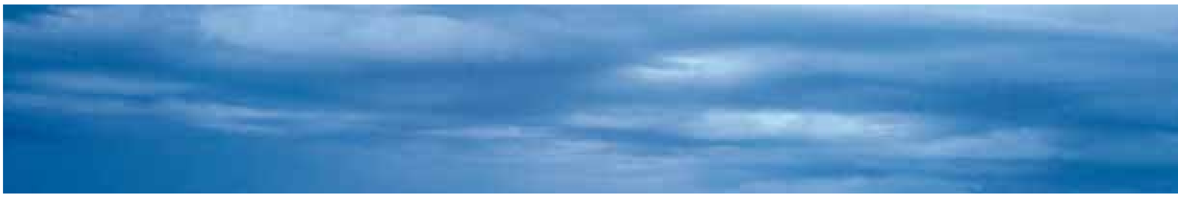
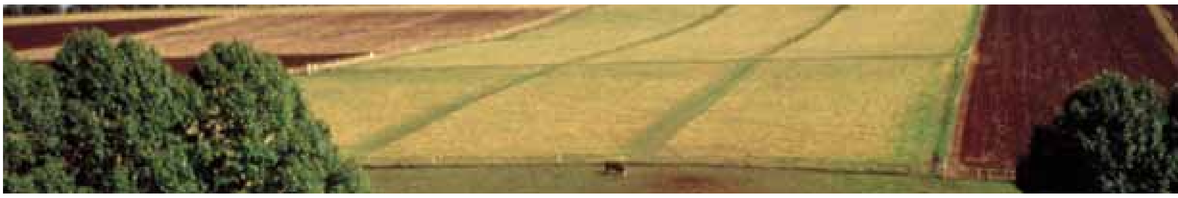
COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

# THE IMPACT OF RAINFALL SEASONALITY ON MEAN ANNUAL WATER BALANCE IN CATCHMENTS WITH DIFFERENT LAND COVER

**TECHNICAL REPORT**
**Report 03/11**
November 2003

**Klaus Hickel / Lu Zhang**





COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

Hickel, Klaus, 1974-

**The Impact of Rainfall Seasonality on Mean Annual Water Balance in Catchments with Different Land Cover**

Bibliography.
**ISBN 1 920813 01 2.**

1. Water balance (Hydrology) - Mathematical models. I. Zhang, Lu. II. Cooperative Research Centre for Catchment Hydrology. III. Title. (Series : Report (Cooperative Research Centre for Catchment Hydrology) ; 03/11).

551.48

## Keywords

Water balance
Seasons
Storage
Evapotranspiration
Catchment areas
Rainfall/Runoff Relationship
Modelling (Hydrological)
Stream flow
Water data
Water-Soil-Plant Interactions
Climate
Rain

# The Impact of Rainfall Seasonality on Mean Annual Water Balance in Catchments with Different Land Cover

**Klaus Hickel and Lu Zhang**

Cooperative Research Centre for Catchment Hydrology,
CSIRO Land and Water, Canberra ACT

Technical Report 03/11
November 2003

## Preface

Rain falling on a catchment feeds both streamflow and evapotranspiration. The partitioning of rainfall between these two pathways is a foundation concept of catchment hydrology. Measurement of many catchments for many years has shown us that the land-use in the catchment and the seasonality of the rainfall are important factors that influence this partitioning. Our understanding of catchment hydrology is approaching the point where we can confidently predict the partitioning of rainfall and how it changes when we change the land-use.

This report describes some of the research that supports this important development. By enabling the consideration of seasonality, it enables more confidence in our prediction of how catchment hydrology changes when land-use changes.

The research reported here is a product of the Cooperative Research Centre (CRC) for Catchment Hydrology's Land-use Impact on Rivers Program. The program is focused upon the impact of man's activities upon the land and stream environment upon the physical attributes of rivers. We are concerned about managing impacts for catchments ranging in size from a single hillslope to several thousands of square kilometres. The specific impacts we are considering are changes in streamflow, changes to in-stream habitat by the movement of coarse sediment and changes to water quality (sediment, nutrients and salt). If you wish to find out more about the program's research I invite you to first visit our website at http://www.catchment.crc.org.au/programs/projects/index.html.

Peter Hairsine
CSIRO Land and Water
Program Leader - Land-Use Impacts on Rivers
CRC for Catchment Hydrology

## Acknowledgements

This study was supported by the CRC for Catchment Hydrology under Project 2.3 “Predicting the effects of land-use changes on catchment water yield and stream salinity” and the Murray-Darling Basin Commission (MDBC) funded project “Integrated assessment of the effects of land-use changes on water yield and salt loads “ (D2013). We would like to thank Tim Ellis and Warrick Dawes for their constructive comments on the report.

# Abstract

Seasonal variations of climate and catchment water storage affect the partitioning of rainfall into evapotranspiration and runoff. This report provides a new approach to estimate the seasonality effect on catchment scale mean annual water balance. The approach is based on observed climate (rainfall and potential evapotranspiration) and streamflow data obtained from over 200 unregulated catchments in Australia. It assumes that catchment scale annual evapotranspiration consists of climate-controlled and storage-controlled evapotranspiration. The climate-controlled evapotranspiration can be accurately represented by Budyko type relationships using a dryness index for different rainfall regimes, while the storage-controlled evapotranspiration relates more closely to effective seasonal water storage. When rainfall and potential evapotranspiration are in phase, the effect of seasonality is to increase climate-controlled evapotranspiration. However, storage-controlled evapotranspiration tends to be relatively smaller under this rainfall regime and showed the opposite trend with mean annual evapotranspiration. This finding suggests that the seasonality effect on mean annual evapotranspiration can not be adequately represented by phase difference between rainfall and potential evapotranspiration alone and the effect of water storage needs to be considered. Results showed that inclusion of seasonal water storage significantly improved evapotranspiration predictions for catchments with winter-dominant rainfall.

# List of Figures

# List of Tables

# 1. Introduction

It has long been recognized that evapotranspiration is the result of complex interactions between the atmosphere, soil and vegetation (Brutsaert, 1982). Despite the complex processes and interactions that are associated with evapotranspiration, it can be assumed that available energy and water are the primary factors that determine the rate of evapotranspiration (Budyko, 1958). On a mean annual basis, actual evapotranspiration will approach precipitation under very dry conditions, while under very wet conditions, actual evapotranspiration will asymptotically approach the potential evapotranspiration. Based on these considerations, Budyko (1974) proposed an empirical relationship for describing mean annual evapotranspiration and a number of similar relationships have been developed (Schreiber, 1904, Pike, 1964, Fu, 1981). Choudhury (1999) generalised these relationships by introducing an adjustable parameter. More recently, Zhang *et al*., (2001) developed a similar model with a parameter expected to be controlled by soil water storage.

