4 Australian Perspectives on Predictions in Ungauged Basins

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INTRODUCTION

This chapter was invited to provide an Australian setting for the Australia–Japan Workshop on PUB (Predictions in Ungauged Basins) held in Perth, February 2004. Following a brief description of the Australian continent, key features of Australian streamflows and teleconnections are discussed. Next, the length and the magnitude of Australian droughts are examined relative to droughts observed in other continents. This discussion is followed by several examples of anthropogenic and natural features of Australian rivers. The penultimate section describes several applications of predictions and forecasts within a PUB setting and, finally, the chapter ends with several conclusions.

Arising out of this chapter, readers are left with the following five messages:

– Australian streamflows are highly variable yet predictable.
– Drought lengths are similar worldwide but the magnitude of Australian droughts are larger than for most other places.
– Significant impacts on the stream hydrology result from inter-basin transfer and river regulation.
– Evapotranspiration can be a significant factor in baseflow recession analysis.
– Regionalization is important in Australia and some progress has been made in implementation.

THE AUSTRALIAN CONTINENT

Geologically, Australia is an old continent. The western two-thirds has developed from Precambrian shield material. It is also known as the driest (inhabited) and the flattest continent with only 2% of the land over 1000 m above sea level and about 60% at between 200 and 1000 m (Jennings & Mabbutt, 1986). One third of the Australian landscape, mainly the arid zone, has internal drainage. One basin, the Lake Eyre Basin, within this region has a catchment area of 1 200 000 km^2. Australia's best known river system, the Murray-Darling Basin, has a catchment area of 1 100 000 km^2. Thirty percent of the continent is forested, covered with evergreen vegetation (Macquarie Library Pty Ltd, 1984). This is an important feature that has a dramatic influence on the hydrological characteristics of the continent.

To explore in a very general way the overall hydrological characteristics of the Australian continent, the long-term precipitation, runoff (and runoff coefficient[1]) and

[1] In this chapter, runoff coefficient is the ratio of surface runoff divided by precipitation.

actual evapotranspiration are compared in Table 1 with values for other continents. The table shows clearly that Australia has the lowest precipitation of the six continental areas identified, the lowest runoff and the lowest runoff coefficient. Nevertheless, we are able to find a large range of precipitation and runoff characteristics across the continent. For example, the Mulgrave River catchment (~500 km^2) located on the northeast coast has an average annual precipitation of 3200 mm, of which 2070 mm runs off yielding a runoff coefficient of 0.65 (Smith, 1999). Smith also reports that the driest catchment in Australia is Lake Frome, which is located in the arid zone; it has an average rainfall of 156 mm, with only 3 mm of runoff.

Table 3.1 *Continental hydrology.*

Continent	Precipitation (mm)	Total runoff (mm)	Baseflow (%)	RC (%)	Actual evapo-transp. (mm)
Africa (a)	686	140	35	20	550
Asia (a)	726	293	26	40	433
Australia (b)	455	52	n.a.	11	399
Europe (a)	734	319	34	43	415
North America (a)	670	287	29	43	383
South America (a)	1648	583	36	35	1065

Sources: (a) L'vovich (1979); (b) Smith (1999). n.a., not available

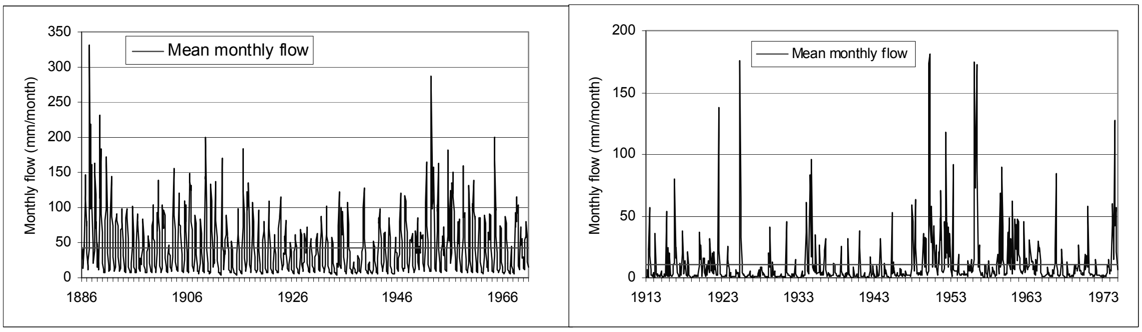
There are several ways that one could characterize Australian streams. For example, we could use the seasonal regime classification developed by Haines *et al.* (1988) which is based on the mean monthly patterns of streamflow. Another is to examine the general pattern of low flow sequences. For Australia we have identified four types of sequences: perennial streams that under extreme low flow conditions would not be expected to cease-to-flow; perennial streams that would be expected to dry up under extreme conditions; ephemeral streams where cease-to-flow is a regular feature and, lastly; highly variable ephemeral arid zone streams (McMahon & Finlayson, 2003). Examples are shown in Fig. 4.1.

