Seasonal Rainfall Anomalies and the Level of Lake Goran

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Abstract Annual rainfalls have varied significantly in the Lake Goran study area. The straight line of best fit shows a very slow increase over 116 years. An examination of the seasonal distribution of the rainfall reveals significant changes during that time. The October to December and the January to March quarters have shown significant reductions and subsequent increases during the period of record. In the early 1990s the April to June rainfalls have shown a significant increase, and coupled with comparatively low evaporation and transpiration at that time of the year, this has lead to significant increases in runoff. The excess water has been determined using a WATBAL type model for the current land use distribution. The depth of the lake has been modelled using rainfall and excess water as inputs and evaporation as the only output. Given the simplicity of the model the agreement between measured depth and predicted depth is very good.

1. Introduction

Rainfall is probably the most widely measured meteorological parameter and is certainly the meteorological parameter in which the general public is most interested. The accurate estimation of areal rainfall is not easy as its temporal and spatial heterogeneity is high. The locations of rainfall measurement sites, within Australia at least, are generally selected for convenience, not representativeness. Recently there has been considerable interest in examining Australian rainfall records to see if evidence of climate change or any El Nino - Southern Oscillation connection is present, (see for example Drosdowsky 1993a and 1993b). In this paper we will examine the effects of long term variations in seasonal rainfall distribution on the water level of a small semi-closed basin in north east NSW.

The study area chosen is the Lake Goran Catchment (LGC), an area of approximately 1550 km^2 located south of Gunnedah (30° 59' S and 150° 15' E). Lake Goran itself is an ephemeral lake located on the Liverpool Plains approximately 30 km south of Gunnedah and covering an area of 8,240 ha when full. When dry the fertile black soils of the lake bed are cropped. In summer the major crop is sorghum and in winter the major crop is wheat. Over the last 40 years lake levels have fluctuated with the seasons but the lake has been mostly dry (see Russell, 1993). In the early 1990s the lake levels have been near full, which has flooded much of the fertile plains and removed these lands from agricultural production. The region is acknowledged as one with a highly variable rainfall and as having extremely variable hydrologic characteristics (see Findlayson and McMahon, 1988).

2. Rainfall Data

The rainfall data set is a composite data set from the NSW Dept of Land and Water Conservation Gunnedah Research Station and the Australian Bureau of Meteorology at the Gunnedah Post Office. The data set records daily rainfall for the period 1 January 1877 to 30 June 1993. The annual rainfall for this period is shown in Figure 1 and the straight line of best fit has also been plotted. The average annual rainfall for the 116 year data set is 613.7 mm and the standard deviation is 172.3 mm giving a coefficient of variation of 0.28. The line of best fit reveals a slow but significant increase of about 0.6 mm/yr in average annual rainfall over this period.

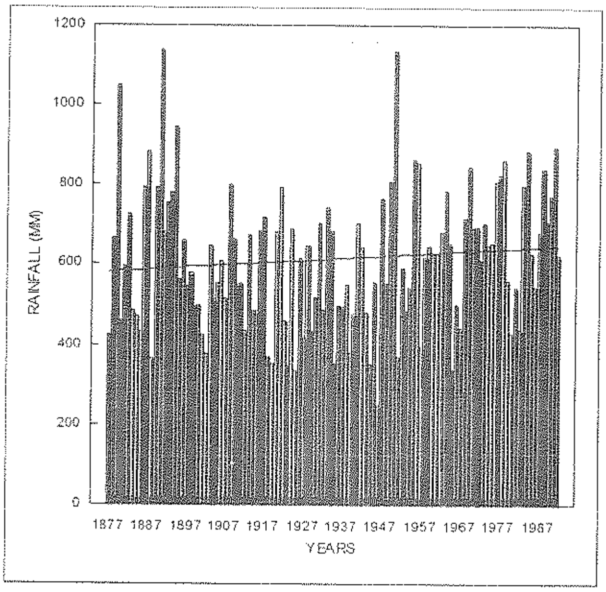

Figure 1 Annual rainfall distribution for the period 1877 to 1992. The line of best fit has also been plotted.