These relationships for mean annual evapotranspiration only considered the first order factors and would yield good predictions for catchments where evapotranspiration is dominated by these factors. Budyko (1974) showed that his model was in excellent agreement with observed data for 29 large catchments (e.g. areas exceeding 10,000 km$^2$) in Europe and there was almost no scatter around the relationship. However, other studies showed that there can be large scatter around the relationship, especially in catchments where the dryness index, defined as potential evapotranspiration divided by rainfall, is about unity (Milly, 1994, Zhang *et al*., 2001, Zhang *et al*., 2003). These studies suggest that there are other factors that affect the partitioning of mean annual evapotranspiration, and these include rainfall seasonality (e.g. uniform rainfall, summer-dominant rainfall, and winter-dominant rainfall), seasonal water storage and catchment slopes.

The impact of seasonality and seasonal water storage on the mean annual water balance is important for better understanding the hydrology of catchments located in different climatic regions. For example, two catchments with the same mean annual rainfall and potential evapotranspiration may have different runoff or evapotranspiration partitioning if rainfall distribution or water storage capacity are different. If rainfall is more intensive and episodic, it is likely to yield more runoff even though the two catchments have the same dryness index. Similarly, under the same climatic conditions a catchment with limited water storage capacity and steep slope will have larger runoff coefficient compared to a catchment with large water storage capacity and gentle slope. Understanding of the relationships between climate and catchment characteristics and their integrated effect on the water balance can help to improve predictions of mean annual evapotranspiration.

A number of studies have tackled the problem of seasonality and storage impact on mean annual evapotranspiration using process-based models (Schaake and Liu, 1989, Wood, 2003). Milly (1994) developed a theoretical framework for mean annual evapotranspiration using statistical-dynamical modelling. The model was based on the hypothesis that the long-term evapotranspiration is determined by the local interaction of rainfall and potential evapotranspiration, mediated by soil water storage. With his theoretical framework, he identified several key variables including seasonality believed to be responsible for the partitioning of rainfall into evapotranspiration and runoff.

In this study we seek to develop a simple method to quantify the effect of seasonality on mean annual evapotranspiration based on observed climatic and water balance data. The focus of the study is not on how to include very individual processes responsible into a water balance model, but rather on representing the integrated effect of the interactions between seasonal climate and catchment water storage on evapotranspiration. The specific objectives of the study were two-fold: (1) to investigate seasonal storage changes in relation to climatic and catchment characteristics; (2) to incorporate the seasonal storage changes into a mean annual water balance model to account for seasonality effects on mean annual evapotranspiration. Section 3 presents the development of the water balance model by assuming that annual total evapotranspiration consists of two components: "climate-controlled" and "storage-controlled" evapotranspiration. It is shown in Sections 4, 5 and 6 that the climate-controlled evapotranspiration is linked strongly with the dryness index, while the storage-controlled evapotranspiration can be estimated from effective seasonal water storage. In Section 7, the model is tested using observed rainfall, potential evapotranspiration, and streamflow.

## 2. Data

The catchments included in this study have at least 5 complete years of unimpaired streamflow data and a catchment area between 50 and 2000 km$^2$. Unimpaired streamflow is defined as streamflow that is not subject to regulation or diversion. The streamflow data was assembled by Peel *et al*., (2000). In total, 255 gauging stations were selected. Of these, 125 catchments with at least 10 complete years of unimpaired streamflow data were used for the calibration dataset, and the remainder of 130 catchments with 5 up to 20 complete years of unimpaired streamflow was used as an evaluation dataset.

Monthly rainfall was estimated from gridded daily rainfall (Peel *et al*., 2000). The spatial resolution of the gridded daily rainfall is 5 km by 5 km based on interpolation of over 6000 rainfall stations in Australia. The interpolation uses monthly rainfall data, ordinary Kriging with zero nugget and a variable range. Monthly rainfall for each point is converted to daily rainfall using daily rainfall distribution from the station closest to that point. Catchment average rainfall was estimated from the daily rainfall. Mean monthly potential evapotranspiration was calculated based on the Priestley-Taylor equation (Priestley and Taylor, 1972). Details of the calculation can be found in Raupach *et al*., (2001).

For each of the catchments, information about land-use, topographic characteristics, and soil properties was also obtained. Land-use data included percentage of forest cover, cropping areas, and open water. The topographic data (median surface slope and relief ratio) comes from 30 m resolution digital elevation maps. The soil properties included upper and lower soil-horizon soil-moisture content, soil types, and depths of A- and B-horizon. Based on the soil properties and the topographic data, plant available water-holding capacity (PAWC) was calculated using the method of McKenzie *et al*., (2002). In addition, catchments with less detailed information were used so a total of 202 points was used in the validation dataset. Long-term average rainfall, streamflow and potential evapotranspiration are from Zhang *et al*., (1999) with vegetation data from Ritman (1995).

# 3. Method

## 3.1 Conceptualisation of Seasonal Water Balance

The water balance equation for any period of time can be written as

$$P = E + Q + \Delta S \tag{1}$$

where $P$ is rainfall, $E$ is evapotranspiration, $Q$ is runoff and $\Delta S$ is a change in catchment soil water storage. For the purpose of investigating the impact of seasonal storage on evapotranspiration, it is useful to split the annual water balance into effective storage recharge and storage discharge periods.

Storage recharge occurs when rainfall exceeds potential evapotranspiration and runoff is less than the difference between the two. During this period, evapotranspiration is not limited by water availability and it can be assumed that actual evapotranspiration equals potential evapotranspiration. When Equation 1 is written for the storage recharge period and rearranged for all unknown variables to be on the right hand side of equation, it reads:

$$P^+ - E_0^+ = Q^+ + S^+ \tag{2}$$

The term ($P^+ - E_0^+$) is the amount of water that is not evaporated, but either stored in the catchment or discharged as runoff. $Q^+$ is the actual runoff that occurs during the storage recharge period and $S^+$ represents the effective storage increase during the storage recharge period.

The water balance for the storage discharge period that follows, can be written as

$$P^- + S^- = Q^- + E^- \tag{3}$$

where $S^-$ is the effective storage release and $Q^-$ is the measured runoff during this period. Potential evapotranspiration exceeds rainfall during the storage discharge period and it is therefore assumed that all of the rainfall that occurs in this period ($P^-$) is evaporated. As a result of this assumption, $Q^-$ must come entirely from the storage release ($S^-$). The partitioning of $S^-$ into runoff and evapotranspiration for the mean annual water balance will be examined in Section 3.2.

