normalised curve can be used to make reasonable predictions of total rainfall by the end of the year.

4. A probability curve of the ratio between rainfall at a given date and rainfall at the year end, has been produced from actual data and can be used with a normalised curve to set levels of confidence of predicted rainfall being exceeded.

5. The Jabiru rainfall data appear to match the Oenpelli data better than they match any of the other regional data examined.

6. If only the Jabiru data (1971-1987) are used and a normal distribution assumed (without adjustment for the small size of the data set) the 1-in-10 exceedance rainfall is about 1900 mm. If, however, synthetic data based on the Oenpelli data are used (giving 77 years of data), a value of about 1750 mm would be appropriate. If only the most recent 30 years of the synthetic data are used the value becomes about 1850 mm. On the basis that the actual data set is small, that the most recent data are more relevant than those gathered further in the past, and that there is some uncertainty about the future on account of the greenhouse effect, it is recommended that the 30-year 1-in-10 rainfall value of 1850 mm be used for design purposes.

7. Using the 30-year 1-in-10 rainfall, the normalised distribution of rainfall and the probability curve of rainfall ratio, a set of 'trigger' values of rainfall (shown in Fig. 17) is recommended for deciding when the Commonwealth Government's frequency of release criterion is met.

8. Due to the possibility of trends and cycles in the Wet season rainfall, these recommended values will need to be revised periodically. Annual revision would seem to be unnecessarily frequent, so revision at 5-year intervals is suggested.

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REFERENCES

Brooks, C.E.P. & Carruthers, N. (1953). Handbook of statistical methods in meteorology, HMSO, London.

Cornish, P.M. (1977). Changes in seasonal and annual rainfall in New South Wales. *Search* **8**, 38-40.

Craddock, J.M. (1979). Methods of comparing annual rainfall records for climatic purposes. *Weather* **34**, 332-346.

Craddock, J.M. (1981). Monitoring a changing climate series. *Journal of Climatology* **1**, 333-343.

Doran, D.G. & McGilchrist, C.A. (1983). On the detection of climate change, Institute of Engineers Australia, Hydrology and Water Research Symposium, 1983, National Conference Publication 83/13, pp. 113-117.

Filliben, J.J. (1975). Probability plot correlation coefficient test for normality. *Technometrics* 17(1), 111-117.

Gani, J. (1975). The use of statistics in climatological research. *Search* **6**, 504-508.

Graham, N.E. & White, W.B. (1988). The El Nino cycle: a natural oscillator of the Pacific Ocean - atmosphere system. *Science* **240**, 1293-1302.

Lamb, H.H. (1982). Climate, history and the modern world. Methuen, London.

Lamb, P.J. & Changnon, S.A. (1981). On the 'best' temperature and precipitation normals: the Illinois situation. *Journal of Applied Meteorology* **20**, 1383-1390.

Mandelbrot, B.B. & Wallis, J.R. (1968). Noah, Joseph and operational hydrology. *Water Resources Research* **4**, 909-918.

Pittock, A.B. (1975). Climate change and the patterns of variation in Australian rainfall. *Search* **6**, 498-504.

Sabin, T.E. & Shulman, H.D. (1985). A statistical evaluation of the efficiency of the climatic normal as a predictor. *Journal of Climatology* **5**, 63-77.

Stahle, D.W., Cleaveland, M.K. & Hehr J.G. (1988). North Carolina climate changes reconstructed from tree rings: AD 372 to 1985. *Science* **240**, 1517-1519.

Taylor, J.A. & Tulloch, D. (1985). Rainfall in the wet-dry tropics: extreme events at Darwin and similarities between years during the period 1870-1983 inclusive. *Aust. Journal of Ecology* **10**, 281-295.

USGS (1982). Interagency Advisory Committee on water data: guidelines for determining flood flow frequency. US Department of the Interior Geological Survey, Office of Water Data Co-ordination.

Vardavas, I.M. (in press). Annual rainfall statistics for stations in the Top End of Australia: normal and log-normal distribution analysis. Technical Memorandum 27, Office of the Supervising Scientist. AGPS, Canberra.

World Meteorological Organisation (1967). A note on climatological normals. Technical Note 84, Geneva.

World Meteorological Organisation (1983). Guide to climatological practice, Geneva.

Table 1. Long-term and short-term mean rainfall for various sites

Site	Long-term				Short-term (i.e. overlap with Jabiru)			
	Years	Mean	S.D.	S.E.	Years	Mean	S.D.	S.E.
Jabiru	-	-	-	-	1972-1987	1540	281	70
Darwin Airport	1942-1986	1658	332	50	1972-1986	1807	314	81
Darwin PO	1870-1961[a]	1542	283	30	-	-	-	-
Darwin[b]	1870-1986	1566	292	26	-	-	-	-
Oenpelli	1911-1987[c]	1412	266	36	1972-1987[d]	1584	288	96
Oenpelli 2[e]	1911-1987	1399	281	32	1972-1987	1572	249	62
Nabarlek	-	-	-	-	1980-1987	1506	232	82
Katherine	1873-1985	970	261	25	1972-1985	1115	245	65
Pine Creek[e]	1875-1986	1147	246	23	1972-1986	1210	328	85
Daly River	1885-1899) 1963-1983)	1246	329	55	1972-1983	1198	357	103