The cumulative sum (CUSUM) technique (see McGilchrist and Woodyer, 1975) has been used to examine the temporal sequence of rainfall. Cumulative sum techniques have proved to be a valuable tool in detecting intermediate term changes in the mean value of a sequence of regularly spaced observations. The cumulative sum s_i can be defined as

$$s_i = \sum_{i=1}^{i} (x_i - \bar{x})$$

where x_i is the regularly spaced observation. The CUSUM distribution is a normalised distribution and it reveals runs of observations greater than the long-term mean with a positive slope and less than the long-term mean with a negative slope. Such persistent positive or negative slopes can be used to detect intermediate term changes in the mean value. The actual ordinate values are not relevant, it is the slope that is important. The CUSUM distribution for the annual rainfall is shown in Figure 2. An examination of Figure 2 reveals that annual rainfalls for the 116 years of record can be treated as three distinct average rainfall periods. The first period from 1877 to 1900 consisted of a period of greater than average rainfall, with some uncertainty in the 1880s; the second period from approximately 1900 to 1950 was a period of below average rainfall and from 1950 there has been a period of average rainfall, followed by above average periods in the early 1970's and then in the 1980's. These trends are apparent in Figure 1 but much more difficult to discern.

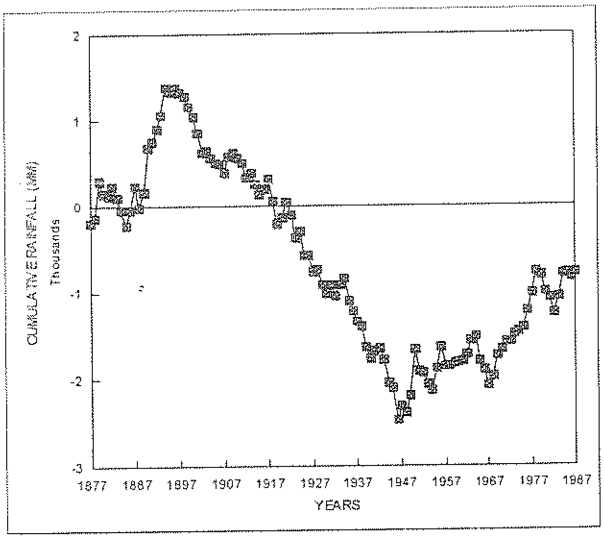

Figure 2 A CUSUM plot of annual rainfall.

The annual rainfall distributions presented in Figures 1 and 2 conceal all within year variations. In Figure 3 the average monthly rainfall for the entire record has been presented. From this plot it can be seen that the rainfall is very much summer dominated with January being the highest rainfall month. The average monthly rainfall from April to September is approximately uniform. The rainfall standard deviations for each month have also been plotted in Figure 3 and show the standard deviations for the summer months greater than for the winter months. This was anticipated because the large summer rainfalls are usually associated with highly irregular inflows of tropical air masses.

CUSUM plots can be applied to seasonal rainfalls for the detection of trends in the seasonal averages. There can be compensating shifts in the values in adjacent periods which may negate any comparison with the annual CUSUM trends. With that caution, Figures 4 and 5 show CUSUM plots for the summer and winter six month periods and the four quarterly periods JFM, AMJ, JAS, OND.

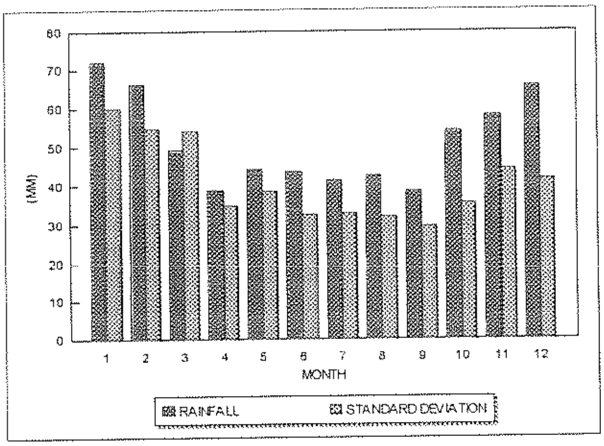

Figure 3 Long term monthly average rainfall and standard deviation.

