



INTERNATIONAL HYDROLOGICAL PROGRAMME



Droughts in small coral islands: Case study, South Tarawa, Kiribati

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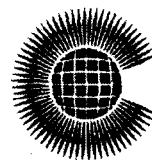
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Summary

Droughts are frequent events in small coral islands and small island nations across the Indian and Pacific oceans. Many of these are correlated with El Niño-La Niña events. Limited water storages on small islands mean that domestic water supplies are severely threatened by these dry periods. In this work, meteorological or climatological drought is used to define drought relevant to domestic water supplies. South Tarawa, the capital of the Republic of Kiribati is used as a case study. It is argued that drought depends on the characteristics of the water sources. Three sources of water are identified, rain tanks, domestic water wells and reticulated water supplied from large freshwater lenses and these need to be treated separately for drought declaration.

Since the key components of the water balance are not known for rain tanks or domestic wells, a method of ranking rainfalls totalled over different periods is needed to identify and rank droughts. The Palmer Drought Index, the Standardised Precipitation Index, the Decile Method, and the Rainfall Depreciation Method are all examined critically. Here the decile method is explored and droughts are defined as periods when the rainfall drops below the 10 percentile level of all rainfalls for the totalling period in question. For Tarawa, it is suggested for meteorological drought that the appropriate totalling periods are: 4 to 6 months for rain tanks; 12 to 30 months for domestic wells; and 60 to 120 months for large freshwater lenses.

Using this method of ranking dry periods, it was found that severe droughts for rainwater tanks in South Tarawa occur on average approximately every 4 to 5 years and have an average duration of 5 to 6 months. For domestic wells, severe droughts occur on average 5.5 to 6 years and last, on average, 7 to 8 months. Because these events are frequent, policy can be developed to address response to drought. For the large freshwater lenses, drier periods occur on average every 6 years and last on average about 12 months. However, significant recharge of large freshwater lenses still occurs in these drier periods because of the long period over which rainfall is summed and the small variation in rainfalls over these long periods.

It was found that the Standardised Precipitation Index and the Rainfall Depreciation Method gave identical results to the Decile Method. The greater simplicity of the decile method and the ease of understanding of its rainfall rankings suggests that it has advantages over other methods. The impact of seasonal variation in rainfall on rainfall rankings was examined. It was found for the case study that seasonality has insignificant impact on rainfall rankings for rainfall periods of 12 months or longer. For periods of less than 12 months, while an effect was discernible it did not affect the identification of drought periods. For shorter duration rainfalls, in regions with marked seasonal rainfalls, seasonality will need to be taken into account.

The correlation between ranked rainfalls deficits and the negative Southern Oscillation Index (SOI) over a range of rainfall periods was considered. It was found that the correlation increased from 1 monthly data (0.52) to a maximum at 12 monthly data (0.82) then decreased for longer periods. The reason for this decrease is not apparent. It was also found from the maximum correlation for totalling periods of 12 months or more that rainfall preceded the negative SOI by between 1 and 5 months.

It is suggested that prediction of the onset of severe dry times be made when the accumulated rainfall first drops below the 40 percentile level. For rain tanks and domestic wells this will result in 1.3 to 2 times as many warnings as severe droughts, but all severe droughts will be predicted. The average time lag between predictions using the 40 percentile and the onset of severe drought (accumulated rainfall below the 10 percentile) for these rainwater tanks was 3 to 4 months and for domestic wells was found to be 6 to 10 months. For both these sources of water, the warning period could be as little as one month. For large freshwater lenses, the 40 percentile level over-predicts drier times by about 1.5 times with an average time between prediction and the onset of the drier period of between 12 and 26 months. Most drought periods were found to have a similar pattern with drought periods lasting 15 to 18 months. The 1954-7 drought was a notable exception and lasted 34 months.

The rainfall analyses were used to rank the severity of the 1998/9 drought in South Tarawa. The 1998/9 was between the worst on record (for 4 month totalling period) to the lowest 1.6 percentile. For domestic wells, it was between the lowest 2.6% and the lowest 34.7%. For the large freshwater lenses, the dry period was between the lowest 16.8% and 87.5% and the 1998/9 posed no threat to water supply. Rather, water supply from the freshwater lenses in dry times is restricted by the inefficiencies in the water reticulation system and the lack of demand management. However, during dry periods, prolonged failure of the electrical supply system could impose major problems.

The validity of the accumulation times used to assess rainfall rankings to identify dry periods relevant to large freshwater lenses was tested using data on the thickness of the freshwater lens at Bonriki. From this preliminary test it seems that the 60 month totalling time is appropriate to large groundwater sources. This is consistent with the 5.5 year residence time for water estimated from the drawdown of the lens. The data showed that there was still abundant water in the lens in the 1998/9 drought. This analysis was, however, incomplete due to the unavailability of monthly rainfall data for 1998, and due to vandalism of the central salinity monitoring borehole. This analysis also highlights the need to monitor salinity and water use in a range of domestic water wells for islands with a range of widths and a range of demands as an indicator of pending problems.

The appropriateness of the 10 percentile level as an indicator of severe drought and the 40 percentile level as a warning trigger for droughts, compared to other levels, remain to be examined in detail. Likewise the appropriateness of the rainfall totalling periods suggested here also should be tested against experience for a range of small island nations and conditions. Data on the size of rainfall catchments, rain tanks and details of water usage from them and from domestic wells should be collected. While the methodologies used here are applicable elsewhere, the results and conclusions are specific to Betio, South Tarawa. It is therefore suggested that donor agencies could use this system of ranking rainfall as a method of determining support in dry periods for small island nations. To do this, appropriate rainfall statistics, information on water sources and testing of concepts will be required for small island nations.

Recommendations

Following this work, it is recommended that:

- standard, broadly applicable drought indices be developed for all drought-prone, small island nations to identify the severity of drought and to provide a trigger for water conservation and relief strategies;
- the characteristics of the various water storages in small islands be assessed and that the demand functions for those storages be identified;
- the relation between agricultural productivity and drought be examined particularly for coconut trees;
- the use of the decile rainfall ranking method to provide warnings of droughts be examined;
- the relation between the Southern Oscillation Index and ranked accumulated rainfall deficits be examined for periods longer than 12 months;
- a risk analysis be undertaken of small island water supplies in dry periods in relation to power failure;
- that routine monitoring of the salinity of a range of domestic water wells and large freshwater lenses be undertaken to test the assumptions in this analysis;
- given the frequency of drought relevant to rain water tanks and domestic water wells, educational and planning policy be developed to manage water use and optimise storages.

1. Droughts and their impacts in small coral islands

1.1 Introduction

Rainfalls in low coral atolls in the central Pacific are strongly correlated to variations in central and eastern Pacific sea surface temperatures (Evans *et al.*, 1998), the *El Niño-Southern Oscillation* (ENSO) events. Because of this, annual rainfalls have characteristically large coefficients of variation (Falkland and Brunel, 1993; Falkland, 1999a). This variability results in periods of sometimes over 12 months with small, infrequent rainfalls followed by periods of high rainfalls. During extended low rainfall periods, the unique hydrogeology of low coral islands severely limits freshwater, and has sometimes forced the expatriation of islanders.

Extended low rainfall periods occurred in 1998 and the early part of 1999 in the Republic of Kiribati, particularly in South Tarawa (the Capital, with over one third the Republic's population), in the former phosphate island of Banaba (a high coral island with no substantial fresh groundwater resources) and certain remote, narrow, outer islands with limited groundwater. This resulted in rainwater tanks running dry, dramatic increases in salinity in domestic wells, the death of some trees, die-back in others and an increasing demand on potable, reticulated water. The drought and its impacts led to the declaration, by the President, of a State of Disaster in the Republic on 26 February 1999. This declaration highlighted the need for appropriate quantitative measures of the severity of droughts (Falkland, 1999b) or a drought index for small coral islands which takes into account the different sources of water for domestic supplies. This report provides a systematic approach for assessing the severity of prolonged dry periods and for providing warning of their onset

1.2 Drought

Drought, like "bad weather" is a relative term. It is generally associated with a sustained period of significantly lower soil moisture and water supply than the normal levels to which the local environment and society have adapted. The relative nature of drought, the fact that a low rainfall period in a tropical environment can be the equivalent of a high rainfall period in a semi-arid environment, makes the definition of drought difficult (Smith *et al.*, 1992) as well as complicating the identification of its onset and its conclusion. Only abnormally dry conditions, which lead to a lack of sufficient water to meet normal requirements, should be recognised as drought (Gibbs, 1975).

Emphasis on droughts has centred on their impacts on crop and animal production. However, there are broader issues which go beyond agriculture, such as potable water supply, which require different approaches. Consequently, there are at least four common definitions for drought based on meteorological, agricultural, hydrologic and economic considerations (Rasmussen *et al.*, 1993).

1.2.1 Meteorological or climatological drought

Meteorological or climatological drought is an interval of time during which the supply of moisture at a given place cumulatively falls below the climatologically appropriate moisture supply. This sort of drought has been defined as a prolonged abnormal moisture deficiency (Palmer, 1965). In areas with marked seasonal dry periods, the interval of time over which supply of moisture is considered has to be long enough to cover wet and dry seasons.

1.2.2 Agricultural drought

Agricultural drought is an interval of time when soil moisture cannot meet the evapotranspiration demand for crop initiation, to sustain crops and pastures or supply water for livestock or irrigated crops. With this definition, crops with different water demands and water-use strategies, such as deep-rooted trees and shallow-rooted grasses experience onset of drought at differing times (Rasmussen *et al.*, 1993).

1.2.3 Hydrologic drought

Hydrologic drought is an interval of time of below-normal streamflow, or depleted reservoir or groundwater storage. Because of the residence time for water in different storages, hydrological drought can lag behind and extend beyond regions of meteorological drought. It can be also influenced by landuse changes, particularly those which alter runoff, infiltration and ultimately deep drainage.

1.2.4 Socio-economic Drought

Socio-economic drought is the impact of physical processes on human economic activities as a result of drought, such as returns from crop sales. It occurs when demand for an economic good (e.g. water, food, forage, fish and hydropower) exceeds supply due to a deficit of water as a result of the weather.

The sequence of drought impacts is first felt in systems with short water residence times. Thus topsoil water, typically of order 100 mm, upon which dryland crops and pastures depend is the first depleted. Rainwater tanks and shallow surface storages generally follow. Systems which rely on surface pondages are more robust and deep groundwater systems are the most robust. When droughts break, systems with the smallest water residence time recover first.

1.3 Droughts in small coral islands

The unique hydrology of low coral islands means that they are particularly sensitive to extended dry periods. Their small areas limit any harvesting of water. Additionally, the high permeability of their coral sands means that runoff collection is limited to artificial rainwater

catchments and constructed surface storages, such as rain tanks of limited capacity (Falkland, 1999b). The main storage is the shallow groundwater which exists as a relatively thin freshwater lens floating over seawater. The tidally-forced mixing of the freshwater with seawater thins the freshwater lens further and creates a thick brackish water transition zone (Wheatcraft and Buddemeier, 1981).

Much of the native vegetation in low coral islands, particularly trees and palms, has evolved to use the shallow groundwater to supply most of their evaporative demand (Falkland and Brunel, 1993; White *et al.*, 1999). For these, as for humans, drought is intimately connected with the viability of the groundwater storage. The groundwater storage is governed by the groundwater recharge rate, the width of the island and its geology (Falkland and Woodroffe, 1997). To a first approximation, for a uniform aquifer, the relationship between the maximum thickness of freshwater (actually the depth from the watertable to the midpoint of the saline transition zone) in the centre of a lens, H_m , is related to the island width, W and the recharge rate, R , the hydraulic conductivity of the lens K_0 , and the density of sea and fresh water, ρ_s and ρ_0 through (Chapman, 1985):

$$\begin{aligned} \frac{H_m}{W} &= \frac{1}{2} \left(\frac{\rho_s R}{(\rho_s - \rho_0) K_0} \right)^{1/2} \\ &= \frac{1}{2} \left((1 + \alpha) \frac{R}{K_0} \right)^{1/2} \end{aligned} \tag{1-1}$$

where $\alpha = \rho_0 / (\rho_s - \rho_0)$.

With typical values for recharge and hydraulic conductivity, this equation predicts that viable freshwater depths are not expected to occur in islands whose widths are less than about 100 m.

In addition, the high permeability of the coral sands and their small water holding capacities mean that, in the absence of irrigation, shallow rooted crops, such as vegetables, which do not tap into the groundwater, experience agricultural drought within one or two days without rain. In small coral islands, droughts of most concern are those that affect the already limited quantities of drinking water for human survival. For these reasons, we shall concentrate here on meteorological drought.

2. Drought indices

A central problem in identifying droughts is how to compare dry periods at different times and in different locations. One way of doing this is to use drought indices which are designed to remove these spatial and temporal dependencies. The most frequent use of drought indices is in farming situations where decisions are required on crop planting, irrigation, stocking densities and providing support or drought relief to farmers and communities who rely on cropping or grazing.

There are a number of existing indices which are largely irrelevant to small coral islands. Indices such as: the surface water supply index, which is mountain water dependent and incorporates mountain snowpack; the crop moisture index, introduced to measure the impact of short-term moisture conditions on a developing crop (Palmer, 1968); the national rainfall index, developed to compare spatial and temporal variability of precipitation on a continental scale (Gommes and Petrassi, 1994); and dependable rains, an index for agricultural production planning which is the amount of rain that occurs statistically in four out of every five years (Le Houérou *et al.*, 1993) will not be examined here. In addition, percent of normal rain, the actual precipitation divided by the long term (30 year) mean rain and expressed as a percentage is not considered in this work, because of its unrealistic assumption of a normal distribution for rain, and the fact that spatial comparisons are not possible (Willeke *et al.*, 1994).

Water balance calculations of the relevant water storages, are the best approach for considering droughts and their impacts. Such water balance considerations are used in estimating the probability of failure, the reliability and critical drawdown of surface water storage reservoirs (McMahon, 1993). These appear appropriate for domestic water supplies in low coral islands. At their simplest, these water balances over a time period t can be expressed as:

$$\text{Change in storage} = \text{sum of inputs} - \text{sum of outputs} \quad (2-1)$$

When the decrease in storage during dry times reduces the storage volume to a critical level, a drought is frequently declared and procedures are adopted to conserve the remaining water. In order to use the water balance approach for drought declarations, the storage volume, critical storage (volume below which problems arise), as well as the water inputs and outputs need to be known. Outputs are the demand for water together with natural losses. Fig. 2.1 shows the historic series of annual rainfalls for Betio, South Tarawa, Kiribati together with a hypothetical, population-dependent demand for water.

In this example, the hypothetical demand for water is shown as a simple function increasing with time as population increases. Deficits occur when demand is greater than the inputs from rainfall (Salas, 1993). One of the several periods of hypothetical deficit is highlighted in Fig. 2.1. The demand deficit periods are characterised by the length of time of the deficit and the total amount of the deficit.

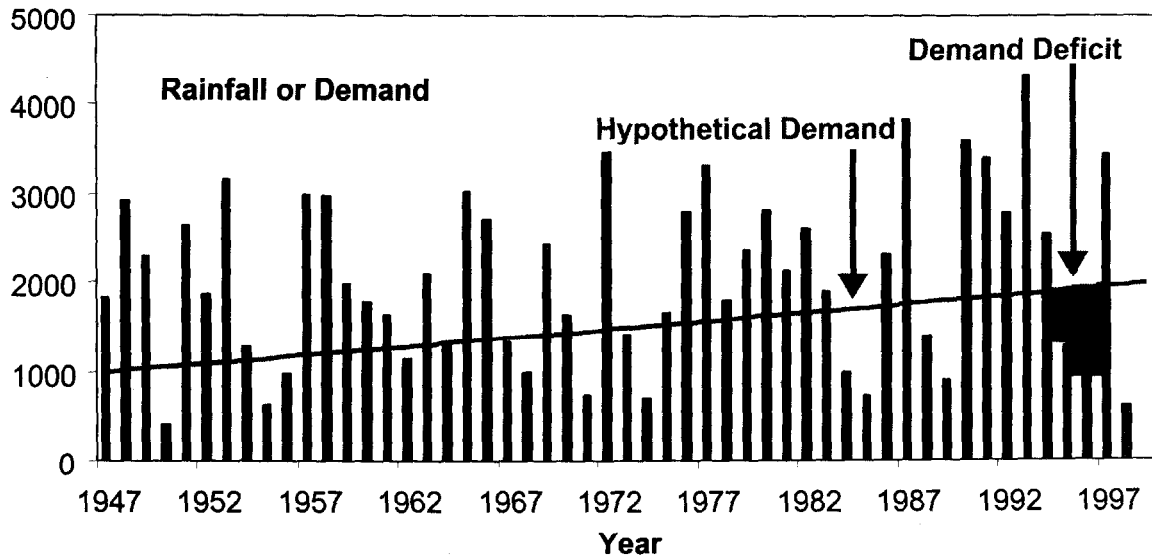


Fig. 2.1 Historic annual rainfalls for Betio, Tarawa atoll in Kiribati and a hypothetical demand for water which increases with increasing population. One of the demand deficits, resulting from lower than normal rainfalls is illustrated.

2.1 Drought indices for small coral islands

In low coral atolls such as South Tarawa, there are three sources of water for domestic consumption: rainwater catchments, domestic wells, and reticulated water drawn from groundwater reserves. In order to define droughts unambiguously, information on the size of storages, critical storage volumes, inputs and outputs are required. Storage, demand values and natural losses for rainwater and domestic water wells in low coral atolls are usually poorly known. Because of negligible atoll runoff, the inputs are directly related to rainfall and are therefore better known, although the areas of rainwater catchments for rainwater collection are, in general, poorly characterised. The outputs consist of the demand, leakages and natural losses due to evaporation, as well as for groundwater outflow and mixing losses. These outputs are often only approximately known for major groundwater sources for reticulation systems (Falkland, 1999a; White *et al.*, 1999). In addition, the time period over which water balances need to be estimated depend on the capacity of the storages and the residence time of water in them. These are not well-characterised for rainwater or domestic water wells.

The time period over which water balances should be calculated depends on the residence time of water in the storage which is estimated from (Chapman, 1985):

$$\text{residence time} = \text{volume of storage} / \text{inflow or outflow rate(demand)} \quad (2-2)$$

Neither the volumes of storage nor demands are known for rainwater tanks and domestic wells. Only one of the components of the water balance, rainfall, is known in general for the sources of domestic water on low coral atolls.

2.2 The Palmer drought severity index

The Palmer drought severity index (Palmer, 1965) was developed for semiarid to subhumid regions in the United States, central Iowa and western Kansas, but is now applied across the entire US. It was designed to use weekly or monthly estimates of the soil water balance. The index is calculated as a function of the difference (accumulated through time) of the actual rainfall from the climatologically appropriate rainfall for the existing conditions at any locality. This index uses temperature to estimate evapotranspiration and requires estimation of the local, available water content of the soil (McMahon, 1993).

Palmer normalised the output and arbitrarily selected a classification scale which returns a numerical index (below -4.0 is extreme drought, above 4 is extremely wet), that has been used to decide on the onset and completion of droughts and to assist in contingency planning and the allocation of drought relief in the US for the last 30 years (Alley, 1984; Willeke *et al.*, 1994). The net result of the Palmer normalisation procedure is to essentially remove evapotranspiration effects so that it effectively is an index of available moisture (Smith *et al.*, 1992). Its use in regions with highly variable rainfalls, such as Australia and South Africa, is problematic (Smith *et al.*, 1992). Table 2.1 lists advantages and disadvantages of the Palmer and other drought indices.

While the Palmer drought severity index is appropriate for agricultural droughts, it may not be relevant to domestic water supplies or impacts at longer time scales (McKee *et al.*, 1995). To cope with these situations, the standardised precipitation index was developed.

2.3 Standardised precipitation index, SPI

Deficits in precipitation have different impacts on the range of natural and constructed water storages and stream flows across different time scales. Soil moisture in the root zone responds to deficits over a much shorter time period than does groundwater. The standardised precipitation index was introduced to measure precipitation deficit over a range of relevant time scales (McKee *et al.*, 1993).

The standardised precipitation index is calculated by taking the difference between the accumulated normally-transformed rainfall over a particular time period and the mean accumulated rainfall for that period and then dividing the difference by the standard deviation.

$$SDI_n = \frac{[{}^T P_0 + \sum_{i=1}^{n-1} ({}^T P_{-i})] - \mu_n}{\sigma_n} \quad (2-3)$$

Here n is the number of months over which rainfall is summed, ${}^T P_0$ is the normally transformed rainfall for the current month, ${}^T P_{-i}$ is the normally transformed rainfall for the previous i th month ($i = -1$ is the preceding month and so on), μ_n is the mean of all rainfalls accumulated over a period of n months and σ_n is the standard deviation for the same period.