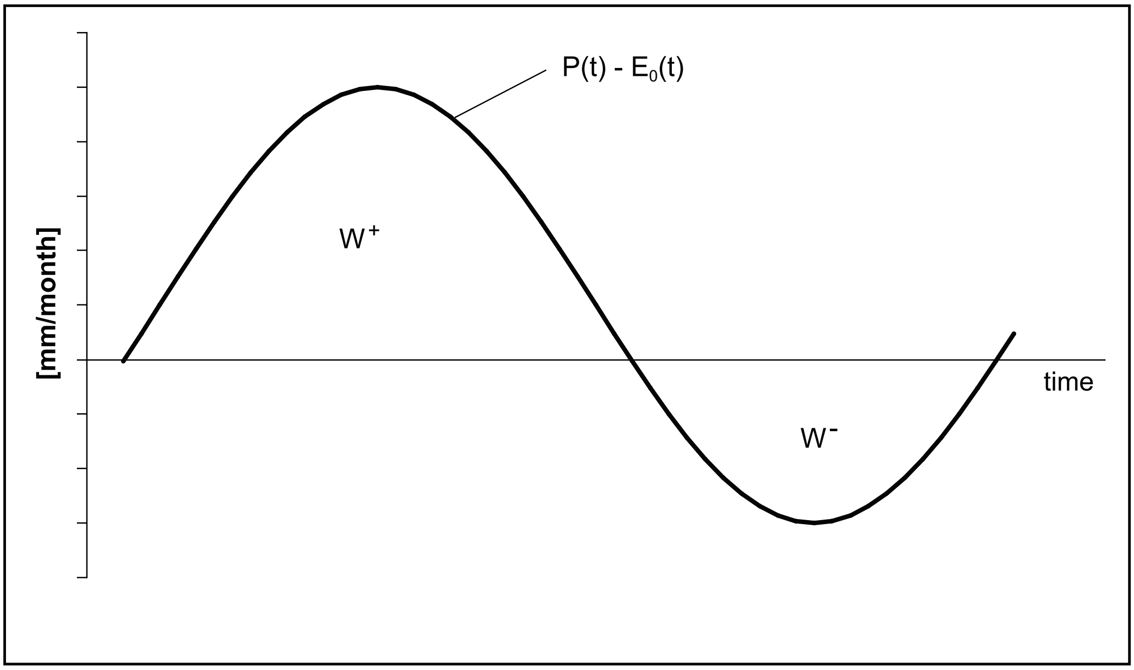
On an annual basis, the water balance equation can be expressed as:

$$(P^+ + P^-) - (E_0^+ + E^-) - (Q^+ + Q^-) - (S^+ + S^-) = 0 \tag{4}$$

For any given year, storage increase ($S^+$) does not necessarily equal the storage release ($S^-$). The difference between $S^+$ and $S^-$ becomes the interannual storage change $S$. For the consideration of the mean annual water balance in the following sections, however, it is assumed that $S = 0$, so that storage increase $S^+$ equals to storage release $S^-$.

Figure 1 provides a schematic representation of the seasonal water balances described in Equations 2 and 3. It is useful to define the residual rainfall in the storage recharge period and the residual potential evapotranspiration in the storage discharge period, because they are important limits for average seasonal water storage and average storage-controlled evapotranspiration. The *residual rainfall* ($W^+$) occurs in the storage recharge period and is defined as the difference between rainfall ($P^+$) and evapotranspiration ($E^+$) in the storage recharge period, i.e. $W^+ = P^+ - E^+ = P^+ - E_0^+$. *The residual potential evapotranspiration* ($W^-$) occurs in the storage discharge period and is defined as the difference between potential evapotranspiration ($E_0^-$) and rainfall ($P^-$) in the storage discharge period, i.e. $W^- = E_0^- - E^- = E_0^- - P^-$.

A number of time series extracts for catchments from various regions within Australia are shown in Appendix A to demonstrate the validity of the relationships and assumptions used.



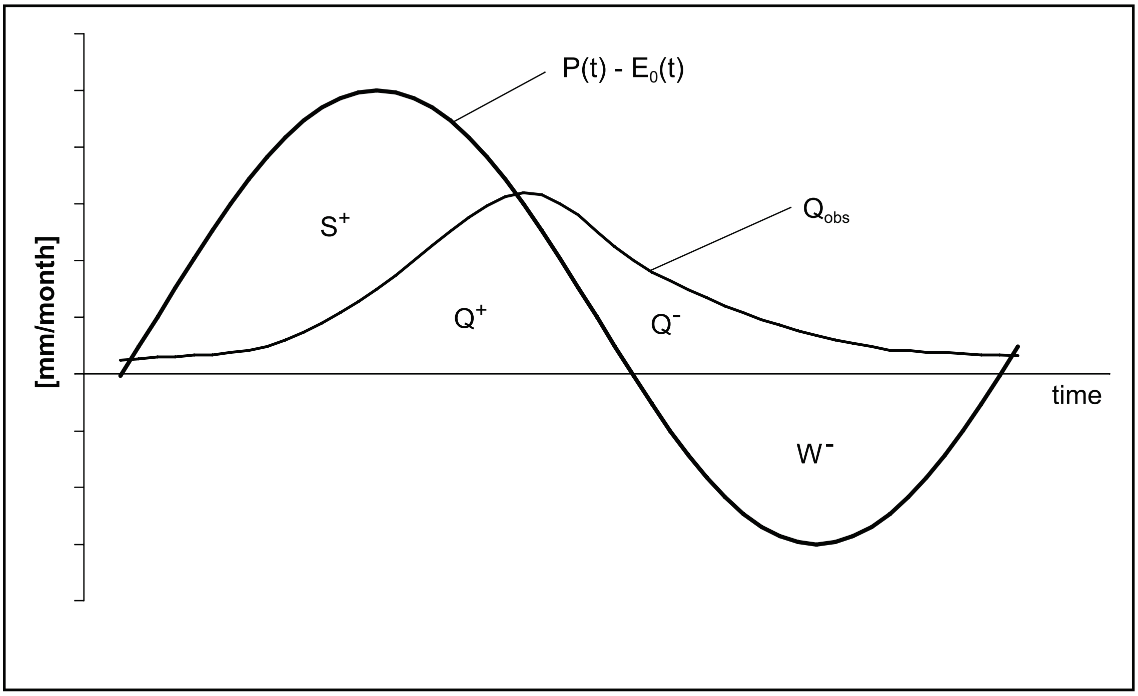


Figure 1. (top) Residual rainfall ($W^+$) and residual potential evapotranspiration ($W^-$). (bottom) Partitioning of $W^+$ into wet period discharge ($Q^+$) and storage increase ($S^+$). Part of $S^+$ is released as dry period discharge ($Q^-$).

