CLIMATIC AND AGRICULTURAL DROUGHT: PAYMENTS AND POLICY

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2.3 The Palmer Index

The derivation of the Palmer Index from the monthly water balance calculation in two stages. The first stage derives the monthly moisture anomalies, which are a measure of the differences between actual precipitation and the *CAFEC* (Climatically Appropriate For Existing Conditions) precipitation. These anomalies are normalised so that different places have similar moisture anomalies for their driest twelve-month periods.

The second stage accumulates weighted values of the monthly moisture anomalies to derive the Palmer Index. The basic accumulation procedure used in this second stage is modified in order to recognise both wet and dry spells.

Details of the two stages in the Palmer Index calculation have been provided in succinct form by Alley (1984a). We describe the general form of these calculations only in sufficient detail to describe our modifications to the original procedure.

2.3.1 Moisture Anomalies

The water balance used by Palmer identifies two moisture supply components and three demand components. The two supply components are precipitation (*P*) and loss from soil moisture (*L*). The three demand components are evapotranspiration (*ET*), recharge to the soil (*R*) and runoff (*RO*). The basic water balance equation is thus

$$P + L = ET + R + RO. \tag{1}$$

The detailed operation of our version of this water balance is as described by Palmer (1965) and Alley (1984a).

Palmer identified three potential components of the water balance in addition to potential evapotranspiration (*PE*). These are potential recharge (*PR*), potential loss (*PL*) and potential runoff (*RO*). Potential recharge is defined as the amount of moisture required to bring the soil to field capacity. It is simply the difference between the available soil water capacity and the actual soil moisture. Potential loss is the amount of moisture that could be lost from the soil to evapotranspiration provided precipitation for the month is zero. Potential runoff is potential precipitation minus potential recharge. As discussed by Alley (1984a), potential precipitation is somewhat arbitrarily defined as being the available soil water capacity. We have adopted McDonald's modification and added one sixth of the precipitation *P* to the potential runoff.

The four potential values are used to compute four coefficients for each month of the year which reflect the climate of the area. These are:

$$\begin{aligned} \alpha &= \overline{ET}/\overline{PE} \\ \beta &= \overline{R}/\overline{PR} \\ \gamma &= \overline{RO}/\overline{PRO} \\ \delta &= \overline{L}/\overline{PL} \end{aligned} \tag{2}$$

where the overbar denotes the average for the month over all years.

The raw moisture anomaly d for each month is then defined as

$$d = P - \hat{P} \tag{3}$$

where $\hat{P}$ is the *CAFEC* precipitation defined by

$$\begin{aligned} \hat{P} &= \hat{ET} + \hat{R} + \hat{RO} - \hat{L} \\ &= \alpha\ PE + \beta\ PR + \gamma\ PRO - \delta\ PL. \end{aligned} \tag{4}$$

This last equation corresponds to the basic water balance equation (1) but with the actual water balance components replaced by their *CAFEC* quantities.

The normalised moisture anomaly index Z is then defined by Palmer as

$$Z = K_j d \tag{5}$$

where K_j is the normalising factor for month j. The two stages in the rather complicated procedure for calculating this normalisating factor are described in Appendix 1. The first stage calculates a normalising factor $\hat{K}_j$ which adjusts the raw moisture anomalies in relation to annual mean moisture demand and moisture supply. The second stage ensures that values of Z are comparable between different sites by scaling the factors $\hat{K}_j$ to produce the normalising factors K_j. The normalisation is such that the means of the values of $K_j d$ over all months and years are the same for each site.

The constants in the equation used by Palmer to define $\hat{K}_j$ were adjusted to give good results for the nine regions investigated. In Appendix 1 we describe a slightly different form for this equation. The constants were derived by linear regression using 211 sites across Australia. We found that the modified equation, unlike Palmers's original, is reasonably stable when different sets of sites are used in the calibration. Further details of the modified calibration procedure are given in Appendix 1. A plot of the monthly progression of the Palmer moisture anomalies for Seymour, Victoria is given in Figure 2.6

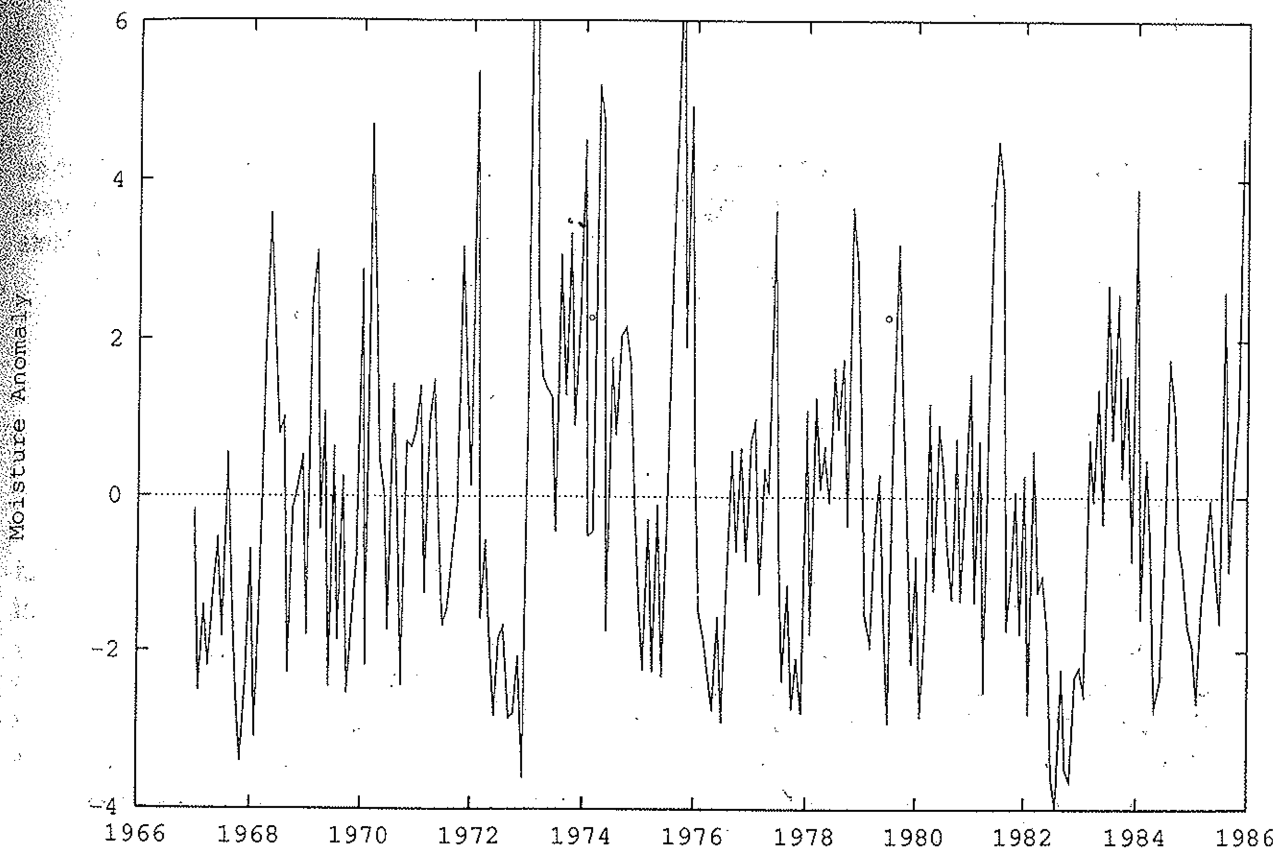

Figure 2.6. Monthly moisture anomalies from 1967 to 1986 for Seymour, Victoria.

2.3.2 Palmer Index

The basic accounting procedure devised by Palmer to convert the moisture anomalies into an index of drought severity is to accumulate successive moisture anomalies according to the formula

$$X_i = 0.897\ X_i + Z_i/3 \qquad (6)$$

where Z_i is the moisture anomaly in month i and X_i is the drought severity index in month i. The constant 0.897 in this equation was designed so that the index is maintained at a constant level when accumulated values of the moisture anomalies maintain a drought of constant severity according to the criterion described in figure 1 of Palmer (1965). This constant also ensures that the drought index returns to zero in the near normal conditions when the moisture anomalies are approximately zero. Values of X_i between -1 and -2 correspond to mild drought. Values between -2 and -3 correspond to moderate drought. Values between -3 and -4 correspond to severe drought. Values less than -4 correspond to extreme drought. A similar classification applies to wet spells which correspond to values of X_i which exceed +1. Values of X_i between -1 and +1 correspond essentially to normal or near normal conditions.

Palmer found that the basic accounting procedure of equation (6) was too stringent for an adequate determination of the beginning and end of drought. He then developed an elaborate procedure for reworking the accounting procedure in order to determine start and end points of both wet spells and drought. This involved the calculation of three separate indices:

X_1 = severity index for incipient wet spells;

X_2 = severity index for incipient drought;

X_3 = severity index for established wet spells and drought.

The variable X_1 is restricted to be nonnegative and X_2 to be nonpositive. The values of X_1 and X_2 are set to zero when the computations of equation (6) violate these restrictions. A drought is then defined to begin when X_2 falls below -1 for the first time after a previously established drought or wet spell has ended. A wet spell is defined to begin when X_1 goes above +1 for the first time after a previously established drought or wet spell has ended. At these times X_3=X_2 for an established drought and X_3=X_1 for an established wet spell. A drought or wet spell is defined to end when the index returns to near normal values between -0.5 and +0.5. At this point X_3 returns to zero.

Palmer modified this definition by calculating a "percentage probability" that a drought has ended. This takes into account later moisture anomaly values to determine whether an apparent cessation of a drought is confirmed by ensuing normal or above normal moisture anomalies or whether the drought has only been temporarily interrupted and later moisture anomalies return to below average. In this case the drought is considered to have continued and the drought index is modified accordingly. The detailed computations supporting these actions are described in Palmer (1965), Alley (1984a) and Smith and Callahan(1988). It is important to note that the modified definition of the beginning and end of droughts and wet spells cannot be enacted in real time it involves consideration of later moisture anomaly values. We have not modified this section of the Palmer Index.

A plot of monthly values of the Palmer Index for Seymour, Victoria, for the same period for which the monthly moisture anomalies were plotted in Figure 2.6, is given in Figure 2.7. The integrating effect of the Palmer Index calculations on the moisture anomalies is apparent. Three periods of extreme drought, when the Palmer Index fell below -4, occurred in 1967-in 1967-68, 1972 and 1982-83. A further two periods of severe drought, when the Palmer Index fell between -3 and -4, occurred in 1976 and late 1977.

