Temporal and spatial relationships between rainfall, runoff, land-use and climatic variability in the Bogan River drainage system.

Margriet Nakken
Climatic Impacts Centre, Macquarie University, Sydney, Australia

Abstract Continuous wavelet transforms (CWTs) are used to identify the temporal variability of rainfall and runoff and their relationship in the upper Bogan River in central western New South Wales. The relationship of rainfall-runoff patterns to the large-scale circulation index SOI is also examined. Preliminary results show that the variability of both rainfall and runoff as well as their relationship has changed over time. A wavelet spectrum analysis shows a change in dominant frequency since the 1950s. A method utilising wavelet analysis is being developed to identify and isolate the climatic components of the hydrological record as well as to distinguish the influence of other non-stationary trends, such as land-use changes, on runoff records over time. Preliminary results show a climate-induced catchment response at short time scales (26 to 32 months) as well as an influence of SOI at 28 months. Spatial patterns and relationships will be identified to aid in floodplain management and flood frequency prediction for data limited catchments.

1 Introduction

In April 1990, widespread flooding occurred in inland New South Wales and Queensland. The town of Nyngan, in the central west of NSW, was inundated by the Bogan River and subsequently evacuated. Unfortunately for the town residents both the height and timing of the peak were under-forecast. The devastating immediate effects, and subsequent long term impacts upon the catchment caused by the flood have brought into focus the need for a review of hydrologic modelling techniques used in the catchment.

For the Bogan River catchment, a barrier to adequate floodplain management is the lack of hydrological data for determining flood risk, such as flood magnitude and the frequency of occurrence. The first gauging station on the Bogan River was established in 1925, at the Peak Hill water supply weir. Flood records of between 20 and 40 years from only eight other gauging stations are available. Despite the limited data, a methodology to quantify and relate information of temporal and spatial patterns utilising wavelet analysis is being developed. Trends in both precipitation and runoff records are identified and compared, to detect and isolate the climate induced components of the hydrological record. Temperature time series will be incorporated in the analysis at a later stage. Besides climate trends, changes in land-use and catchment characteristics are assumed to be reflected in runoff trends.

The Fourier spectral analysis has often been used in identifying trends, but its use is limited for non-stationary data such as precipitation and discharge records. The continuous wavelet transform (CWT) provides a time-frequency representation of the signal and has recently been used for analysing climatic and oceanographic data [e.g., Wang and Wang 1996; Gu and Philander 1995; Bradshaw and McIntosh 1994; Meyers et al. 1993].

A wavelet analysis is performed in a similar way to the short time Fourier transform (STFT), in the sense that the signal is multiplied with a function, the wavelet, similar to the window function in the STFT, and the transform is computed separately for different segments of the time-domain signal. However, the width of the wavelet is changed as the transform is computed for every single spectral component.

The continuous wavelet transform is defined as the sum over all time of the signal multiplied by the scaled (stretched or compressed), shifted versions of the wavelet function ψ:

$$C(\text{scale, position}) = \int_{-\infty}^{\infty} f(t)\psi(\text{scale, position}, t)dt \quad (1)$$

or

$$C(a,b) = \int s(t)\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)dt \quad (2)$$

where the wavelet coefficients C are the result of the CWT of signal s. The appropriate wavelet should have a similar pattern to the signal. The wavelet functions used in the present analysis are the Morlet and Sombrero (or Mexican Hat) wavelets, both appropriate functions for revealing peaks and troughs in wavelike signals such as rainfall and runoff records. The complex-valued Morlet function (a modulated Gaussian) is represented by:

$$\psi(t) = e^{-ict}e^{-t^2/2} \quad (3)$$

with $c = \pi\sqrt{2/ln2}$, whereas the real-valued Mexican Hat wavelet is proportional to the second derivative function of the Gaussian probability density function:

$$\psi(t) = \left(\frac{2}{\sqrt{3}}\pi^{-1/4}\right)(1-t^2)e^{-t^2/2} \quad (4)$$

The integral of the wavelet ψ is zero ($\int \psi(t)dt = 0$).