TABLE 2.1 Strengths and weaknesses of selected rainfall indices

| Rainfall Index | Strengths | Weaknesses |
|----------------------------------|---|--|
| Palmer Drought Severity Index | <ol style="list-style-type: none"> 1. Used widely in US. 2. Soil water balance approach to assessing droughts. 3. Normalised Index. 4. Can be used for comparison between locations. | <ol style="list-style-type: none"> 1. Not universally used. 2. Normalisation essentially removes evapotranspiration. 3. Arbitrary index with extreme drought occurring 10% of time and doubtful applicability in some locations. 4. Requires information on rainfall, temperature and soil-moisture. 5. Questionable applicability in areas with highly variable rains. |
| Standardised Precipitation Index | <ol style="list-style-type: none"> 1. Recognises different time scales are needed for different water storages. 2. Standardised Index. 3. Needs less data than Palmer Index. 4. Can be used for comparison between locations. | <ol style="list-style-type: none"> 1. Requires transformation to normal distribution. 2. Not widely used or tested. 3. Requires long rainfall record (>30 years). 4. May require different transformations for different rainfall accumulation periods. 5. Ignores water demand and other losses. |
| Rainfall Deciles | <ol style="list-style-type: none"> 1. Recognises different time scales are needed for different water storages. 2. Non parametric method, does not assume any rainfall distribution. 3. Does not require transformation of data. 4. Can be used for comparison between locations. 5. Needs less data than the Palmer Index. 6. Simple to calculate. 7. Meaning is clear and easily understood. | <ol style="list-style-type: none"> 1. Requires long rainfall record (>30 years) 2. Used mainly in Australia 3. Ignores demand and losses. |
| Rainfall Depreciation Method | <ol style="list-style-type: none"> 1. Surrogate, pseudo-water balance method. 2. Depreciates progressively previous months' rainfalls. | <ol style="list-style-type: none"> 1. In its present form it cannot be used for comparisons between locations. 2. In its present form is not a drought index. 3. Depreciation rate is <i>ad hoc</i>. |

4. Fixed depreciation rate, independent of monthly rainfall is physically unrealistic.

The standardised precipitation index tells us how many standard deviations that rainfall is from the mean over the selected period. Wetter periods show positive values while drier periods show negative values. A classification system for drought intensity based on this index is shown in Table 2.2 together with the theoretical percentage of occurrence of that class.

TABLE 2.2 Classification system for the standardised precipitation index (SPI).

| SPI Range | Climate Classification | Theoretical Occurrence (%) |
|-----------------|------------------------|----------------------------|
| +2.0 and above | Extreme wet | 2.3 |
| +1.5 to +1.99 | Severe wet | 4.4 |
| +1.0 to +1.49 | Moderate wet | 9.1 |
| 0 to +0.99 | Mild wet | 33.9 |
| 0 to -0.99 | Mild drought | 33.9 |
| -1.0 to -1.49 | Moderate drought | 9.1 |
| -1.5 to -1.99 | Severe drought | 4.4 |
| -2.00 and below | Extreme drought | 2.3 |

This index assumes that the rainfall variable is normally distributed. Because rainfalls for accumulation periods of less than at least 12 months are not normally distributed, the rainfall distribution for the period in question must be transformed to a normal distribution (McKee *et al.*, 1993). Theoretically, this transformation ensures that the standardised precipitation index follows a normal distribution with mean 0 and variance 1. The transformation step is an additional complication. In the original use of the standard precipitation index, rainfall was summed over time periods of 3, 6, 12, 24 and 48 months, however more recent treatment have adopted a broader approach and sum over all monthly time periods from 1 to 24 months.

The standardised precipitation index is similar in form to the definition of the Southern Oscillation Index. An advantage of this index is that a drought event can be defined for any time span as a period when the index is continuously at or below a value of -1.0 (lowest 15.9% of rainfalls). Drought ends when the index becomes positive. The magnitude of a drought can also be measured by summing the index over the drought period to produce a drought magnitude (McKee *et al.*, 1993). The strengths and weakness of the SPI are also summarised in Table 2.1.

It is clear that treatment of the variability of rainfall is the key to the analysis of meteorological drought (Smith *et al.*, 1992). It is therefore useful to examine the statistics of rainfall as a method deciding the occurrence and severity of droughts. The monthly or annual decile method (Gibbs and Maher, 1967) provides a non-parametric method of examining meteorological drought which enables comparisons of rainfalls between different locations.

2.4 The decile method

Rainfall deciles rank the rainfall over the period of interest in terms of the relative quantity of rain that fell in that period compared with the total distribution of all recorded rainfalls over the same period. The total quantity of rain, TP_n , for an n month accumulation period is just:

$$TP_n = P_0 + \sum_{i=1}^{n-1} P_{-i} \quad (2-4)$$

Here P_0 is the rainfall for the current month, P_{-i} is the rainfall for the previous i th month (-1 is the previous month and so on). The ranking of rainfall against the total record is expressed as a percentile of the total distribution. Thus rainfalls in the lowest 10 percentile, or lowest decile, are in the lowest 10% of all recorded rainfalls. Because this ranking is relative to the total distribution of rainfall over the time period of interest at a location, it is relative to the climatologically appropriate moisture supply at that location, as required by the definition of meteorological drought.

Rainfall deciles are a non-parametric measure of drought since, unlike the standardised precipitation index, they are calculated without any assumptions about how rainfall is distributed in time. Moreover, they directly provide a normalised measure of dry and also wet conditions that can be compared between different sites and times. Deciles of 6-monthly rainfalls are closely connected to the Palmer Index and are as efficient in identifying periods of declared agricultural drought. In addition, rainfall deciles have a much higher spatial coherence than actual monthly rainfall totals. This is because deciles are essentially normalised departures from average conditions and are related to broadscale synoptic patterns (Smith *et al.*, 1992). The decile method is used in the Australian Drought Watch System and forms the basis for declaring drought and providing drought relief (White and O'Meagher, 1995). The classifications used in this system are listed in Table 2.3.

TABLE 2.3 Classification system for the decile method as used in Australia.

| Decile | Percentile Range (%) | Climate Classification |
|--------|----------------------|-------------------------|
| | 100 | Highest of record |
| 10 | 90 to <100 | Very much above average |
| 8-9 | >70 to <90 | Above average |
| 4-7 | >30 to <70 | Average |
| 2-3 | >10 to <30 | Below average |
| 1 | >0 to <10 | Very much below average |
| | 0 | Lowest on record |

Fig. 2.2 shows the cumulative decile distribution of rainfall for one month periods in Betio, Tarawa atoll. It can be seen in Fig. 2.2 that monthly rainfalls of 19.6 mm or less are in the lowest decile (10%) while monthly rainfalls of 390 mm or more are in the highest decile (90%). The median (50%) rainfall is 134 mm compared with a mean of 171 mm. The difference between the mean and median indicates that the rainfall distribution is skewed towards low rainfalls. The coefficient of variation ($CV[\%] = 100 \times \text{standard deviation}/\text{mean}$)

of the monthly data is 85.9%. Fig. 2.3 gives the corresponding frequency (or probability) distribution for monthly rainfalls and shows the 10, 50 and 90% deciles. The distribution of monthly data is, as expected, a non-normal distribution, skewed towards smaller rainfall events. Transforming the data by taking the square root of the monthly rainfall produces a near-normal distribution (M. Hutchinson pers.com. 1998) as shown in Fig. 2.4.

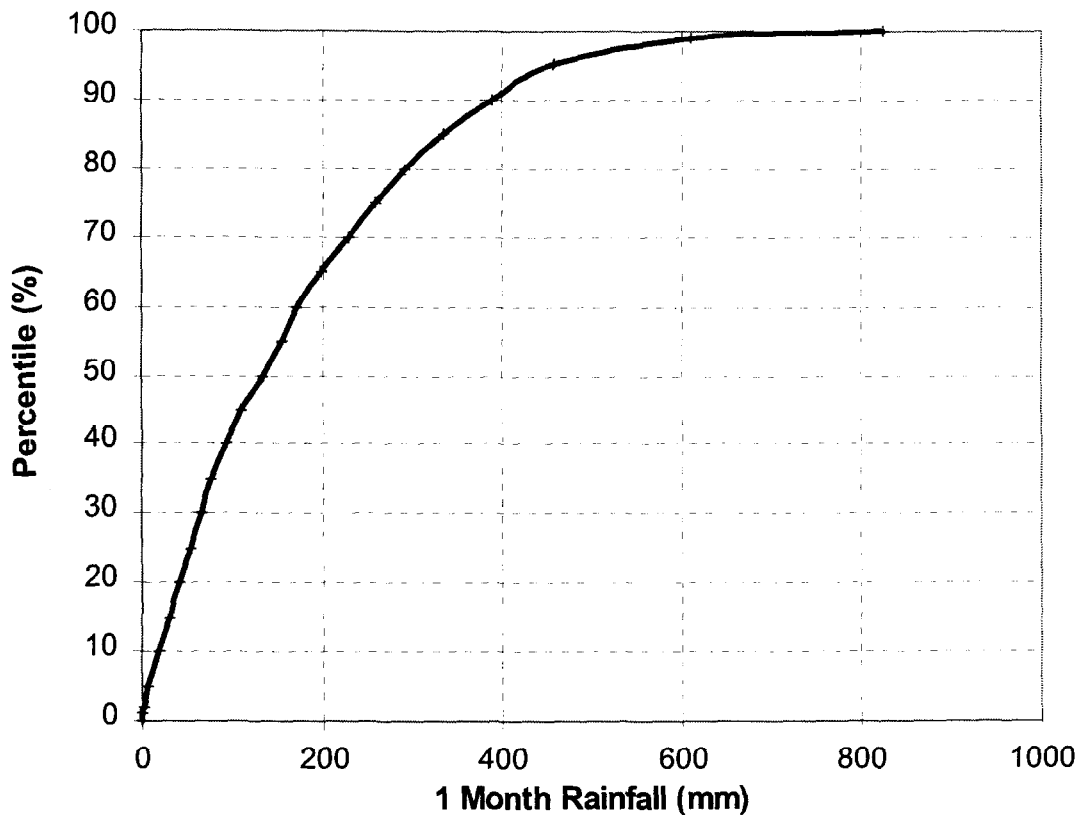


Fig. 2.2 Cumulative rainfall distribution for 1 month rainfall, Betio, Tarawa atoll, Republic of Kiribati.

When the time over which rainfall is totalled increases to 12 months or more, the coefficient of variation decreases and the distribution of longer term rainfall approaches a near normal distribution with the mean and median values lying closer together, as shown in Fig. 2.5 for 30 month aggregated rainfalls. When rainfall for a time scale is normally distributed, then the decile and standardised precipitation index have an exact relationship. For example, rainfalls in the first decile (<10%) correspond to a standardised precipitation index of -1.282. Identifying drought with rainfall totals in the bottom 10% of all rainfalls is more stringent than the standardised precipitation index which identifies drought when the index is less than -1.0 or the bottom 15.9% of rainfalls. The strengths and weaknesses of the decile method are also listed in Table 2.1.

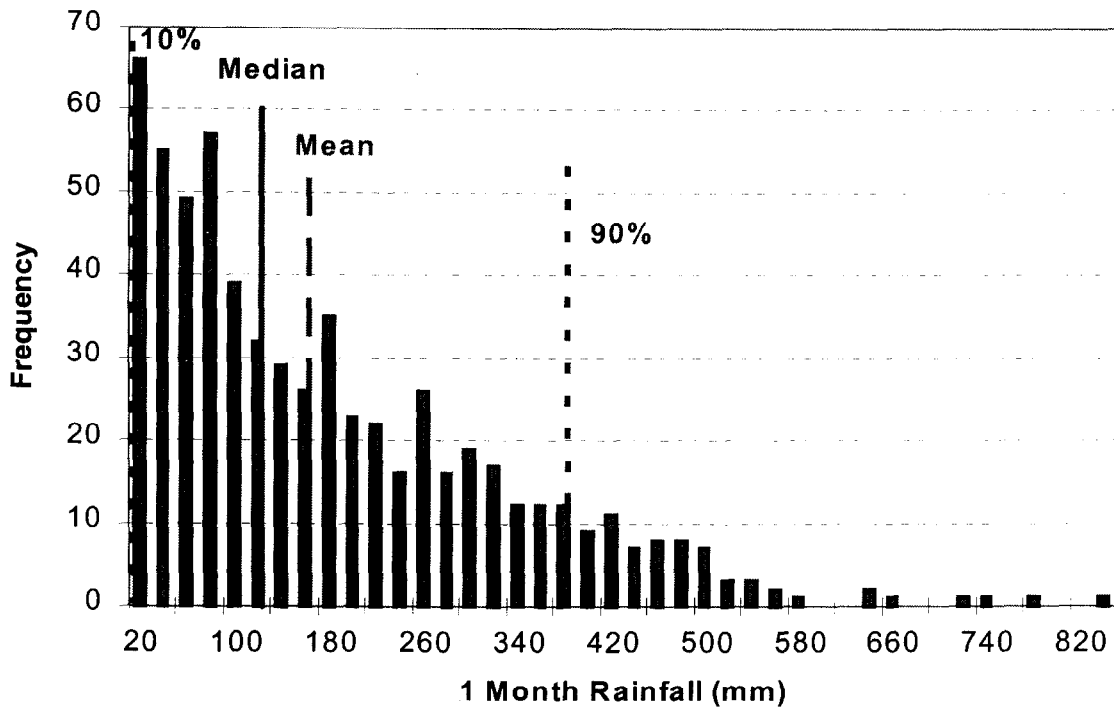


Fig. 2.3 The frequency distribution for 625 one monthly rainfalls for Betio, South Tarawa, Kiribati showing the lowest (10%), highest (90%) and the median (50%) deciles.

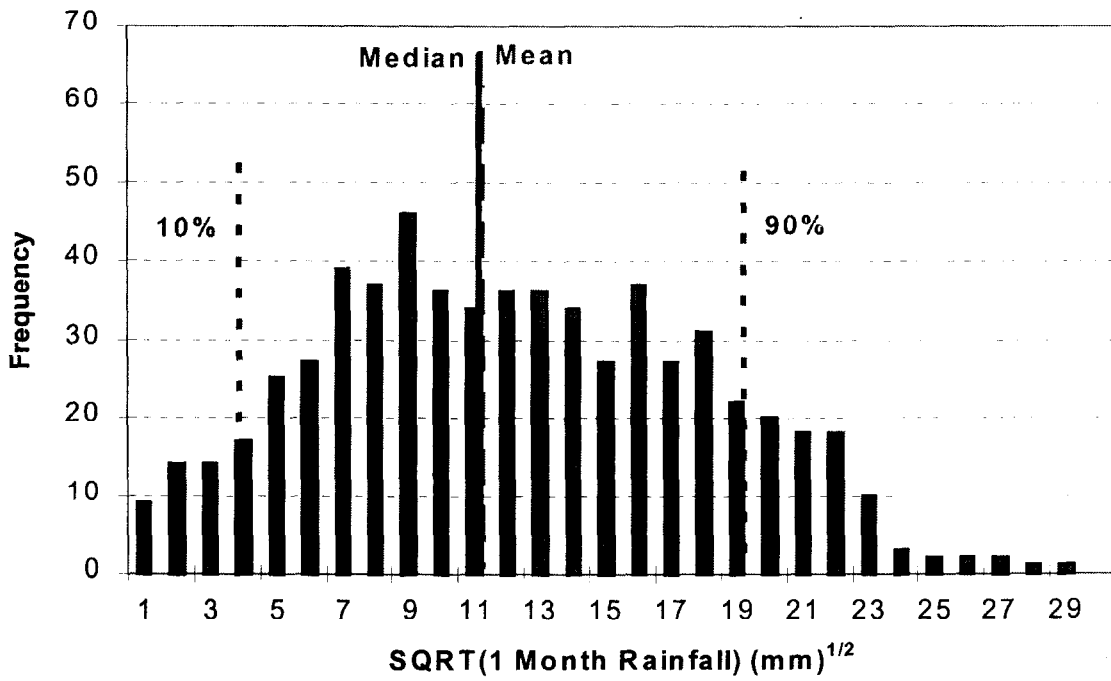


Fig. 2.4 Frequency distribution for monthly rainfall in Betio transformed using the square root of monthly rainfall.

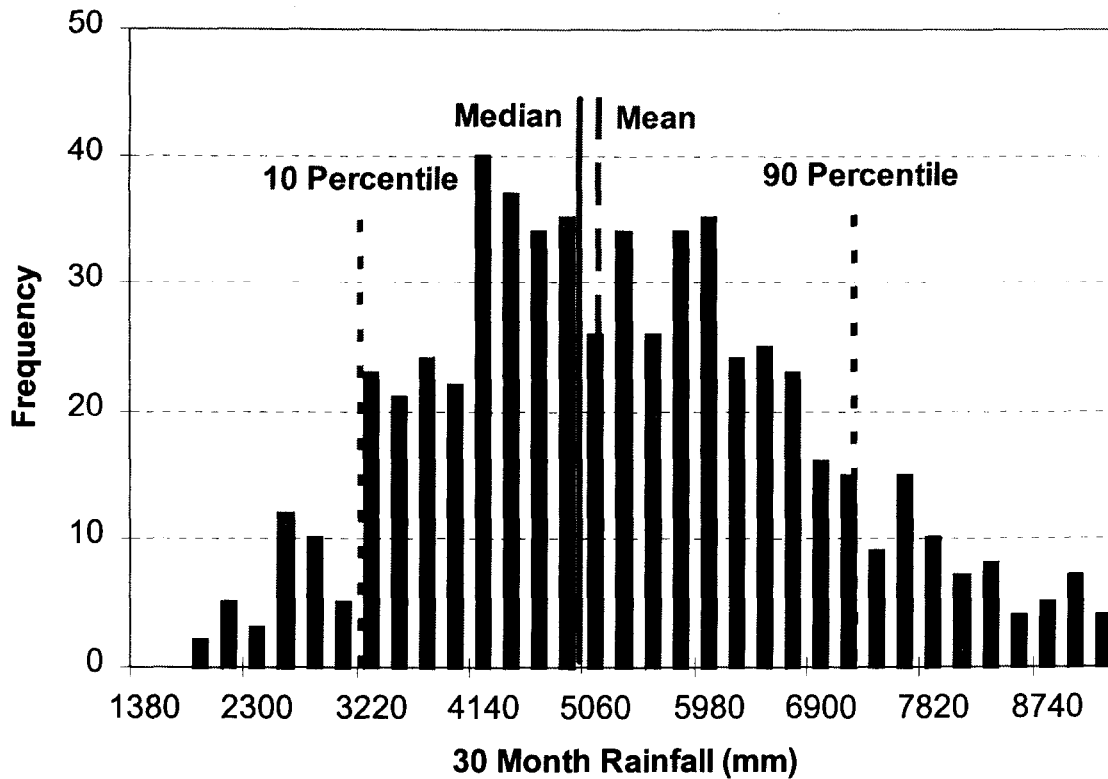


Fig. 2.5. Frequency distribution for rainfalls summed over 30 month periods. A near normal distribution, with mean close to the median can be seen for this longer rainfall period.

2.5 Rainfall depreciation method

The rainfall depreciation method is essentially a surrogate, pseudo water balance method. It assumes that some fraction of the previous months' rainfall has been lost and, therefore, must be subtracted or depreciated from the water storage of interest (Falkland, 1999b). This method is under development, but appears to have, under certain assumptions, a close correlation with the standardised precipitation index (Ricci and Scott, 1998). Two forms of this rainfall depreciation method are possible. In both, there is no depreciation of the current month's rainfall. The first form is a compound depreciation method with the total rainfall over n months (current month plus $n-1$ previous months), DP_n , given by:

$$DP_n = P_0 + \sum_{i=1}^{n-1} P_{-i} \left(1 - \frac{1}{d}\right)^i \quad (2-5)$$

In equation 2-5, P_0 is the rain in the current month, P_{-i} is the rain in the previous month and so on. The factor $1/d$ is the depreciation rate. Its value is important. Alternately, a simple, arithmetic depreciation can be considered in which,

$$DP_n = P_0 + \sum_{i=1}^{n-1} P_{-i} \left(1 - \frac{i}{n-1} \right) \quad (2-6)$$

With the simple, arithmetic depreciation, the rain in the $(n-1)$ th previous month is weighted to zero. Using either equation 2-5 or 2-6, a central issue is the period over which depreciated rains should be summed. In its original use, a single 12 month accumulation period and a monthly depreciation rate of 10% ($d = 10$) were used.

Several problems arise with this method (see Table 2.1). Because it has the dimensions of rainfall (mm) it cannot be used directly as a drought index nor can it be used for comparisons between locations. This can be easily overcome by ranking all values of DP and expressing the rankings as a percentile. A more serious problem is that the fixed depreciation rate, $1/d$ or $i/(n-1)$, assumes that a fixed fraction of each month's precipitation is removed through demand and losses, irrespective of the magnitude of precipitation. This is physically unrealistic. For example in months with very low rainfall, all rainfall can be lost through interception losses alone. This problem could be overcome by having a rainfall-dependent depreciation rate. Because information on the rainfall depreciation is not available, this would simply introduce additional *ad hoc* assumptions. If the necessary information were available, a water balance for the relevant water storage would appear more appropriate than refining this pseudo water balance.