UNDERSTANDING STREAMFLOW VARIABILITY

Although the mean condition as discussed above is important, variability is considered in many situations to be a more significant parameter in understanding a region's hydrology. Here, we explore variability as expressed as the coefficient of variation of annual streamflow. This metric is adopted as it is a key parameter in surface water resources management (McMahon & Adeloye, 2005) and has been helpful in understanding why Australian aquatic ecology is different to that of other continents (McMahon & Finlayson, 2003).

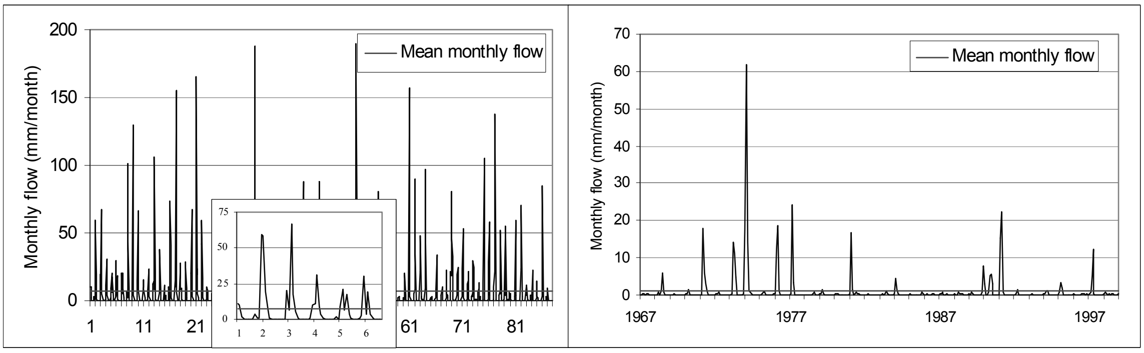
To illustrate the importance of variability in the Australian context we have plotted in Fig. 4.2 variability expressed as the coefficient of variation (Cv) of annual streamflows against mean annual runoff for 1282 stream gauging stations worldwide[2]. The Australian stations and those for southern Africa are separately identified from the remainder. The plot clearly shows that the variability of Australian streams (and those of southern Africa) is approximately double that found in other continents. An

[2] For a description of the data and the station locations readers are referred to Peel *et al*. (2001).



(a) Perennial stream with no CTF
(Thomson River, station no. 225210)

(b) Perennial stream with rare CTF conditions
(Queanbeyan River, station no. 410701)



(c) Ephemeral stream with annual CTF conditions
(Ord River, station no. 809302, modelled data)

(d) Ephemeral stream with no regular seasonal flow
(Todd River, station no. 060046)

Fig. 4.1 *Main types of streams in Australia (CTF is cease-to-flow). (Adapted from McMahon & Finlayson, 2003).*

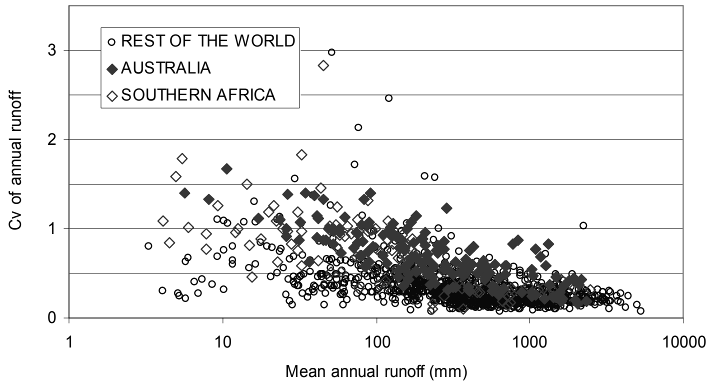


Fig. 4.2 *Relationship of variability (coefficient of variation) of annual streamflows and mean annual runoff.*

alternative plot, not included here, of annual *Cv versus* catchment area also shows a similar feature to that described above, namely that the variability of Australian annual streamflows (and southern African streams) are about double those in other continents. More details about this feature can be found in Peel *et al*. (2001).

Peel *et al*. (2001) have concluded that this phenomenon is primarily due to the fact that Australian (and southern African) catchments are populated mainly by evergreen vegetation, whereas catchments in the remainder of the world have deciduous vegetation. Consequently, during the colder months little interception takes place and transpiration is negligible. On the other hand, in Australia, both interception and transpiration occurs during winter and hence effective precipitation (and therefore runoff) is more variable than in deciduous landscapes.