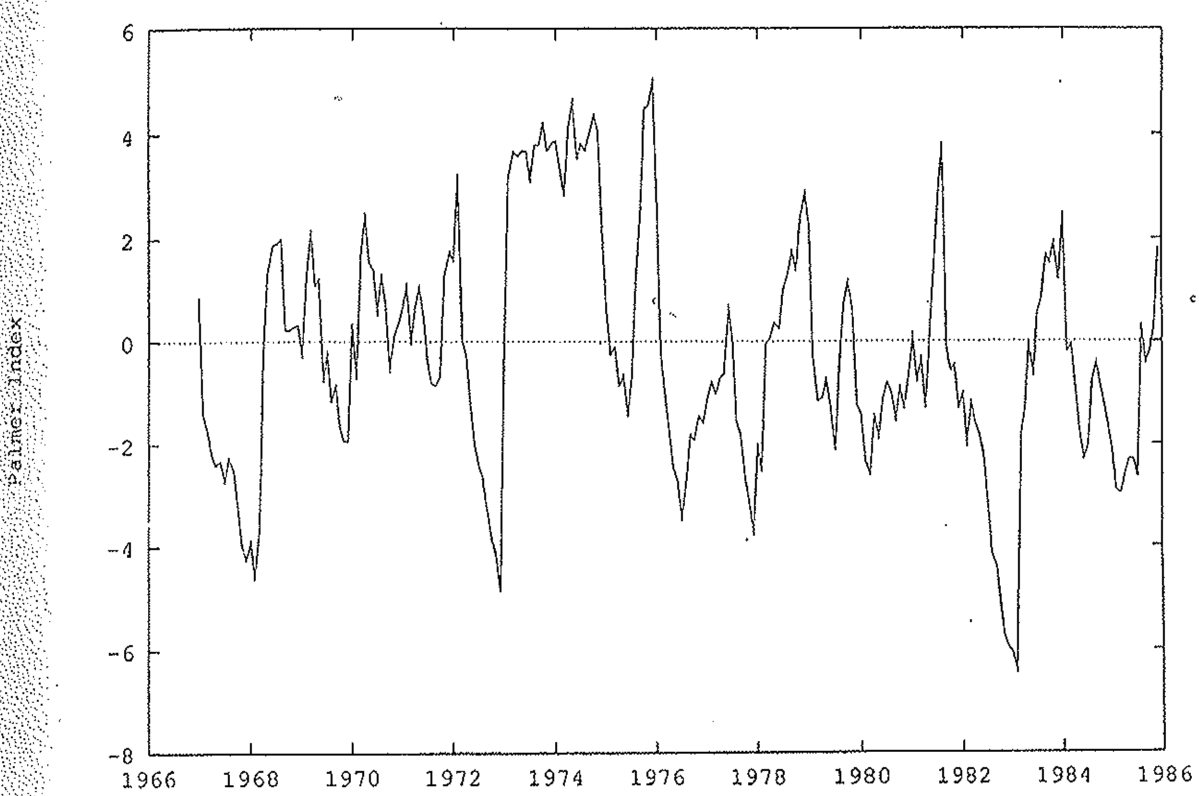

Figure 2.7 Monthly values of the Palmer Index from 1967 to 1986 for Seymour, Victoria.

2.4 Rainfall deciles and percentiles

Rainfall deciles for various periods ranging from several months to a year have been proposed by Gibbs and Maher (1967) and have been used by the Australian Meteorological Bureau to gauge the severity of dry conditions across the continent (Gibbs,1975). The two most notable features of rainfall deciles, especially when compared with the elaborate calculations required for the Palmer Index, are their simplicity and their lack of dependence on any water balance calculations.

The rainfall decile for a particular period of the year is defined by ranking the total rainfall received for the nominated period with respect to the total received for the same period in all years of record. Thus the first decile (or 10 percentile) is the rainfall amount not exceeded by 10% of all totals. The fifth decile or median is the amount not exceeded in 50% of all years. Decile ranges are the ranges of values between deciles. Thus the first decile range is that below the first decile, and the eighth decile range lies between decile seven and decile eight. The interplay between deciles and decile ranges is illustrated in Figure 2.8. Rainfall percentiles are similarly defined by dividing each decile range into ten percentile ranges.

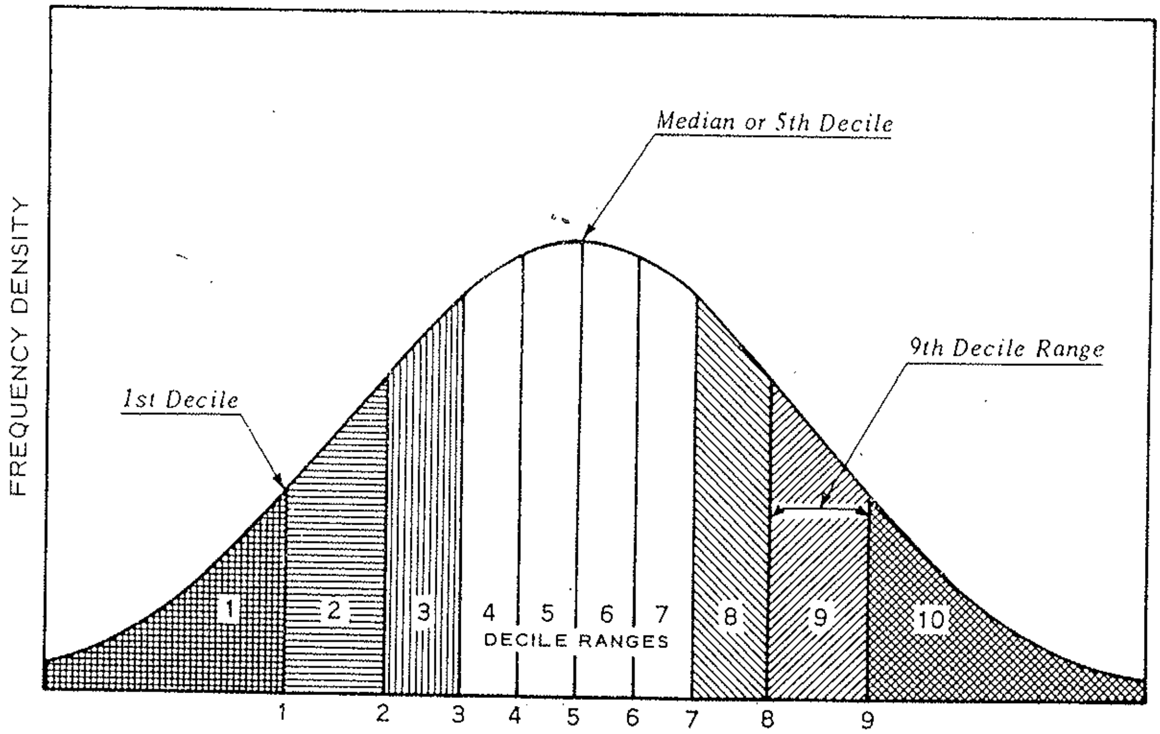

Figure 2.8 The deciles and decile ranges for a hypothetical probability distribution of rainfall. The probability of rainfall falling in each decile range is 10%. Figure adapted from figure 2 of Gibbs (1975).

Gibbs and Maher (1967) found that the occurrence of the first decile range of annual rainfall during the period 1885 to 1965 corresponded well with droughts for the same period listed by Foley (1957) on the basis of reported effects on crop yield and livestock populations. Gibbs (1975) noted further that the most damaging droughts in Australia have coincided with the occurrence of large areas of the first decile range over successive years.

With the onset of relatively dry conditions in Australia in 1965, the Australian Meteorological Bureau commenced a drought alerting service. Serious drought was defined to occur when the rainfall total over a period of three months fell between the fifth and tenth percentile of all such three month periods. Severe drought was defined to occur when the rainfall fell below the fifth percentile. Aggregate rainfall totals were maintained from the beginning of the drought and used to produce maps of the extent of areas covered by the fifth and tenth percentiles. These maps were issued monthly and were found by the farming community and government authorities to be a useful objective measure of rainfall deficiency.

Motivated by the apparent success of rainfall deciles and percentiles, and by the simplicity of their derivation, we have considered monthly, six-monthly and annual rainfall percentiles as measures of rainfall deficiency. Unlike the annual rainfall deciles considered by Gibbs and Maher (1967), we have calculated six-monthly and twelve-monthly percentiles on a month by month basis. For each month the six(twelve)-monthly percentile is the total rainfall for the preceding six(twelve) months, up to and including the nominated month, ranked in percentage terms with respect to the rainfall totals for the same sequence of six(twelve) months over all years of record. This gives rise to monthly sequences of rainfall percentiles in a similar fashion to Palmer's moisture anomalies and the Palmer Index.

Monthly, six monthly and twelve-monthly percentiles for the period 1967 to 1986 for Seymour, Victoria are plotted respectively in Figures 2.9, 2.10 and 2.11. To aid comparison with the Palmer Index, the percentiles have been rescaled to lie between -4 and +4, the nominal extreme values of the Palmer Index. The progressive smoothing imposed by the six-monthly and twelve-monthly percentiles is apparent. Moreover it may be noted that there is an approximate correspondence between the monthly deciles in Figure 2.9 and the monthly moisture anomalies for the same site, as plotted in Figure 2.6. There is an even closer correspondence between the six-monthly deciles in Figure 2.10 and the monthly values of the Palmer Index for the same site, as plotted in Figure 2.7. We show in the next sub-sections that these correspondences are general.

2.4.1 Monthly rainfall percentiles and Palmer moisture anomalies

The monthly moisture anomalies, which have been described in section 2.3.1 and Appendix 1, were normalised by Palmer so that they were essentially independent of time and space. This was to facilitate comparisons between different sites at different times. Monthly rainfall percentiles, which vary between 0% and 100% for each month at each site, are plainly already normalised.

It should be noted however that for sites where a significant proportion of the months receive no rainfall, the percentile value of zero rainfalls is not well defined. We overcome this by setting the percentile of zero rainfall to the mid-point of the relative frequency that the month is dry. The significance of this problem reduces as the number of months used to define the percentile increases. Thus, there are very few six-monthly or twelve-monthly periods at any site in Australia which are completely dry.