2.6 Appropriate time periods for rainfall accumulation

The problem of choosing an appropriate period of time over which to accumulate monthly rainfalls in low coral islands is common to the decile, standardised precipitation index and rainfall depreciation methods. Current standardised precipitation index techniques simply sum over all periods from 1 month up to 24 months. For water sources in low coral islands, we can be more prescriptive. We propose here that the appropriate rainfall totalling period should be the average residence time of water in rainwater tanks, domestic wells or reticulation groundwater reservoirs in question. This, in turn, depends on storage capacity and on the demand. Information on these is only available for the large freshwater lens which supplies the reticulation system (Falkand, 1992, White *et al.*, 1999).

In South Tarawa, at the 1995 Census, the household usage of piped water from the public reticulation system was 55%, domestic well water was 58% and rainwater catchments was 23% (Secretariat of the Pacific Community, 1998). For rainwater tanks the critical parameters are the size of the storage and the demand. Data on these for South Tarawa is sparse. Domestic tanks range from approximately 500 L to 12,000 L with per capita use of water from these ranging from approximately 150 to 600 L/month. If we take a representative storage of 10,000 L and a conservative per capita use of water of 300 L/month, then for a household of 8 people, a 10,000 L rainwater tank should last about 4 months with 6 months being the outside limit for larger tanks and lower demand. We will therefore consider the deciles for rainfalls totalled over 4 monthly and 6 monthly periods as appropriate for rainwater tanks.

For domestic wells the situation is less clearly defined. The thickness of the freshwater lenses in low coral islands tapped by domestic wells depends on the recharge rate (itself directly dependent on rainfall), the width and geology of the island (see equation 1.1), the aquifer's hydraulic conductivity, direct evapotranspiration losses by trees tapping into the freshwater lens, mixing and outflow losses to the surrounding seawater and the levels of withdrawal by people (Falkland, 1999a). Withdrawals will increase as the number of local

people using the well increase. These factors will vary from island to island. In general, groundwater in smaller, narrower islands and islands with larger populations will be more vulnerable to drought. The appropriate time period for summing rainfall to estimate deciles for domestic wells will therefore vary. In the absence of specific information, we will assume that the deciles for 12 and 30 month periods may be applicable to domestic wells. A way of testing the appropriateness of this time period would be to monitor the salinity of a range of representative domestic water wells.

Finally, the major freshwater lens storages for the reticulated water supply in South Tarawa have been characterised, particularly the Bonriki freshwater lens (Falkland, 1992; Falkland and Woodroffe, 1997; White *et al.*, 1999). The thickness of the freshwater lens has been monitored since 1985. Assuming a specific yield of 0.3, and a mean freshwater depth of 10 m, the lens holds approximately 3.2×10^6 m³ of freshwater. The current pumping demand at Bonriki is 1000 m³/day and at the neighbouring island water reserve of Buota, 300 m³/day. At Bonriki, the approximate direct evapotranspiration and other losses are about 420 m³/day. This gives a total demand of 1420 m³/day and a residence time of water in the lens of 5.5 years. This suggests that a rainfall accumulation period of 5 to 10 years is appropriate for this and similar, large freshwater lenses.

So, for the three separate water sources, we require rainfall deciles over different time period ranges to estimate the severity of drought in South Tarawa: 4 to 6 months for rainwater tanks, 12 to 30 month for domestic wells and 60 to 120 months for the reticulated water supply.

2.7 Seasonality of rains

If the rainfall in a particular location has marked seasonality, care must be taken in applying the above indices. For example, a location with a 6 month dry period each year cannot be classified as in regular drought each year because the definition of meteorological drought is based on the concept of climatologically appropriate moisture supply for any given location. Drought in this context is defined as a prolonged, *abnormal* moisture deficiency. Regular, seasonal dry periods cannot be considered abnormal. Fig. 2.6 shows the seasonality of rainfall for Betio, South Tarawa. It can be seen in Fig. 2.6 that the months of June to November inclusive are, on average drier than the months of December to May. The median wet season monthly rainfall (Dec-May) is 192 mm while the median dry season (Jun-Nov) monthly rainfall is 84 mm, a factor of 2 different between seasons.

In order to handle seasonal rains, for shorter rainfall accumulation periods (less than about 12 months), the rainfall for the month in question summed over the preceding months has to be compared with that of all rainfalls for the month in question, not the total population of all monthly rainfalls. A disadvantage of this procedure is that the number of rainfalls against which the comparison is made is reduced by a factor of twelve. This means that, in order for seasonality to be included, a minimum of at least 30 years of rainfall records are required.

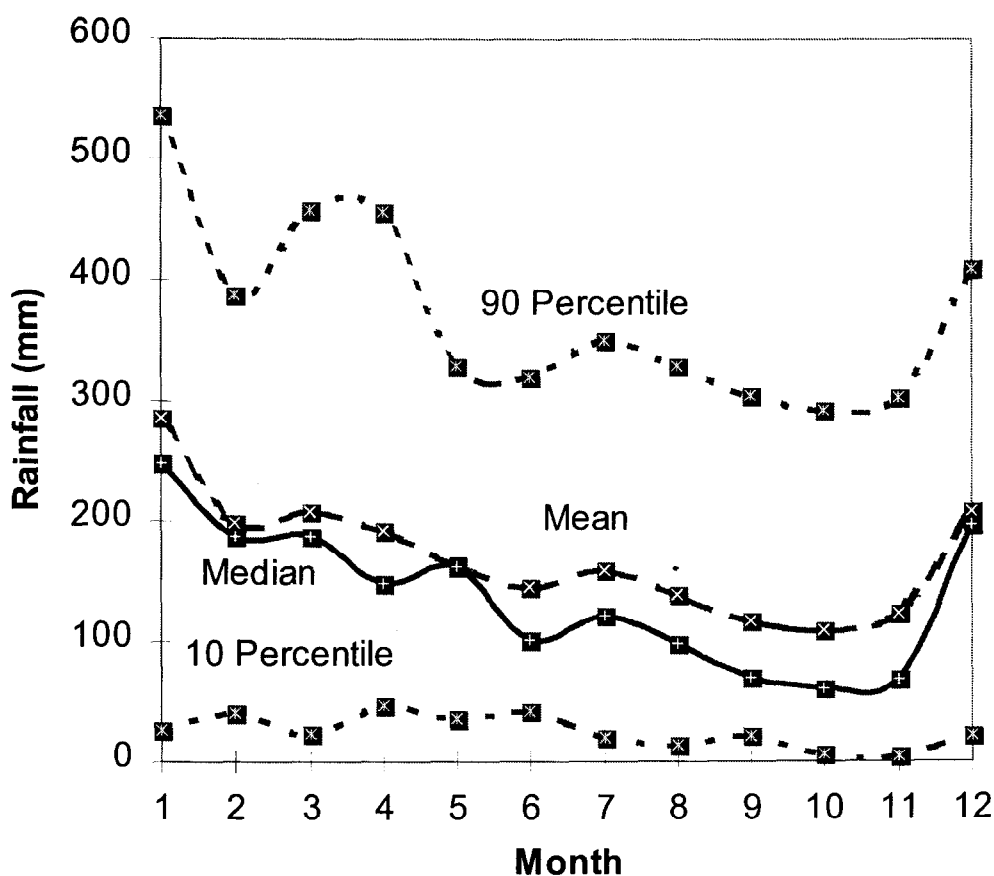


Fig. 2.6 Seasonality of monthly rainfalls, Betio, South Tarawa showing median, mean, 10 and 90 percentiles rainfalls.

2.8 Assessment of indices

All of the above indices are substitutes for calculating the water balance of various water storages, which is the appropriate measure of the effect of prolonged dry periods on a water storage. However, because, the components of the water balance are not known for some of the storages, techniques have been developed which concentrate on one essential driver of the process, rainfall.

The Palmer drought severity index, developed for agriculture drought, purports to be based on the soil water balance of the soil root zone. It has been claimed, however, that the method of normalisation of the index, essentially removes evapotranspiration, making the index predominantly a rainfall index for agricultural drought (Smith *et al.*, 1992). Moreover, the index is arbitrary and requires data on temperature and soil water content (Table 2.1). Since we are primarily concerned with the impact of prolonged dry periods on drinking water supplies, this index is of secondary importance and will not be used here.

The standardised precipitation index, a parametric method, recognises that different water storages require rainfalls to be summed over different periods. For shorter summation periods (*ca.* less than 12 months), this technique requires the rainfall data to be transformed into a variable with a normal distribution. Since rainfall summed over longer periods (*ca.* 12 months or more) approaches a normal distribution, differing transformations are required for

different summation periods. In addition, different transformation may be required for different seasons of the year (Table 2.1). Because of these, the nonparametric decile method, is more attractive in that it makes no assumption of the form of rainfall distribution and is easier to calculate since it does not require any data transformation. In addition, the decile method provides a direct, easily understood ranking of the actual rainfall, providing immediate information on whether the rainfall for the period in question is above normal, above or below normal, or extremely wet or dry. As well, for longer rainfall periods over which rainfall is more normally distributed, the decile and standardised precipitation index methods should be almost identical.

The rainfall depreciation method is a surrogate water balance method which recognises demand and losses need to be subtracted. Its assumption of constant proportional losses, however, is unrealistic and, in its present form, it is not an index (Table 2.1). We will therefore concentrate here on the decile method and make limited comparisons with the standardised precipitation index and the discounted rainfall method.

3. Estimation of Drought Indices for South Tarawa

3.1 Procedures

For the decile method we follow Smith *et al.*, (1992) and calculate 4, 6, 12, 30, 60 and 120 month deciles on a month by month basis. This differs from the annual rainfall deciles proposed by Gibbs and Maher (1967). The procedure is, for each month of the rainfall record, the rainfall for the preceding 4, 6, 12, 30, 60 and 120 months up to and including the month in question is totalled. This is then ranked in percentage terms against the rainfall totals for each sequence of months (totalled over 4, 6, 12, 30, 60 and 120 months) over the whole rainfall period. Ranking can be done conveniently using the PERCENTRANK function in EXCEL spreadsheets. As the totalling period becomes longer, variations are smoothed and the coefficient of variation decreases.

In order to test for the effect of seasonal rainfall variation on rainfall rankings, data were also ranked against rainfall totals for the month in question. This procedure reduces the number of rainfall records by 1/12. It is expected that seasonality will only be an issue for rainfall accumulation times of less than 12 months.

The standardised precipitation index was calculated for 4 and 6 month data by transforming the accumulated rainfall data using a square root transformation. The mean of the transformed rainfalls was subtracted from the value of transformed rainfall for any period and the difference divided by the mean to form the standardised precipitation index. Results were compared with the decile method for 4 and 6 month rainfalls.

The rainfall depreciation method was calculated using equation 2.5 with a depreciation rate of $1/d = 0.1$ and over a period of $n+1 = 12$ months. Results were converted to deciles by ranking the data. The results were compared with the decile method for the same 12 month period.

3.2 Calculated drought indices

3.2.1 Decile method

The results of the decile method presented as percentile ranking time series are shown in Figs 3.1, 3.2, 3.3 and 3.4 for the selected totalling periods of 1 to 120 months. The smoothing which occurs with longer accumulation time periods is evident in these figures (and in the coefficients of variation, CV, in Table 3.1). Also highlighted in these figures are the critical lowest 10 percentile and the 40 percentile. The lowest 10 percentile indicates

extreme dry periods, the 40 percentile level, as is argued later, may provide an appropriate indicator of impending severe dry periods.

We here will identify severe droughts as periods when the accumulated rainfall drops below the 10 percentile level for rainwater and domestic wells. For the large freshwater lenses, this is identified as a period of drier, but not necessarily threatening conditions.

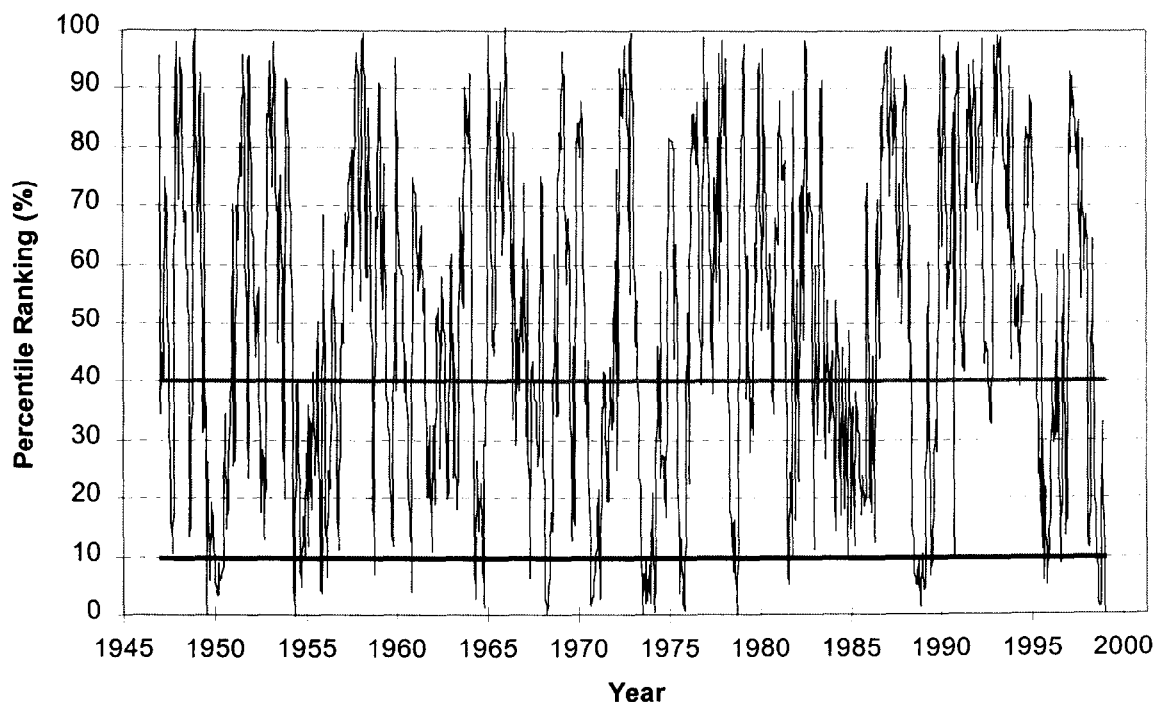


Fig. 3.1. Percentile ranking for monthly rainfall data for the available rainfall record, 1947-1999, for Betio, South Tarawa.

The monthly data in Fig. 3.1 is clearly noisy. It shows that there were 32 times between 1947 and 1999 when the rainfall dropped into the lowest 10% ranking, or, on average, about 6 very dry months per decade. Not all of these dry months can be classed as a drought. In all, 20 out of the 32 very dry periods only lasted one month with the average duration below the 10% level being 1.9 months. Many of these dry periods would, most probably, not have been a problem for rainwater tanks or domestic wells.

Table 3.1 summarises the statistics of the data in Figs 3.1 to 3.4 and lists the lowest and highest rainfalls, mean rainfall for the totalling period over the entire rainfall record, coefficient of variation, value of rainfall at the 10 percentile, the number of extremely dry periods (< 10 percentile) since 1947, the average time between extreme dry periods as well as the CV and range of that time, and the average duration of those dry periods together with the CV and range of that duration. With our estimates of the rainfall totalling time periods relevant to rain tanks (4 to 6 months), domestic wells (12 to 30 months) and the freshwater lens at Bonriki (60 to 120 months) we can use the results in Table 3.1 to construct the expected period between extreme dry periods and the expected duration of those dry periods for these three sources of water. These are shown in Table 3.2. Extreme dry periods are clearly relatively frequent in South Tarawa, particularly for rainwater tank storage. Because of this, plans can be made for responses before dry periods occur.

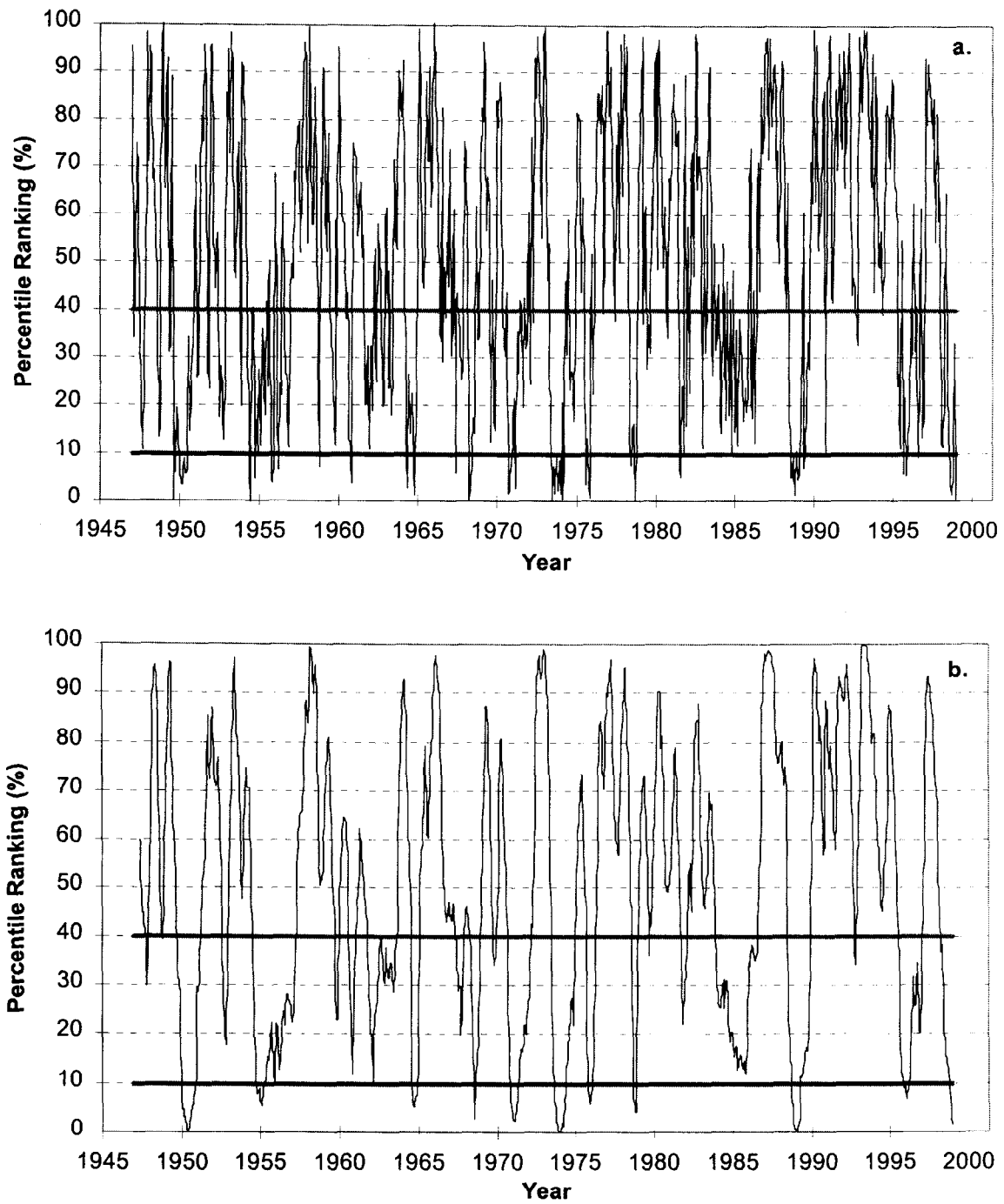


Fig. 3.2 Percentile ranking of rainfall for Betio relevant to rainwater storages for a. 4 and b. 6 month accumulated rainfall.