The assumptions involved in this approach are *a)* that evapotranspiration $E^+$ is equal to potential evapotranspiration $E_0^+$ during the storage recharge period and *b)* that all rainfall $P^-$ in the dry period becomes evapotranspiration. If the mean annual water balance is investigated, a further assumption is that cumulative interannual storage change is zero, i.e. S = 0.

Assumption b) allows evapotranspiration to be split up into two proportions for the storage discharge period: evapotranspiration resulting from rainfall $P^-$ and evapotranspiration ($E_{stor}$) due to storage release. Total annual evapotranspiration can therefore be written as

$$E = E^+ + E^- = E_0^+ + [P^- + E_{stor}] \qquad (5)$$

From these conceptual distinctions, the sum of $E_0^+$ and $P^-$ can be called *"climate-controlled evapotranspiration"*. $E_{stor}$ occurs only during the storage discharge periods and can be called *"storage-controlled evapotranspiration"*. Using these terms, the total evapotranspiration for any given year can be calculated as:

$$E = E_{clim} + E_{stor} \qquad (6)$$

Equation 6 is the basis for estimating the impact of seasonality on mean annual evapotranspiration. In what follows, both climate-controlled and storage-controlled evapotranspiration will be determined based on climate and storage characteristics.

## 3.2 Estimating Seasonal Storage Impact on Mean Annual Water Balance

The seasonal water balance model described above provides a conceptual framework for investigating the effect of seasonal water storage on evapotranspiration. However, as is shown in Section 3.1, all terms in the model were derived from monthly values of rainfall, potential evapotranspiration, and runoff to allow identification of seasonal water balance. These monthly values have to be accumulated into annual totals to suit the framework. In order to apply this framework in a predictive sense, i.e. without *a priori* knowledge of the gross water balance, it is necessary to estimate climate-controlled evapotranspiration ($E_{clim}$) and storage-controlled evapotranspiration ($E_{stor}$) from available climate and catchment characteristics.

For this purpose, the seasonal water balance terms of the framework must be averaged into long-term annual means to allow comparison on a catchment-to-catchment basis. The terms involved are climate- and storage-controlled evapotranspiration ($E_{clim}$, $E_{stor}$), residual rainfall ($W^+$), residual potential evapotranspiration ($W^-$) and storage increase ($S^+$) in the storage recharge period. The assumption that there is no change in catchment storage on mean annual basis implies that storage decrease ($S^-$) in the storage discharge period is equal to the storage increase ($S^+$) in the storage recharge period. In the following sections, the term *average effective water storage* ($S_{avg}$) refers therefore to mean annual storage increase ($S^+$) and also storage decrease ($S^-$).

## 4. Estimation of Climate-controlled Evapotranspiration

The conceptual framework described above means that the relationship between annual rainfall, residual rainfall ($W^+$) and climate-controlled evapotranspiration ($E_{clim}$) can be presented as:

$$P = P^+ + P^- = (P^+ - E_0^+) + (P^- + E_0^+) = W^+ + E_{clim} \tag{7}$$

In the following, a method for the prediction of residual rainfall $W^+$ will be established and climate-controlled evapotranspiration $E_{clim}$ will be calculated as the difference between $P$ and $W^+$ using Equation 7.

It can be shown that:

$$W^+ - W^- = P - E_0 \tag{8}$$

Based on observed data, the following relationship can be established:

$$\frac{W^-}{W^+} \approx \left(\frac{E_0}{P}\right)^b \quad ,b \geq 1 \tag{9}$$

Figure 2 shows the above relationship for different climatic regimes with the *b*-parameter regionalised. Catchments were grouped primarily based on rainfall regime.

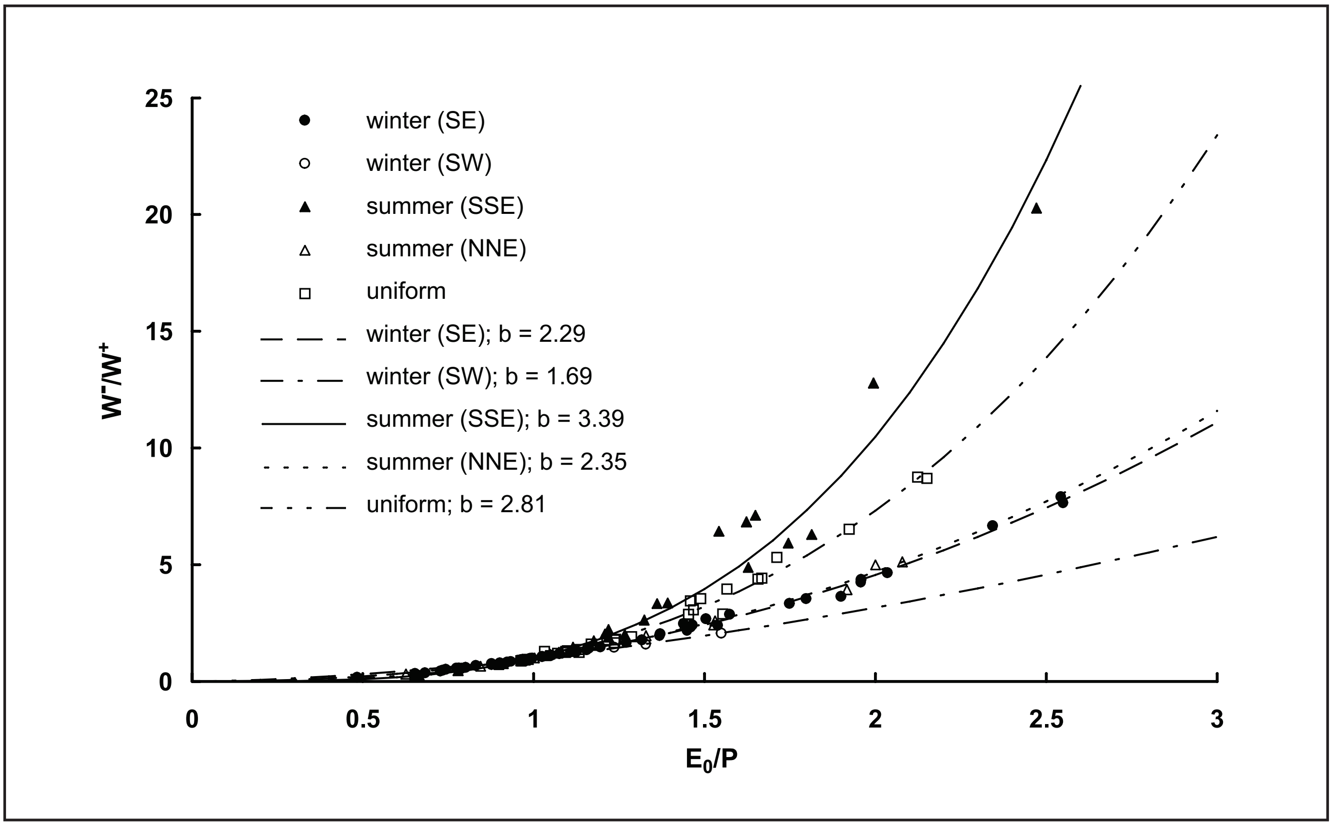


Figure 2. The relationship between $E_0/P$ and $W^-/W^+$ can be described by Eq 9 and rainfall regime.