One can identify many impacts as a result of this high variability (see Finlayson & McMahon, 1991), but we will examine only two. The first deals with water resources planning. Because of the higher variability the yield from a reservoir located in Australia is about 70% of that from a reservoir built in the northern hemisphere. If we assume that capital cost of dam construction is proportional to reservoir volume to the power 0.7 (Dawdy *et al*., 1970), then the cost of water at a headwater storage in Australia will be about three times that in the northern hemisphere[3]. In Australia these costs have been borne either by the general community through State and Federal taxes for irrigation projects, or by the urban water consumers in the case of municipal supplies.

The second impact relates to the evolutionary response of aquatic flora and fauna to high variability. Many Australian researchers, e.g. Brock (1986) on aquatic plants, Lake *et al*. (1985) on macro-invertebrates, and Walker *et al*. (1995) on fish, show how Australian aquatic flora and fauna exhibit an adaptive response to the variable Australian environment. Such opportunism characterizes the flora and fauna as they have evolved in conditions of high streamflow.

TELECONNECTIONS?

To explore this question of teleconnections we applied a Ropeleski & Halpert (1986) harmonic analysis to our world data set of annual streamflows (in this set 581 catchments) (Chiew & McMahon, 2002). The teleconnections were examined by fitting a first harmonic to 24-month El Nino streamflow composites. The results are plotted against a world map in Fig. 4.3, which also shows the continental variability of annual streamflows. It is evident that there is a strong teleconnection between ENSO and Australian streamflow as well as for New Zealand, the Pacific Coast of South America and central America. Medium correlations are noted for north and southeast Africa and parts of North America. Europe exhibits a low ENSO relationship.

A strong ENSO signal means that there is a relatively high correlation between ENSO and streamflow which, in conjunction with streamflow autocorrelation, can be exploited to provide a forecast of streamflow some months in advance. This is useful to be able to forecast streamflow several months ahead, particularly in the spring and summer irrigation season. For example, in eastern Australia, excluding those streams flowing to the coast, the Jul-Aug-Sep SOI is correlated (the correlation coefficient R is about 0.4–0.5) with Oct-Nov-Dec streamflow. However, incorporating streamflow autocorrelation can lift R up to more than 0.5. Serial correlation in runoff is usually

[3] Based on Dawdy *et al*. (1970), headwater storage cost is proportional to (storage volume)$^{0.7}$ and storage volume is approximately proportional to Cv^2 (McMahon & Adeloye, 2004). Assuming the annual Cv of Australian streams is double that of northern hemisphere streams, for streams with similar mean flows the cost of headwater storages in Australia is approximately three times the cost of storages in the northern hemisphere.

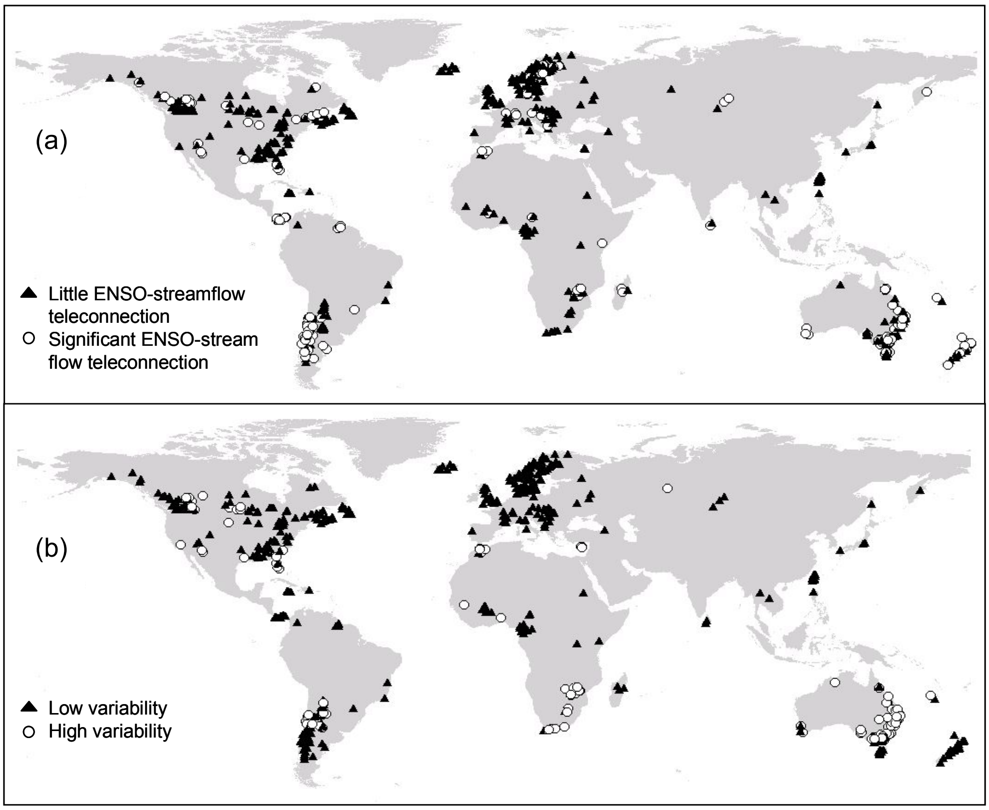


Fig. 4.3 *(a) Strength of the ENSO signal. (b) Magnitude of the coefficient of variation of annual streamflows.*

similar or stronger that runoff–SOI correlation, particularly in the southeast and southwest of Australia. Runoff serial correlation is also significant throughout the year.