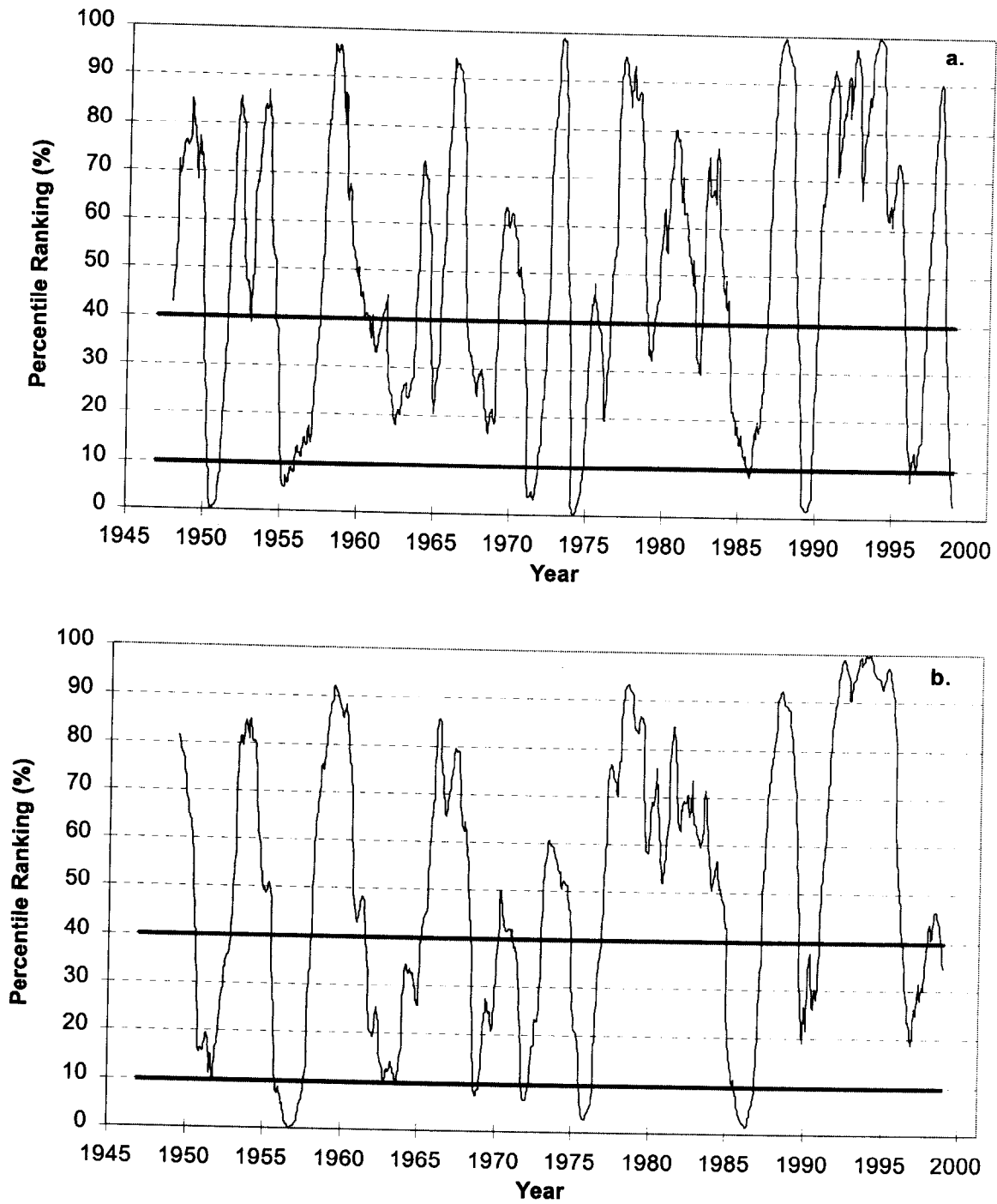


Fig. 3.3 Percentile ranking of rainfall for Betio relevant to domestic wells in narrow islands for a. 12 and b. 30 month accumulated rainfall.

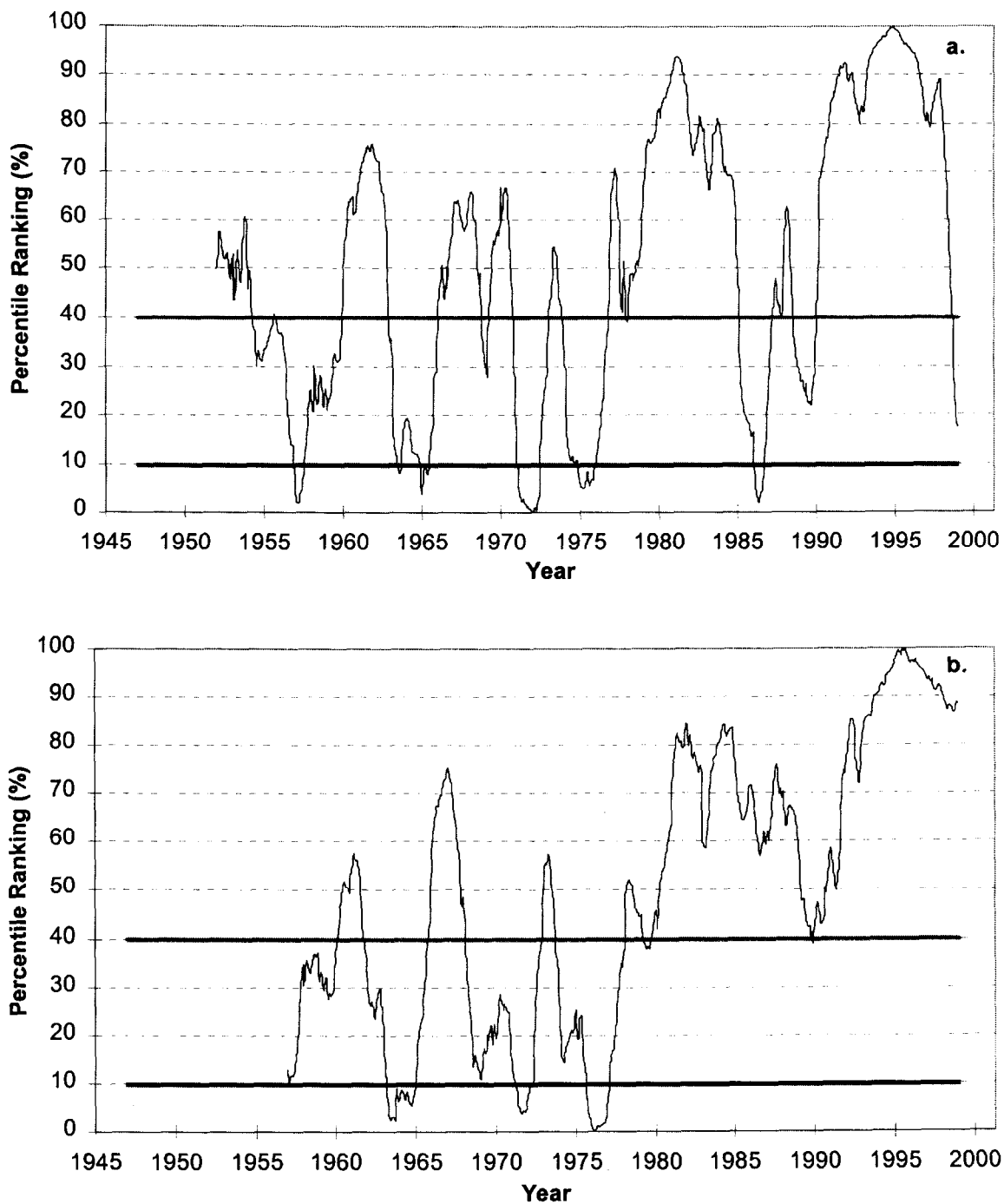


Fig. 3.4. Percentile ranking of rainfall for Betio relevant to the large freshwater lenses at Bonriki and Buota for a. 60 and b. 120 month accumulated rainfall.

TABLE 3.1 Rainfall statistics for Betio, South Tarawa, for Jan 1947 to Jan 1999.

| Parameters | Totalling Period (months) ¹ | | | | | | |
|--|--|-------------|--------------|-------------|--------------|--------------|-------------|
| | 1 | 4 | 6 | 12 | 30 | 60 | 120 |
| No. of data points | 625 | 622 | 620 | 614 | 596 | 566 | 506 |
| Lowest rain(mm) | 0 | 13 | 55 | 217 | 1809 | 7053 | 15949 |
| Highest rain (mm) | 825 | 1989 | 2855 | 4479 | 9161 | 16660 | 26633 |
| Mean rain in period (mm) | 171.2 | 685.3 | 1030 | 2070 | 5158 | 10381 | 20491 |
| CV (%) ² | 86 | 67 | 61 | 48 | 30 | 18.5 | 11.6 |
| 10 percentile Rain (mm) | 19.6 | 154 | 285 | 735 | 3222 | 8086 | 17730 |
| No. of extreme dry times <10 percentile | 32 | 14 | 11 | 9 | 7 | 6 | 4 |
| Average time between extreme dry periods (mth) | 19 | 45 | 59 | 73 | 67 | 70 | 75 |
| CV (%) ² | 88 | 47 | 63 | 88 | 49 | 65 | 28 |
| Range of times between extreme dry periods (mth) | 2 to 59 | 12 to 83 | 27 to 121 | 5 to 194 | 37 to 121 | 16 to 138 | 54 to 96 |
| Average duration of extreme dry periods (mth) | 2 | 5 | 6 | 7 | 8 | 10 | 13 |
| CV (%) ² | 76 | 66 | 53 | 67 | 95 | 58 | 69 |
| Range of durations of extreme dry periods (mth) | 1 to 7 | 1 to 11 | 3 to 11 | 1 to 12 | 1 to 22 | 3 to 18 | 1 to 22 |

¹ The totalling period is the number of preceding months over which rainfall has been totalled

² CV(%) = 100x(Standard Deviation)/Average.

Table 3.2 shows that for rainwater tanks on South Tarawa we can expect, on average, that water shortages will be experienced approximately every 4 to 5 years and that these shortages will last, again on average, between 5 and 6 months. For domestic wells, water shortages will be experienced, on average approximately, every 6 years and will last, on average, between 7 and 8 months. Spectral analyses of the relationship between coral ¹⁸O concentrations and rainfall suggest ENSO correlated events have occurrence frequencies centred on 5.6, 3.6, 3.0 and 2.2 years, with a possible increase in events occurring with a frequency of 5.6 years taking place between 1930 and 1950 (Cole *et al.*, 1993). This frequency is consistent with the crude mean interval between droughts in Table 3.2.

The frequency and severity of dry periods and the difficulties they pose for providing secure water supplies for an expanding population in South Tarawa has been recognised for some time. It was one reason for the development of the more secure Bonriki and Buota freshwater lenses and the associated, reticulation system. For the freshwater lenses at Bonriki or Buota, periods of lower recharge will occur, on average also about every 6 years and will last for 10 to 13 months. For these storages, the 10 percentile rainfalls for the 5 and 10 year accumulation periods are equivalent to 1617 and 1733 mm/year over the 5 and 10 year

period. The water demand on this lens through interception losses, evapotranspiration from groundwater and pumping losses amounts to about 1420 mm/year (White *et al.*, 1999). Therefore, even in these “extreme dry” periods for the 5 and 10 year rainfall accumulation periods, there is still significant rainfall for recharge of the freshwater lens, provided demand and losses are controlled. Finally, it is noted that the “average” expected values of duration and period between droughts are drawn from a range of possible lengths of times which are also listed in Table 3.2.

Table 3.2 Characteristics of extreme dry periods relevant to the different water sources in Betio, South Tarawa for the period 1947 to 1999.

| Parameters | Water Source | | |
|---|-----------------|----------------|--------------|
| | Rainwater Tanks | Domestic Wells | Bonriki Lens |
| No. of extreme dry periods (<10 percentile) | 11 to 14 | 7 to 9 | 4 to 6 |
| Average time between extreme dries (mth) | 45 to 59 | 67 to 73 | 70 to 75 |
| Range of times between dries (mth) | 12 to 121 | 5 to 194 | 16 to 138 |
| Average duration of extreme dries (mth) | 5 to 6 | 7 to 8 | 10 to 13 |

3.3.2 Comparison of Standardised Precipitation Index with the Decile Method

Fig. 3.5 shows a comparison between the standardised precipitation index, calculated for 4 and 6 monthly rainfall summation periods using square rainfall transformation with the decile method for the entire rainfall record. Fig. 3.6 shows the same comparison for the 4 month data for the period 1980 to January 1999. There is clearly little difference between the methods. The added complication involved in transforming the data therefore suggests that the decile method is adequate for identifying extreme conditions.

3.2.3 Comparison of Rainfall Depreciation Method with the Decile Method

Fig. 3.7 shows the comparison between the rainfall depreciation method (RDM ranked as a percentile) using 10% monthly rainfall depreciation and the decile method for 12 month rainfalls. The figure shows the comparison for the whole rainfall record and the period from 1980 onwards. The close correspondence between the two methods is obvious. Examination of the expanded record from 1980 onwards reveals that the rainfall depreciation method leads the standard decile method by about 1 month in terms of the occurrence of extreme dry periods. Since the rainfall depreciation method involves extra assumptions and computations, and since it provides no extra information over simple summation for the identification of extreme events, its use may not be warranted. However, the lead time of one month, may make it worthwhile in terms of drought prediction.

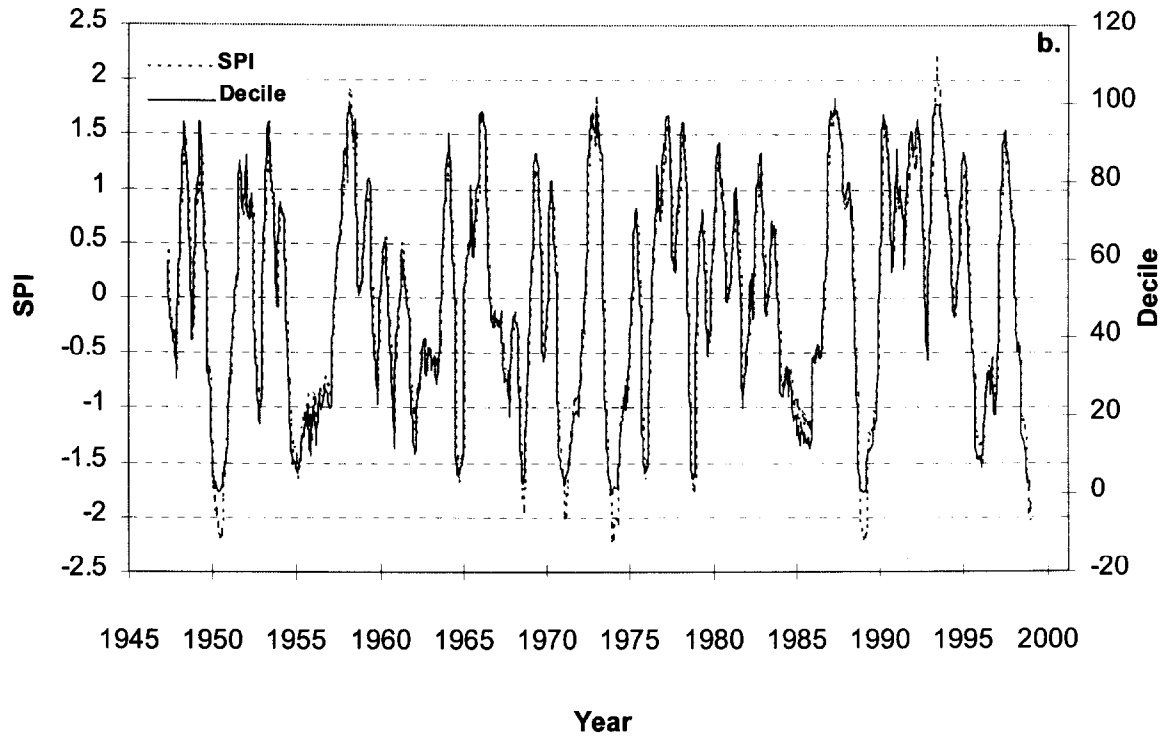
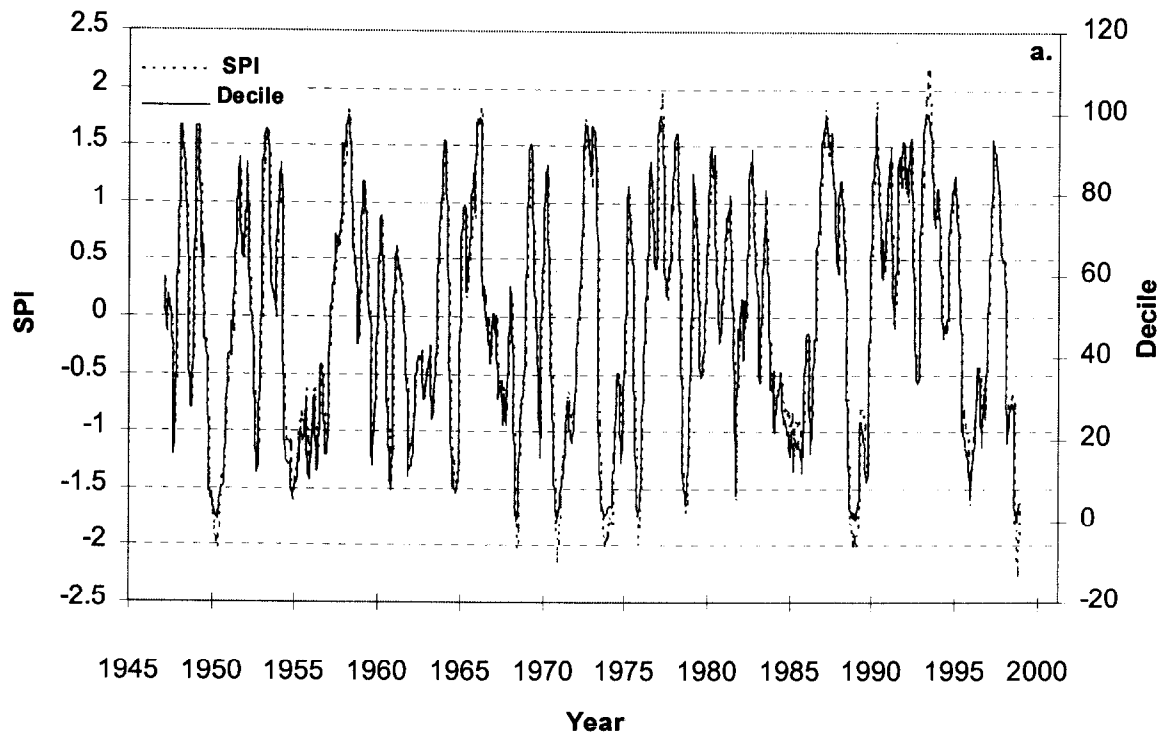


Fig. 3.5 Comparison between the standardised precipitation index, SPI, (dashed line) and decile method (solid line) for a. 4 and b. 6 month rainfall accumulation periods.

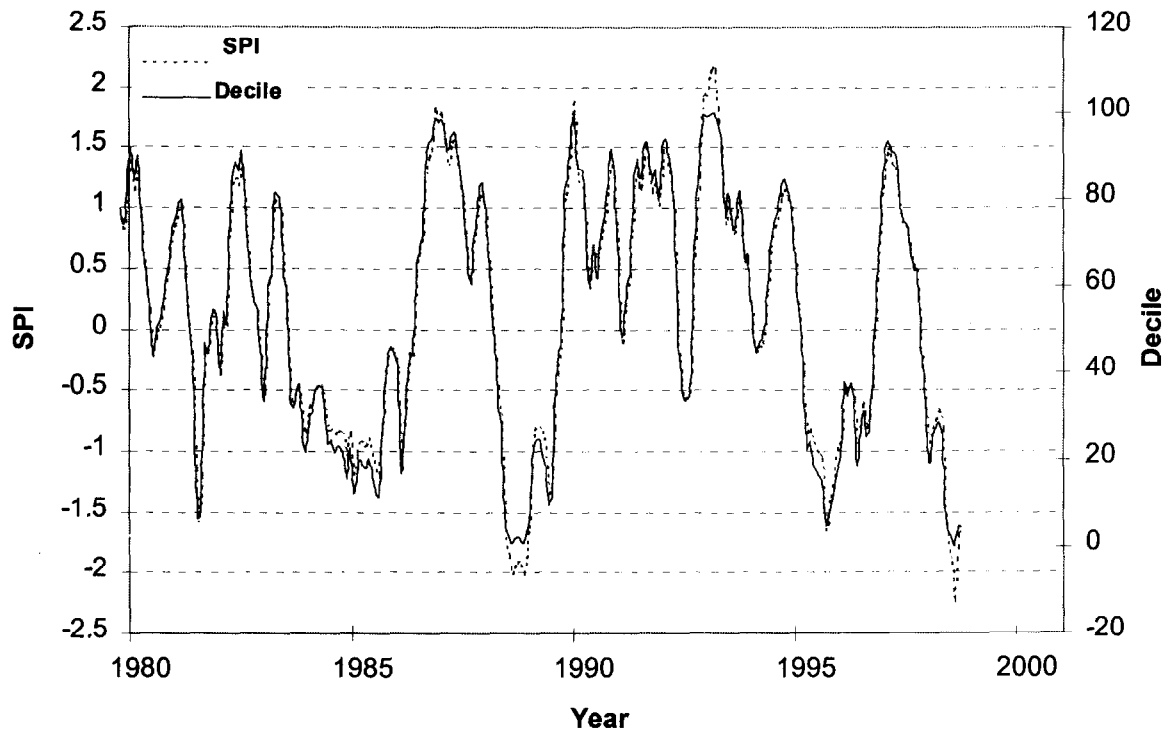


Fig. 3.6 Comparison of the standardised precipitation index, SPI, (dashed line) with the decile method (solid line) for 4 monthly rainfall accumulations for the period 1980 to Jan 1999.