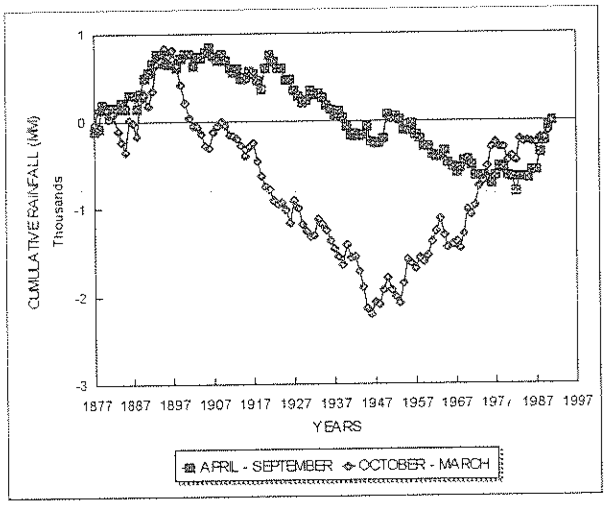

Figure 4 A CUSUM plot of half yearly rainfall.

The drier six month period (April to September) shows again the three distinct periods observed in the annual rainfalls but this time the initial increase lasts until approximately 1910 and is then followed by a long period of slowly decreasing CUSUM or slightly below-average seasonal rainfall until approximately 1980 and then a recent increase in seasonal rainfall. The wetter six month period (October to March) shows very similar characteristics to the annual rainfall, as anticipated.

The CUSUM plots for the quarterly rainfall are more scattered than the annual or six-monthly plots as each point represents the average of only three values. The January to

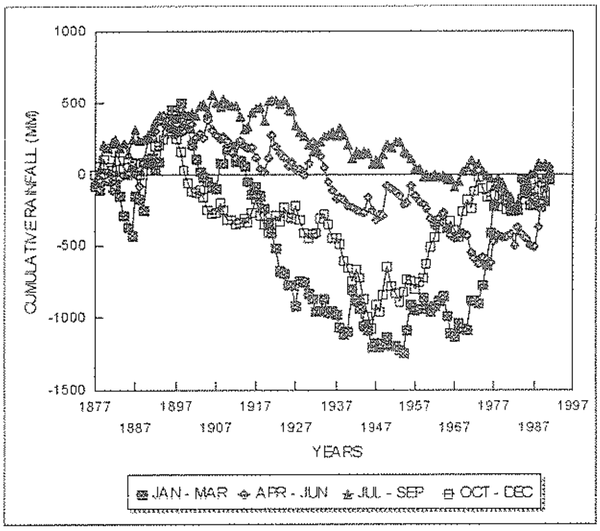

Figure 5 A CUSUM plot of quarterly rainfall

March (JFM) CUSUM trend shows an initial decrease followed by a rapid increase then a long-term decrease from 1915 to about 1955, then a rapid increase until 1975, or a period of above-average rainfall, and approximately average conditions since then. The April to June (AMJ) CUSUM trend was more constant in the early part of the record and then showed a slow decline from 1935 to 1985 followed by a sharp increase, or above-average rainfall. The July to September (JAS) CUSUM trend showed a slow increase until about 1920 followed by slow decrease until about 1965 and rainfall has been average since then. The October to December (OND) CUSUM trend showed an initial increase followed by a slow decrease until about 1950, followed by an increase until 1970 and about average rainfall since then. Thus the significant change in recent history is the sudden increase in the AMJ rainfall.

3. Land Cover data

In order to model the effect of seasonal changes in rainfall distribution on water use, it is necessary to know the total areas of the different types of land cover within the catchment and the water requirements of each type of land cover. The land cover data set used comes from Australian Bureau of Statistics (ABS) and NSW Department of Agriculture figures. The ABS data are aggregated to the shire level and unfortunately the Lake Goran Catchment contains parts of Gunnedah Shire (formerly Gunnedah Municipality and Liverpool Plains Shire), the Quirindi Shire (formerly Quirindi Municipality and Tamarang Shire) and a very small part of the Murrindi Shire. As parts of the catchment are very flat there has been some ambiguity in the total catchment area. In particular, the contribution of the Yarraman Creek subcatchment depends on cropping conditions in the final floodout area. We have assumed that 50% of the Yarraman subcatchment flows into Lake Goran. This results in a total catchment area of 1550 km^2 and consists of 42.6% Gunnedah Shire and 57.4% Quirindi Shire.

The land cover data show considerable short-term trends due to fluctuating commodity prices and variations in climate and a significant longer term trend away from pastures and grassland to cropping. As we are interested in the effect of the recent change in seasonal rainfall distribution, we have only treated the present land cover distribution. This distribution consists of 39% pasture and grassland, 17% summer crops, 25% winter crops, 14% woodland and 5% lake bed.