Combining this discussion with that in the previous section, we conclude that Australia as a whole is characterized by highly variable hydrology, yet there is a useful level of prediction of streamflow over much of the significant irrigation region in Australia. Letcher *et al*. (2003) show how gains in farm profitability can be made by utilizing ENSO forecasts with known streamflow autocorrelation.

AUSTRALIAN DROUGHTS

Drought is a human induced phenomenon. Relatively low and extremely low rainfall over extended periods is a natural feature of any landscape. However, depending on the enterprise, rainfall less than say the median value for an extended period can have an impact on human activity and, depending on the significance, may be termed drought. In this paper we have not defined extended periods of low or no rainfall as droughts *per se* but simply as “periods of low rainfall” so that we do not have to spell out under what conditions such a period may or may not be a drought. Thus in this section we report on an analysis of rainfalls and streamflows less than the long-term median values.

Figure 4.4 shows a plot for Alice Springs (station no. 015540, at 23.82°S, 133.88°E), located in central Australia, of annual rainfall less than the median value for each year

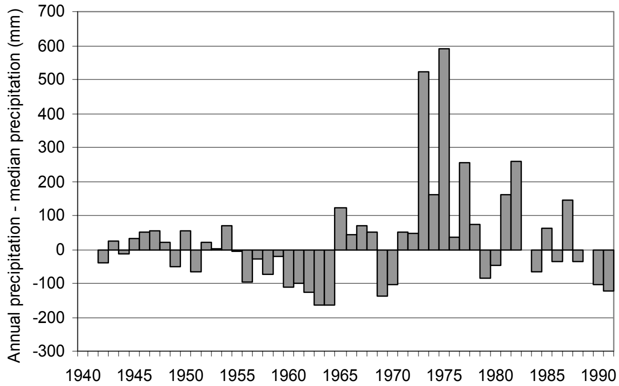


Fig. 4.4 *Length of runs and magnitude of deficits for the Alice Springs (station no. 015540) annual rainfall relative to median value (1942 to 1991). (Adapted from Peel et al., 2004).*

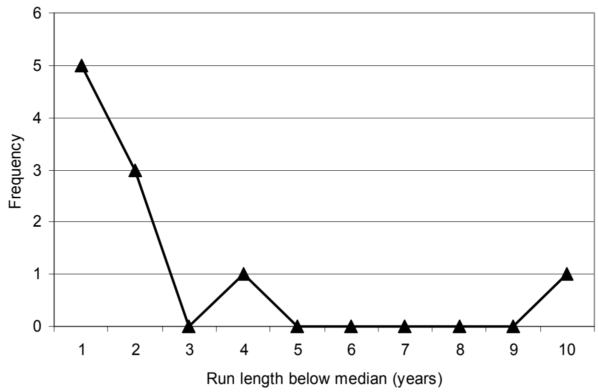


Fig. 4.5 *Frequency plot of run length below the median for Alice Springs (station no. 015540). (Adapted from Peel et al., 2004).*

from 1942 to 1991. The plot shows runs of various lengths of rainfall deficits between one and 10 years. Figure 4.5 shows the frequency of various lengths of rainfall deficit.

To explore whether long run lengths of low rainfall and low streamflow in Australia are different to those observed in the rest of the world, the time series process of annual rainfall and annual streamflow is assumed to be represented as a first order Markov (AR(1)) process. For our global data set of 3863 rainfall stations and 1236 streamflow stations, we examined whether the distribution of run lengths by continent are different to those expected from the AR(1) process calibrated to each of the 5099 annual time series. Details of the study are published in Peel *et al*. (2004). From this analysis it was concluded that the lengths of consecutive periods of below median annual rainfalls and annual streamflows in Australia are no different to those found for the rest of the world except for the tropical Sahel where the rainfall run lengths are generally longer, but this may be an artefact of the rainfall data (Chappell & Agnew, 2004).

However, exploring the relative magnitude of the deficits showed that for annual rainfalls, no differences were observed between continents where relative magnitude is defined as:

$$\text{Relative magnitude} = \frac{\frac{\sum_{i=1}^{n_j} M_{ij}}{n_j}}{x_m} \qquad (1)$$

where M_{ij} is the ith run magnitude of length j, and $j = 1, 2 \ldots n_j$; n_j is the number of runs of length j and x_m is the sample median.

However, as shown in Fig. 4.6 for streamflow, Australia (and southern Africa) exhibit considerably larger deficits compared with those estimated for other continents. As shown in Peel *et al.* (2005), this result is consistent with the fact that these two continental areas have considerably higher annual streamflow variability (Fig. 4.2).