Substitution of Equation 9 into Equation 8 gives a set of two explicit functions for the estimation of $W^+$ and $W^-$ using only annual rainfall $P$ and potential evapotranspiration $E_0$:

$$W^+ = \frac{P - E_0}{1 - \left(\frac{E_0}{P}\right)^b} \tag{10a}$$

$$W^- = \frac{E_0 - P}{1 - \left(\frac{E_0}{P}\right)^{-b}} \tag{10b}$$

Equation 10a can be combined with Equation 7 to yield the following expression:

$$\frac{E_{clim}}{P} = 1 - \frac{1 - \frac{E_0}{P}}{1 - \left(\frac{E_0}{P}\right)^b} \tag{11}$$

Equations 10 and 11 are valid for $E_0 \neq P$. For $E_0 = P$, the function for $E_{clim}/P$ in Equation 11 can be defined as its limit. Substituting $x = E_0/P$, it can be shown that

$$\lim_{x \to 1}\left(1 - \frac{1-x}{1-x^b}\right) = 1 - \frac{1}{b} \tag{12}$$

Therefore,

$$\frac{E_{clim}}{P} = \begin{cases} 1 - \dfrac{1 - \frac{E_0}{P}}{1 - \left(\frac{E_0}{P}\right)^b}, & E_0 \neq P \\ 1 - \dfrac{1}{b}, & E_0 = P \end{cases} \tag{13}$$

Figure 3 shows the observed behaviour of climate-controlled evapotranspiration in its regional context as a function of different climatic conditions expressed as the dryness index. The curves represent the relationships in Equation 13 and dots are climate-controlled evapotranspiration ratio ($E_{clim}/P$), where $E_{clim}$ equals $P^-$ + $E_0^+$. It is clear that always $E_{clim} \leq E_0$ and $E_{clim} \leq$ P. These theoretical limits are displayed by the bisecting line ($E_{clim}/P = E_0/P$) and the horizontal line ($E_{clim}/P = 1$) in Figure 3.

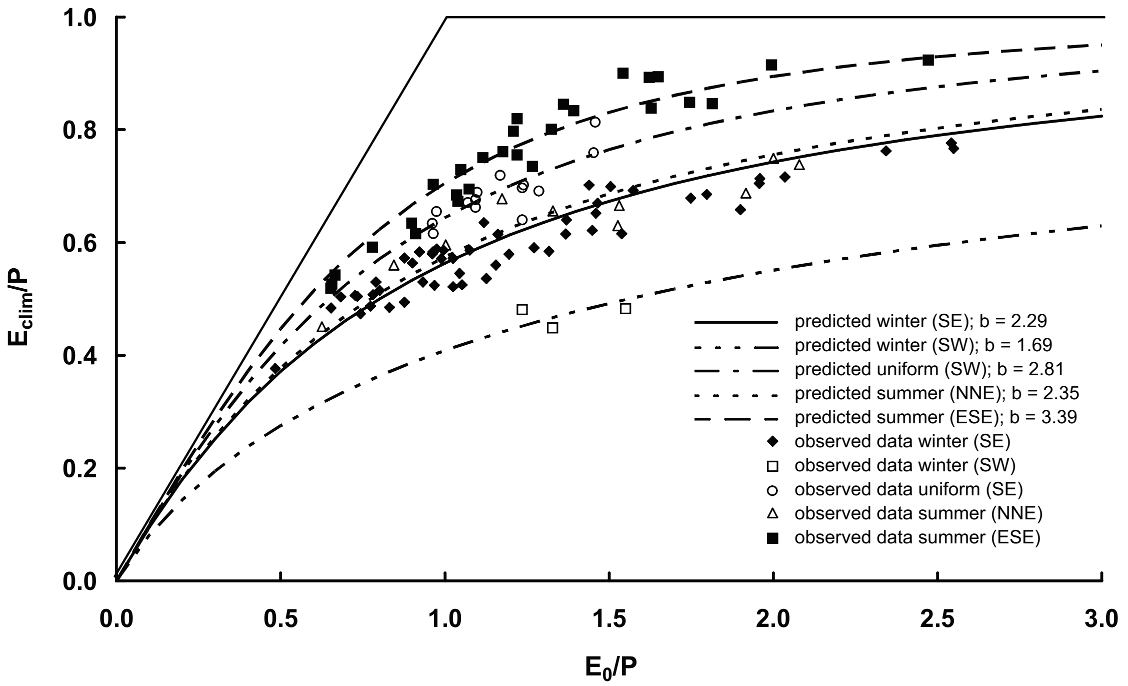


Figure 3. Relationship between climate-controlled evapotranspiration ratio and dryness index.

Using the least squares method, it was found that *b*=2.29 for catchments with winter-dominant rainfall in south-eastern Australia (SE), and *b*=1.69 for Western Australia (SW). However, only three catchments from Western Australia were available in the calibration data set. For catchments with summer-dominant rainfall, a distinction needs to be made between catchments in the South/South East (SSE) and North/North East (NNE) of Australia. For catchments in the South/South East, (south of the 24th parallel), the best fit is *b*=3.39, and for catchments (north of the 20th parallel), *b*=2.35. Between the 20th and the 24th parallel, the two available catchments had values of *b* between 2.35 (NNE) and 3.39 (SSE). For catchments that have uniform rainfall distribution, *b*=2.81. It was found that *b*-values are increasing with altitude in catchments with summer-dominant rainfall.