4. Water Balance Model

The water balance model used has its origins in the work of Slatyer (1960) and Fitzpatrick and Arnold (1964). Based on these works, Keig and McAlpine (1974) developed an integrated model (WATBAL) to estimate the availability of soil moisture. This model has seen extensive use throughout Australia for assessment of agricultural productivity and given its limitations produces results which show a high correlation with actual crop yields. These limitations include the use of a weekly time step and difficulties in estimating the maximum soil water storage, the variation of the crop coefficient with different crops and the season and the soil moisture retention curve. Water surpluses generated in the model can be used as an estimate of surface runoff and are so used later in this study. This prediction would generally be an overestimate as it takes no account of aquifer recharge.

The WATBAL model requires weekly values of precipitation and potential evaporation (PET) as input data . The precipitation data has already been presented. However, PET data is not generally available in rural Australia and when available it is only post 1950. As between-year variations in weekly PET are relatively low, it is possible to use long term weekly mean values. The PET value used was the Penman value (as calculated in the AUSTCLIMWEEKLY data set) multiplied by 0.75. This PET value approximates the reference crop evapotranspiration ET_0, for well watered but non-irrigated grass in light to moderate winds. Doorenbos (1984), (the FAO publication Crop Water Requirements) defines ET_0 as "the rate of evaporation from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water". The PET of other crops or vegetation is then given by

$$PET_{crop} = k_c * ET_0$$

The values used for the crop coefficient k_c for the different classes of land cover and the variation during the year are given in the Diagram 1. These values were estimated using the FAO publication. The k_c variation during the year for pasture and grassland is not simple as it depends on the type and percentage of the different grasses. Two annual k_c distributions were considered: a twelve-months growth distribution and a winter six-months growth and summer six months senescence distribution. After extensive discussions (see Acknowledgments) we decided that the twelve-months growth distribution was a more accurate representation of the growth distribution given the diverse mixture of native and introduced grasses. This agrees with the observations of Hayman (undated). Also the WATBAL model reduces actual evapotranspiration (AET) during periods when PET is greater than rainfall.

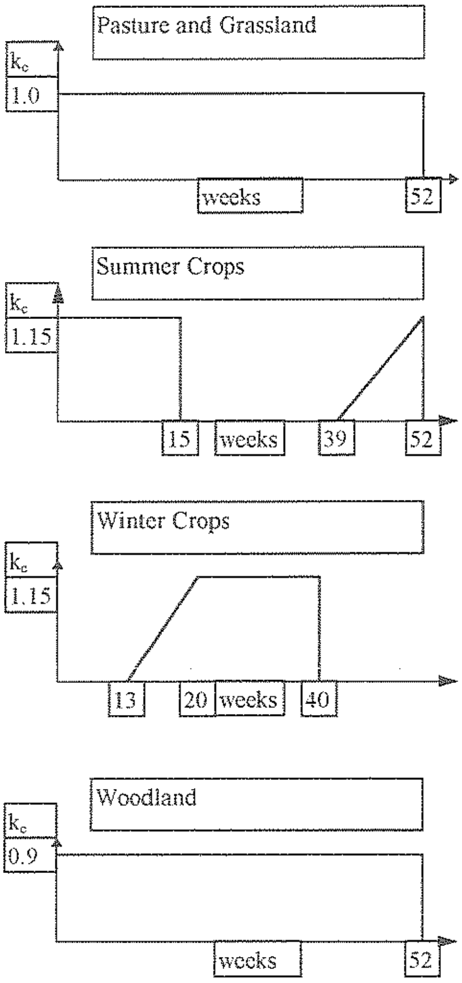

Diagram 1

In order to apply the WATBAL model it is necessary to specify:
(1) The maximum available soil moisture storage in the root zone (ST_{max}). This will vary depending on the type of land cover as trees have a much greater rooting depth than grasses, thus a higher effective ST_{max}.
(2) The relationship between AET/PET and relative available water storage Θ, where Θ is given by