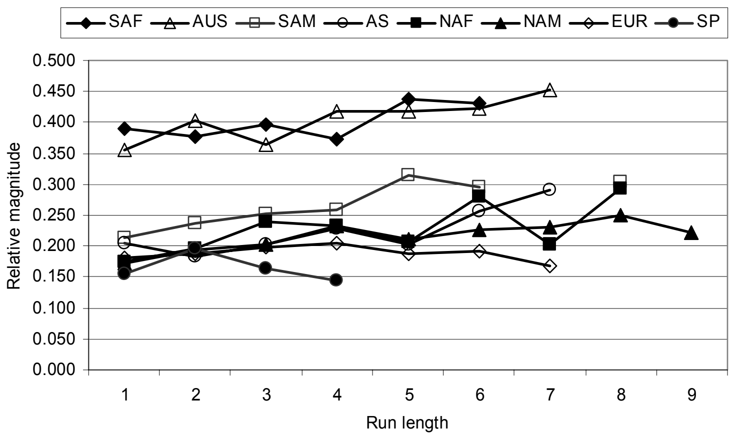


Fig. 4.6 *Relationship of relative magnitude and run length by continent. SAF: southern Africa; AUS: Australia; SAM: South America; AS: Asia; NAF: northern Africa; NAM: North America; EUR: Europe; SP: South Pacific. (Adapted from Peel et al., 2005).*

EXAMPLES OF ANTHROPOGENIC AND NATURAL FEATURES OF STREAMFLOW

In the context of PUB it is worth discussing some hydrological issues dealing with anthropogenic and natural features of streamflow that may need to be considered in a move to model ungauged or poorly gauged catchments. Three topics are raised: inter-basin transfers, anti-drought and streamflow recession.

Effects of inter-basin transfers

Inter-basin transfers can have a devastating effect on the aquatic environment of both the source basin as well as the receiving basin. To illustrate the hydrological effect on the source basin we show in Fig. 4.7 the flow duration curve for the pre- and post-regulation of the Snowy River at Dalgety (station no. 222006). The effect of inter-basin transfer in this case is to transfer about 98% of the flows out of the basin resulting in a devastating effect on the aquatic ecology (Davies *et al.*, 1992) immediately down-stream of the diversion point (Erskine *et al.*, 1999).

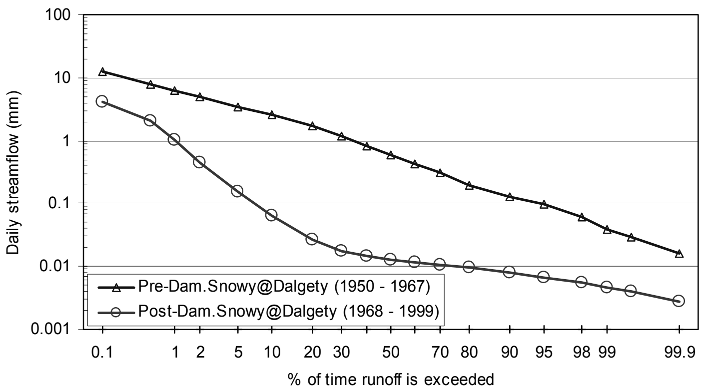


Fig. 4.7 *Flow duration curves for pre- and post-regulation of the Snowy River at Dalgety (station no. 222006).*

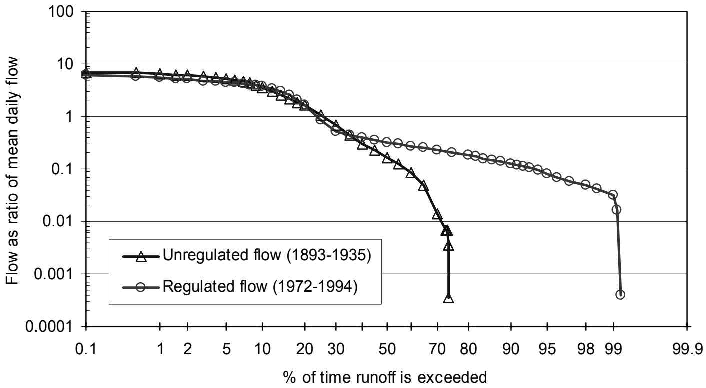


Fig. 4.8 *Flow duration curves for pre- and post-regulation of the Lachlan River at Booligal (station no. 412005).*

Anti-droughts

Figure 4.8 contrasts with the picture presented in Fig. 4.7. The former shows that under the modified flow regime, cease-to-flow (CTF) conditions of the Lachlan River at Booligal (station no. 412005), which is about 600 km downstream from the headwater storage, Wyangala Dam, now rarely occur, yet under natural conditions CTF were expected about 20% of time. We have called this changed condition of increased flows "anti-drought", which causes severe disruption to the flora and fauna that are expecting a drying period during most years (McMahon & Finlayson, 2003).