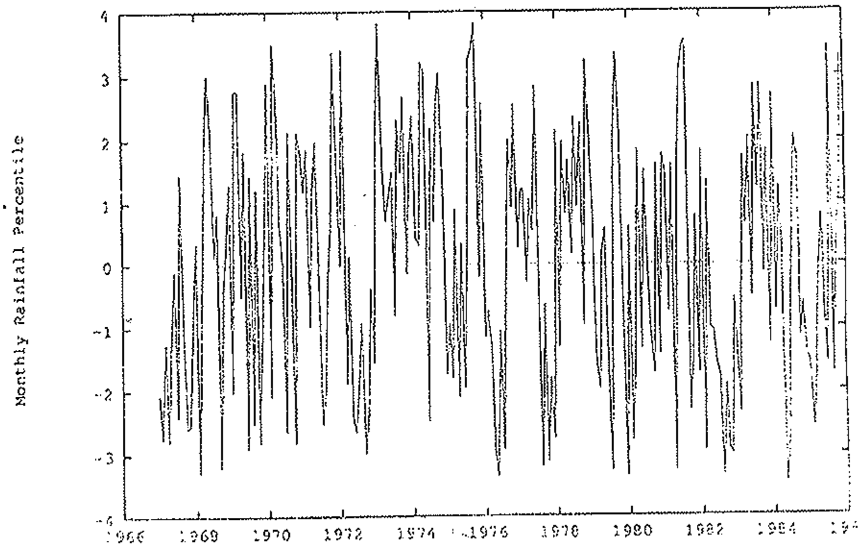

Figure 2.9 Monthly rainfall percentiles from 1967 to 1986 for Seymour, Victoria

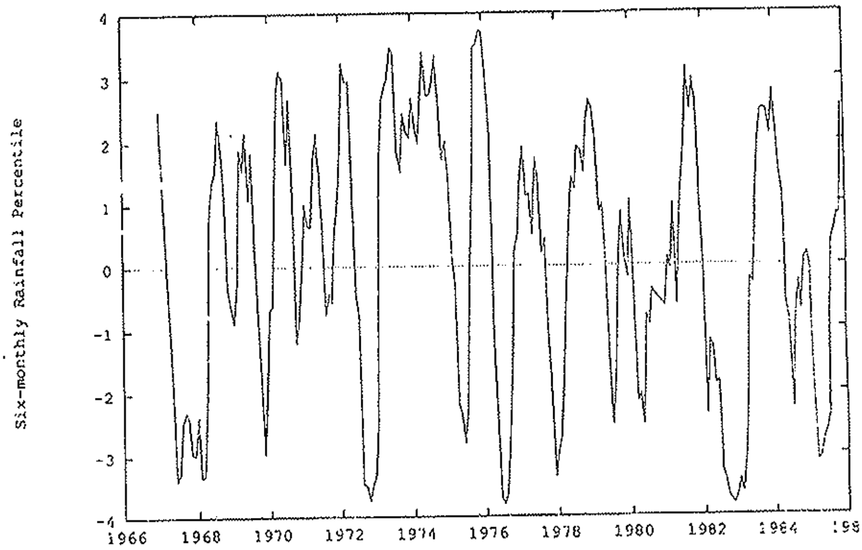

Figure 2.10 Six-monthly rainfall percentiles from 1967 to 1986 for Seymour, Victoria

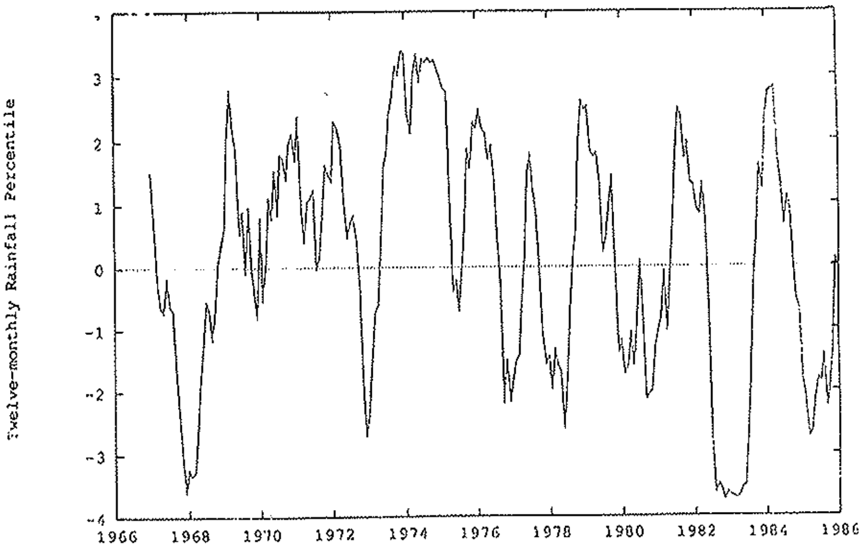

Figure 2.11 Twelve-monthly rainfall percentiles from 1967 to 1986 for Seymour, Victoria

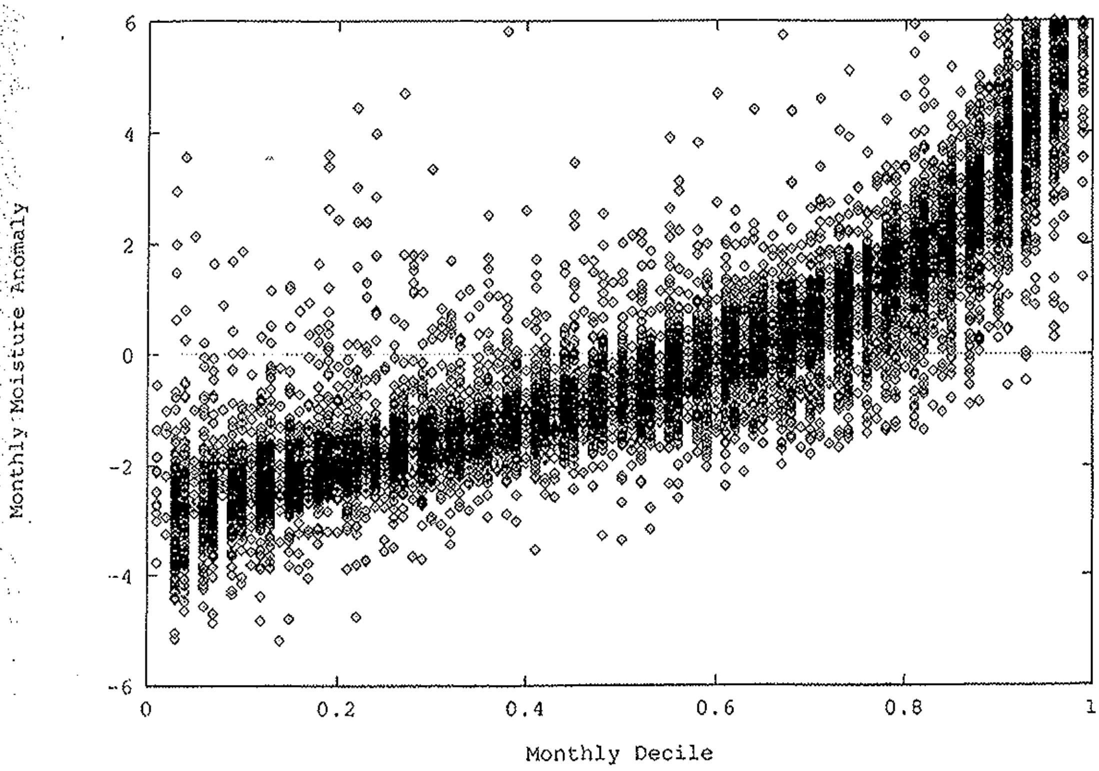

Figure 2.12 Monthly moisture anomalies vs monthly rainfall percentiles at 20 sites across Australia from 1921 to 1985.

Monthly moisture anomalies versus monthly rainfall percentiles for all months between 1921 and 1985, at 20 stations selected across Australia, are plotted in Figure 2.12. A broad one to one correspondence between the two variables is apparent. Using the GENSTAT Statistical Analysis Package (Nelder et al.,19**) a non-linear function was fitted to these data. The fitted function is

$$Z = -3.11 + 0.41/(1.0 - 0.974RP) + 3.3RP \tag{7}$$

where Z is the monthly moisture anomaly and RP the monthly rainfall percentile expressed as a proportion between 0 and 1. This equation accounted for 75% of the variance in the moisture anomalies. The relationship is essentially linear for negative moisture anomalies and rainfall percentiles less than 50%, the main region of interest for this study.

Since the moisture anomalies depend on evapotranspiration, via the underlying soil water balance calculations, and the rainfall percentiles do not, it may be concluded from this relationship that the effect on the moisture anomalies of the considerable spatial variability in potential evapotranspiration displayed previously in Table 2.1 has been largely removed.

This could be attributed both to Palmer's normalisation procedure and to the fact already noted that the variability in actual evapotranspiration is much less than the variability in potential evapotranspiration because the actual evapotranspiration is scaled by the relative water content of the soil.

2.4.2 Six-monthly rainfall percentiles and the Palmer Index

Since the Palmer Index is calculated directly from the monthly moisture anomalies the relationship established above between moisture anomalies and monthly rainfall percentiles immediately suggests that a similar relationship might hold between the Palmer Index and a suitable percentile based measure of rainfall. The Palmer Index can be interpreted loosely as a moving average of present and previous moisture anomalies over a period of about six months. The six-monthly rainfall percentile can also be loosely interpreted as a moving average of the last six-monthly rainfall percentiles. We note in passing that another drought index based on normalised monthly rainfall has been proposed by Herbst et al. (1966). In Figure 2.13 we plot the Palmer Index and the rescaled six monthly percentiles for Seymour from 1967 to 1986. Considering the vastly different procedures used to calculate the two variables, and that no calibration has been employed apart from an *a priori* scaling of the rainfall percentiles to lie between -4 and +4, the concordance of much of the fine time scale structure in the two curves is remarkable. This strong concordance is not evident when overlaying either three-monthly or twelve-monthly rainfall percentiles on the Palmer Index.