2 The Bogan River Catchment

2.1 General physiography

The Bogan River is part of the Macquarie River catchment. It is nearly 600 km long and rises in the low hills of the western slopes in central western New South Wales north of Parkes. The river level falls from an elevation of 250 m near Peak Hill to 170 m at Nyngan. The total catchment area at Nyngan is 18,040 km^2. Below Nyngan the river breaks into distributary streams flowing across the Bogan-Macquarie alluvial fan and eventually joins the Darling River just upstream of Bourke. It is fairly typical of a low gradient inland stream on the margin of the semi-arid zone.

The Bogan River catchment is mostly flat plains country, with slopes of less than 2 percent, except for some hilly areas near Peak Hill. The sub-catchment analysed in this paper is the unregulated catchment upstream from Peak Hill (1036 km^2), in the upper reaches of the Bogan River Basin. The headwaters have a major influence on flooding downstream and are therefore of principal interest in flood studies.

2.2 Precipitation and stream flow

Arid and semi-arid zone river systems in Australia show remarkable flow variability, with up to a thousand times more variation in mean annual discharge than in humid zone rivers. The active channel systems are able to expand to exceptional widths (tens of kilometres) during floods. Flood pulses are of long duration (weeks to months) and the flood wave moves slowly down long, low-gradient channels [Gale and Bainbridge 1990] whilst flood discharge tends to decrease systematically downstream.

River flow records are represented here as time series of runoff expressed in millimetres of equivalent water depth over a catchment area, for ease of comparison with precipitation. Average annual rainfall at Peak Hill is 564 mm, while the annual runoff through Peak Hill gauging station is approximately 35 mm (see Table 1). The monthly rainfall total at Peak Hill for April 1990 was 370 mm, or 66% of the annual average rainfall. The rainfalls causing the April 1990 flood had a return period of about 200 to 250 years [DWR 1990].

Table 1: List of precipitation and gauging stations used in the analysis.

Station number	Station name	Variable	Annual mean (mm)	Period
50031	Peak Hill	precip.	563.9	1890–1996
421010	Peak Hill 1	runoff	34.65	1925–1967
421076	Peak Hill 2	runoff	37.21	1967–1996

2.3 Land-use changes and other non-stationary trends

Since European settlement, approximately 70% of the catchment area has been cleared to improve grazing, a management practice that was dominant until the 1950s after which substantial areas of grazing land have been converted to cereal cropping. It would seem likely that these ongoing changes in land management practices have, had and will continue to have, profound impacts upon stream flow, flood heights and channel morphology. However, because there have been no investigations into the impacts, generalisations such as these must be treated with caution.

By 1990 only about 30% of the catchment retained any near natural vegetation and perhaps another 30% would have been cultivated immediately prior to the floods. It is likely that these changes have had profound impacts on stream flow, flood heights and channel morphology over the past century but none have yet been documented. Given that: Australian rivers have such a huge range in flow conditions; catchments like the Bogan have been extensively modified; and that we have little more than 70 years of gauging record, the task of predicting recurrence intervals for larger and less frequent floods is little better than guesswork. Several attempts have been made to improve prediction reliability but all have their limitations and even one of the more widely adopted patterns of Flood Dominated Regimes (FDR) and Drought Dominated Regimes (DDR) [e.g., Erskine and Warner 1988] has recently been shown to rest on a less than adequate statistical base [Kirkup 1996; Brizga et al. 1993].

In order to better appreciate flow variability in Australian streams, and thus make more reliable estimates of flood risks and costs, we need to return to basics. Land use changes and the surface condition of the catchment need to be quantified; a fundamental analysis of the raw data on precipitation needs to be linked to flood history; the hydrological impacts of changed channel conditions caused by major flood events need to be assessed: and the likely effects of greenhouse climate changes need to be included in predictive modelling. Wavelet analysis and especially the use of wavelet variance are important means in determining the non-stationary trends and relationships and are invaluable to evaluate the impacts of future climate changes as well as the specific effects of land-use changes on runoff.