Effect of evapotranspiration on streamflow recession

An interesting feature, which has implications for both hydrologists and aquatic ecologists, relates to the effect that evapotranspiration can have on the slope of the recession of a hydrograph during periods of high potential evaporation. Figure 4.9 illustrates such an effect for the Wullwye Creek at Woolway (station no. 222007) which is a 520 km^2 catchment located in a region with a mean annual catchment rainfall of about 700 mm and a potential areal evaporation of about 1050 mm.

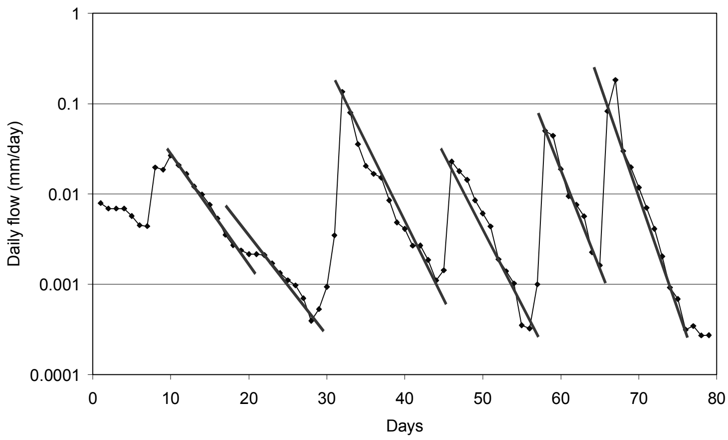


Fig. 4.9 *Recession hydrograph for Wullwye Creek at Woolway (station no. 222007) beginning on 1 November 1980.*

In Fig. 4.9 the magnitude of the daily streamflow series for Wullwye is plotted on a logarithmic scale against time (in days) for a period of 80 days beginning on 1 November 1980. As expected, the recessions are linear on the logarithmic–linear scales. The plot also reveals that the recessions become steeper as they move further into the (southern hemisphere) summer. The respective recession constants, as defined by the baseflow recession equation:

$$Q_t = Q_0 K_t \tag{2}$$

where Q_t and Q_0 are, respectively, the streamflow at time t and 0 after the cessation of surface runoff, and K_t is the recession constant, for the five slopes are: 0.77, 0.72, 0.63, 0.60 and 0.56, whereas a typical value is 0.95 (Pilgrim & Cordery, 1993). It is postulated that the steep recessions are a combination of evaporation from the stream surface and evapotranspiration of the riparian vegetation, which together are greater than the recharge to the stream by local groundwater which is probably from bank storage.

EXAMPLES OF PUB IN AUSTRALIA—A HISTORICAL PERSPECTIVE

Sivapalan *et al.* (2003), in their commentary on predictions in ungauged basins, observed that PUB is about prediction and forecasting. Prediction is defined as estimating the magnitude of an event for a given probability of occurrence plus/minus uncertainty (e.g. flood frequency analysis), whereas forecasting is estimating the magnitude of an event for a stated point in time plus/minus uncertainty (e.g. flow estimates from a rainfall–runoff model). As stated earlier, one of the purposes of this chapter is to provide an Australian setting for the chapters that will follow with an Australian bias. It is therefore appropriate to identify papers that have been published over the past decade or so that have a distinctly Australian flavour or have been written by Australians.

Prediction

The first example deals with estimating the average recurrence interval of an n-year low flow event. The key issue here is that in a record length of N years, a specific n

consecutive year sequence cannot be considered to be independent of all other n-year sequences. In fact there will be $(N - n + 1)$ overlapping sequences which will exhibit a very high autocorrelation. Srikanthan & McMahon (1986) solved this by assuming the annual flows are either Normal or Gamma distributed and then using the basic properties of these two distributions, namely that:

– for a Normal distribution

$$\mu_n = n\mu \text{ and } \sigma_n^2 = R_n n \sigma^2 \quad (3a, 3b)$$

– for a Gamma distribution

$$\alpha_n = \frac{n\alpha}{R_n} \text{ and } \beta_n = R_n \beta \quad (4a, 4b)$$

where μ and σ^2 are the mean and variance of the annual streamflows, μ_n and σ_n^2 are the mean and variance of the n-year sums, R_n is a correction for the autocorrelation in the annual flows, α and β are the shape and scale parameters of Gamma distributed annual flows and α_n and β_n are the shape and scale parameters of Gamma distributed n-year sums. An empirical relationship is used to adjust the Normal or Gamma n-year event to an equivalent non-overlapping series. The probability of non-exceedence of the n-year event in a N/n sized sample is next estimated and then corrected for the n-year base as follows:

Average recurrence interval (years) of n-year event =

$$\frac{n}{\text{Prob}\,(n\text{ - year low flow} \leq Q_n \text{ for an } n\text{ - year base})} \quad (5)$$

where Q_n is the magnitude of the n-year event.