[a] Does not include data from 1941-42 to 1947-48
[b] Combination of Airport and Post Office data
[c] Only includes the 56 years without missing data
[d] Only includes the 9 years without missing data
[e] Includes interpolated data

Table 2. Average Darwin rainfall for wetter and drier periods

Year	Mean (mm)	S.D.	% Significance of difference from long-term mean
All years			
1870-1986	1566	292	-
Drier periods			
1899-1907	1368	344	90
1911-1915	1431	127	NS
1924-1930	1333	324	95
1935-1952	1402	235	95
1958-1966	1367	279	90
Wetter periods			
1870-1898	1611	218	90
1916-1923	1725	271	95
1967-1984	1647	291	90

Table 3. Return frequency and probability of exceedance based on Darwin data

Return frequency (years)	% Exceedance probabilty	Log Pearson	Normal
2	50	1568	1566
5	20	1819	1811
10	10	1938	1940
25	4	2089	2077
50	2	2175	2165
100	1	2251	2246

Table 4. Average normalised cumulative rainfall data

		Month									
		S	O	N	D	J	F	M	A	M	J
Darwin 117 years	Normalised rainfall	0.01	0.05	0.13	0.28	0.53	0.75	0.92	0.99	1.0	1.0
	% S.D.	148	69	37	29	20	13	10	6	3	0.5
Darwin 10 driest years	Normalised rainfall	0.00	0.05	0.16	0.32	0.53	0.80	0.96	1.0	1.0	1.0
	% S.D.	147	115	59	23	20	9	3	0.6	0.1	0.1
Darwin 10 wettest years	Normalised rainfall	0.01	0.05	0.11	0.26	0.52	0.73	0.92	0.98	0.99	0.99
	% S.D.	138	73	49	47	23	15	6	5	0.9	0.9
Jabiru 17 years	Normalised rainfall	0.01	0.03	0.13	0.28	0.51	0.73	0.94	0.99	1.0	1.0
	% S.D.	264	82	40	27	20	15	5	1	1	0.8
Oenpelli 77 years	Normalised rainfall	0.00	0.02	0.10	0.26	0.50	0.73	0.93	0.99	1.0	1.0
	% S.D.	195	125	58	37	20	12	7	3	0.9	0.6

Table 5. Ratio between rainfall to end of month and minimum total rainfall

% Confidence[a]	January	February	March
95	1.41	1.11	1.01
90	1.49	1.13	1.01
85	1.54	1.17	1.02
80	1.59	1.22	1.03
75	1.64	1.24	1.03
70	1.70	1.25	1.04
65	1.75	1.26	1.04
60	1.77	1.30	1.05
55	1.81	1.31	1.05
50	1.85	1.34	1.06
45	1.89	1.35	1.07
40	1.96	1.36	1.08
35	2.02	1.39	1.09
30	2.09	1.43	1.10
25	2.14	1.45	1.11
20	2.20	1.49	1.13
15	2.31	1.54	1.16
10	2.43	1.57	1.18
5	2.88	1.68	1.22

[a] Confidence that the ratio between end of month rainfall and total rainfall will be at least that given in the table

Table 6. Comparison between Jabiru and other stations

Site	Linear correlation coefficient	Spearman rank coefficient	Annual ratio
Darwin Airport	0.25	0.18	1.18
Oenpelli	0.69	0.67	1.03
Katherine	0.53	0.36	0.71
Nabarlek	0.66	0.67	1.00
Pine Creek	0.34	0.18	0.84
Daly River	0.39	0.06	0.78

Table 7. Summary of comparisons between Jabiru and other stations

Station	Mean	Regression	Spearman rank	Annual ratio	Cusum	Cumulative deviations
Darwin	3	5	4	Yes	Yes	Yes(?)
Oenpelli	1	1	1	Yes	Yes	Yes(?)
Nabarlek	2	2	1	Yes	Yes	Yes
Katherine	6	3	3	Yes	Yes	No
Pine Creek	4	-	6	Yes	No	Yes(?)
Daly River	5	4	5	No	Yes	Yes

Table 8. Synthetic data sets calculated using simple ratios

Synthetic Jabiru data, based on:	Oenpelli	Katherine	Pine Creek	Darwin
Mean (mm)	1372	1339	1617	1410
S.D.	282	354	328	267
S.E.	32	33	31	25
1-in-10 rainfall (mm)	1733	1792	2037	1752

Table 9. Return frequency rainfall for the Jabiru synthetic data

	Rainfall (mm)			
Return frequency (years)	Assuming normal distribution		Assuming Log Pearson distribution	
	30-y set	77-y set	30-y set	77-y set
2	1478	1372	1387	1371
5	1716	1609	1673	1612
10	1840	1733	1884	1734
25	1974	1865	2176	1887
50	2062	1953	2413	1941
100	2138	2029	2648	2011

Table 10. Trigger values to indicate a 1-in-10 year

Date	Rainfall (mm)
1 February	1220
14 February	1330
1 March	1460
15 March	1580

In order to facilitate day-to-day operation, the above values may be replaced by the expression:

$R_c = 1220 + 8.5n$

Where R_c = minimum cumulative rainfall (from 1 September) which would allow releases to be approved, subject to compliance with other regulatory criteria on dilution, quality and flow rates.

n = number of days after 1 February in that Wet season.