Table 1. *b*-values used in Equation 8-13.

| | **Rainfall Dominance** | | |
|---|---|---|---|
| | **Winter** | **Summer** | **Uniform** |
| ***b*** | South East: 2.29 | North/North East: 2.35 | 2.81 |
| | South West: 1.69 | East/South East: 3.39 | |

# 5. Estimation of Storage-controlled Evapotranspiration

## 5.1 Dependence of Average Effective Storage on Climatic and Catchment Characteristics

### Climatic Impact on Effective Storage

Figure 4 plots effective seasonal storage ($S_{avg}$), residual potential evapotranspiration ($W^-$) and residual rainfall ($W^+$) for all catchments. The catchments are sorted according to the ratio ($W^-/W^+$), which can be considered as a measure of catchment dryness similar to the dryness index $E_0/P$. $S_{avg}$ is clearly affected by the magnitudes of $W^-$ and $W^+$: when evapotranspiration in a catchment is limited by the supply of water ($W^+<W^-$), effective storage $S_{avg}$ follows residual rainfall $W^+$, whereas if energy is limiting evapotranspiration ($W^+>W^-$), $S_{avg}$ is close to $W^-$. $S_{avg}$ appears to be determined by seasonal water demand and supply, characterised by $W^-$ and $W^+$.

Catchments with summer-dominant rainfall exhibit different relationships between $S_{avg}$, $W^-$ and $W^+$ than those with winter-dominant rainfall. In the case of summer-dominant rainfall, the calculated $S_{avg}$ does not follow the minimum of the residual rainfall ($W^+$) and residual potential evapotranspiration ($W^-$) as closely as it does in the case of winter-dominant rainfall (See Figure 4).

Figure 4 confirms that $S_{avg}$ is strongly linked to the climatic conditions of a catchment and can be estimated from $W^-$ and $W^+$. A distinction needs to be made, however, between catchments with uniform, winter- and summer-dominant rainfall as well as between wet and dry conditions.

***a) Winter-dominant rainfall***

For winter-dominant dry catchments, i.e. $W^-/W^+>1$, $S_{avg}$ can be explained by $W^+$ with a linear regression (Figure 5) since $W^+$ can be seen as a factor that is limiting the recharge of the effective seasonal water storage $S_{avg}$ in dry catchments. It was also found that slightly wet catchments with $0.7 \leq W^-/W^+<1$ show a behaviour similar to that of dry catchments but not to that of wetter catchments ($W^-/W^+<0.7$). However, while $W^+$ is the limiting factor for estimation of $S_{avg}$ in dry catchments, $W^-$ is the limiting factor in wet catchments. This gradual transition can also be observed in Figure 4. The linear regression for the estimation of $S_{avg}$ using the limiting factor $W_{lim} = min\{W^+, W^-\}$ is shown in Figure 5.

For catchments with $W^-/W^+ < 0.7$, i.e. for very wet winter dominant catchments, the relationship between $S_{avg}$ and $W^-$ is shown in Figure 6. It is clear that the relationship in Figure 6 is not as good as that shown in Figure 5. This difference can be explained with the fact that $W^+$ represents the upper limit of the effective seasonal storage $S_{avg}$. Residual potential evapotranspiration $W^-$ on the other hand is the maximum possible evapotranspiration out of the effective seasonal water storage $S_{avg}$. It represents the potential discharge of the effective seasonal storage $S_{avg}$ by evapotranspiration which is affected by plant characteristics such as rooting depth and root distribution. Effective seasonal water storage $S_{avg}$ can also be emptied by sub-surface runoff in the dry period, as a result residual potential evapotranspiration $W^-$ is not the only factor that controls the effective seasonal storage during the dry period. It is clear that for wet catchments estimation of effective storage $S_{avg}$ using climatic variables alone may introduce some errors. However, no better predictor for the effective seasonal storage was found in the study.

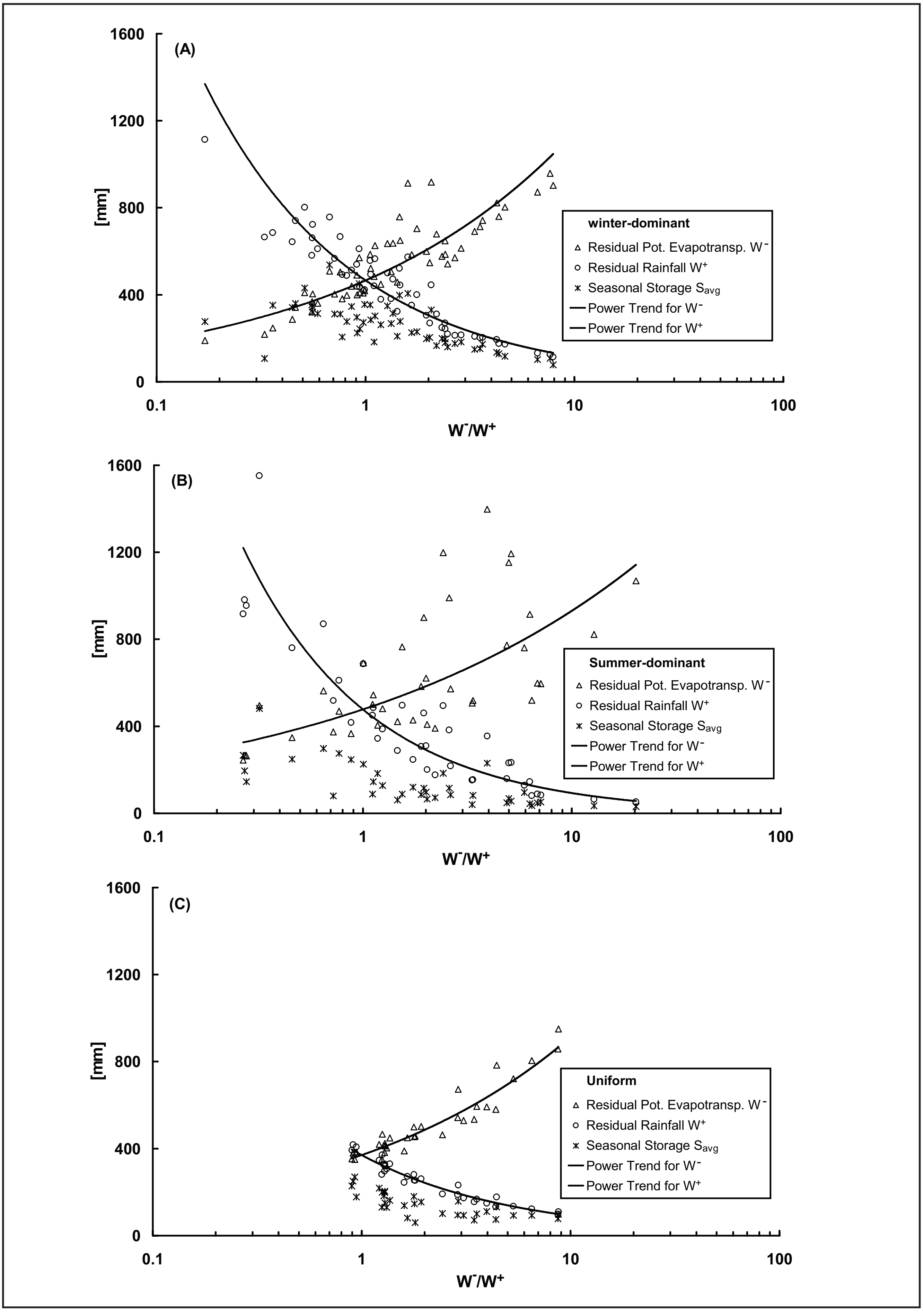


Figure 4. Longterm average of $W^-$, $W^+$ and $S_{avg}$ for (A) winter-dominant rainfall, (B) summer-dominant rainfall, (C) uniform rainfall.