3 Rainfall-Runoff Trends and Relationships

To distinguish climate-induced patterns from land-use patterns in the runoff signal, a methodology utilising wavelet analysis is being developed. The method detects and isolates temporal and spatial patterns across scales and is critical to identify the climatic components of the hydrological record. The wavelet analysis is applied to rainfall and runoff records from Peak Hill. Yearly stratified monthly anomalies for rainfall and runoff are shown in Figure 1. The raw signal for continuous wavelet analysis is dyadic, i.e. to the power 2, which in this case encompasses 1024 (2^{10}) months from September 1911 to December 1996. The runoff signal is extended with the long-term anomaly. Both the monthly precipitation and runoff values show a periodic component, and are therefore non-stationary series. The trend component is assumed to be caused by long-term climatic changes and gradual changes in the catchment's response owing to land-use changes.

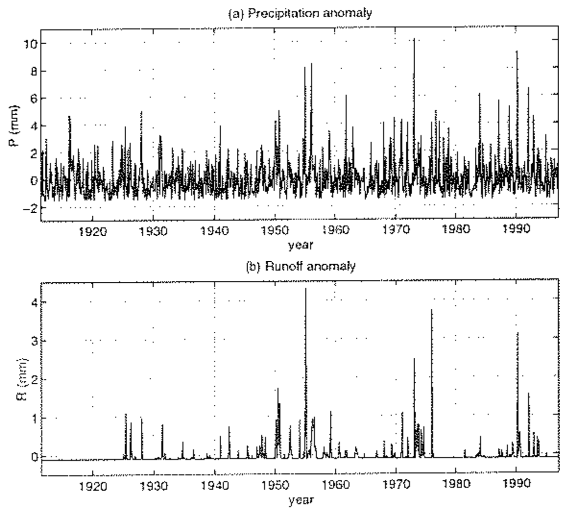

Figure 1: Time series of (a) monthly precipitation anomaly and (b) monthly runoff anomaly, Peak Hill, September 1911–December 1996.

Figure 2 shows the CWT for both rainfall and runoff, using the Morlet wavelet with 32 voices. The higher the voice used in the analysis, the closer the similarity between the wavelet and the signal. A high correlation between the wavelet and the signal returns large values of wavelet transform coefficients; in Figure 2 this is reflected in the light colours. Dark colours relate to troughs or low values of the transform coefficients. The major flood events in the Bogan River catchment in 1925, 1955, 1976 and 1990 are readily discernible. Annual, inter-annual (3.5 to 3.5 years), and inter-decadal (10 to 20 years) frequencies are also recognisable. The variability over time changes dramatically for both rainfall and runoff at around 1950. The 1.5 to 5.5 year inter-annual cycle for runoff and the 10 to 20 year inter-decadal cycles for both rainfall and runoff become more pronounced after the 1950s. For rainfall, a shift from an intense 7 to 10 year cycle in the period from 1911 to approximately 1930 to a 10 to 20 year cycle since the 1960s is visible.

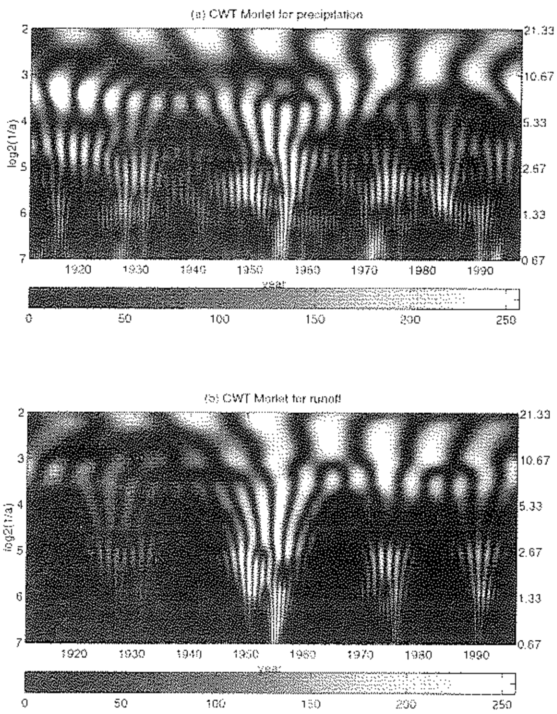

Figure 2: Real part of CWT for (a) monthly precipitation anomaly and (b) monthly runoff anomaly, using Morlet 32 voices. The left y-axis shows frequency expressed in terms of scale, while the right y-axis shows frequency in years.