Table 11. Range of expected rainfalls corresponding to trigger values

	End Jan	Mid-Feb	End Feb	Mid-March
Trigger value	1220	1330	1460	1580
Confidence limit				
20%	1952	1862	1781	1754
50%	2257	2101	1942	1896
80%	2684	2461	2175	2070
Return years	19 to > 100	10 to > 100	7 to > 100	6 to 50

i.e. If cumulative rainfall by mid-February is 1330 mm there is a 20% chance that the year's rainfall will exceed 2461 mm (greater than a 1-in-100 year rainfall) and a 20% chance that it will be less than 1862 mm (a 1-in-10 year rainfall).

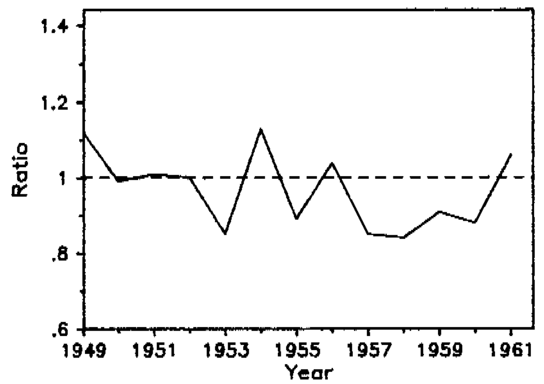

Figure 1. Ratio of rainfall at Darwin Post Office to rainfall at the Airport between 1948-49 and 1961-62