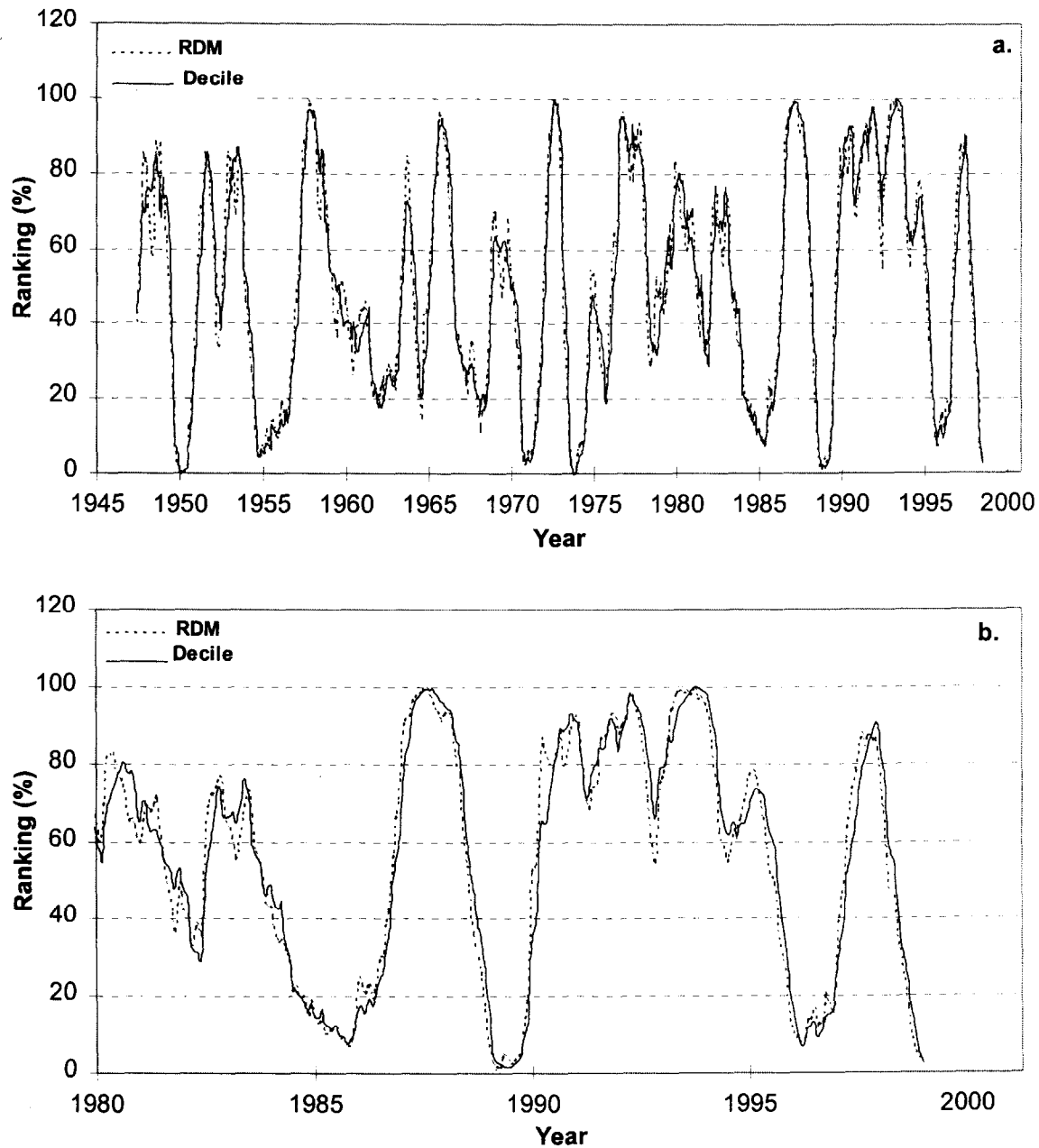


Fig. 3.7 Comparison of the rainfall depreciation method expressed as a decile (dashed line) with the decile method (solid line) for 12 month rainfall periods for a. the full rainfall record and b. the period from 1980 to 1999.

3.3 Impact of Seasonality of Rain

The impact of assuming that the rains are seasonal on the rainfall rankings was considered for periods of 1, 4, 6 and 12 months by comparing rankings calculated for the month in question only (seasonal) with those calculated using all the rainfall record (non-seasonal). The comparison between ranking methods is shown in Fig. 3.8 for 4, 6 and 12 month periods. It can be seen, as expected, that the inclusion of seasonality makes only small difference for the 4 and 6 month data and insignificant differences for the 12 month interval.

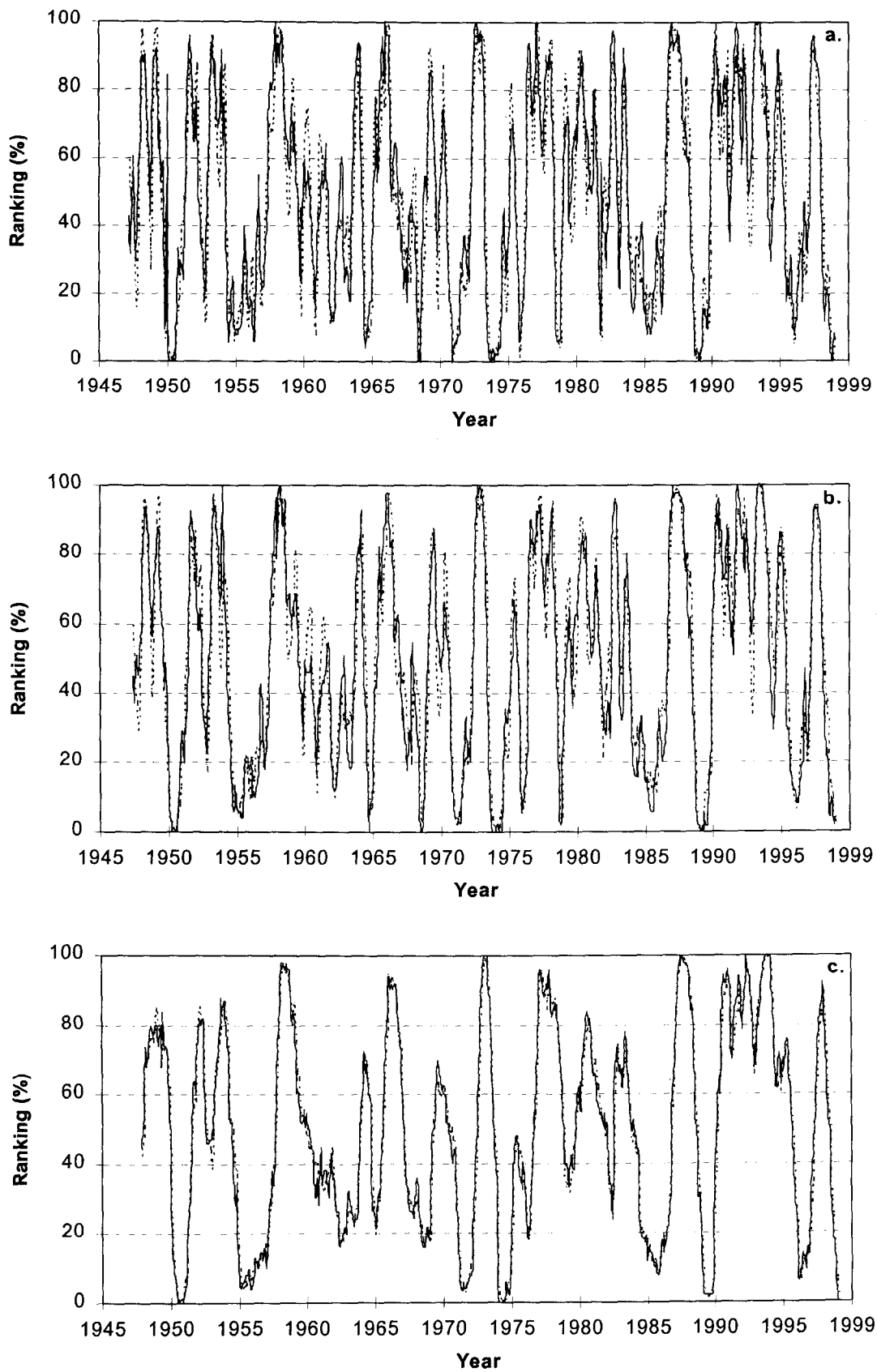


Fig. 3.8 Comparison between the rankings for rainfall which take into account seasonal rainfall (solid line) with those which do not (dashed line) for a. 4, b. 6 and c. 12 month intervals.

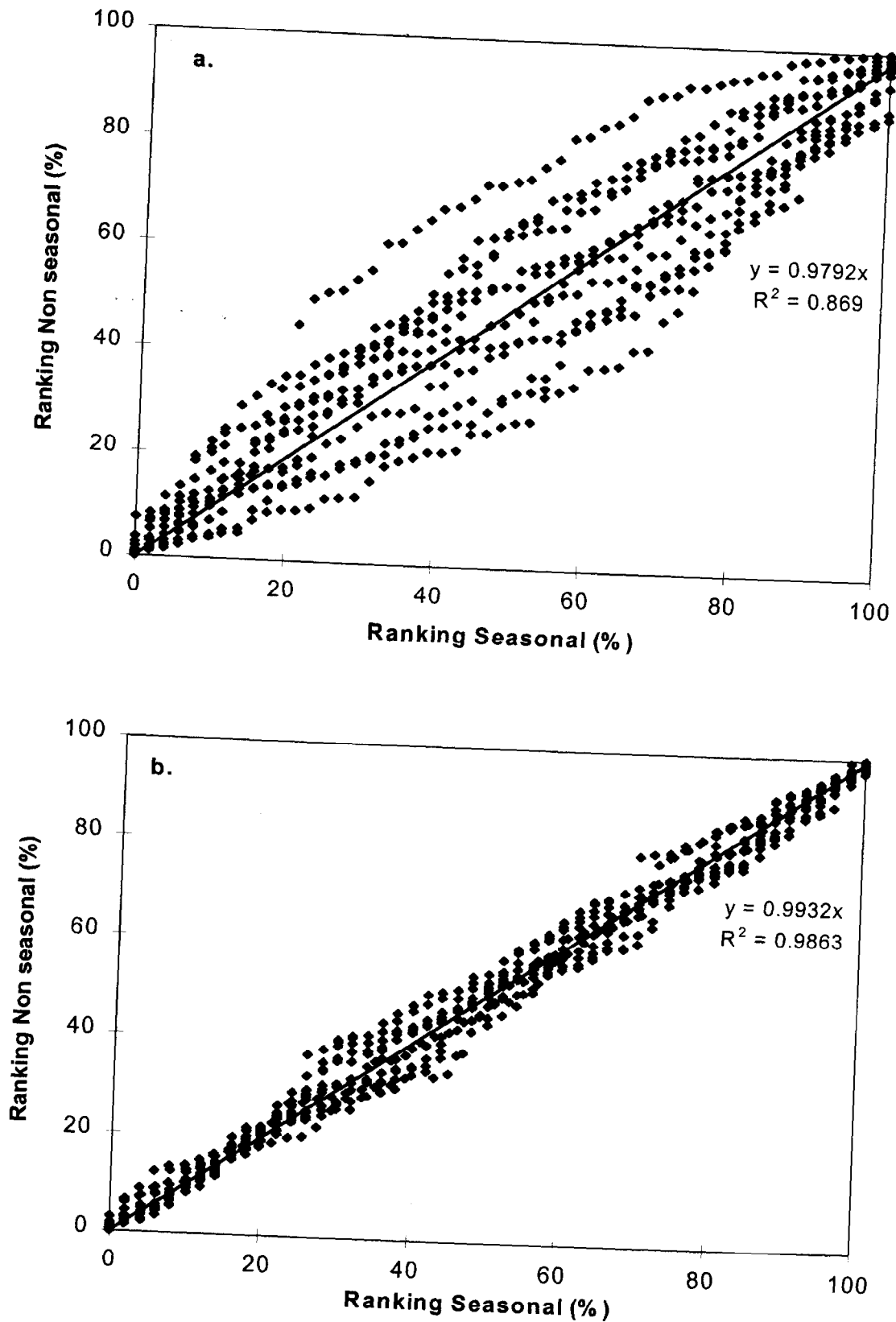


Fig. 3.9. Correlations between rankings for rainfall adjusted for seasonal dependence with rankings with no seasonality for a. 1 month and b. 12 month rainfall accumulation periods.

The correlation coefficients between the ranking for seasonal and nonseasonal treatments are listed in Table 3.3 and the correlations for 1 and 12 months are shown in Fig. 3.9.

TABLE 3.3 Correlation between seasonal and nonseasonal rainfall rankings for selected rainfall accumulation periods.

| Rainfall Period (mths) | Correlation Coefficient |
|---------------------------|-------------------------|
| 1 | 0.9352 |
| 4 | 0.9344 |
| 6 | 0.9539 |
| 12 | 0.9934 |

It can be seen from Figs 3.8 and 3.9 as well as Table 3.3 that, as expected, for the 12 month data the impact of including seasonality of rain is insignificant. For the shorter time scales, 1, 4 and 6 months there is a discernible impact of the seasonal variation of rains. Examination of Fig. 3.8 shows, however, that the inclusion of seasonal variation does not effect the identification of extreme dry periods. We caution that, while this conclusion for rainfall periods of 12 months or longer is probably generally valid, for shorter periods it is specific to the case considered here, South Tarawa.

4. Severity, relation with the SOI, corals and drought warnings

4.1 Severity of droughts

The results of the rainfall rankings can be used to compare the severity of droughts for different rainfall periods. This severity can be ranked in three ways; the lowest percentile ranking obtained; the duration of the drought (period <10%); and the average ranking over the drought period. Here we shall concentrate on the lowest ranking obtained. Tables 4.1, 4.2, and 4.3 show the 5 worst droughts in the period 1947-1999 for rain tanks (4 to 6 months), domestic wells (12 to 30 months) and the large freshwater lenses (60 to 120 months).

TABLE 4.1 Ranking of the five worst droughts over the period 1947-1999 for rain tanks. (The lowest percentiles attained are shown in parenthesis.)

| Ranking of Worst Droughts | 4 Month Rainfalls | | 6 Month Rainfalls | |
|---------------------------|-------------------|-----------------|-------------------|-----------------|
| | Start Date (%) | Duration (mths) | Start Date (%) | Duration (mths) |
| 1. | Sep 98 (0.0) | ? | Sep 73 (0.0) | 10 |
| 2. | Nov 70 (0.1) | 6 | Nov 88 (0.6) | 6 |
| 3. | Nov 49 (0.3) | 11 | Jan 50 (0.8) | 11 |
| 4. | Sep 88 (0.6) | 8 | Nov 98 (1.6) | ? |
| 5. | Oct 75 (1.2) | 3 | Nov 70 (2.2) | 7 |

It is noted here that for longer rainfall periods the onset of drought is delayed by approximately half the rainfall period. It is clear from Tables 4.1 to 4.3 that there is no unique 'worst drought' for all water storages. However we can say that the 1949/50, 1973/74, 1988/89 and 1998/99 droughts were all significant droughts which would have had major impacts over most of the water storages. It is interesting that the concentrations of the isotope ^{18}O in coral records show similar anomalies at these periods (Cole *et al.*, 1993).

TABLE 4.2 Ranking of the five worst droughts over the period 1947-1999 for domestic wells. (The lowest percentiles attained are shown in parenthesis.)

| Ranking of Worst Droughts | 12 Month Rainfalls | | 30 Month Rainfalls | |
|---------------------------|--------------------|-----------------|--------------------|-----------------|
| | Start Date (%) | Duration (mths) | Start Date (%) | Duration (mths) |
| 1. | Jan 74 (0.0) | 12 | Nov 55 (0.0) | 22 |
| 2. | Apr 50 (0.1) | 12 | Aug 85 (1.5) | 16 |
| 3. | Feb 89 (1.4) | 9 | Jul 75 (2.6) | 10 |
| 4. | April 71 (2.0) | 9 | Nov 71 (6.7) | 5 |
| 5. | Dec 98 (2.6) | ? | Oct 68 (7.5) | 4 |

TABLE 4.3 Ranking of the five worst droughts over the period 1947-1999 for large freshwater lenses. (The lowest percentiles attained are shown in parenthesis.)

| Ranking of Worst Droughts | 60 Month Rainfalls | | 120 Month Rainfalls | |
|---------------------------|--------------------|-----------------|---------------------|-----------------|
| | Start Date (%) | Duration (mths) | Start Date (%) | Duration (mths) |
| 1. | Feb 71 (0.0) | 18 | Oct 75 (0.0) | 16 |
| 2. | Mar 86 (1.7) | 7 | Apr 63 (2.1) | 22 |
| 3. | Dec 56 (1.9) | 8 | Apr 71 (3.9) | 12 |
| 4. | Nov 64 (3.7) | 8 | Jan 57 (9.9) | 1 |
| 5. | Sep 74 (4.9) | 16 | | |

4.2. Relationship with the Southern Oscillation Index

The relationship between extreme wet and dry periods in the central Pacific and El Niño and La Niña events respectively is well documented (Falkland and Brunel, 1993; Evans *et al.*, 1998). Rainfall in Tarawa is strongly negatively correlated with the Southern Oscillation Index, SOI, which is defined as:

$$SOI = 10. \frac{\Delta p - \mu_{\Delta p}}{\sigma_{\Delta p}} \quad [8]$$

with Δp the mean monthly sea level pressure difference between Tahiti and Darwin, $\mu_{\Delta p}$ and $\sigma_{\Delta p}$ the long term mean and standard deviation of the pressure difference for the month in question. As defined, the SOI is a standardised index which takes into account seasonality of pressure differences between Tahiti and Darwin. The monthly SOI for the period 1947 to

1999 is shown in Fig. 4.1. The extreme dry conditions in Tarawa are normally associated with strongly positive values of the SOI (*La Niña* events).

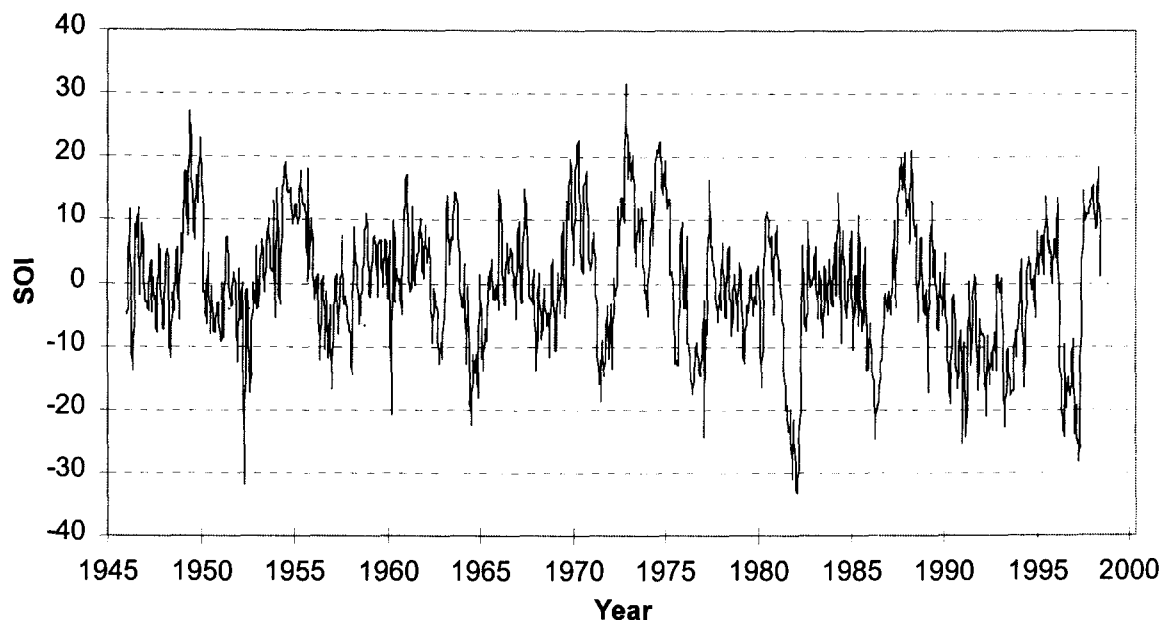


Fig. 4.1 The monthly Southern Oscillation Index (SOI) for 1947 to 1999.

Because drought events in Tarawa are associated with *La Niña* events when the SOI is strongly positive, we will here examine the rankings of rainfall over selected periods with the rankings of the accumulated negative SOI over the same period.