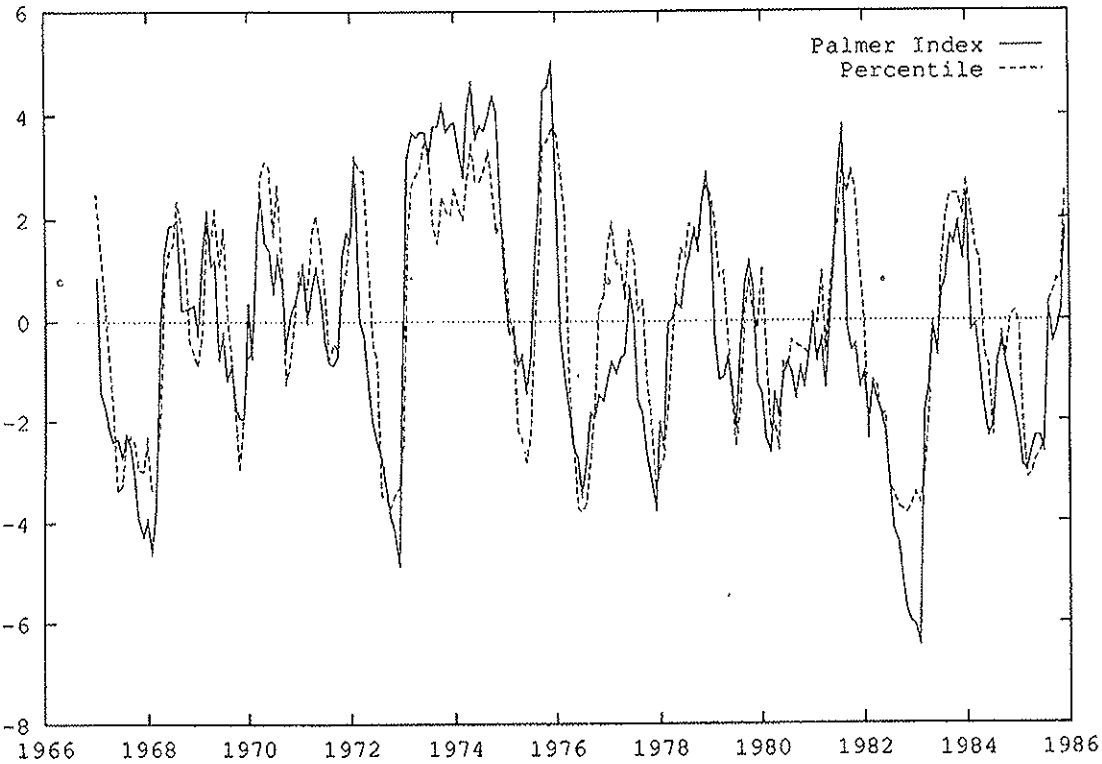

Figure 2.13 Palmer Indices (solid curve) and six-monthly rainfall percentiles (dashed curve) from 1967 to 1986 for Seymour, Victoria.

Values of the Palmer Index and six-monthly rainfall percentiles at 20 sites across Australia are plotted in Figure 2.14. This figure shows that the relationship exhibited in Figure 2.13 for Seymour is a general one. Although the relationship between the two variables is slightly non-linear, linear regression yielded a regression coefficient of 0.72.

The agreement between the Palmer Index and six-monthly rainfall percentiles is one of the central findings of this study. An immediate consequence is the question of the utility of the Palmer Index given that its calculation is far more involved than the calculation of rainfall percentiles and that the Palmer Index depends on knowing monthly evapotranspiration. The net result of the normalisation procedure designed by Palmer is to essentially remove evapotranspiration effects and produce a normalised index of available moisture which can be just as effectively calculated from six-monthly rainfall totals. The comparisons between agricultural and climatic drought in Chapter 3 will confirm this conclusion.

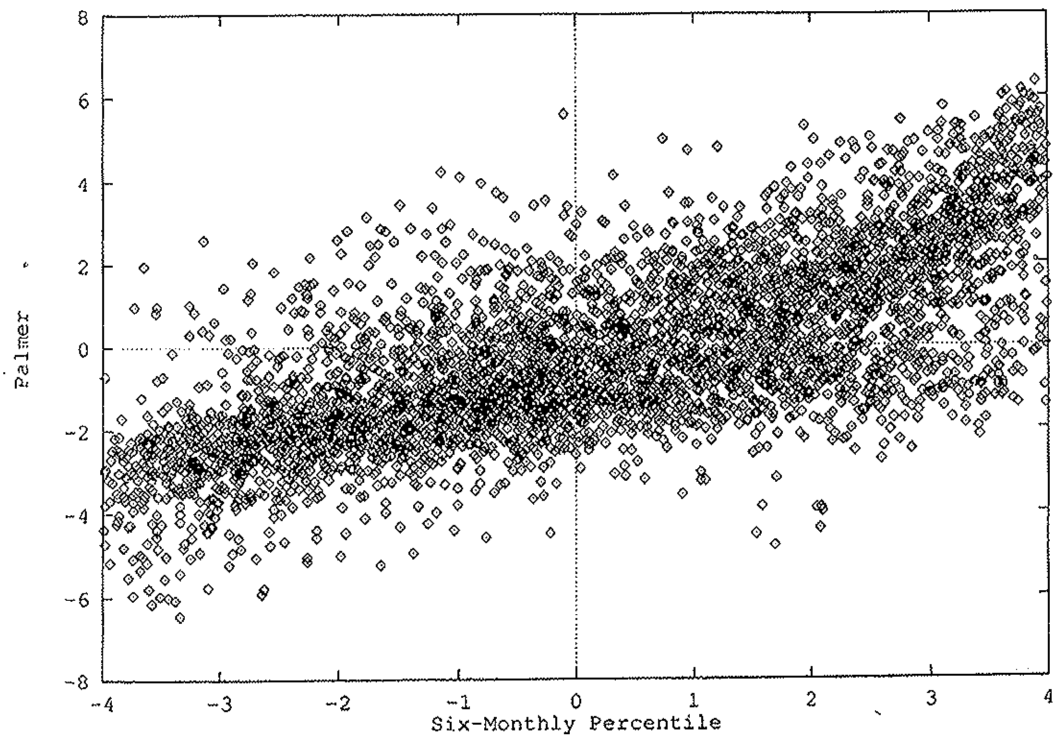

Figure 2.14 Palmer Indices vs six-monthly rainfall percentiles at 20 sites across Australia from 1967 to 1985

2.5 Spatial analyses of climatic drought indices

The maps of rainfall deciles displayed in Gibbs and Maher (1967) and Gibbs (1975) were produced manually but indicate that there is broad spatial coherence in monthly rainfall deciles and percentiles. This is distinctly not the case for actual monthly rainfall totals which exhibit, even in their long-term mean values, extremely complicated spatial patterns which are heavily dependent on topography. However, rainfall percentiles are really a measure of departures from the normal. The major cause of such departures are broad scale changes in synoptic patterns which are essentially independent of topography. Thus, while two nearby sites may have very different monthly mean rainfalls, if the actual monthly rainfall at one site is half of the long-term average, then the actual rainfall at the neighbouring site is likely to be half of the average. Because the underlying causes for the rainfall anomalies are broad scale, it should be possible to interpolate the rainfall percentiles and other drought indices, including the Palmer Index, from the network of rainfall stations used in this study.

The two immediate results of successfully interpolating the drought indices are to provide a means of mapping their distribution across Australia and to provide a means of regionalising the drought indices which removes local departures from the regional trend. The latter was a stated objective of Palmer (1965).

The method chosen to investigate the spatial interpolation of drought indices was the method of thin plate splines as developed by Wahba (1990). This procedure has been implemented by Hutchinson (1991a) in a suite of computer programs making up the ANUSPLIN package. The SPLINB procedure in this package, which is specially designed to handle large data sets, was used to interpolate the monthly drought indices. In its simplest two dimensional form, SPLINB fits a surface f to n noisy data points z_i at positions (x_i,y_i) $(i=1,\ldots,n)$ by minimising

$$\sum_{i=1}^{n} (f(x_i,y_i) - z_i)^2 + \rho \iint (f_{xx}^2 + 2f_{xy}^2 + f_{yy}^2)\, dx\, dy \qquad (8)$$

where ρ is a positive number which controls the degree of data smoothing. As ρ approaches zero, the surface becomes an exact interpolator of the data. On the other hand, as ρ becomes very large, the surface reduces to a least squares plane fit to the data. The method of generalised cross validation (Wahba,1990) is used to determine the value of ρ which gives an appropriate amount of data smoothing. This minimises the predictive error of the fitted surface by minimising the departures of fitted surfaces from omitted data points. The method has been used to calculate accurate interpolation surfaces across Australia of monthly mean values of the climate variables of most importance in determining crop growth (Hutchinson,1991b; Hutchinson and Bischof,1983). Most of these monthly mean surfaces, including temperature, rainfall and class A pan evaporation, depend critically on having elevation as a third independent variable in addition to the usual two position variables of longitude and latitude.

Surfaces were fitted to the month by month values of monthly, six-monthly and twelve-monthly rainfall percentiles and to monthly values of the Palmer Index. The behaviour of the surface fitting procedure was similar for all four variable types. In each case there was the surface fitting procedure was similar for all four variable types. In each case there was no improvement in the predictive errors of the fitted surfaces when elevation was included as an independent variable compared to when the surfaces were fitted as functions of longitude and latitude only. Standard errors of the fitted surfaces functions of longitude and latitude for the four variable types for the mid-season months for the years 1970 and 1983 are given in Tables 2.3 and 2.4. In 1970 the network means of the percentiles indicate approximately average conditions, as do the mean Palmer Index values. Under such conditions the standard errors of all the percentile surfaces are quite small, between 3% and 4%. The standard errors of the Palmer Indices are in good agreement with this, as can be determined by rescaling the percentiles to lie between -4 and +4. This divides the percentile standard errors by 12.5. The year 1983 includes the end of a major drought, as indicated by the network means of both the six-monthly percentiles and the Palmer Indices in January. The higher standard errors for the six-monthly and twelve-monthly percentiles indicate less spatial coherence in this case.

Table 2.3 Network means and standard errors of Australia-wide interpolated surfaces of drought indices for the mid-season months in 1970.

Month	Monthly Percentile		Six-Monthly Percentile		Twelve-Monthly Percentile		Palmer Index	
	Mean	Std Err	Mean	Std Err	Mean	Std Err	Mean	Std Err
January	60	3	46	3	52	3	-0.5	0.4
April	63	3	54	4	48	4	-0.2	0.4
July	23	3	38	3	39	3	-1.4	0.3
October	40	4	39	3	45	4	-0.2	0.4

Table 2.4 Network means and standard errors of Australia wide interpolated surfaces of drought indices for the mid-season months in 1983.