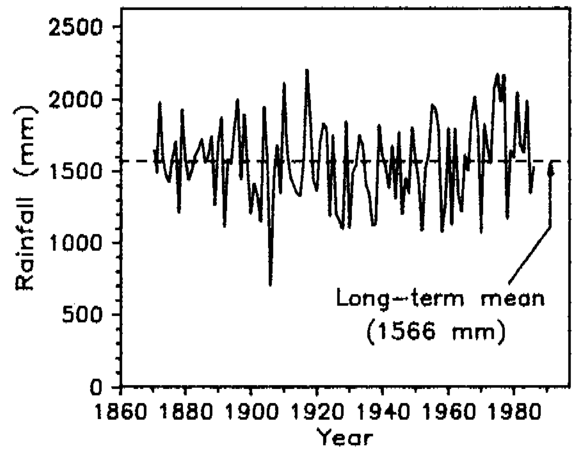

Figure 2. Yearly rainfall for Darwin between 1869-70 and 1985-86

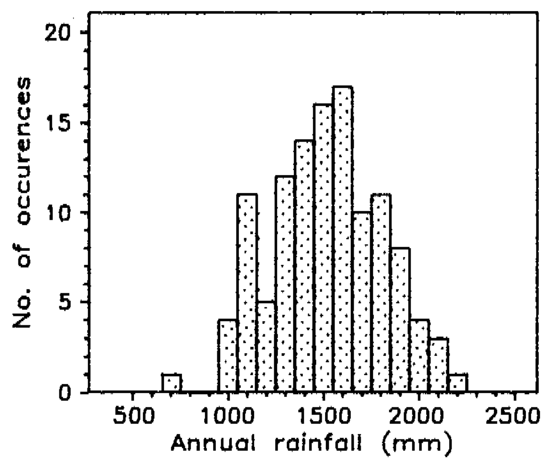

Figure 3. Frequency distribution of Darwin rainfall

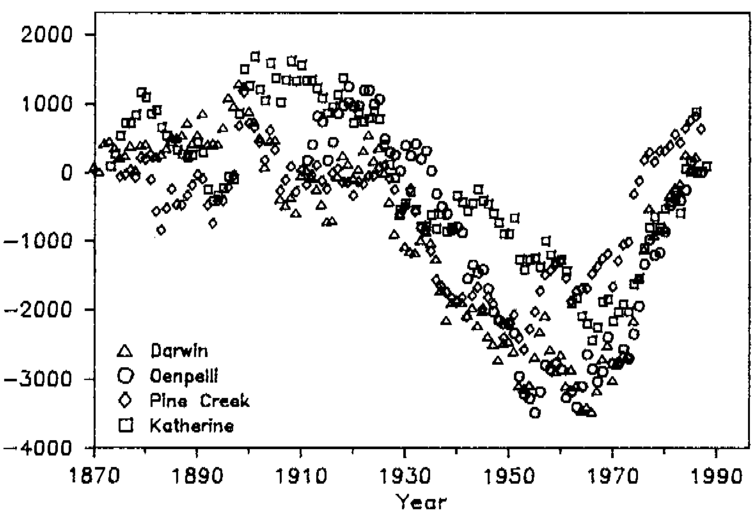

Figure 4. Cusum plots of rainfall data from 4 sites in the Region

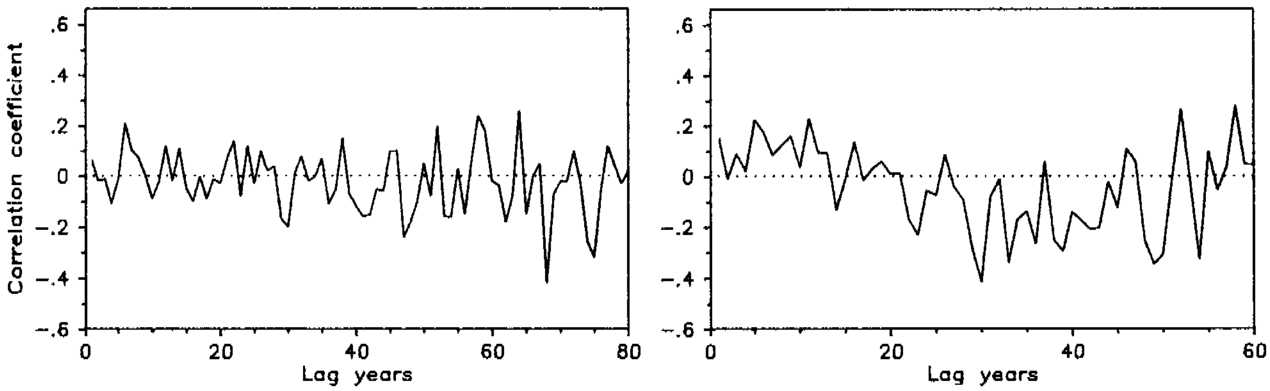

Figure 5. Correlogram of (a) Darwin and (b) Oenpelli rainfall data

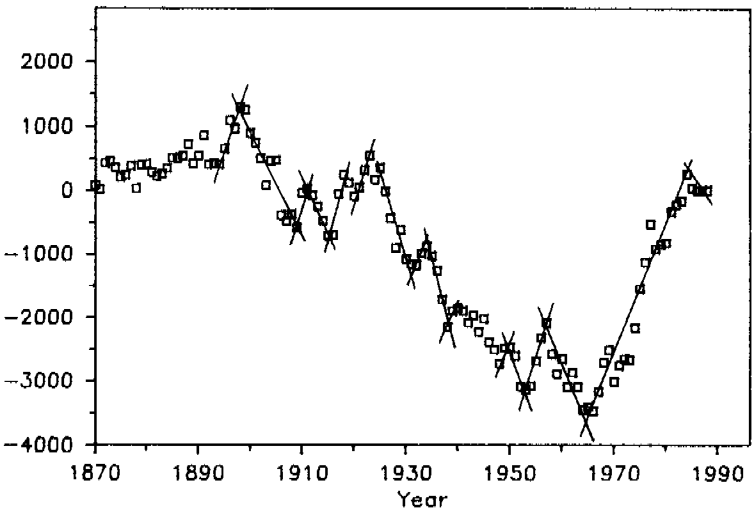

Figure 6. Cusum plot of Darwin rainfall data. Lines have been fitted by eye.

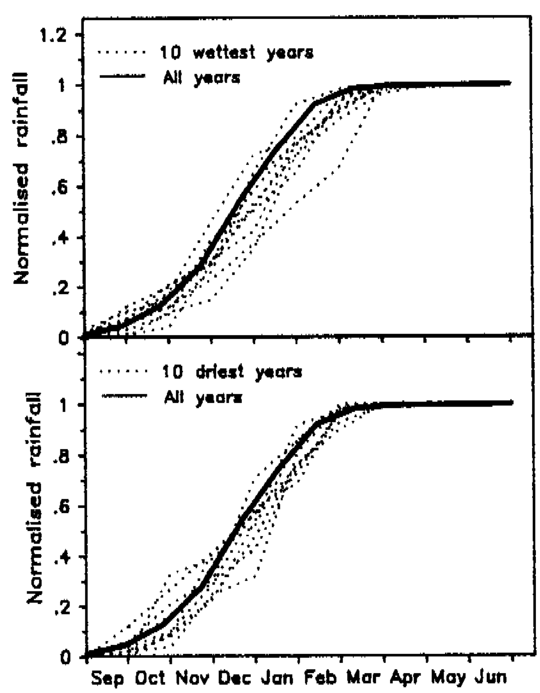

Figure 7. Normalised cumulative rainfall for (a) the 10 wettest years, and (b) the 10 driest years compared to the average for all years in Darwin