Where the CWT analysis identifies patterns in the temporal domain, the dominant climatic component in the hydrological record can be specified using the wavelet variance. The wavelet variance is the integration of the wavelet transform over the temporal record. To identify dominant frequencies, wavelet spectrums are analysed for the complete period 1911–1996, as well as for 1911–1949 and 1950–1996 (see Figure 3). Results using the Morlet wavelet (four voices) are shown. The smaller voice is used to avoid smoothing the signal and to improve the visualisation of dominant frequencies.

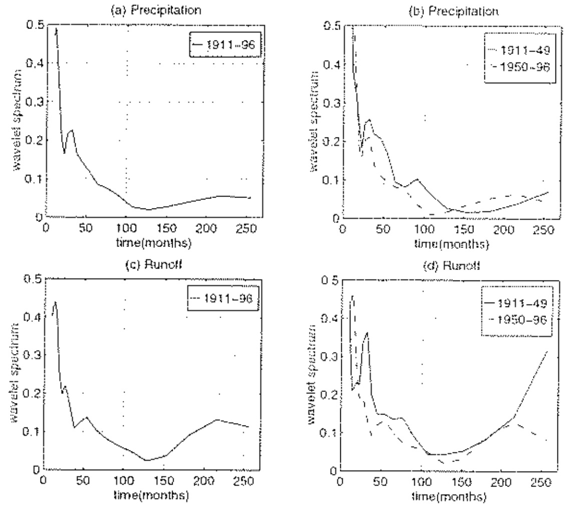

Figure 3: Wavelet spectrum for (a,b) monthly precipitation anomaly and (c,d) monthly runoff anomaly, using Morlet four voices.

Similarities between the rainfall and the runoff wavelet spectrum are apparent. The dominant frequency for both precipitation and runoff is 26 to 32 months from 1911 to 1949, while the dominant frequency after 1950 is 27 months. CWT analyses using the Sombrero wavelet show similar results.

The wavelet variance loses the point of time along the record. Mean runoff is generally dependent on moisture conditions of the previous month and runoff shows a lag compared to precipitation. Therefore, a model will be developed to perform a wavelet cross-covariance to identify dominant scales of interaction between the time series of rainfall and runoff and to identify the lag time at which the maximum correlation occurs, following Bradshaw and McIntosh's proposal [1994]. The scales where rainfall and runoff (and temperature) are strongly correlated are assumed to be a measure of climate-induced catchment response. These scales will be removed and the signal reconstructed. Dominant scales in the reassembled filtered signal are related to other factors controlling runoff – the most important of which is believed to be land-use. Land-use, riparian vegetation and channel condition changes will be evaluated using historical records (from explorers and surveyors, portion plans, etc.) and aerial photographs.

4 SOI relationship with rainfall-runoff events

The impact of the ENSO phenomenon on climatic variability in Australia has been well documented and is summarised by Allan et al. [1996]. During strong El Niño phases (negative SOI values), Australia receives less than average rainfall during the austral winter to early summer period, while during strong La Niña events (positive SOI values) rainfall patterns are enhanced and extensive flooding occurs.

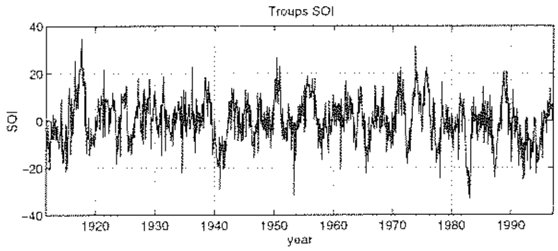

Figure 4: Time series of Troup's monthly SOI for September 1911 to December 1996.

Troup's monthly SOI time series from September 1911 to December 1996 is given in Figure 4. Preliminary results for the real part of the CWT for Troup's SOI (Figure 5) show some similarities with the CWT for rainfall and runoff (Figure 2) in the strengthening of the inter-decadal signal after the 1950s. Before the 1950s the 2.5 to 5.5 year cycle is dominant in the SOI series, whereas after 1950 there is a shift to 8 to 20 year cycles.