Month	Monthly Percentile		Six-Monthly Percentile		Twelve-Monthly Percentile		Palmer Index	
	Mean	Std Err	Mean	Std Err	Mean	Std Err	Mean	Std Err
January	34	4	19	3	15	3	-3.5	0.5
April	71	3	40	4	18	3	0.3	0.5
July	58	3	68	3	40	4	1.2	0.4
October	52	4	71	3	57	4	1.5	0.5

2.5.1 Maps of six-monthly percentiles

To illustrate the results of the surface fitting process, we present maps of our favoured measure of drought, the six-monthly percentile, for a sequence of months through the severe 1982-83 drought which ravaged much of eastern Australia. The maps are shown in Figure 2.15. They were produced by calculating the corresponding fitted surfaces on a regular 0.5 degree longitude by 0.5 degree latitude grid and displaying the grid using the GMT plotting package (Wessel and Smith, 1991). The percentiles have been lumped into quartile ranges to simplify the display.

The sequence begins in June 1982 with near average or above average moisture for much of the continent. Moisture deficiency in eastern Australia becomes more pronounced in July and rapidly expands thereafter so that by September 1982 most of eastern Australia is in drought. Apart from a small coastal area of northern New South Wales, the extensive drought pattern persists until March 1983 when relieving rains occur in southern Queensland and northern New South Wales. By May 1983 eastern Australia has returned to above average moisture conditions, although western Australia and Cape York Pensinsula remain in the lowest quartile.

2.5.2 A spatial data base of monthly moisture percentiles

The procedure used to produce the maps of Figure 2.15 can be enacted for any month within the period of acquired monthly rainfall data from 1921 to 1985. Coefficients of the surfaces fitted to the six-monthly percentiles are stored by year. They can be used to calculate values of the six-monthly percentiles for any month at any site using the LAPPNT program in the ANUSPLIN package. Alternatively, regular grids across Australia of monthly moisture percentiles for any month can be calculated using the LAPGRD program in ANUSPLIN and displayed by any of a number of commonly available computer programs which can display raster images. These procedures could be used to set up an operational procedure for interrogating and displaying the spatial distribution of monthly rainfall percentiles. The system could be updated to incorporate later years as new monthly rainfall became available.

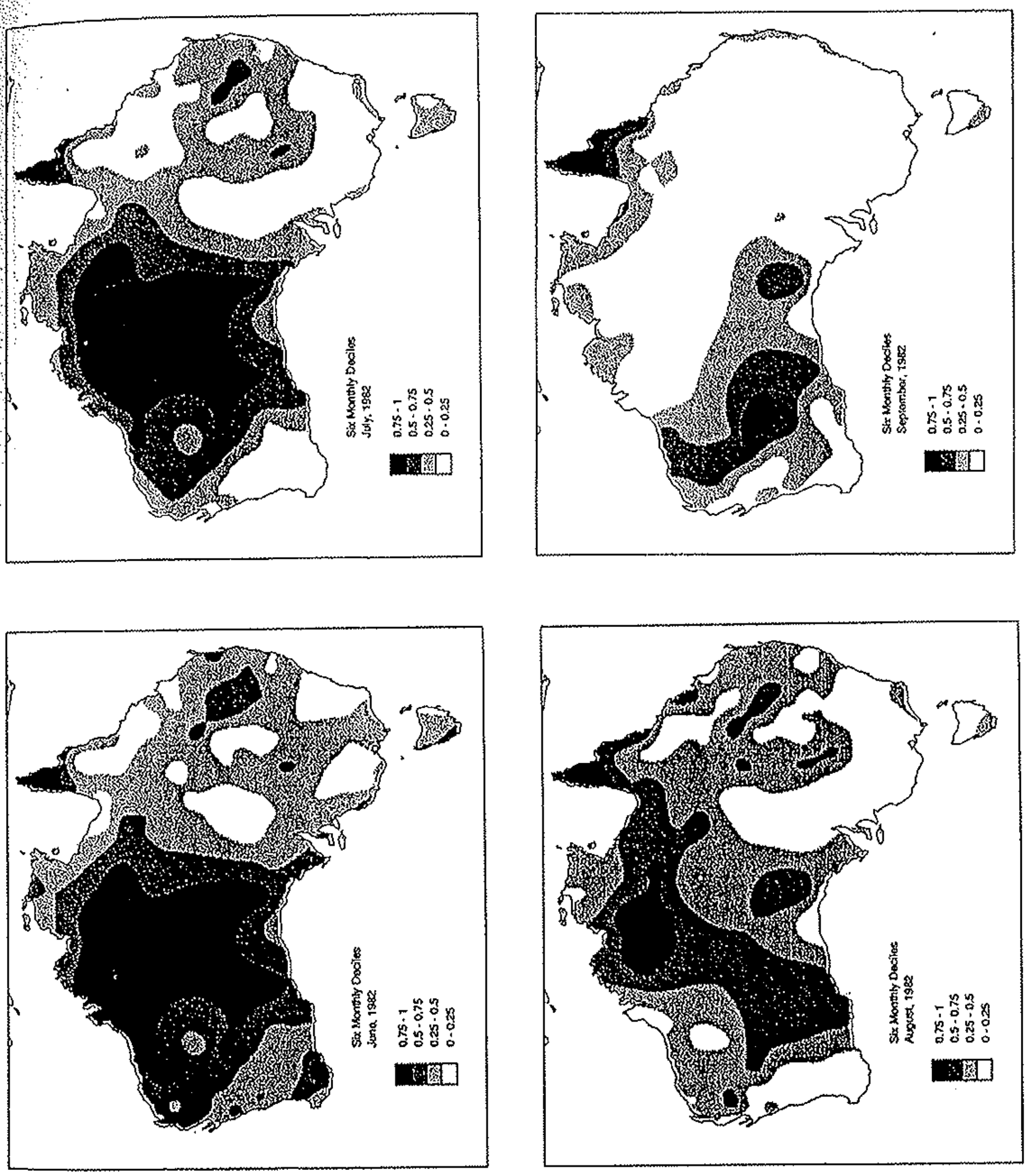

Figure 2.15 Maps of six-monthly percentiles across Australia from June 1982 to May 1983

NOTE: In the Key 0.75 to 1 corresponds to the 75 to 100 percentiles, 0.5 to 0.75 to the 50 to 75 percentiles etc.

CHAPTER 3

THE RELATIONSHIP BETWEEN CLIMATIC AND AGRICULTURAL DROUGHT

The matching of climatically defined drought with declared agricultural drought will always be a difficult task. While there may be reasonable agreement on the occurrence of drought, it is conceivable that a variety of administrative factors could vary the timing of particular drought declarations and drought revocations in ways which have little to do with climatic factors. We illustrate this in Figure 3.1 which shows the relative frequencies of declared drought durations across Victoria. The relative frequency of durations between 12 months and 13 months is more than three times the relative frequency of all other duration classes. This reflects the fact that the timing of drought revocation in Victoria is not of great practical importance.

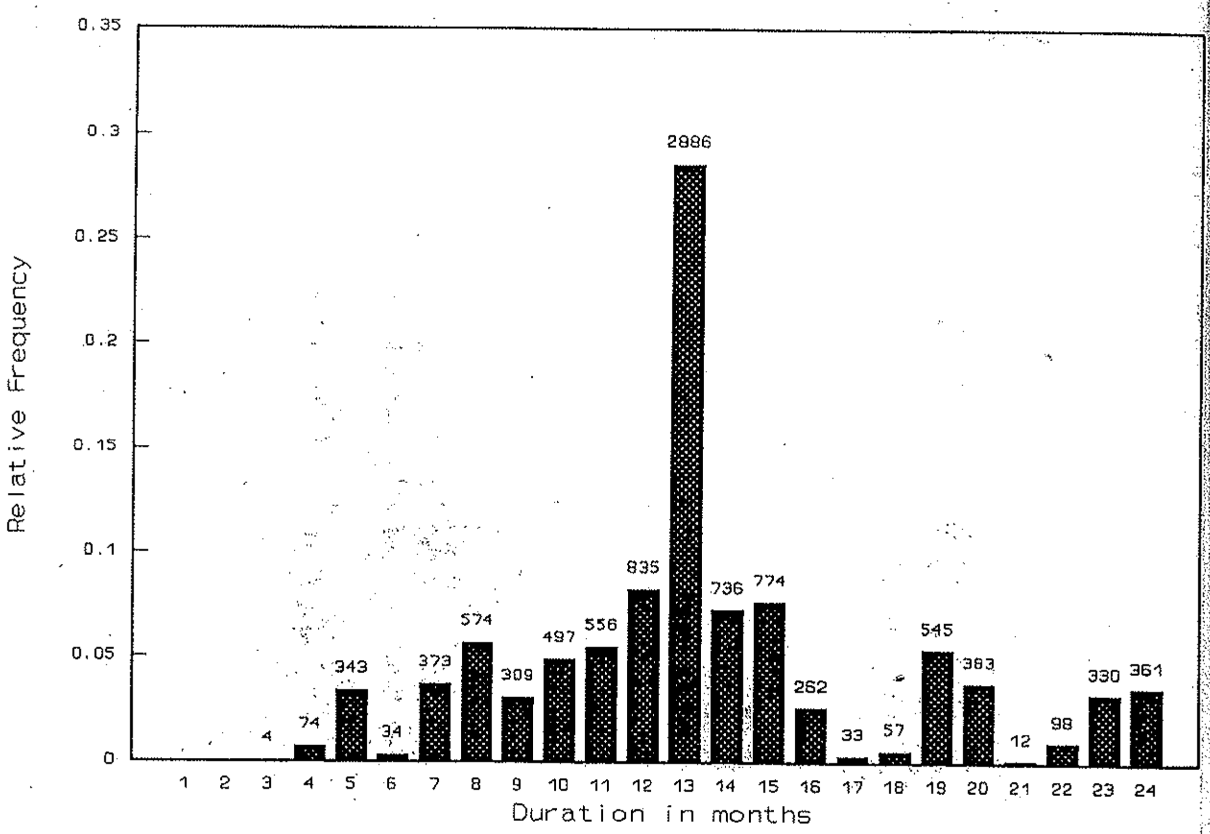

Figure 3.1 Histogram of relative frequencies of duration of declared drought from 1967 to 1988 for all Local Government Areas in Victoria.