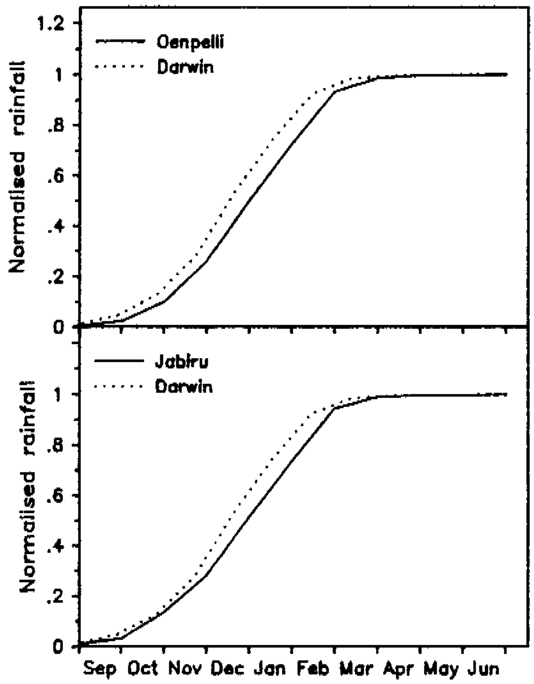

Figure 8. Normalised cumulative rainfall for Oenpelli and Jabiru compared to Darwin

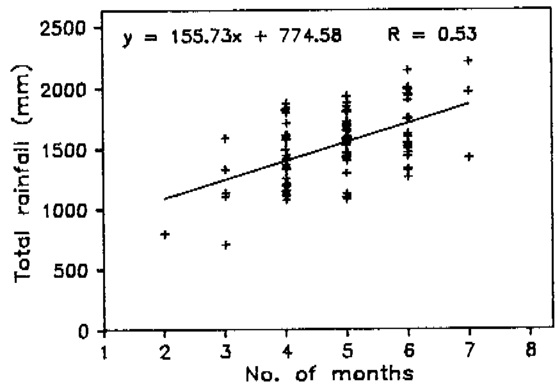

Figure 9. Relationship between total rainfall and the number of months with more than 100 mm rainfall

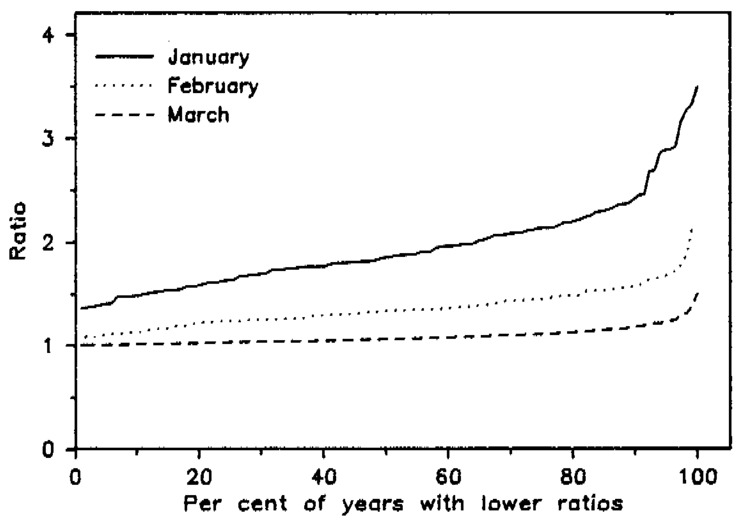

Figure 10. Ratio between cumulative rainfall to the end of the month (for January, February and March) and the total yearly rainfall

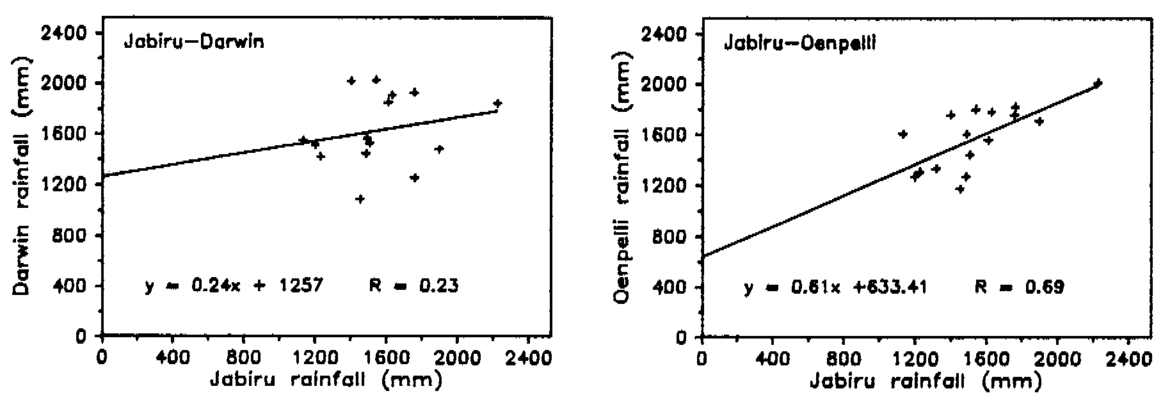

Figure 11. Linear regression between Jabiru and (a) Darwin, and (b) Oenpelli annual rainfall