Figs 4.2, 4.3 and 4.4 show the relationship between the rankings of rainfall and the negative SOI for 4, 6, 12, 30, 60 and 120 month periods. Table 4.4 lists the correlation between the ranking of the negative correlation index and the ranking of the rainfall over selected periods. The form of that correlation is shown in Fig. 4.5 for the 12 month data..

TABLE 4.4 Correlations between ranked negative SOI and ranked accumulated rainfalls for selected accumulation periods.

| Time Period (mths) | Correlation Coefficient |
|--------------------|-------------------------|
| 1 | 0.5155 |
| 4 | 0.7206 |
| 6 | 0.7571 |
| 12 | 0.8219 |
| 18 | 0.8019 |
| 24 | 0.7622 |
| 30 | 0.7189 |
| 60 | 0.6222 |
| 120 | 0.7759 |

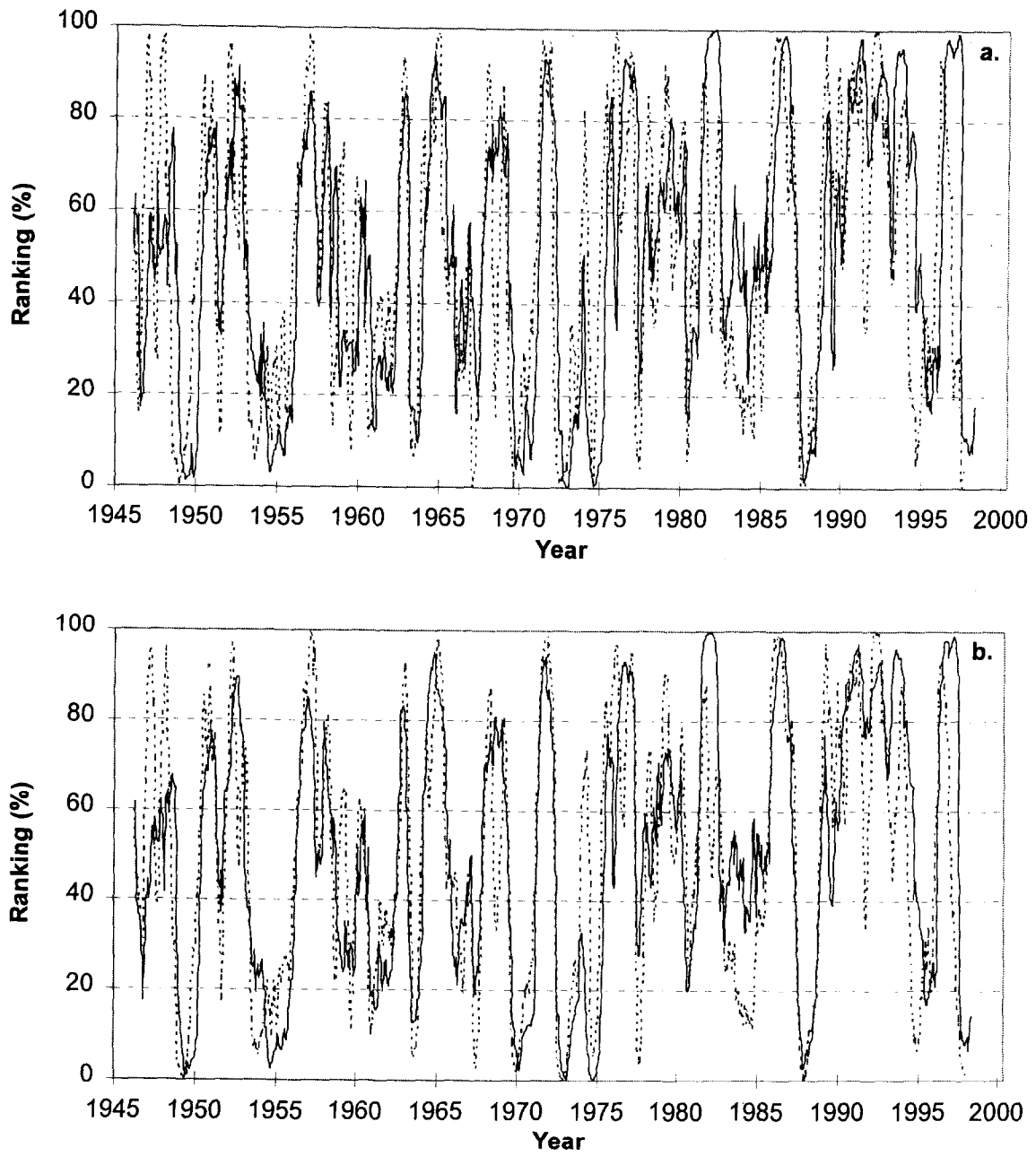


Fig. 4.2 Comparison of percentile rankings for rainfall (solid line) and for the negative SOI (dashed line) for a. 4 and b. 6 month accumulation periods.

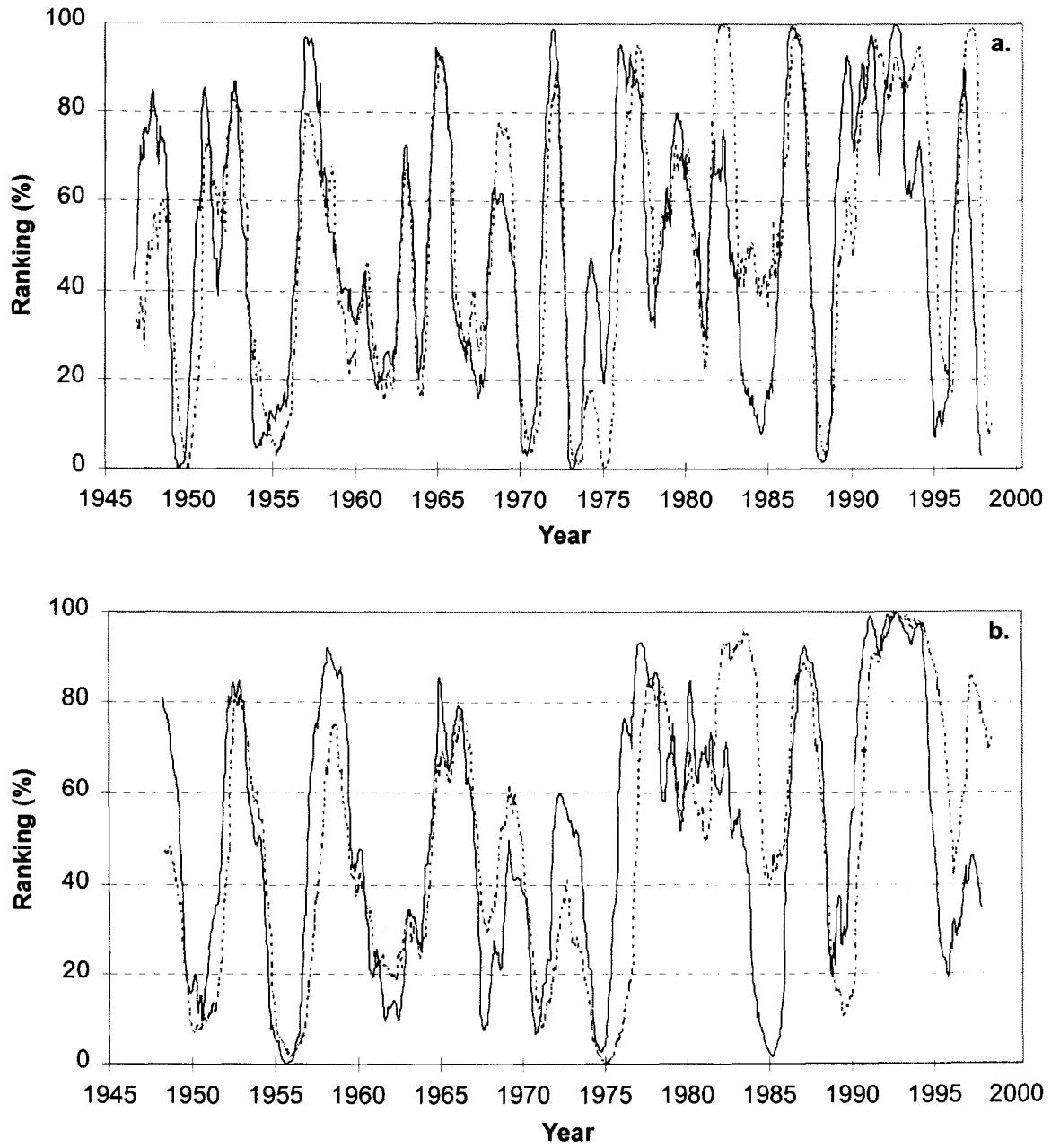


Fig. 4.3. Comparison of percentile rankings for rainfall (solid line) and for the negative SOI (dashed line) for a. 12 and b. 30 month periods.

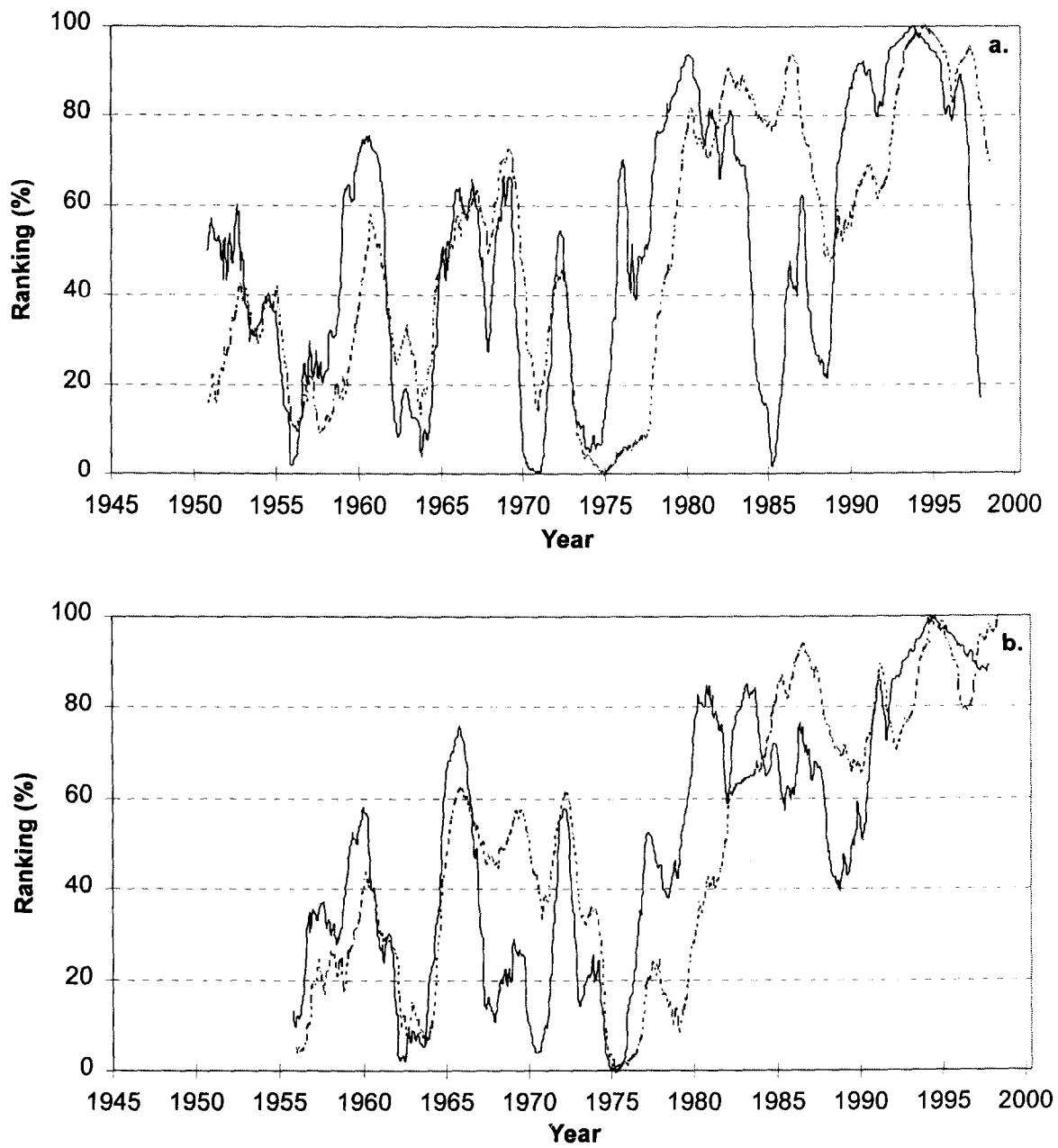


Fig. 4.4. Comparison of percentile rankings for rainfall (solid line) and for the negative SOI (dashed line) for 60 and 120 month periods.

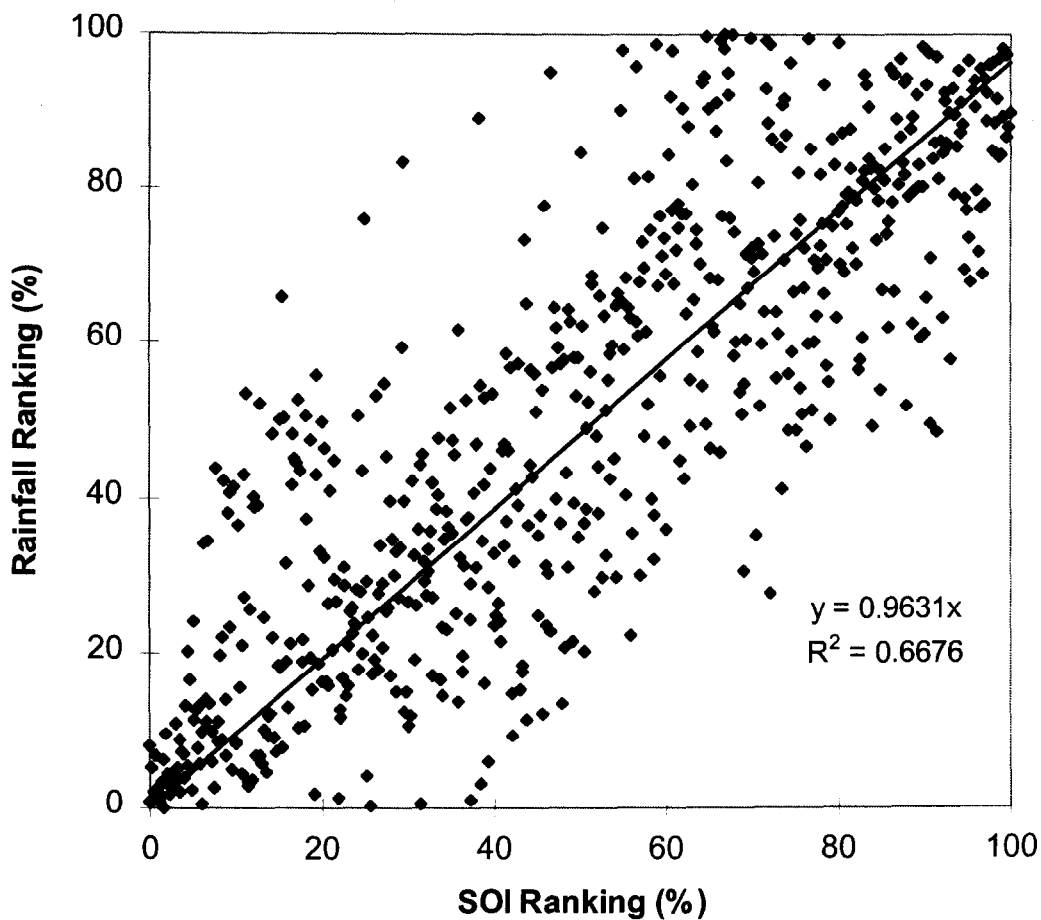


Fig. 4.5 Correlation between rainfall percentile ranking and SOI percentile ranking for 12 month accumulation periods.

It can be seen in Table 4.4 that the correlation between rankings increases from 0.52 for 1 month data to a maximum of 0.82 for 12 month data and then decreases for longer accumulation periods. For the 12 month data, 67% of the variance is attributable directly to the SOI. The maximum correlation at the 12 month time span is somewhat surprising given the recurrence interval of 3 to 8 years for ENSO events.

The above treatment has assumed that the SOI and rainfall are perfectly in-phase. Examination of Figs 4.2 to 4.4 shows that there appears to be a lag between the SOI and rainfall with rainfall leading the SOI, particularly for summation periods of 12 months or longer. For the 12 month data it was found that the maximum correlation between SOI ranking and rainfall ranking occurred at a lag of -1 month, that is rainfall deficit preceded the SOI by 1 month. For longer accumulation periods this lag was between -2 months and -5 months. A possible explanation of rainfall preceding the SOI could be that the mid-Pacific warm pool reaches Tarawa before it reaches Tahiti. This also indicates that SOI is an imperfect correlator of local rainfall events even in the central Pacific.

4.4 Relationship with Coral Chemistry

The variability of the oxygen isotope, ^{18}O concentration in the coral mineral aragonite is a function of both the temperature and ^{18}O concentration of the surface seawater in which

the coral skeleton is secreted (Cole *et al.*, 1993; Fairbanks *et al.*, 1997; Evans *et al.*, 1998). It has been shown that the interannual variability of ^{18}O concentration in corals, together with other tracers such as the ratio of strontium to calcium, can be used to reconstruct past climate records, or at least past ENSO events or sea surface temperatures, and extend them beyond the relatively short period of instrumental measurements (Cole *et al.*, 1993, Fairbanks *et al.*, 1997). This means that coral cores have the potential to provide much longer records of droughts in the region than exist at present.

Concentrations of ^{18}O are usually expressed as $\delta^{18}\text{O}$ (in parts per thousand or per mil), with:

$$\delta^{18}\text{O} = 1000 \cdot \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \quad (4-1)$$

Here, R_{sample} is the concentration in the sample and R_{standard} is a reference standard (for coral aragonite the usual standard is Pee Dee belemnite (PDB)).

The intense rainfalls at Tarawa atoll can alter the salinity of the ocean surface by up to 4 parts per thousand. The surface mixed layer in the region is highly variable averaging 29 ± 26 m and reflects the influence of rainfall variability and winds. The concentration of ^{18}O in the sea surface is a linear function of salinity [measured in parts per thousand] (Fairbanks *et al.*, 1993):

$$\delta^{18}\text{O}_{\text{seawater}} (\text{‰ SMOW}) = 0.273 \cdot \text{Salinity (ppt)} - 9.14 \quad (4-2).$$

Here the ^{18}O concentration is measured as in equation 4-1 but relative to mean standard ocean water (SMOW). The coral, growing at rates of between 5 and 15 mm/day, reflects those changes in concentration and salinity. Fig 4.6 shows the ^{18}O record from a coral core at Tarawa (Cole, 1993).