Nevertheless, declared droughts should bear some relationship to climatic measures of drought. We have developed a procedure for converting both six-monthly percentiles and Palmer Indices into surprisingly good predictors of the timing and duration of declared droughts, despite the obvious inconsistencies in the latter. The procedure was initially developed using Victorian drought declaration data and then applied to New South Wales. It shows that there are marked differences between the two states in nature of the relationship of declared drought to climatic drought. In neither case are declared droughts adequately represented by the times either the Palmer Index or the six-monthly percentile is below a fixed low threshold.

One of the obvious differences between Victoria and New South Wales is the size of the drought declaration areas. In Victoria droughts are declared for each Local Government Area, of which there are more than 3,000 across the state. On the other hand, New South Wales declares droughts on the basis of 57 Pasture Protection Districts. In both cases it was necessary to have a regional estimate of climatic drought for each drought declaration district. Since the interpolated surface values of the drought indices described in section 2.5 are already regionalised, the regional climatic indices were simply obtained by calculating the interpolated surfaces at the centroid of each drought declaration district. Both six-monthly percentiles and Palmer Indices were investigated for possible relationships with declared agricultural drought.

Two procedures were finally selected to predict drought declarations. Firstly, six-monthly rainfall percentiles were rescaled to lie between -4 and +4 in keeping with the limits of extreme drought and extreme wet of the Palmer Index. The first accounting procedure was then applied to the drought indices which summed the magnitudes of the indices below -1, the upper limit of "mild drought" for the Palmer Index. The sum was set to zero each time the drought index rose above -1 and restarted each time the drought index fell below -1. A threshold was then determined so that when the summed magnitudes exceeded this threshold, a period of declared drought was deemed to have occurred. The second procedure for predicting declarations differs in that the number of months below -1 are counted until the index rose above -1, and restarted each time the index fell below -1. The aim of these approaches was to take account of droughts which were either very severe but not necessarily of very long duration and of droughts which were less severe but nevertheless of sufficient duration to have a significant effect on agriculture. The procedures should be viewed as preliminary and capable of further refinement should there be a demonstrated need. The detailed application of the procedures is first described for Victoria and then for New South Wales. The first procedure produced better results for Victoria and the second for New South Wales.

3.1 Victoria

The boundaries of the 3244 Local Government Areas (LGAs) for Victoria are shown in Figure 3.2. Drought declaration data for these LGAs were obtained in ARC/INFO format from the Victorian Department of Agriculture. Of these, 239 LGAs are essentially urban areas for which agricultural drought is not applicable. This is illustrated in Figure 3.3 where the LGAs for which there were zero, one, two and more than two drought declarations between 1967 and 1988 are displayed. Apart from the suburban area of Melbourne, the total area of those LGAs with no more than one drought declaration for the period is very small. It was therefore decided to remove from further consideration all LGAs for which there was at most one declaration between 1967 and 1988.

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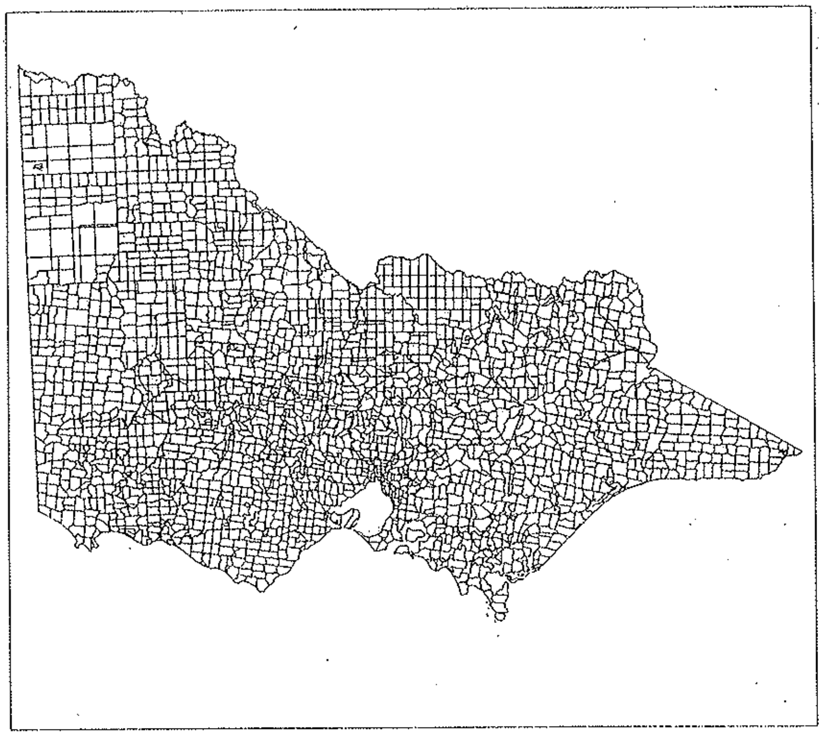

Figure 3.2 Boundaries of Local Government areas for Victoria.

Figure 3.3 Number of declared droughts between 1967 and 1988 in all Local Government areas of Victoria.

The percentage of time between 1967 and 1988 which was spent in declared drought is plotted in Figure 3.4. The spatial coherence of these percentages is apparent. It can also be seen that most of the state spent between 17 and 25% of the time in drought. Areas with less time in declared drought include some coastal areas, some of the higher elevation areas in the east of the state and irrigation areas adjoining the Murray River.

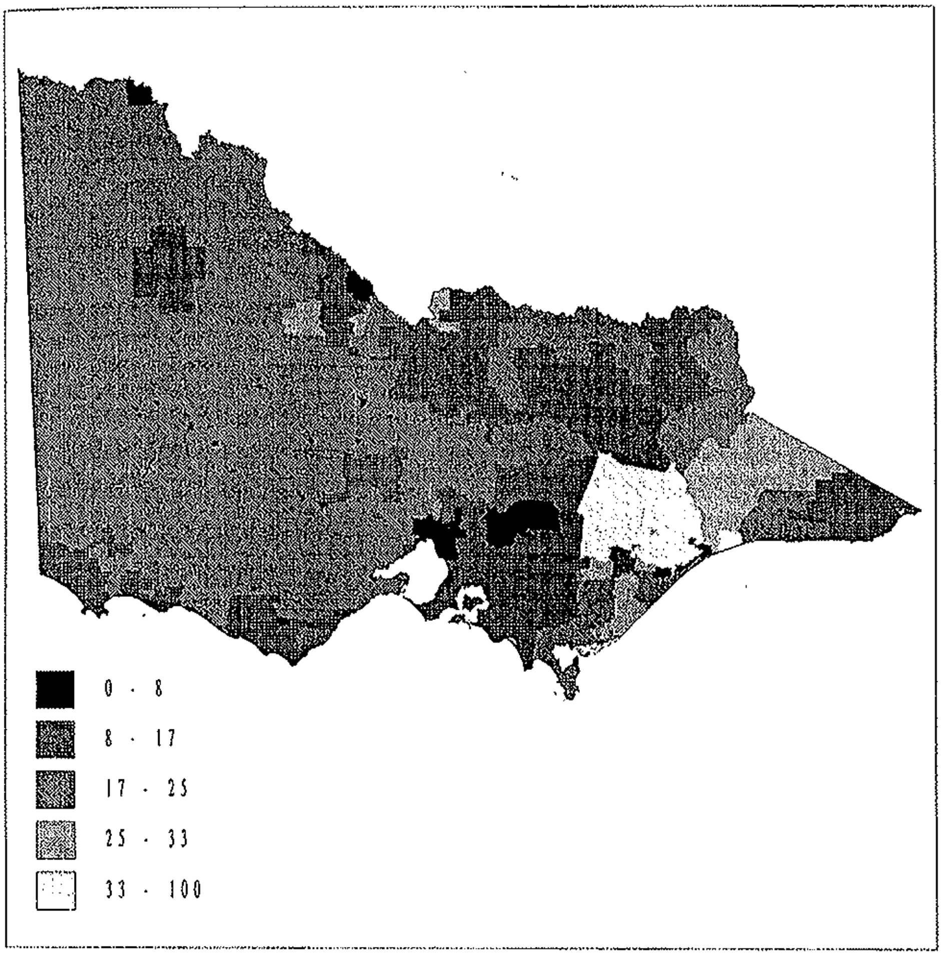

Figure 3.4 Percentage of time spent in declared drought between 1967 and 1988 for all Local Government areas of Victoria.

The operation of the first accounting procedure imposed on six monthly percentiles and Palmer Indices is illustrated in Figure 3.5 for Seymour, Victoria. Plots of the underlying drought indices have already been given in Figures 2.7, 2.10 and 2.11. Four periods of declared drought between 1967 and 1988 are indicated by the horizontal arrows. Integrated values below -1 for the six-monthly percentiles are indicated by the solid lines and corresponding values for the Palmer Index by the dashed lines. The chosen threshold for Victoria of -17.5 is also shown. It can be seen that, between 1967 and 1988, the integrated values of both climate indices exceed the nominated threshold in four cases, exactly matching in this case the number of declared droughts.