$$\Theta = \frac{ST_{avail}}{ST_{max}}$$

$$\text{and} \quad \frac{AET}{PET} = C - \exp\{K\Theta\}$$

where ST_{avail} is the actual soil moisture, Θ is fractional soil moisture. The later relation is dependent on the soil type and C and K are constants which, for the clay-loam type soils of the Lake Goran catchment, have the values $C = 1.03$ and $K = -3.5$. Evaporation from bare soil, fallow, standing dead vegetation or a dry lake is governed by a different relationship as the ability of the vegetation to extract water from the root zone is now removed. The relationship used is

$$AET_d = k_d * ET_0$$

where $k_d = 1$, for $0.8 < \Theta < 1$ and $k_d = 0.1 * \Theta$ for $0 < \Theta < 0.8$. This relationship is required as outside the cropping season the soil is bare. Thus the water balance model can be applied to weekly data at time step i, where ST_i is the soil water storage (mm) in the specific root zone at the start of the time step, as follows:

$$ST_{est} = RAIN_i \;/\; 2 + ST_i$$
$$\text{where } 0 \leq ST_{est} \leq ST_{max}$$

The term ST_{est} is an approximation to ST_{avail} and is meant to represent the average conditions during the week.

$$\begin{aligned} \Theta &= {}^{ST_{est}}\!/\!_{ST_{max}} \\ AET_d &= k_d * PET \\ AET_l &= [C - \exp\{K\Theta\}] * PET \\ AET_i &= \max(AET_d, AET_l) \\ ST_{i+1} &= ST_i + RAIN_i - AET_i \\ EXCESS_i &= ST_{i+1} - ST_{max} \\ \text{where } EXCESS_i &\geq 0 \text{ and } 0 \leq ST_{i+1} \leq ST_{max} \end{aligned}$$

The model calculates the water required during the time step and the excess water at the end of each time step, where the excess water is defined as the amount of water in excess of the maximum soil water storage. This excess water has not been partitioned into deep drainage and runoff because of the spatial and temporal variability of this partitioning and because a significant but unknown amount of this deep drainage will ultimately finish up in Lake Goran. Thus it is anticipated that the model will overestimate the actual runoff into the lake.

The WATBAL model was run for the current land cover distribution and the four different crop coefficients to yield weekly values for the excess water (mm) for each type of land cover for the 116 years of record. The lake bed was not included in the calculations for several reasons. Firstly the evaporation from the lake or lake bed depends critically on whether it is flooded, saturated or dry and this was not known for the 116 year data set. Secondly the lake does not contribute to runoff as it is at the bottom of the catchment and finally it represents at maximum only 5% of the total catchment area.

5. Excess Water Results

The excess water for the whole catchment was determined by multiplying the excess water for each type of land cover by the area of the land cover and adding the four values. The excess water was calculated at a weekly time step (6032 weeks) but when displayed the results were hard to interpret because of the large number of points, the high variability of the rainfall and seasonal effects. These weekly values for excess water were aggregated to annual values and are shown with the annual rainfall as CUSUM plots in Figure 6. When compared with the rainfall plot (Figure 1) the three years of rainfall above 1000 mm (1879, 1890 and 1950) can be easily identified. The plot also responds to a rapid increase in rainfall and excess water in the period 1987 to 1992 (the most recent data).

In order to separate out seasonal effects the weekly excess water data set was aggregated to monthly and quarterly data, after taking account of the different number of days in each month. The quarterly data is plotted in Figure 7 as a CUSUM plot. This plot clearly shows that it is the increase in the April to June rainfall which has caused the recent increase in excess water. It is interesting to note that in the early 1970s there was a significant increase in the JFM rainfall (see Figure 4). This did lead to an increase in excess water (as shown in Figure 7). Unfortunately there is no lake level data available to see if this increase in excess water did lead to higher lake levels. The monthly rainfall and excess water has been plotted in Figure 8 for the period 1989 to 1992 inclusive. From this plot it can be clearly seen that high monthly summer rainfalls (eg January 1991, December 1991 and February 1992) produce comparatively small amounts of excess water whereas smaller monthly rainfalls in autumn (eg April 1989, June 1989 and May 1991) produce much greater amounts of excess water.