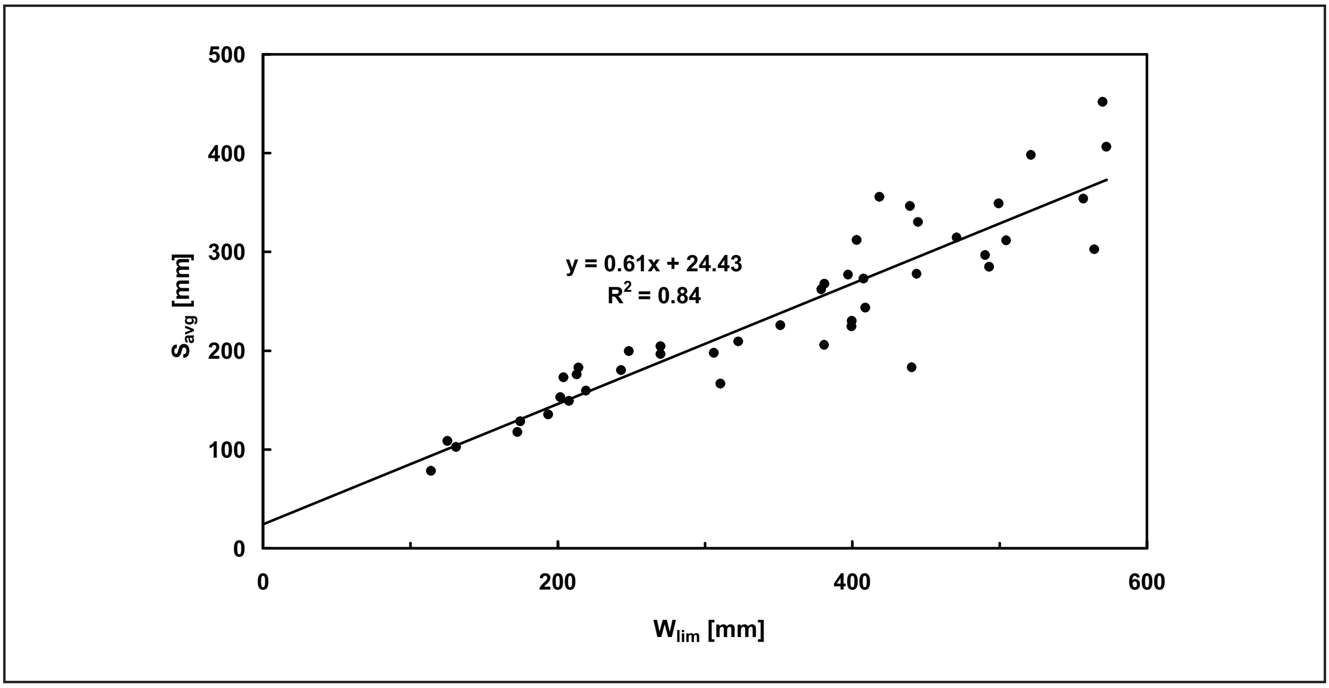


Figure 5. Estimation of average effective storage $S_{avg}$ for catchments with winter-dominant rainfall and $W^{-}/W^{+} > 0.7$.

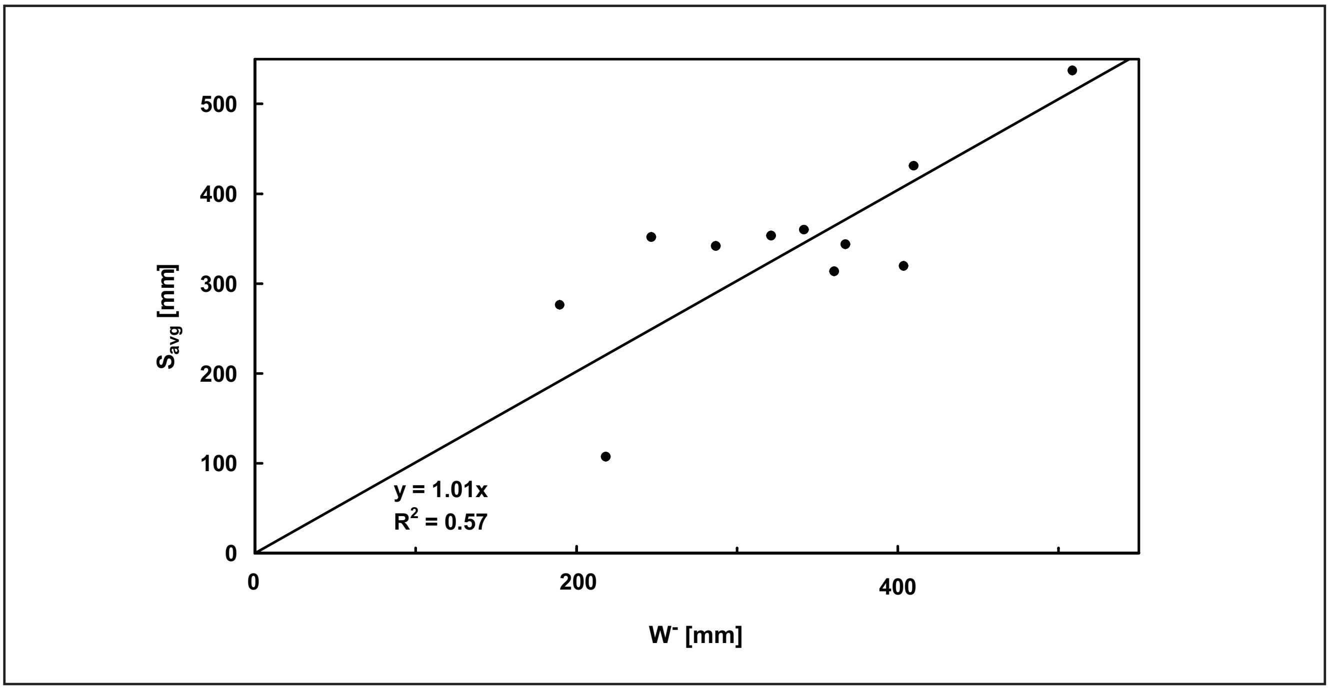


Figure 6. Estimation of average effective storage $S_{avg}$ for winter-dominant rainfall and $W^{-}/W^{+} < 0.7$.