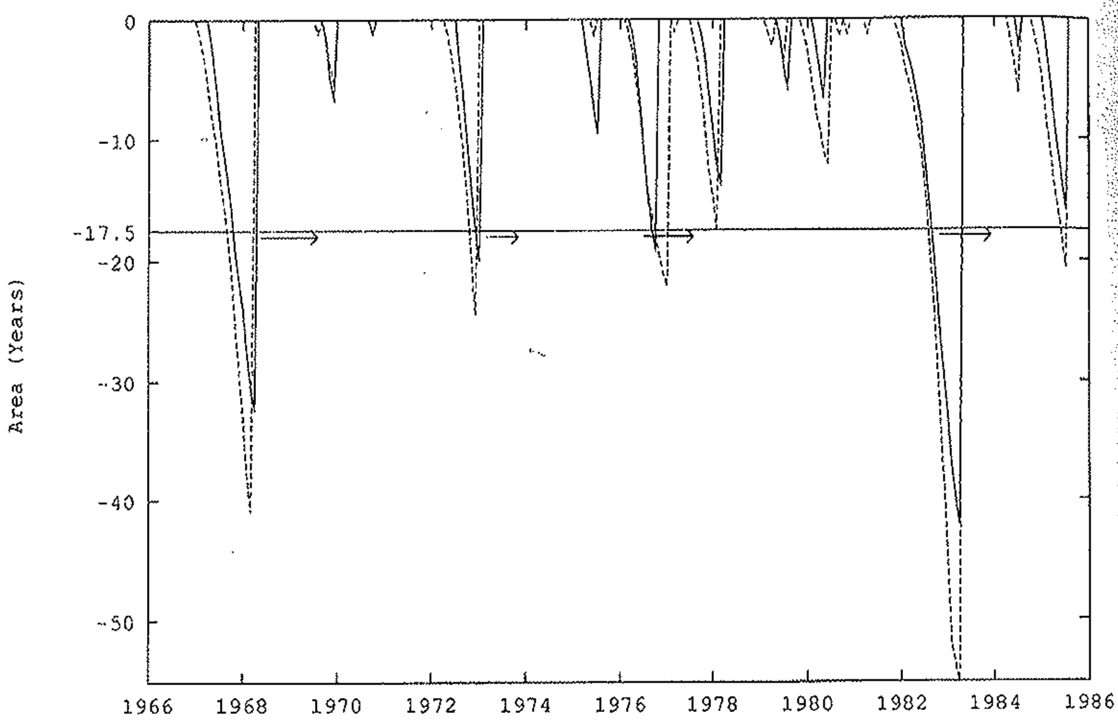

Figure 3.5 Declared droughts (horizontal arrows) and integrated six-monthly percentiles (solid line) and integrated Palmer Indices (dashed line) for Seymour, Victoria.

The integrated values associated with the drought in 1976-77 suggest that the placement of the threshold is moderately well determined, at least in this case. If the magnitude of the threshold were less than -17.5 then the integrated Palmer Index would erroneously indicate an additional declared drought in 1978. On the other hand, if the magnitude of the threshold exceeded -20 then the integrated six-monthly percentiles would miss the declared droughts in 1973 and in 1976-77. It may also be noted that the integrated six-monthly percentiles give a slightly greater discrimination between the declared drought of 1976-77 and the non-declared drought period in 1978.

Given our stated criterion for predicting declared drought, it was natural to estimate the starting point of each predicted drought as the time at which the integrated drought index value exceeded the chosen threshold. The duration of each predicted drought was taken to be the total time for which the drought index remained below -1. These definitions were then used to determine how well the predicted droughts compared with the declared droughts. A declared drought was deemed to have been successfully predicted if it overlapped in time with the occurrence of a predicted drought.

Plainly, the setting of the threshold used to predict the occurrence of drought involves a trade-off between correctly detecting declared droughts and false prediction of non-declared droughts. In Figure 3.6 we plot the percentage of real droughts found versus the number of false drought predictions for six-monthly percentiles, twelve-monthly percentiles and Palmer Indices. Each curve is obtained by successively setting the integration threshold to -15.0, -17.5 and -20.0. This plot provides a way of determining the relative merits of the three measures of drought as predictors of declared drought. The best predictor will be the one which gives rise to the curve closest to the top left hand corner of the graph and the worst predictor will give rise to the curve closest to the bottom right hand corner. The plots show that in these terms, the six-monthly and twelve-monthly percentiles have similar abilities in correctly predicting the occurrence of declared drought, while the Palmer Index performs less well. It will be shown below that the twelve-monthly percentiles do not estimate the durations of declared drought as well as six-monthly percentiles. It was therefore concluded that six-monthly percentiles were the superior predictor. The actual integration threshold chosen was -17.5. For this threshold, 81% of all declared droughts over the period 1967 to 1985 were detected and the average number of falsely predicted declared droughts was 1.0. The average number of predicted droughts per LGA was 2.6.

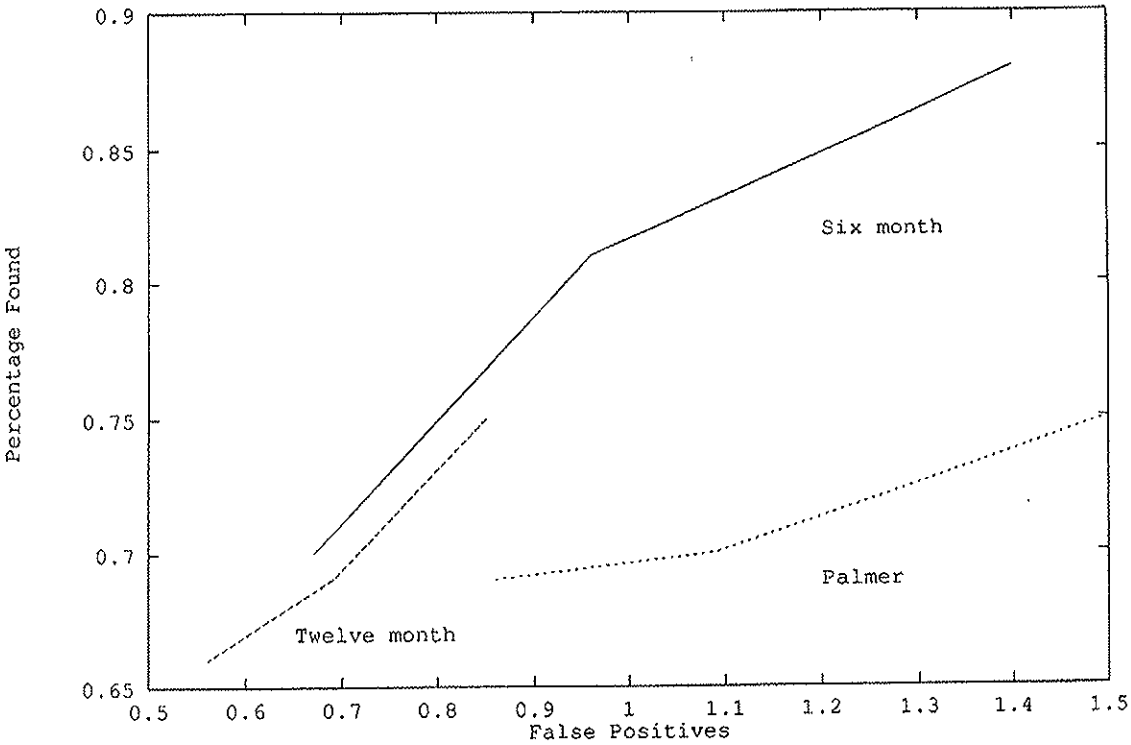

Figure 3.6 Percentage of declared droughts found vs the number of falsely predicted droughts for Victoria between 1967 and 1985 using integrated six-monthly percentiles, twelve-monthly percentiles and Palmer Indices and thresholds of -15.0, -17.5 and -20.0.

The prediction of the start and end points of declared droughts would appear to be more problematic. Figure 3.1 has clearly indicated apparent aberrations in the durations of declared droughts. These could be due to mismatches with climate of both start points and end points of the declared droughts, although failure to promptly revoke a drought which has plainly ended with respect to climatic conditions would appear to be a major cause for the mismatches. We plot in Figure 3.7 the durations of declared droughts versus the durations of droughts as predicted by six-monthly percentiles, twelve-monthly percentiles and Palmer Indices, in each case using the integration threshold of -17.5. Similar patterns for each drought index were obtained using the thresholds of -15.0 and -20.0.

The six-monthly percentiles appear to systematically underestimate the durations of declared droughts. However, both the twelve-monthly percentiles and the Palmer Indices give rise to both significant underestimation and significant overestimation of declared drought durations. If in fact it can be inferred from Figure 3.1 that a significant fraction of droughts are declared for longer than that actually appropriate for the associated climatic conditions, then it would be reasonable to conclude that the six-monthly percentiles give the most consistent and perhaps truly accurate estimates of the durations of agricultural drought.

3.2 New South Wales

Drought declaration data for 57 Pasture Protection Districts (PPDs) of New South Wales for the period 1957 to 1981 were obtained previously by Smith and Callahan (1988) from the New South Wales Department of Agriculture. Declaration data for 1982 to 1985 were also obtained from the New South Wales Department of Agriculture and Fisheries but these have yet to be put into computer form. The boundaries for the PPDs are displayed in Figure 3.8. A listing of the names of the PPDs may be found in Table 3.1 of Smith and Callahan (1988). Districts 43 (Pilliga) and 53 (Walgett North) in Smith and Callahan's table are not displayed. Walgett North has been amalgamated with 52 (Walgett).

The percentage of time between 1957 and 1981 which was spent in declared drought is plotted in Figure 3.9. As for the corresponding plot for Victoria (Figure 3.4), there is strong spatial coherence in the plotted percentages. Also in agreement with the Victorian data, most of the PPDs spent between 17 and 25% of the time in declared drought. The areas which spent least time in declared drought were the far north coast (Tweed-Lismore) and its immediate neighbours, the central coast (Moss Vale) and irrigation areas on the Murray and Murrumbidgee Rivers in the south. The most drought prone areas are the inland districts in the west (Bourke, Brewarrina, Cobar, Wanaaring and Wilcannia) and southern highlands (Bombala and Cooma).

The integration thresholds used in the first procedure to predict Victorian drought declarations were not appropriate for New South Wales. A second procedure was used for New South Wales. This is based on the number of months below -1, and thresholds between 4 and 8. As for Victoria, the relative merits of the different drought indices could be determined by plotting the percentage of declared droughts found versus the number of falsely predicted non-existent droughts. The plots in Figure 3.10 show a slight preference for the six-monthly percentiles and also show that the Palmer Index again performs least well in predicting declared drought. The overall performance of the predictions is inferior to the results obtained for Victoria. Using six-monthly percentiles and a threshold of 4.0 for New South Wales, 69% of all declared droughts were successfully predicted and the average number of falsely predicted droughts per PPD was 2.0. This may be compared with the average number of predicted droughts per PPD of 4.8.