In 1997, Wang (1997) introduced the concept of LH moments. For annual flood frequency analysis he adopted the Generalized Extreme Value distribution and found that higher order L-moments (Hosking, 1990) provided a satisfactory solution to identifying a universal flood frequency distribution. He applied this approach to 107 streams worldwide with very encouraging results.

The third Australian example under the heading of prediction relates to the research of George Kuczera and his colleagues. Pseudo-cyclicity in time series of especially rainfall and streamflow, have presented a difficulty in prediction. Using a hidden state Markov model, Thyer & Kuczera (2000) have developed an alternative model to the currently used auto-regressive lag-one model for modelling long-term persistence in hydroclimatic time series. The model provides an explicit mechanism to simulate the varying wet and dry sequences.

Forecasts

Australian hydrologists have made a significant contribution to the science (or is it still an art?) of streamflow forecasting. While these comments are not the complete story, nevertheless, they illustrate how rainfall–runoff modelling has developed over the past 40 years. Two types of rainfall–runoff models are discussed below: those that have been used extensively in investigations in Australia, and those that have been developed for specific projects.

Generalized conceptual models

Walter Boughton published his first daily rainfall–runoff model (that became known as the Boughton model) in 1964. This was several years after Crawford & Linsley (1962) in the United States of America published their famous Stanford model. However, in Australia the Boughton model was adopted and became a household name among engineering hydrologists. The original Boughton model required nine parameters to be estimated and following a range of studies (e.g. Johnston & Pilgrim, 1973) in 1984 Boughton introduced a three parameter model, known as SFB, and finally he introduced the Australian Water Basin Model (AWBM) in 1993 (Boughton, 1993). This model has wide acceptance in industry and continues to be upgraded. The model now includes a self-calibrating routine and can be run at an hourly time-step (Boughton, 2004).

Another hydrologist, John Porter, studying several years later than Boughton, introduced the daily model HYDROLOG (and an hourly model HRCYCL) (Porter & McMahon, 1971, 1975). The key features of HYDROLOG that were different to previous rainfall–runoff models included Philip's infiltration equation (Philip, 1963), a depression storage function, a nonlinear baseflow recession and a catchment routing procedure. A variation of HYDROLOG known as MODHYDROLOG was introduced by Francis Chiew (Chiew & McMahon, 1991). This model included a feature that simulated both the recharge and discharge to groundwater represented by a water table. As MODHYDROLOG has two additional parameters to the 17 required in HYDROLOG, it was found to model streamflow more satisfactorily than the latter model. In 2001, Chiew introduced the SIMHYD (SIMple HYDrolog) daily rainfall–runoff model consisting of seven parameters, yet simulating both rainfall excess and saturated source area runoff. This model drives the hydrology of EMSS (Environmental Management Support System) (Vertessy, 2001) and also was used to extend the streamflow records in the Australian National Land and Water Resources Audit (Chiew *et al*., 2002).

Within this heading it is appropriate to identify two other models, namely IHACRES and MOSAZ. The IHACRES model has evolved over the past decade. The original rainfall–runoff model required seven parameters to be estimated and was based on a nonlinear store and runoff was calculated through a linear recursive equation (Jakeman *et al*., 1990). The most recent version (2004) includes a new nonlinear module and allows actual evapotranspiration to be computed (Croke & Jakeman, 2004).

MOSAZ, which has only two parameters, was developed with the express purpose of providing a rainfall–runoff model in which the parameters could be regionalized. While this objective was partly achieved (Jayasuriya *et al*., 1991) for a hydrologically homogeneous set of catchments (correlations between each of the two variables and several independent variables were 0.90 and 0.78), the correlations between the two parameters and catchment characteristics are not strong enough for the model to be considered a regular tool in engineering hydrology in Australia without a detailed assessment of hydrologically similar catchments.

Project rainfall–runoff models

Australian hydrologists, like their counter-parts worldwide, have developed conceptual rainfall–runoff models for specific projects across a wide range of scales. The following comments identify three scales of models: small (catchments less than a few km^2), medium (several hundred km^2) and large (more than say 10 000 km^2).

One of the most versatile small catchment models available is TOPOG which is a modelling framework consisting of several models. Details can be found in O'Loughlin (1986), Vertessy *et al*. (1990) and Hatton *et al*. (1992). The yield version, which is known as TOPOG_YIELD, is a distributed parameter model of 21 parameters that allows transient analysis of saturated–unsaturated flow and evapotranspiration and interception over complex catchment terrain. The model operates at a daily time-step and provides estimates of water yield and soil moisture predictions (Vertessy *et al.*, 1993).