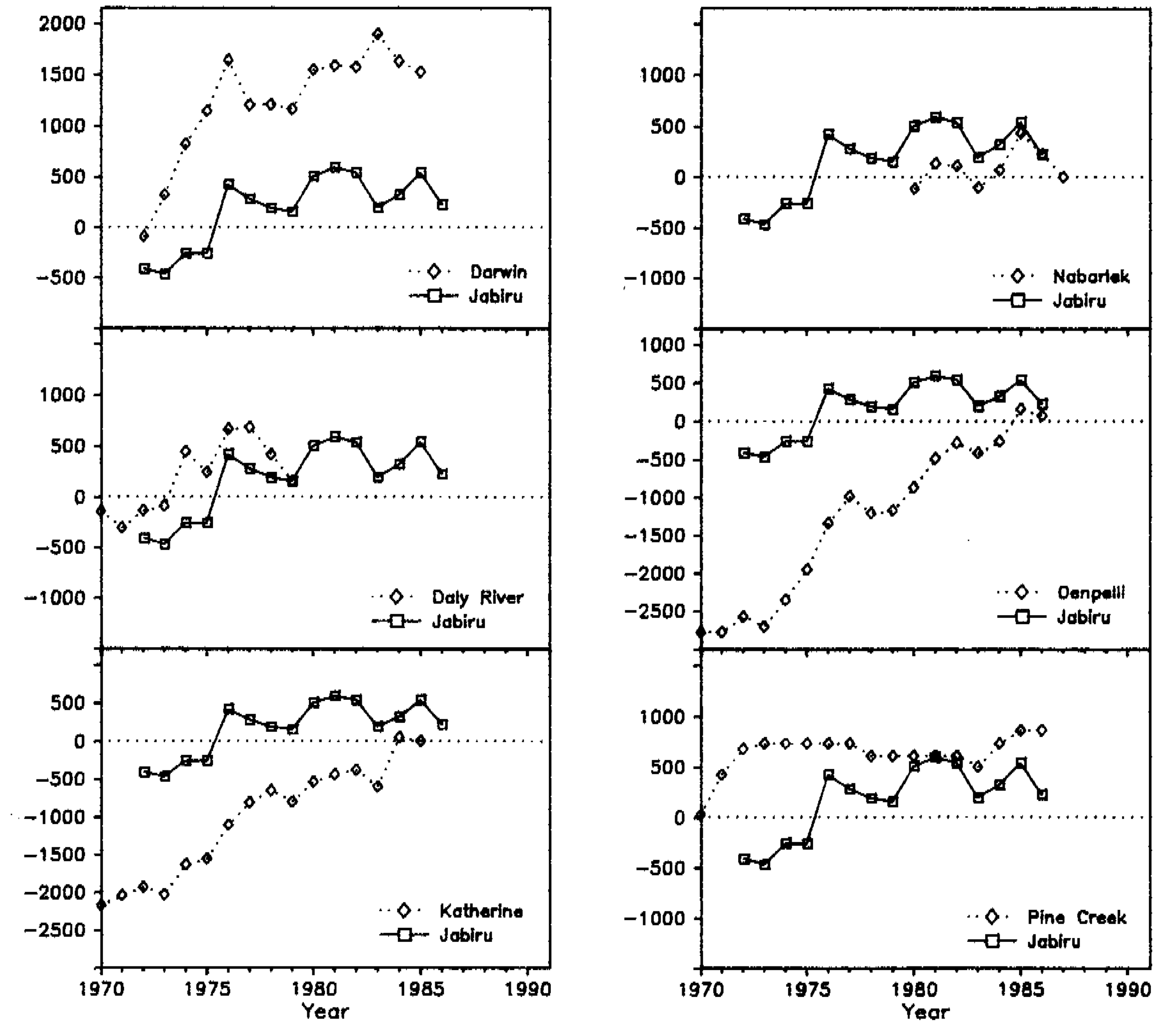

Figure 12. Comparison between the rainfall cusum plot for Jabiru and that for (a) Darwin, (b) Daly River, (c) Katherine, (d) Nabarlek, (e) Oenpelli, and (f) Pine Creek