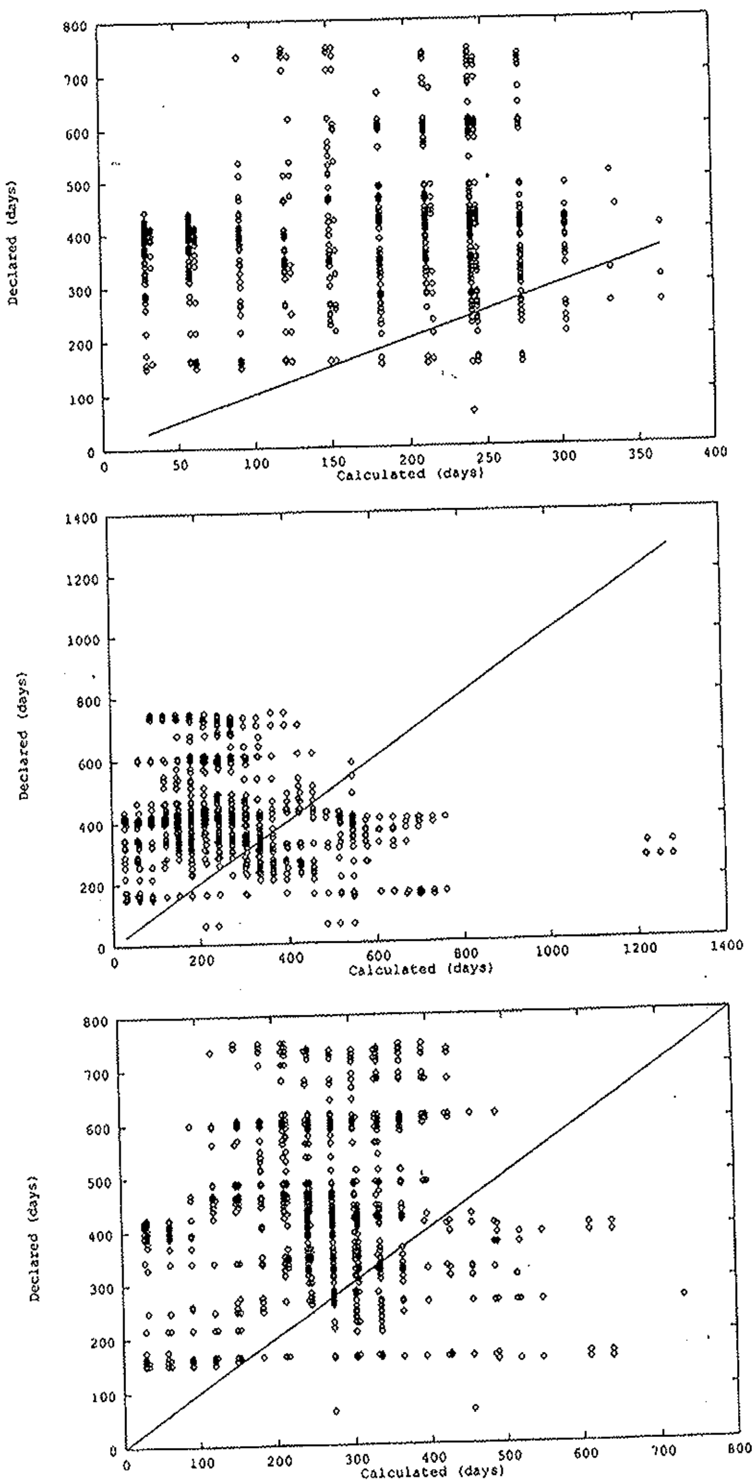

Figure 3.7 Durations of declared drought vs durations as estimated by (a) integrated six-monthly percentiles (b) integrated twelve-monthly percentiles (c) Palmer Indices. Each index calculated using an integration threshold of -17.5.

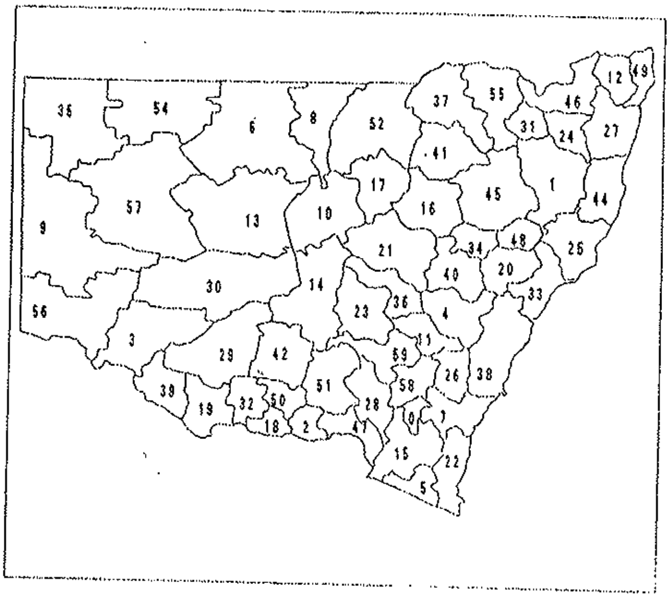

Figure 3.8 Boundaries of the 57 Pasture Protection Districts for New South Wales.

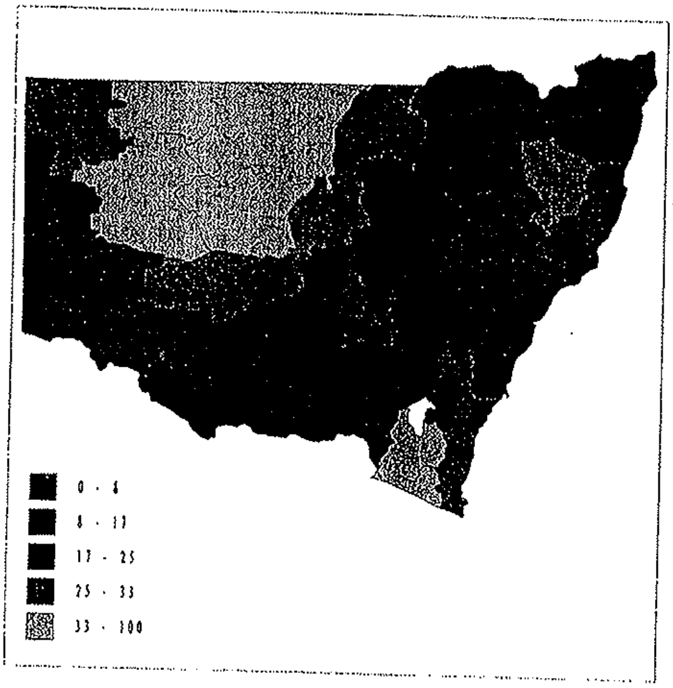

Figure 3.9 Percentage of time spent in declared drought between 1957 and 1981 for all Pasture Protection Districts in New South Wales.

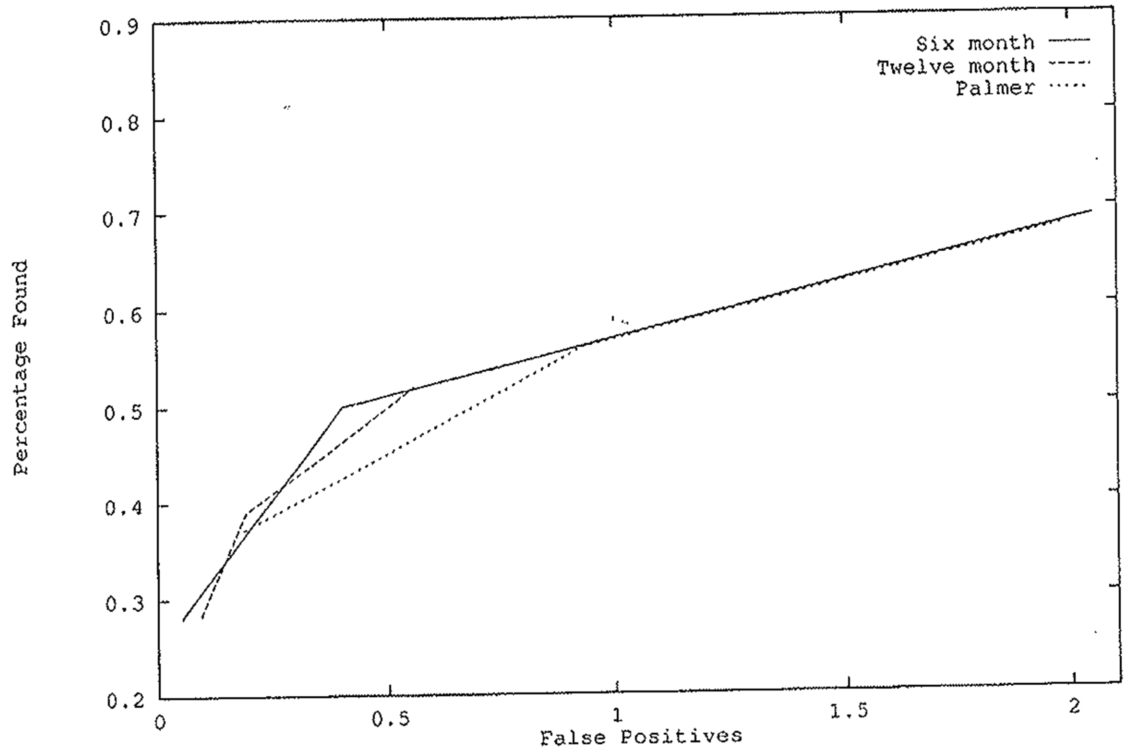

Figure 3.10 Percentage of declared droughts found vs the number of falsely predicted droughts for New South Wales between 1957 and 1981 using six-monthly percentiles, twelve-monthly percentiles and Palmer Indices, the second procedure and thresholds of 4.0, 5.0 and 8.0.

3.3 Conclusion

We have developed a relationship between integrated climatic drought indices and declared agricultural drought. The relationship appears to be workable for six-monthly deciles, twelve-monthly deciles and Palmer Indices but is strongest for six-monthly deciles. Most importantly, in both states the Palmer Index performed least well in predicting declared droughts. This adds further credence to our conclusion that six-monthly rainfall percentiles are a superior predictor of agricultural drought, despite the much more elaborate procedure required to calculate the Palmer Index.

It is clear that the sensitivities of drought declarations to climate in each state are markedly different. We have been able to calibrate these differences by simply changing the threshold used to monitor the integrated drought indices, and by modifying the procedure.

One reason for the apparently superior performance of the climatic drought indices in predicting declared drought for Victoria may be that the smaller size of the Victorian drought declaration areas allows the climatic indices at the centroid of each area to be more truly representative of the area. However, the maps in Figure 2.15 indicate that the spatial patterns of the climatic drought indices are quite broad. This would tend to minimise the effect of the different sizes of areas in each state. It would thus seem reasonable to conclude that drought declarations in Victoria are more closely attuned to climatic conditions than in New South Wales.