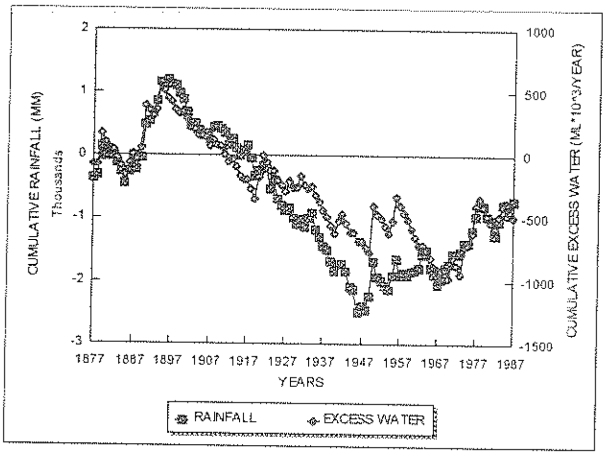

Figure 6 A CUSUM plot of annual rainfall and annual excess water.

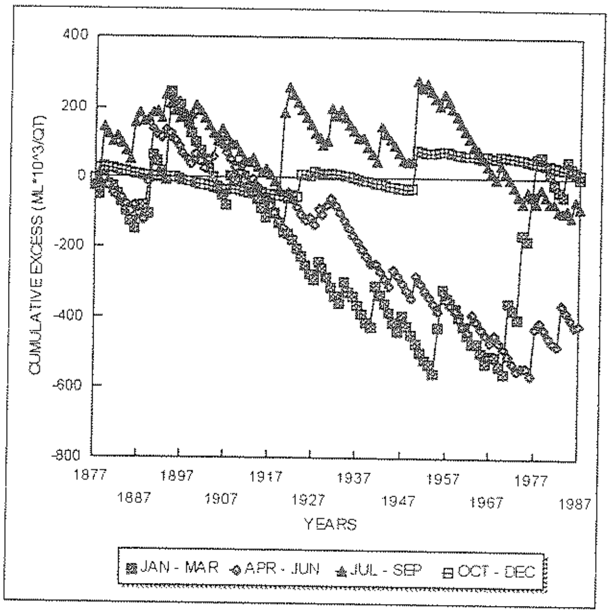

Figure 7 A CUSUM plot of quarterly excess water.

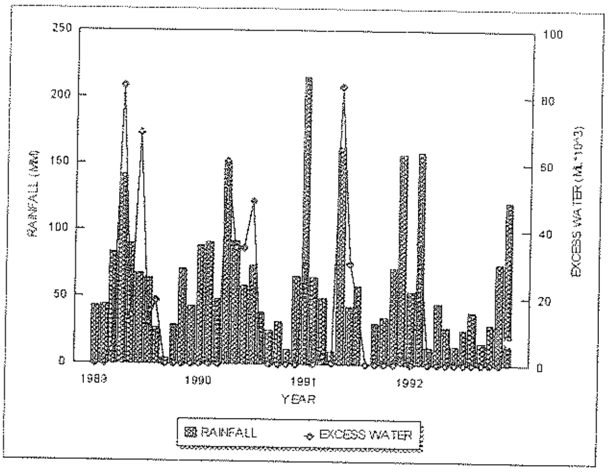

Figure 8 A plot of rainfall and excess water for the period 1989 to 1992 inclusive.

6. Modelling Lake Levels

The level of Lake Goran has been modelled using a simple water balance model. The inputs to the lake are monthly excess water, as calculated previously, and monthly rainfall. The only output considered is evaporation. Daily class A pan evaporation data is available from the Gunnedah Research Station and the evaporation from a large water body E_o has been calculated as follows:

$$E_o = E_{pan} * 0.7$$

The daily evaporation data was then aggregated to monthly data. Small and unquantifiable outputs would also include irrigation and deeper aquifer recharge but these have not been further considered. As a consequence it is anticipated that the model will provide slight overestimates of lake level. The Department of Water Resources has done limited and irregular gauging of lake levels and these are included as Appendix Four in Russell (1993). The relationship between the volume and the depth of Lake Goran is given in Russell (1993) at 100 mm steps and this has been fitted by an equation of the form

$$V = ah + bh^2 + ch^3$$

with an R^2 of 99.99%. If initially we ignore the inflow, then

$$\tilde{h}_{i+1} = \tilde{h}_i + rain_i - (E_o)_i$$

where $\tilde{h}_{i+1}$ and $\tilde{h}_i$ represent the lake depth at the end and start of the month, whilst $rain_i$ and $(E_o)_i$ represent rainfall and evaporation during the month. Thus the volume at the end of the month is given by