Rodger Grayson developed THALES in 1990, a simple terrain-based distributed parameter rainfall–runoff model, to explore some of the barriers to future development of distributed models (Grayson *et al*., 1992a,b). It models the subsurface movement of water by kinematic flow, which becomes direct runoff if the flow exceeds the capacity of the soil profile to transport water. Runoff is also generated by Hortonian overland flow.

MACAQUE was developed to explore the effect of wild fires or major clearing of forests on a 163 km^2 catchment—a major source of water for the Melbourne water supply system (Watson, 1999). MACAQUE is a daily physically-based spatial process model that incorporates topography, climate, vegetation species and physiology, and is capable of forecasting the change in yield with time that is experienced with the regeneration of the specific forest types encountered throughout the catchment post-clearing or post wild fire episodes. The model has been amended to simulate the change in yield of other catchments in Victoria and Tasmania (see for example Peel *et al*., 2003).

LASCAM is an example of a large catchment rainfall–runoff model. It was developed by Murugesu Sivapalan and colleagues (Viney *et al*., 2000) and is an example of a large-scale conceptual hydrological model for estimating daily streamflow as well as forecasting salt, sediment and nutrients. Catchments are divided into a number of sub-catchments that allow spatial heterogeneity to be incorporated. LASCAM includes interception, surface infiltration, deep percolation, groundwater recharge, evapotranspiration and interflow.

FURTHER EXAMPLES OF REGIONALIZATION (PUB) IN AUSTRALIA

Compared with extensive studies in other countries (e.g. Canada, USA, UK) there have been few extensive regionalization studies in Australia. One of the earliest studies was completed for the Hunter Valley in the late 1960s (McMahon, 1969). Reservoir storage–yield-reliability relationships, low flow frequency curves and 90% flow duration values were regionalized through simple graphical techniques that included surface geology as an input parameter.

However, the first national regionalized hydrological study developed a relationship between catchment yield and a number of hydrological, climate and geomorphic parameters as follows (McMahon, 1978):

$$D = 1 - 0.57Cv^{1.14} p^{-0.32} \mu^{0.63} S^{-0.63} - 0.7 \times 204 ES^{0.80} (4 + R)^{-2.16} \mu^{-1} \quad (6)$$

where D is a constant yield from a reservoir expressed as a ratio of mean annual inflow, Cv is the coefficient of variation of the annual inflows, p is the probability of failure (%), μ is the mean annual inflow to the reservoir, S is the estimated reservoir storage size, E is the net annual evaporation loss per unit area of reservoir, R is the catchment relief represented by a value from 0 to 5, and a, b, …, h are empirical coefficients. This equation consists of two terms. The left-hand term determines the storage size and the coefficients are based on an analysis of 156 Australian streams, and the second term makes an approximate correction (based on an analysis of 91 Australian reservoirs) for evaporation losses as a function of the reservoir geomorphology defined by local relief.

The most extensive regionalization study in Australia of surface hydrology, headed by David Pilgrim, relates to the development of intensity–duration–frequency curves of rainfall for the Australian continent (Pilgrim, 1987) and consistent statistical runoff coefficients for the Rational Formula which is the basis for estimating the peak discharge at some level of recurrence interval for small catchments in Australia. Maps of regionalized runoff coefficients for a flood of 10-year average recurrence interval are available for New South Wales and Victoria.

Rory Nathan introduced an interesting regionalization tool to hydrology (Nathan & McMahon, 1991). Andrew's curves (Andrews, 1972) were first proposed in 1972 as a technique to visualize multi-dimensional data and represent n-dimensional space data ($n > 2$) by a two-dimensional curve as follows:

$$f(t) = \frac{x_1}{\sqrt{2}} + x_2 \sin(t) + x_3 \cos(t) + x_4 \sin(2t) + x_5 \cos(2t) + \dots \qquad (7)$$

where x_1, x_2 are variables to specify the catchment characteristics, and $f(t)$ is plotted between $-\pi$ and $+\pi$.

Nathan applied the technique to define homogeneous regions. A particular feature about Andrew's curves that is not available with other techniques is that it will not force an ungauged catchment to be assigned the characteristics of one of the alternatives in the regionalized suite. In such a case it will require the analyst to determine separately the parameters to be assigned to the ungauged catchment.

CONCLUSIONS

The objective of this chapter is to provide the Australian hydrological setting for the Australian contributions on Predictions in Ungauged Basins in this volume, and to review briefly Australian methods of prediction and forecast in ungauged catchments.

Five conclusions can be drawn from the review:

- By world standards, Australian streamflows are highly variable yet predictable.
- Lengths of periods of low rainfall are similar worldwide but the deficits below median rainfall are larger than at most other places.
- Significant impacts on stream hydrology result from inter-basin transfer and river regulation.
- Detailed analysis of hydrograph recessions has illustrated the potential importance of evapotranspiration in understanding baseflow recessions.
- Regionalization is important in Australia and some progress has been made in implementation.

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