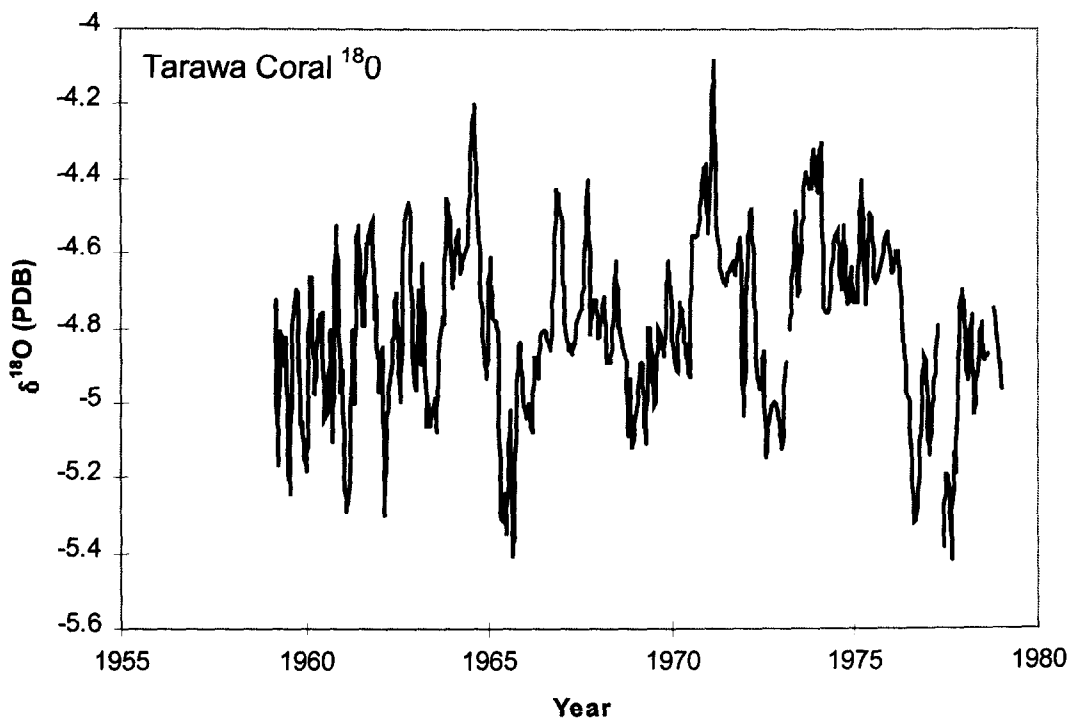


Fig. 4.6 Relative concentration of ^{18}O in coral at Tarawa (Cole, 1993)

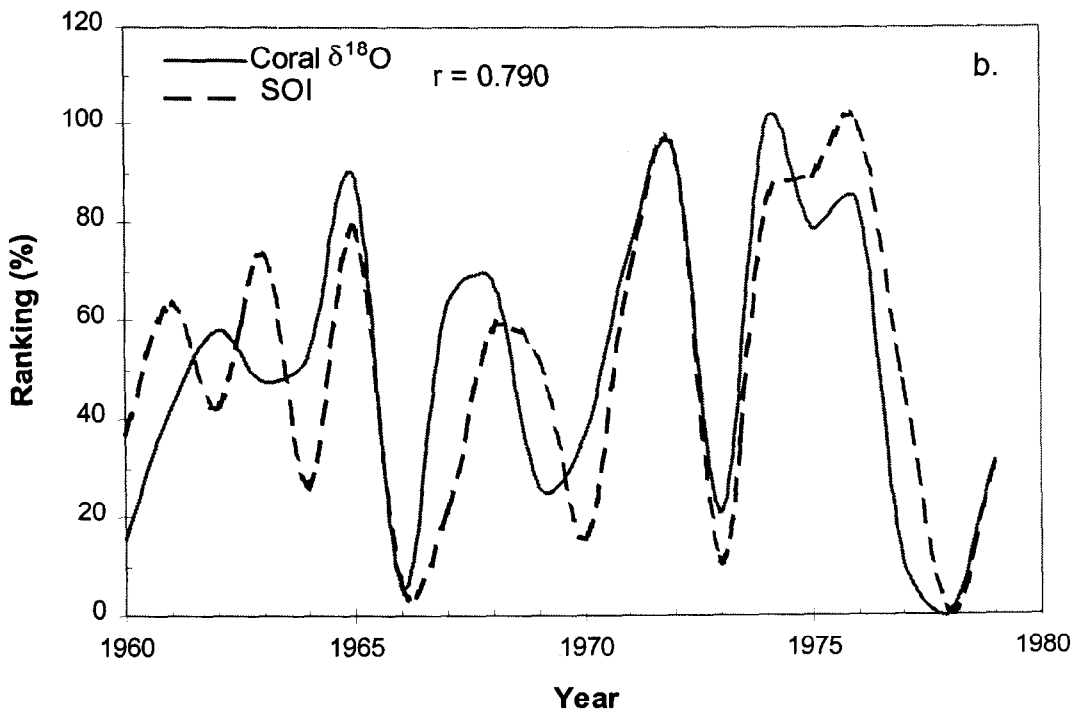
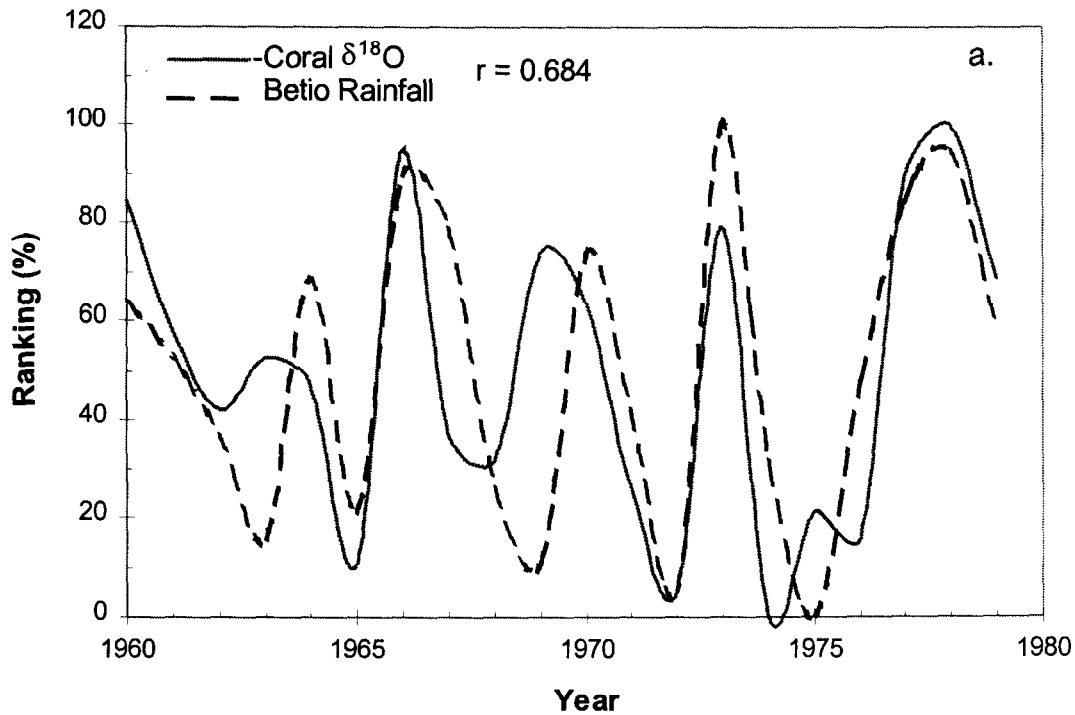


Fig. 4.7 Correlations between annual coral ^{18}O concentrations and rainfall and SOI expressed as rankings: a. rainfall at Betio and negative ^{18}O concentration in coral; b. SOI and ^{18}O Concentration in coral.

The relation between mean annual coral $\delta^{18}\text{O}$ and annual rainfall at Betio and SOI index, all expressed as percent ranking for the actual year, are shown in Fig. 4.7. In Fig 4.7 a the negative ^{18}O concentration in coral. The annual signals can be seen to be highly correlated,

with rainfall and coral ^{18}O having a correlation coefficient of 0.684 while SOI and coral ^{18}O have a correlation of 0.79. It is clear that these relations are encouraging and offer the potential of being able to reconstruct the drought record of Tarawa, beyond the record of rainfall measurement.

4.3 Drought warnings

It is clear from the above that the SOI cannot be used to forecast extended dry periods in Tarawa. A question which arises from this work is: can the rainfall decile rankings themselves be used to give warnings of impending extreme dry conditions? Examination of the results in Figs 3.1 to 3.4 reveals that the rainfall time series are approximately broken up into extremely wet periods and dry periods. The transitions between wet and dry are usually relative rapid. It may be possible to select a percentile as a warning indicator so that once the totalled rainfall drops below that value, a warning is given of impending dry periods and appropriate strategies can be put in place.

Previous work has suggested that the 50 percentile may be an appropriate warning level (Gibbs, 1975). Inspection of the results in Figs 3.1 to 3.4 suggest that the 40 percentile level may provide an indicator which gives fewer false warnings. The 40 percentile level is highlighted in these figures. Table 4.5 and Fig. 4.8 show the number of false relative to correct warnings of extreme dry periods using the drop in rainfall record through the 40 percentile level to provide warnings of impending extreme dry periods.

TABLE 4.5 Use of the descent of the rainfall record through the 40 percentile level to indicate impending extreme dry periods.

| Water Source | Rainwater Tanks | | Domestic Wells | | Bonriki Lens | |
|--|-----------------|--------|----------------|---------|--------------|----------|
| Totalling Period (months) | 4 | 6 | 12 | 30 | 60 | 120 |
| 40% Rain (mm) | 444 | 709 | 1775 | 4646 | 9780 | 19698 |
| Mean warning time at 40 percentile (mth) | 4 | 3 | 6 | 10 | 12 | 26 |
| CV (%) | 102 | 58 | 76 | 74 | 58 | 37 |
| Range of warning periods (mth) | 1 to 14 | 1 to 7 | 1 to 15 | 4 to 25 | 4 to 24 | 18 to 37 |
| No. false /No. correct warnings | 15/14 | 11/11 | 9/9 | 2/7 | 4/6 | 2/4 |

Table 4.5 and Fig. 4.8 show that, on average, if we use the 40 percentile as a warning indicator for impending dry periods we will get 3 to 4 months of warning for rainwater tanks, 6 to 10 months warning for domestic wells and 12 to 26 months warning for the Bonriki freshwater lens. We note, however, for rainwater tanks that the warning time may be as little as 1 month, for domestic wells it may be 1 to 4 months, while for the Bonriki lens the minimum warning time observed so far is 4 months.

Table 4.5 and Fig. 4.8 also suggest that, if we use the rainfall record dropping below the 40% level as a warning, a number of false predictions of extreme dry periods will be made, in addition to correct prediction of all dry periods. Based on the rainfall record to date, Fig. 4.6 shows that, for rainwater storages, these warnings predicted twice as many extreme

dry periods as actually occurred. For domestic wells it predicted between 1.3 to 2 times as many extreme dry periods while for the large freshwater lenses it predicted 1.5 times the number of drier events. While this 40 percentile level predicts more severe dry periods than occurred, these false predictions should be no impediment for its use, since they would trigger water conservation measures.

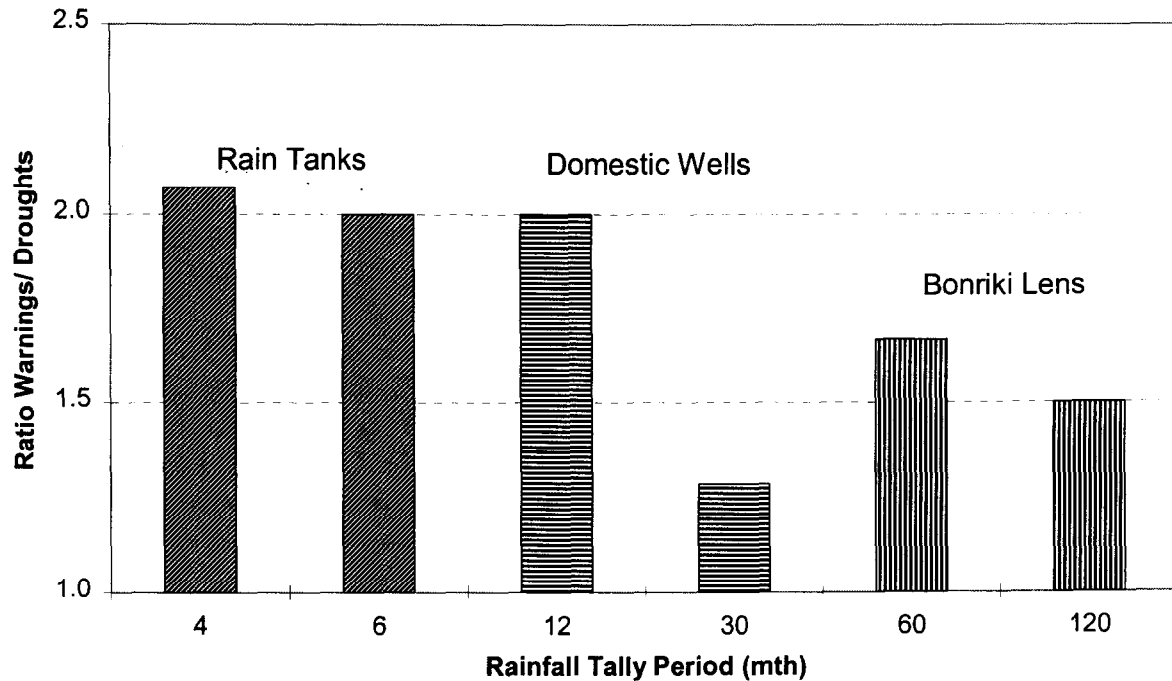


Fig. 4.8 The ratio of total number of warnings to correct warnings of drought (<10 percentile rainfall) for different rainfall tally periods using data for Betio, South Tarawa, from 1947-1999. Note that all severe dry periods were predicted.

5. Patterns of Drought, the 1998-9 Drought and Impacts on Major Groundwater Reserves

5.1 Patterns of Drought

Falkland (1999b), in using the rainfall depreciation method over 12 month intervals, found that many of the extreme dry periods appeared to have similar patterns in time. To test this observation, we plot in Fig. 5.1 the shape of the significant drought periods since 1947. We here assume, arbitrarily, that the drought begins when the rainfall ranking drops below 40% and ends when the ranking rises above 40%. Fig. 5.1 shows the comparison for 12 month rainfall accumulation periods.

A similarity in pattern for most droughts is apparent in Fig. 5.1 with most droughts lasting between 15 and 18 months. The notable exception is the 1954-7 drought which lasted 34 months. It can be also seen that the onset of the 1973-5 drought was more rapid than all the others. We note that, if the 1998-9 drought follows a similar pattern, it still has some months to run.

5.2 Severity of the 1998-9 Drought

The declaration of a national state of disaster in parts of the Republic of Kiribati highlighted the need to assess quantitatively the severity of drought (Falkland, 1999b). Part of the problem in identifying the severity of drought is determining the demands for water from the various sources. In South Tarawa, only the demand on the Bonriki freshwater lens is known with any certainty. With the rapid growth in population that has occurred in South Tarawa since 1945, there has clearly been an escalating demand for water. The water reticulation system at Bonriki was based on initial estimates of per capita demands for water (Harrison, 1980) which have since escalated (Falkland, 1992). Recent estimates of the per capita water demands are as high as 80 L/ day (T. Metutera, pers. com., 1999). The approximate increases in the per capita design demands for water are shown in Fig. 5.2.

The disturbing feature of Fig. 5.3 is that a projected design demand of 80 L/capita/day for the present population of South Tarawa (about 30,000 people) requires abstraction of 2,400 m³/day. This is 1,100 m³/day more than is currently extracted from the Bonriki and Buota water reserves (1,300 m³/day), the only viable large sources of potable water in South Tarawa. At present, restricting water supply is the only method practised for demand management and it is inequitable practiced along South Tarawa. Residents in Betio, at the other end of the atoll, 30 km from the water reserves at Bonriki and Buota, and with the greatest concentration of people, have very limited access, if any to reticulated water due to

leakages and abstractions up stream. While we estimate that an increase in pumping of up to 30% may be possible for the Bonriki freshwater lens (White *et al.*, 1999), an increase of almost 100% is not sustainable.

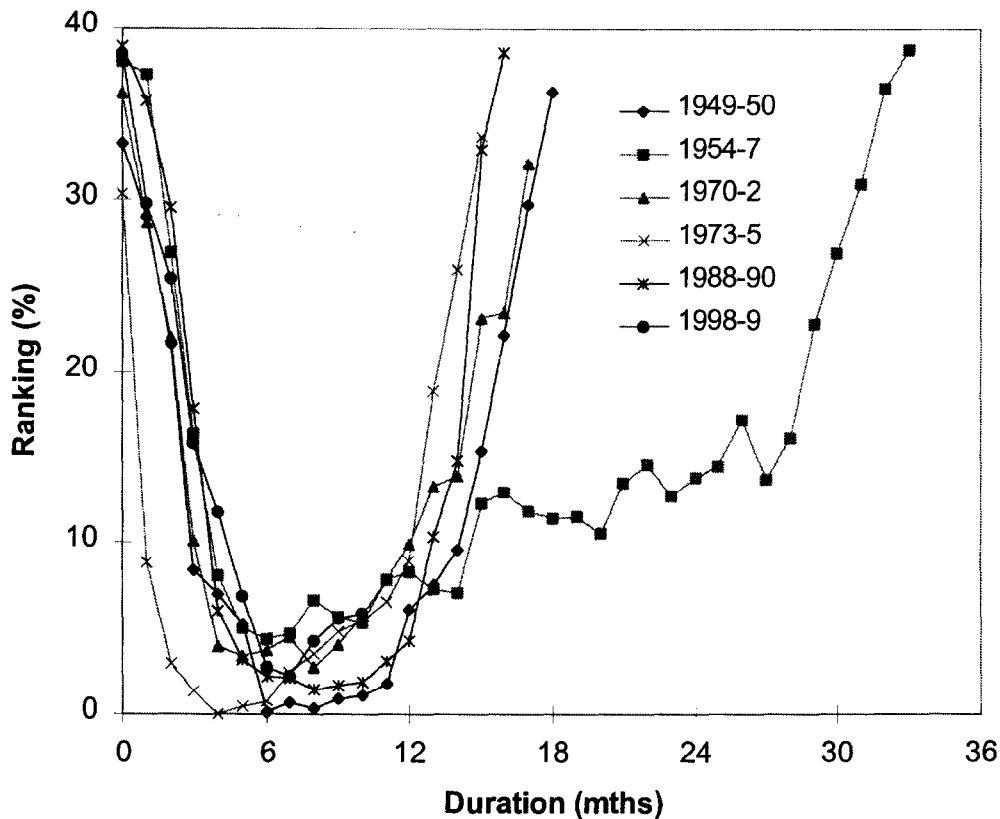


Fig. 5.1 Patterns in time of the major drought periods since 1947 for 12 month rainfall accumulation periods.

The demand for rainwater from storage tanks and from domestic wells appears not to have been quantified despite their importance as sources of water. It is however clear that the increases in population in South Tarawa will have increased pressures on these resources. Since the demand is unknown, but increasing with time, we must solely rely on the rainfall statistics as a means of assessing the severity of the 1998-9 drought.

An additional problem in assessing the severity of the drought is that daily and monthly rainfall data are now not readily available. This is because the Meteorology Division of the Ministry for Environment and Social Development now charges for rainfall data and will not provide monthly data to even other sections within its own Ministry. Despite this, the rainfall record up to May can be ranked against all other rainfalls tallied over the same period for all the available rainfall record. The results are given in Table 5.1.

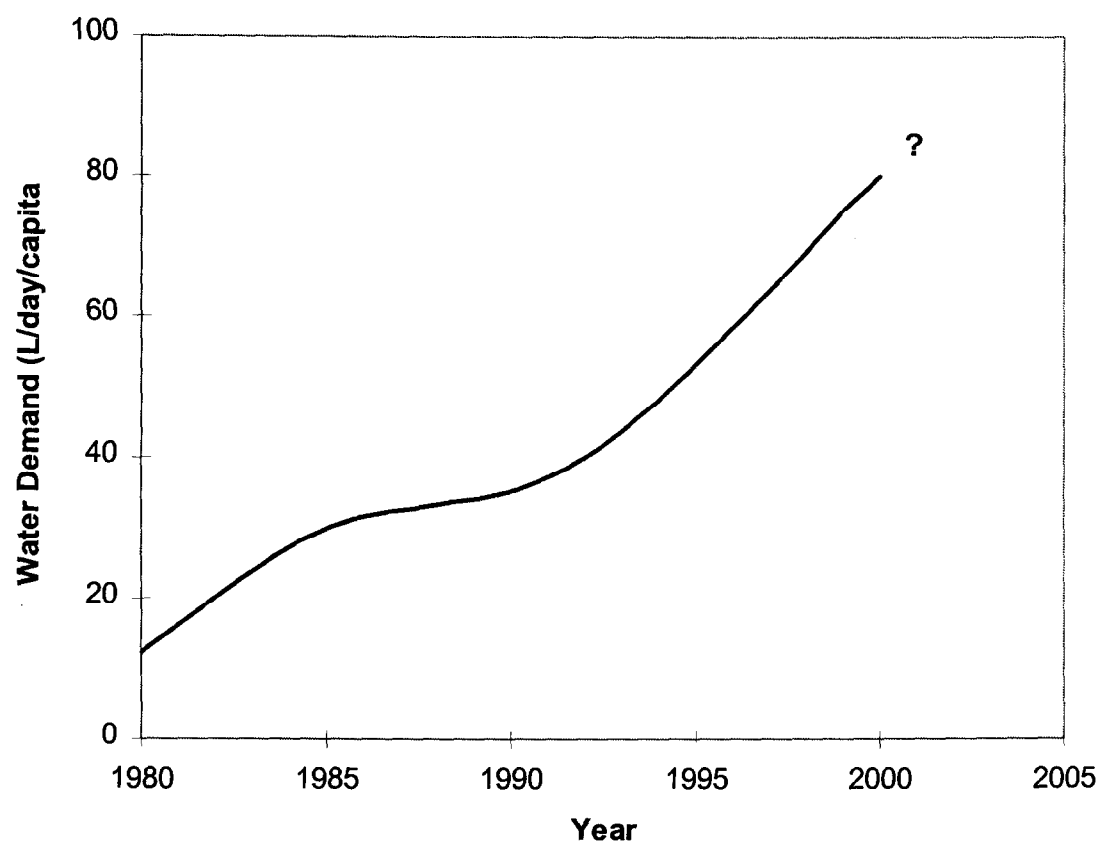


Fig. 5.2. Approximate assumed per capita design demand for water from the water reticulation system for South Tarawa.