$$\tilde{V}_{i+1} = a\tilde{h}_{i+1} + b\tilde{h}^2_{i+1} + c\tilde{h}^3_{i+1}$$

Now if we include the inflow XS_i the total volume at the end of the month V_{i+1} is given by

$$V_{i+1} = \tilde{V}_{i+1} + XS_i$$

From a table of volume versus depth of the lake at steps of 1 mm, it is possible to determine h_{i+1}, the depth at the end of the month. The model has been run from January 1989 until December 1992. This period was chosen as the lake was initially dry and it covered most of the available Department of Water Resources data. In Figure 9 we have plotted the measured and predicted depth of the lake. The agreement is very good and as anticipated the predicted depth is slightly greater then the measured depth.

7. Conclusions

The rainfall record CUSUM plot shown in Figure 2 for the 116 year data set shows a period of above-average rainfall at the end of last century, following by a long period of below long-term average rainfall up to 1950 and more recently a period of above average rainfall. The CUSUM plotting technique is a powerful tool for detecting and showing changes in the intermediate-term average. All the data displayed in Figure 2 is also displayed in Figure 1, but the intermediate term changes in the average are not apparent.

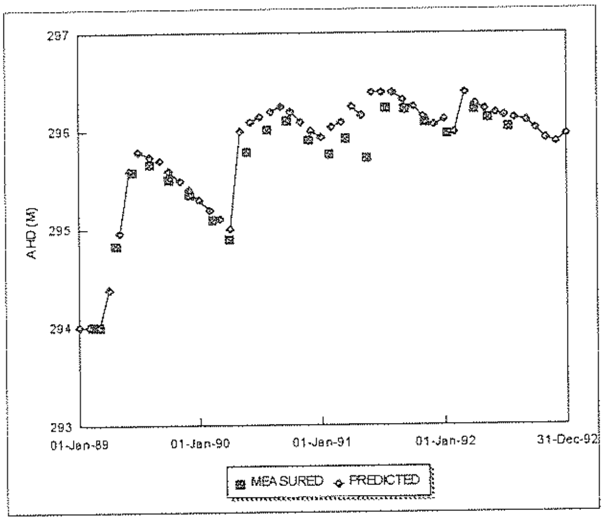

Figure 9 A plot of the predicted level of Lake Goran versus the measured level.

The CUSUM plots in Figure 5 show that seasonal rainfall distributions have varied significantly during the period of record. The AMJ and JAS rainfalls although smaller have been much more consistent than the OND and JFM rainfalls. This was expected because the large summer rainfalls are usually associated with inflows of tropical air masses. These may be remnant rain depressions moving southwards after tropical cyclones have moved inland in Queensland and the Northern Territory. In winter rainfalls are usually associated with the northward movement of fronts and rain depressions from the Southern Ocean. However the largest winter events are normally associated with mid-tropospheric circulations which introduce tropical oceanic air of high wet-bulb potential temperature. Gentilli (1971) called them inter-anticyclonic fronts but they do not always occur between anticyclones and are not frontal anyway. Fleming (1978) has referred to the process as a "mid-tropospheric conveyer belt".

The CUSUM plots of annual excess water exhibit similar trends to the annual rainfall plot (Figure 6). The change from below-average excess water to above-average excess water appears to occur at approximately 1970, whereas for the rainfall a return to the long-term average occurred at approximately 1950, although this change from below average rainfall to average is assisted by the record highest rainfall in 1950. The transition for the rainfall was produced by comparatively small increases in the OND and JFM rainfalls which were largely lost to evaporation. The transition in 1970 to well above-average rainfall and excess water was produced by major increases in the JFM rainfalls (see Figures 5 and 7)

The most recent transition in the late 1980s has been produced by a significant increase in the AMJ rainfall, which produced a significant increase in excess water for that quarter and coupled with seasonally low ET rates has led to the comparatively high recent water levels in Lake Goran

The lake level has been modelled using a water balance approach. The inputs to the lake are rainfall and excess water and the only output considered is evaporation. The model was run using monthly data and the agreement with the Department of Water Resources data is very good.

8. Acknowledgments

The authors gratefully acknowledge useful discussions with Mr F X Dunin and Dr B R Tunstall of the CSIRO, Mr J Kneipp and Mr A Dale of the NSW Agriculture at Gunnedah and Ms J P McMahon of the ANU who helped with the WATBAL implementation.

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