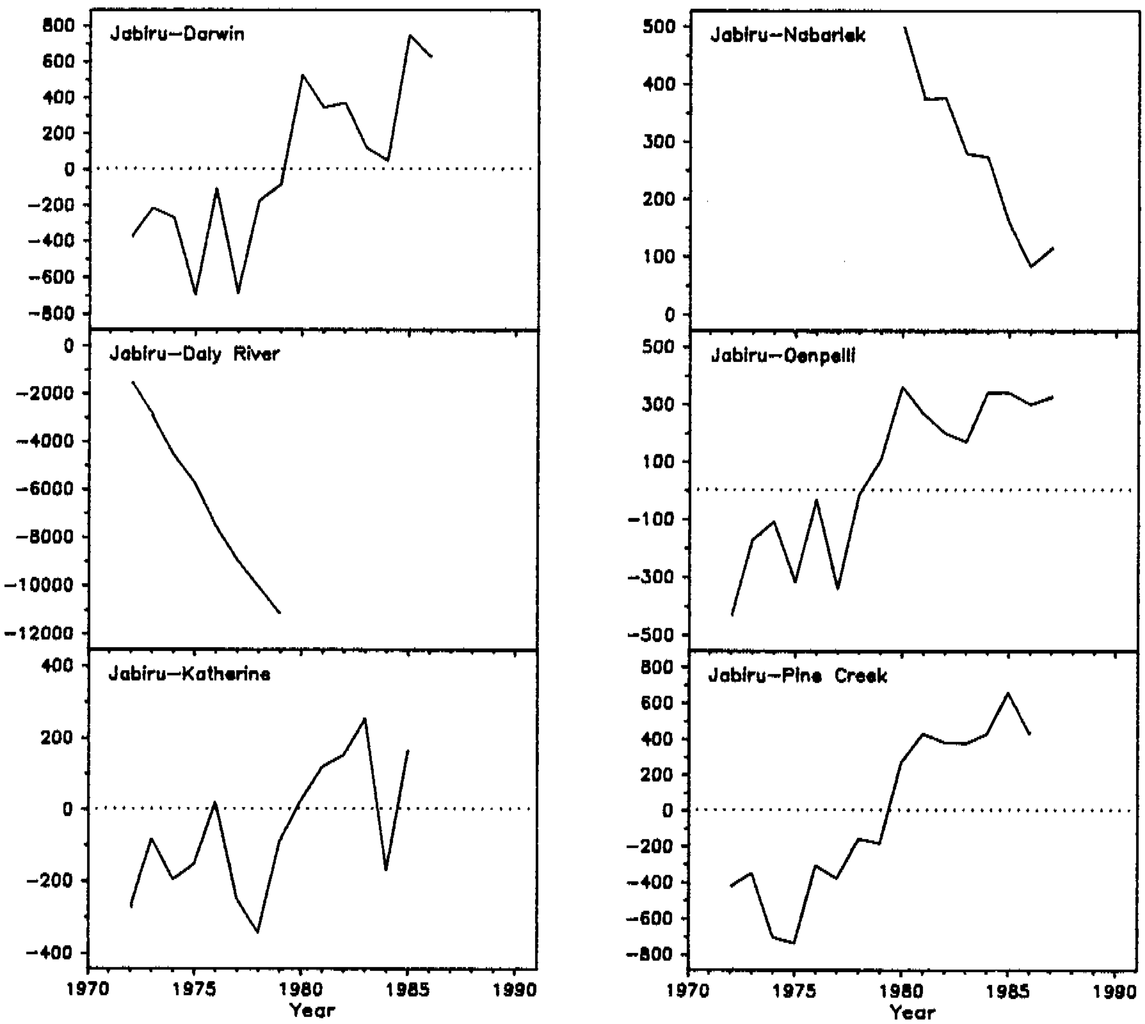

Figure 13. Cumulative deviations between Jabiru and (a) Darwin, (b) Daly River, (c) Katherine, (d) Nabarlek, (e) Oenpelli, and (f) Pine Creek