Table 5.1 Ranking of the 1998-9 drought against all rainfalls, 1947-1999, for different rainfall totalling periods.

| Water Source | Rainfall Totalling Period (mth) | Lowest Ranking against all Rainfalls for 1998/9 (%) | Month of Lowest Ranking |
|--------------------|---------------------------------|---|-------------------------|
| Rainfall (monthly) | 1 | 0.1 | Jan 1999 |
| Rain Tanks | 4 | 0.0 | Nov 1998 |
| | 6 | 1.6 | Jan 1999 |
| Domestic Wells | 12 | 2.6 | Jan 1999 |
| | 30 | 34.7 | Jan 1999 |
| Bonriki Lens | 60 | 16.8 | Jan 1999 |
| | 120 | 87.5 | Oct 1998 |

Table 5.1 shows that for monthly rainfall, January 1999 was in the lowest 0.1% of monthly rainfall totals. There is only 1 month in the entire monthly rainfall record that has a

lower rainfall. For the totalling periods relative to rain tanks, the four months ending in November 1998 were the lowest 4 months rainfall on record (0.0%). For the 6 month rainfall period, the period preceding January 1999 fell in the lowest 1.6% of values. We can thus conclude that the 1998-9 drought was one of the worst droughts on record for water supply from rain tanks.

For domestic wells, the rainfall for the 12 month period up to January 1999 was in the lowest 2.6% of all 12 month rainfall periods (Table 5.1), however for the 30 month period up to January 1999 the rainfall was approximately in the bottom third of all rainfalls. From this we conclude that domestic wells in narrow islands and islands with high population densities and high demand for well water would have been stressed towards the end of the 1998-1999 drought. Other wells in wider islands and with lower population density, with lower well water demands would have had acceptable water. It is important here that regular monitoring of salinity in a range of domestic wells in locations of different island width and a range of demand pressures be used to monitor the impact of climate on water quality.

For the large freshwater lens at Bonriki, the 60 months up to January 1999 fell within the bottom one sixth of rainfalls while the 120 month data show that rainfall totals are within the top 88% (Table 5.1). It should be emphasised here that for these long tallying periods, the lowest 10 percentile still represents substantial rainfall which would continue to permit long term recharge of the groundwater reservoir. We conclude, therefore, that the 1998-9 drought posed no threat to the main groundwater sources for reticulation in South Tarawa (see also Falkland, 1999b). The principle problem for this source of water is that the reticulation system is now inadequate, due to leakages and unauthorised connections and is unable to supply even rudimentary demands, particularly in the population centres of Betio and neighbouring Bairiki. Some residents there have not received any water through the reticulation system for the past three years. No matter what new sources for reticulated water are brought into production, the inefficiencies in the present distribution system will be the major limitation in supplying demand in these centres (Falkland, 1999b).

An additional issue which must be considered in extreme dry periods is the risk of failure of supply. The 1998-9 drought had reduced the number of water sources from three to in most cases one, the large freshwater lenses at Bonriki and Buota. The reticulation system relies on electric pumps for water extraction and pumping. A prolonged power failure (3 or 4 days) in an extreme dry period such as the 1998-9 drought could have serious consequences. It is noted that the desalination plant also relies on electricity and so does not provide any safeguard of supply in the case of power failure. A solution could be a stand-by generator, or solar-powered pumping. The question of risk in the water supply system during prolonged dry periods and methods of minimising that risk should be further examined.

5.3. Rainfall Deciles and the Thickness of the Freshwater Lens

In the above, we have based our estimates of the time period over which rainfall should be summed for the Bonriki and Buota freshwater lense, on their estimated residence times for water. In order to validate this approach for the main freshwater lens at Bonriki, we compare in Fig. 5.3 the variation in freshwater lens thickness at the centre of the lens with variations in percentile rankings for rainfall totalling periods of 12, 30, 60 and 120 months. Unfortunately the salinity monitoring borehole was vandalised in mid-1998 and these measurements could not be continued into 1999. We have assumed here that the shallow watertable is at a depth of 2 m below the ground surface and have used salinity profiles and a

freshwater electrical conductivity limit of 2,500 $\mu\text{S}/\text{cm}$ to determine the thickness of freshwater. Data is shown from January 1995.

Comparison of the fluctuations in lens depth in Fig. 5.3 with the time series percentile rankings for the four longer totalling periods shows that the longest period used, 120 months, does not show the fluctuations evident in freshwater thickness. Instead the maxima and minima in freshwater thickness best correspond to those for the 60 month period. This is close to the estimated residence time for water in the lens of 5.5 years. It should be noted here that the freshwater lens thickness at its centre is at its lowest (19 m) halfway through the 1998-9 drought. At this thickness, which is 79% of the maximum thickness, the lens still contains large and adequate volumes of freshwater. It is, however, no longer possible to monitor the central thickness of the lens because of vandalism to the salinity monitoring boreholes.

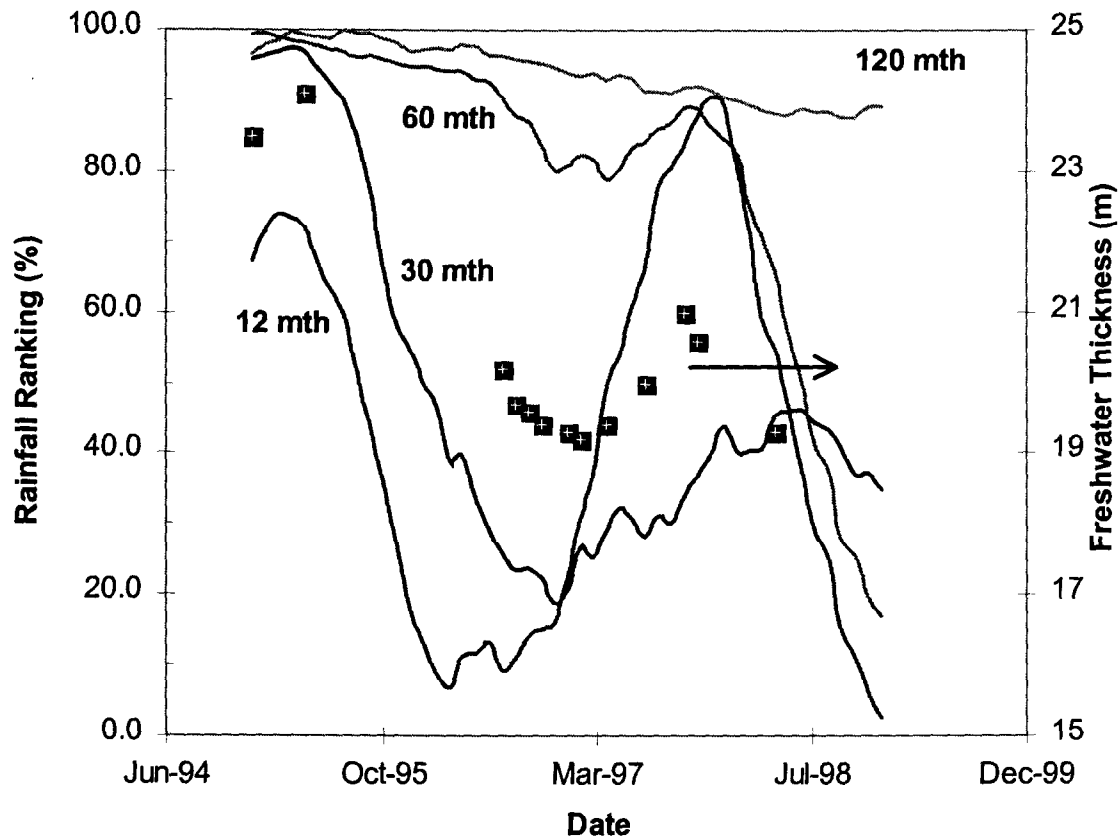


Fig. 5.3 Comparison of the variation in thickness of the freshwater lens thickness (points) with the fluctuations in rainfall percentile rankings for various rainfall totalling times (lines) for the Bonriki freshwater lens.

6. Conclusions

This work has addressed the question of how to assess drought in small, low coral islands, using the particular example of South Tarawa in the Republic of Kiribati. Our concern here is drought which threatens domestic water supplies. We have taken meteorological or climatological drought as the definition of drought to be most appropriate for this situation. We have argued that the question of drought needs to be considered in light of separate sources of domestic water supply. In the case study here in South Tarawa these are rainwater tanks, domestic shallow groundwater wells and the large freshwater lenses used to supply the reticulation system.

A water balance approach is the best way of identifying periods of severe water stress. However, for two of the three water sources, rainwater tanks and domestic wells neither the characteristic volumes nor the demands are known sufficiently accurately for a water balance approach. Faced with this lack of information, we have concentrated on the principal driver for the water balance, rainfall. The techniques considered here were the Palmer Drought Severity Index, the Standardised Precipitation Index, the Decile method and a rainfall depreciation method. The Palmer Index was not used because it essentially applies to agricultural drought; it does not handle different water storages; it requires extra data; and because the assignment of the index is arbitrary. The Standardised Precipitation Index was found to give the same information as the decile ranking of rainfall. It, however, requires an extra step in that rainfall data, particularly for periods less than about 12 months, must be transformed to a normal distribution. The new technique of the rainfall depreciation method, when expressed as a percentile ranking also performs identically to the decile method. Because of the arbitrary assumption of a rainfall discount rate, introduced to place more emphasis on recent rains, this technique is less straightforward than the decile method.

We have used here the decile method with rainfalls expressed as percentile rankings of rainfall, summed over the appropriate time periods, to identify periods of extremely low rainfall, the lowest 10 percentile. We have identified severe drought as the period when the accumulated rainfall drops below the 10 percentile level. The range of rainfall totalling periods were selected to cover the estimated residence time of water in the three storages: 4 to 6 months for rainwater tanks; 12 to 30 months for domestic wells and 60 to 120 months for the large freshwater lenses used to supply the reticulation system. The rainfall record from January 1947 to January 1999 was used to generate the appropriate rainfall statistics. Later data for 1999 was unavailable, apparently due to the charging for data policy of the Meteorological Division of Ministry of the Environment and Social Development.

Using the decile method of ranking dry periods, it was found that severe droughts for rainwater tanks in South Tarawa occur on average approximately every 4 to 5 years and have

an average duration of 5 to 6 months. For domestic wells, severe droughts occur on average every 5.5 to 6 years and last, on average, 7 to 8 months. Because these events are frequent, policy can be developed to address response to drought. The frequency and duration of these events was one of the drivers for the development of the large freshwater lenses as a source of freshwater. For the large freshwater lenses, drier periods occur every 6 years and last on average about 12 months, however, significant recharge still occurs in these drier periods because of the long period over which rainfall is summed and the small variation in rainfalls over these long periods.

The seasonality of rainfall was shown to be only important for rainfall periods less than 12 months, as expected. Even for short periods there was a strong correlation between seasonal and nonseasonal rainfall rankings. For the case study here, South Tarawa, ignoring the seasonal variation in rainfall had no impact on the identification of severe dry periods. By ignoring seasonality a 12 times larger rainfall population is able to be used. For locations with a marked seasonal variation in rainfall, seasonality will need to be taken into account for rainfall periods less than 12 months.

The correlation of rainfall, summed over appropriate periods and expressed as a percentile, with the negative Southern Oscillation Index, also summed over the same period and expressed as a percentile, was examined. For monthly data the correlation was low, 0.52, however this rose to a maximum of 0.82 for 12 monthly intervals after which the correlation decreased for longer periods. The reasons for the decrease in correlations at longer time scales are not obvious. It was found for 12 month or more accumulation periods that maximum correlations between rainfall and SOI occurred when there was a lag between rainfall and the SOI. The rainfall accumulated in these longer time periods was found to lag the SOI between 1 and 5 months.

It was suggested here that an appropriate warning for the onset of severe dry times could be when the accumulated rainfall first drops below the 40 percentile. For rain tanks and domestic wells this will result in 1.3 to 2 times as many warnings as severe droughts, but all droughts will be predicted. The average time lag between the prediction using the 40 percentile and the onset of severe drought (accumulated rainfall below the 10 percentile) for these rainwater tanks was three to four months and for domestic wells was found to be six to ten months. For both these sources of water, the warning period could be as little as one month. For large freshwater lenses, the 40 percentile level over-predicts drier times by about 1.5 times with an average time between prediction and the onset of the drier period of between 12 and 26 months. We note here that with the current rate of water extraction from these large freshwater lenses, these drier periods do not constitute a threat to water supply.

The analyses in this work were used to rank the severity of the 1998/9 drought in South Tarawa. Based on the assumption of the rainfall accumulation periods relevant to the three water sources, the 1998/9 was between the worst on record (for 4 month totalling period) to the lowest 1.6 percentile (for the 6 month totalling period). For domestic wells it was between the lowest 2.6% (for the 12 month totalling period) and the lowest 34.7%. For the large freshwater lenses the dry period was between the lowest 16.8% and 87.5% and the 1998/9 posed no threat to water supply. Rather, supply from these freshwater lenses in dry times is hampered by the inefficiencies in the water reticulation system and the lack of demand management.

The appropriateness of the accumulation times used to assess rainfall rankings to identify dry periods relevant to large freshwater lenses was tested using data on the thickness of the freshwater lens at Bonriki. From this preliminary test it seems that the 60 month totalling time is appropriate for large groundwater sources. This is consistent with the

estimated 5.5 year residence time for water in the lens. The data showed that there was still abundant water in the lens in the 1998/9 drought. This analysis was, however, incomplete due to the unavailability of monthly rainfall data for 1999, and due to vandalism of the central salinity monitoring borehole. This analyses also highlights the need to monitor salinity in a range of domestic water wells for islands with a range of widths and a range of demands.

The use of the 10 percentile level as an indicator of severe drought and the use of the 40 percentile level as a warning trigger remain to be fully examined. Likewise the applicability of the rainfall totalling periods suggested here also should be tested against experience for a range of small island nations and conditions. Data on the size of rainfall catchments, rain tanks and details of water usage from them and from domestic wells should be collected. While the methodologies used here are applicable elsewhere, the results and conclusions are specific to Betio, South Tarawa. It is therefore suggested that support and donor agencies could use this system of ranking rainfall as a method of determining support in dry periods. To do this, appropriate rainfall statistics, details of water supply systems and testing of concepts will be required for small island nations.

Acknowledgments

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Bibliography

- ALLEY, W.M. (1984) 'The Palmer drought severity index: limitations and assumptions.' *J. Climate and Appl. Meteorology*, Vol. 23, p. 1100-1109.
- CHAPMAN, T.G. (1985) 'The use of water balances for water resource estimation with special reference to small islands.' Bulletin No. 4. Pacific Regional Team. Australian Development Assistance Bureau, Canberra, Australia., pp 34.
- COLE, J., 1993 'Tarawa Coral Data Set' IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series # 1993-014. NOAA/NGDC Paleoclimatology Program, Boulder CO, USA.
- COLE, J.E., FAIRBANKS, R.G., AND SHEN, G.T. (1993) 'Recent variability in the Southern Oscillation: Isotopic results from Tarawa coral atoll. *Science*. Vol. 260, pp1790-1793.
- EVANS, M.N., FAIRBANKS, R.G., and RUBENSTONE, J.L. (1998) 'A proxy index of ENSO teleconnections.' *Nature*, Vol. 394, p. 732-733.
- FAIRBANKS, R.G., EVANS, M.N., RUBENSTONE, J.L., MORTLOCK, R.A., BROAD, K., MOORE, M.D., AND CHARLES, C.D. (1997) Evaluating climate indices and their geochemical proxies measured in corals. *Coral Reefs*, Vol. 16, Suppl., pp S93-S100.
- FALKLAND, A. (1992). 'Review of Tarawa Freshwater Lenses.' ACT Electricity and Water, Canberra. Prepared for AIDAB, Canberra.
- FALKLAND, A.C. (1999a) 'Tropical island hydrology and water resources: Current knowledge and future needs.' International Colloquium on Hydrology and Water Management in the Humid Tropics. Panama, 22-25 March, 1999. UNESCO-IHP and CATHALAC, Panama City (in press).
- FALKLAND, A. (1999b). Draft report. Impact of the 1998/1999 drought on Kiribati water supplies and recommended actions. March 1999. Australian Agency for International Development. Canberra, 30 pp.
- FALKLAND, A.C. and BRUNEL, J.P. (1993) Review of hydrology and water resources of the humid tropical islands. *In: M. Bonell, M.M. Hufschmidt and J.S. Gladwell (eds.) Hydrology and Water Management in the Humid Tropics*. Cambridge Univ. Press—IAHS, Cambridge, England, , pp 135-163.
- FALKLAND A. and WOODROFFE C. (1997) 'Geology and Hydrogeology of Tarawa and Christmas Island, Kiribati, Chapter 19. *In: H.L. Vacher, and T.M. Quinn (eds.) Geology and Hydrogeology of Carbonate Islands*, Developments in Sedimentology 54. Elsevier, Amsterdam.

- GIBBS, W. (1975) 'Drought - its definition, delineation and effects.' WMO Special Environment Report no. 5, World Meteorological Organisation, Geneva: 1-39.
- GIBBS, W. and MAHER, J.V. (1967) 'Rainfall deciles as drought indicators.' Bulletin 48. Australian Bureau of Meteorology, Melbourne.
- GOMMES, R., and PETRASSI, F. (1994). 'Rainfall variability and drought in Sub-Saharan Africa since 1960.' Agrometeorology Series Working Paper No. 9, Food and Agriculture Organisation, Rome, Italy.
- HARRISON, G. (1980) *Socio-economic aspects of the proposed water supply project for South Tarawa, Kiribati*. Department of Housing and Construction, Canberra, Australia.
- LE HOUÉROU, H.N., POPOV, G.F., and SEE, L. (1993) 'Agro-bioclimatic classification of Africa.' Agrometeorology Series Working Paper No. 6, Food and Agriculture Organisation, Rome, Italy.
- MCKEE, T.B., DOESKEN, N.J., and KLEIST, J. (1993) 'The relationship between drought frequency and duration to time scales.' Preprints, 8th Conference on Applied Climatology, 17-22 January, Anaheim, CA, p. 170-184.
- MCKEE, T.B., DOESKEN, N.J., and KLEIST, J. (1995) 'Drought monitoring with multiple time scales.' Preprints, 9th Conference on Applied Climatology, 17-20 January, Dallas, TX, p. 233-236.
- MCMAHON, T.A. (1993) 'Hydrologic design for water use.' Chapter 27. *In: D.R.Maidment (ed.) Handbook of Hydrology*. McGraw-Hill Inc, New York, pp 27.1-27.51.
- PALMER, W.C. (1965) *Meteorological Drought*. US department of Commerce, Weather Bureau research paper no. 45.
- PALMER, W.C. (1968) 'Keeping track of moisture conditions nationwide: the new Crop Moisture Index.' *Weatherwise*, Vol. 21, p. 156-161.
- RASMUSSEN, E.U., DICKINSON, R.E., KUTZBACH, J.E., and CLEAVELAND, M.K. (1993) 'Climatology.' Chapter 2. *In: D.R.Maidment (ed.) Handbook of Hydrology*. McGraw-Hill Inc, New York, pp 2.1-2.44.
- RICCI, G., and SCOTT, D. (1998) 'Groundwater potential assessment of Rarotonga coastal plain.' Technical Report 259, SOPAC, Suva, Fiji.
- SALAS, J.D. (1993) 'Analysis and modelling of hydrologic time series.' Chapter 19. *In: D.R.Maidment (ed.) Handbook of Hydrology*. McGraw-Hill Inc, New York, pp 19.1-19.72.
- SMITH, D.I., HUTCHINSON, M.F., and MCARTHUR, R.J. (1992) 'Climatic and agricultural drought: Payments and Policy.' RES 7. Centre for Resource and Environmental Studies, ANU, Canberra, 103 pp.
- SECRETARIAT OF THE PACIFIC COMMUNITY (SPC). (1998) 'Kiribati population profile based on the 1995 census.' Secretariat of the Pacific Community, Noumea, New Calidonia.
- WHEATCRAFT, S.W. and BUDDEMEIER, R.W. (1981) 'Atoll island hydrology.' *Ground Water*, Vol. 19, p. 311-320.
- WHITE, D.M., and O'MEAGHER, B. (1995) 'Coping with exceptional droughts in Australia.' *Drought Network News*, Vol 7, p. 13-17.

- WHITE I., FALKLAND A., ETUATI B., METAI E. and METUTERA T. (1999). 'Recharge of fresh groundwater lenses: Field Study, Tarawa Atoll, Kiribati.' *In Proceedings Second International Colloquium on Hydrology and Water Management in the Humid Tropics*. Panama, 22-25 March, 1999. UNESCO-IHP and CATHALAC, Panama City (in press).
- WILLEKE, G., HOSKING, R.M., WALLIS, J.R., and GUTTMAN, N.B. (1994). *The National Drought Atlas*, Institute for Water Resources Report 94-NDS-4, US Army Corps of Engineers.