The dominant frequencies in the SOI wavelet spectrum (Figure 6) are 28 months and 45 to 61 months. In the time period from 1911 to 1949 a 63 month spectrum is dominant, whereas from 1950 to 1996 the 28 month spectrum is more pronounced. From the wavelet spectrum it can be concluded that the El Niño-Southern Oscillation has an influence on rainfall-runoff events (with a dominant spectrum of 26 to 32 months) at short time scales only. These findings are in agreement with those of Nicholls and Kariko [1993].

The relationship between SOI and rainfall-runoff events will be evaluated further in additional analyses utilising the wavelet cross-covariance, to determine whether the dominant spectra of rainfall, runoff and SOI are in phase with each other and to determine lag times. Other global scale circulation processes such as the quasi-biennial oscillation (QBO) will be included in the assessment. QBOs in rainfall over Australia have been identified by Trenberth [1975] and the inter-annual variability of the QBO is expected to have a dominant frequency close to to those frequencies seen in the rainfall-runoff analysis.

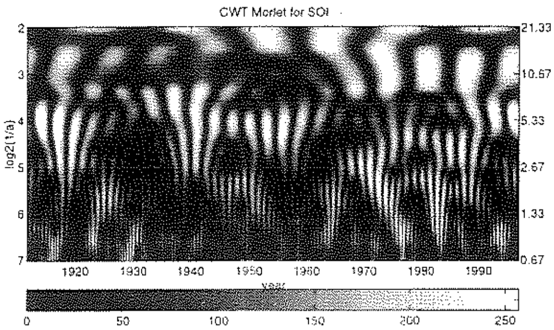

Figure 5: The real part of Morlet CWT, using 32 voices.

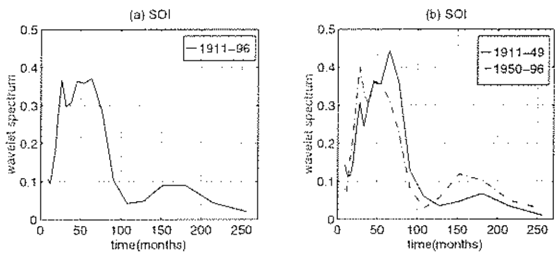

Figure 6: Wavelet spectrum for SOI, using Morlet four voices: (a) 1911–1996, (b) 1911–1949 and 1950–1996.

5 Spatial Analysis

The wavelet analysis presented in this paper is limited to the temporal domain. Ongoing work is extending the analysis in the spatial domain, incorporating runoff records from other gauging stations in the Bogan River catchment as well as records from similar catchments in the Macquarie River valley. It is hoped that the detection of temporal and spatial patterns and the identification of climate and land-use induced components can be extended to ungauged sub-catchments, where only precipitation and land-use records are available. Where flood characteristics must be estimated for a site without flow records, it is common to use flood records from other stations within the region to establish relationships between runoff, rainfall and basin characteristics (such as land-use, area, channel slope, etc.). Generated sequences of rainfall and streamflow data containing similar characteristics as the identified range of patterns will provide better estimates of the frequency of extreme events in ungauged sub-catchments. Having derived statistical relationships expressing the response variable (runoff) in terms of the explanatory variables (rainfall, temperature, land-use, etc.), knowledge of the explanatory variables for the site without flow record can be used to estimate its flood characteristics.

6 Discussion and Future Research

The climate of the next few decades will not be a statistical match of the past because there is now some certainty about the global scale effects of rising atmospheric levels of carbon dioxide and other greenhouse gases. The probability of global warming over the next 20-30 years is widely accepted and modelling indicates that we are likely to experience changes in the frequency of extreme events, including flooding [e.g., Fowler and Hennessy 1995; Whetton et al. 1993].

Wavelet analysis can be used to isolate the climatic component of the hydrological cycle from other trends such as land-use changes. It is, therefore, a first step in the detection of stream flow response to climate change. Having established a set of relationships, the likely effects of past, present and future climate and land-use variations will be presented for gauged sub-catchments. It is hoped that these relationships will be robust enough to be applicable to ungauged sub-catchments, thus providing a useful tool for estimating flood heights and planning for the impacts of future flood events.

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