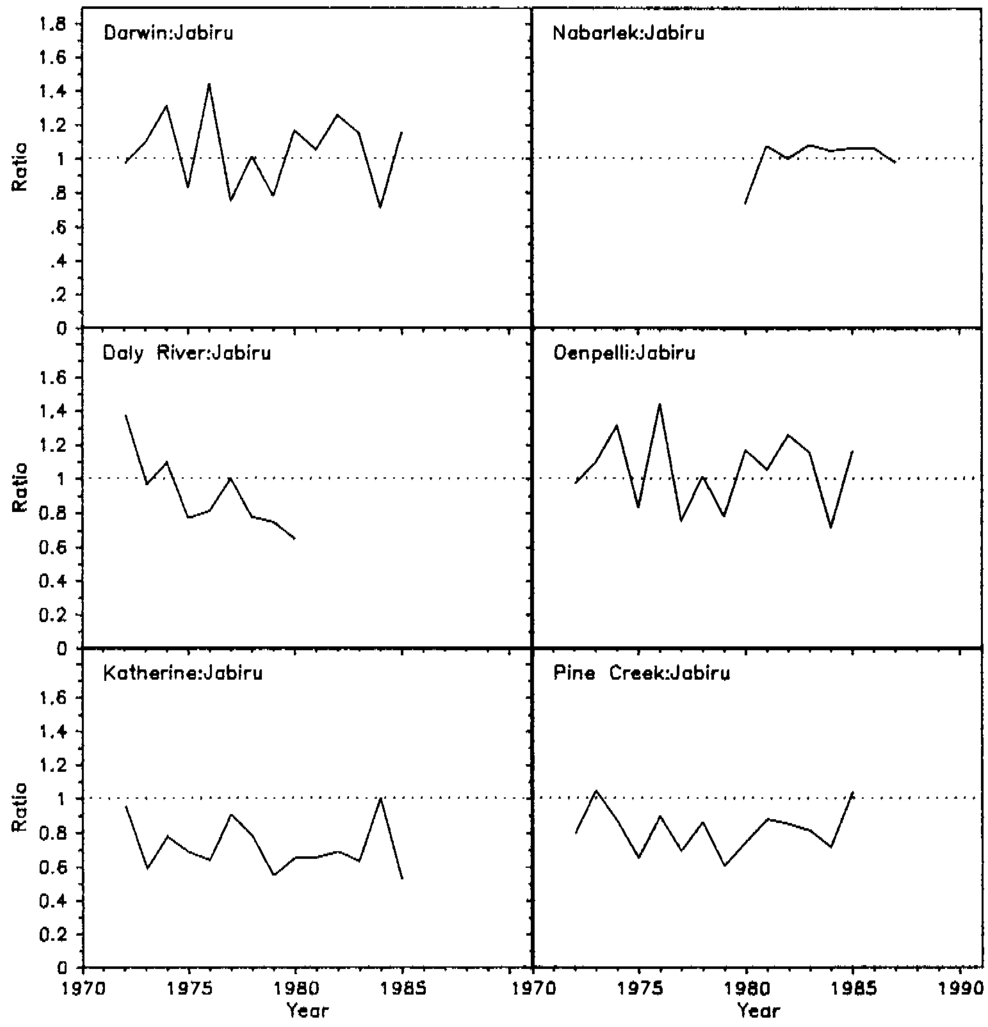

Figure 14. Annual ratios between Jabiru and (a) Darwin, (b) Daly River, (c) Katherine, (d) Nabarlek, (e) Oenpelli, and (f) Pine Creek

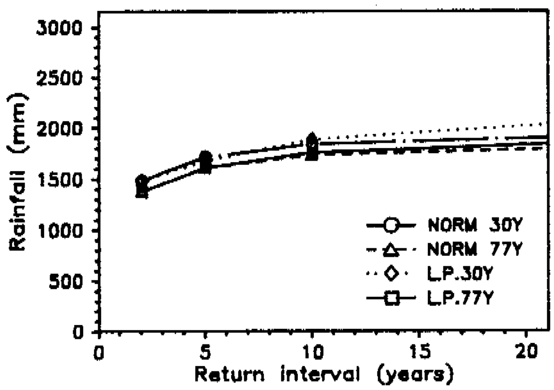

Figure 15. Return frequency of Jabiru annual rainfall based on normal or Log-Pearson distributions using 30 or 77 years of data

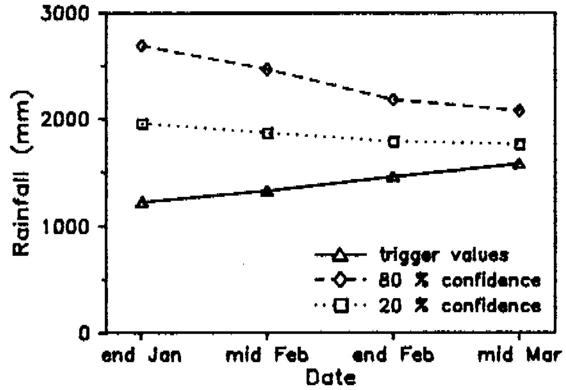

Figure 16. Range of annual rainfall values implied by the selected trigger values. (20% confidence that it will be greater than to 80% confidence that it will be less than the plotted value)

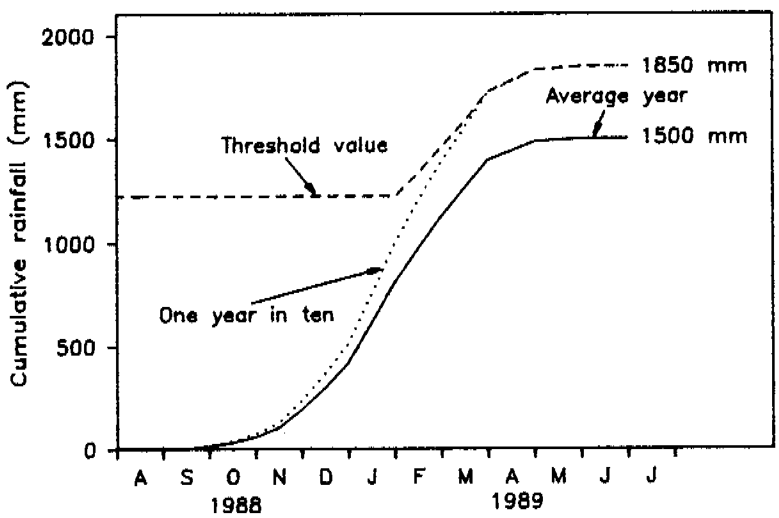

Figure 17. Comparison between the trigger values and the cumulative rainfall in an average year and in a 1-in-10 year

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