***b) Summer-dominant rainfall***

As mentioned earlier, comparison of the top and bottom graph of Figure 4 shows that catchments with summer-dominant rainfall do not follow the limiting factor $W^+$ or $W^-$ as closely as the catchments with winter-dominant rainfall. However, there is still reasonably good correlation between $W^+$ and $S_{avg}$ (Figure 7).

***c) Uniform rainfall***

A single relationship was developed for all the catchments with uniform rainfall and these catchments are all associated with $W^-/W^+\geq 0.9$. The best relationship was found to be between effective seasonal storage ($S_{avg}$) and residual rainfall ($W^+$) and is shown in Figure 8.

### Relationships Between Plant Available Water Holding Capacity and Effective Storage

A comparison of plant available water-holding capacity (*PAWC*) estimated from soil characteristics and landscape analysis (McKenzie, 2002) with average annual effective storage $S_{avg}$ was undertaken. It should be emphasised here that $S_{avg}$ is averaged over many years and is therefore not equal to the maximum seasonal storage, while *PAWC* is an estimate of the maximum water storage.

No correlation was found between the plant available water-holding capacity (*PAWC*) and the effective seasonal water storage for wet catchments ($W^-/W^+<1.5$), while for dry catchments ($W^-/W^+>1.5$) there was reasonable agreement between the two estimates of water storage. Figure 9 shows a comparison between the effective seasonal storage $S_{avg}$ *PAWC* for the dry catchments. For catchments with summer-dominant rainfall the effective seasonal storage is lower than the plant available water holding capacity. Uniform catchments have a high degree of scatter and there was no systematic bias in the results. In the case of winter-dominant rainfall, effective seasonal storage is generally higher than plant available water-holding capacity. This may be a result of the fact that $S_{avg}$ is calculated on annual basis and the occurrence of multiple storage recharge and discharge events per year would increase the magnitude of $S_{avg}$. However, it may also be caused by systematic under-estimation in the *PAWC* estimates.

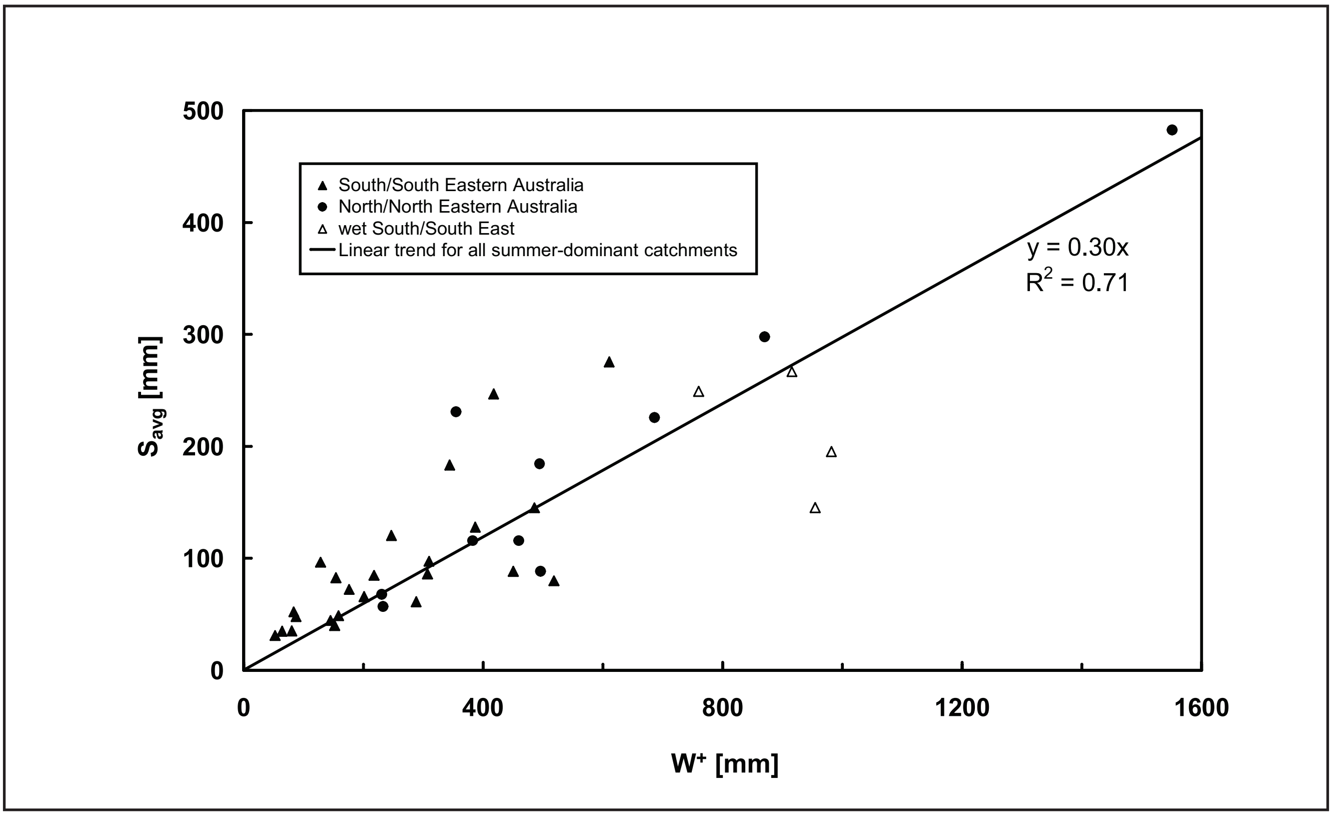


Figure 7. Estimation of average effective storage $S_{avg}$ by $W^+$ for catchments with summer-dominant rainfall.

Ladson *et al.,* (2002) showed that *PAWC* estimates based on soil data could be considered as a lower limit of field-based estimates of the actual dynamic soil moisture store. The results for winter-dominant rainfall shown in Figure 9 are consistent with this finding. It should also be noted that the comparison shown in Figure 9 is not intended to show how well the seasonal water storage estimated from the model compares to the independent estimates of soil water storage using soil and vegetation characteristics. Instead, we are interested in the potential of using *PAWC* for modelling catchment water balance.

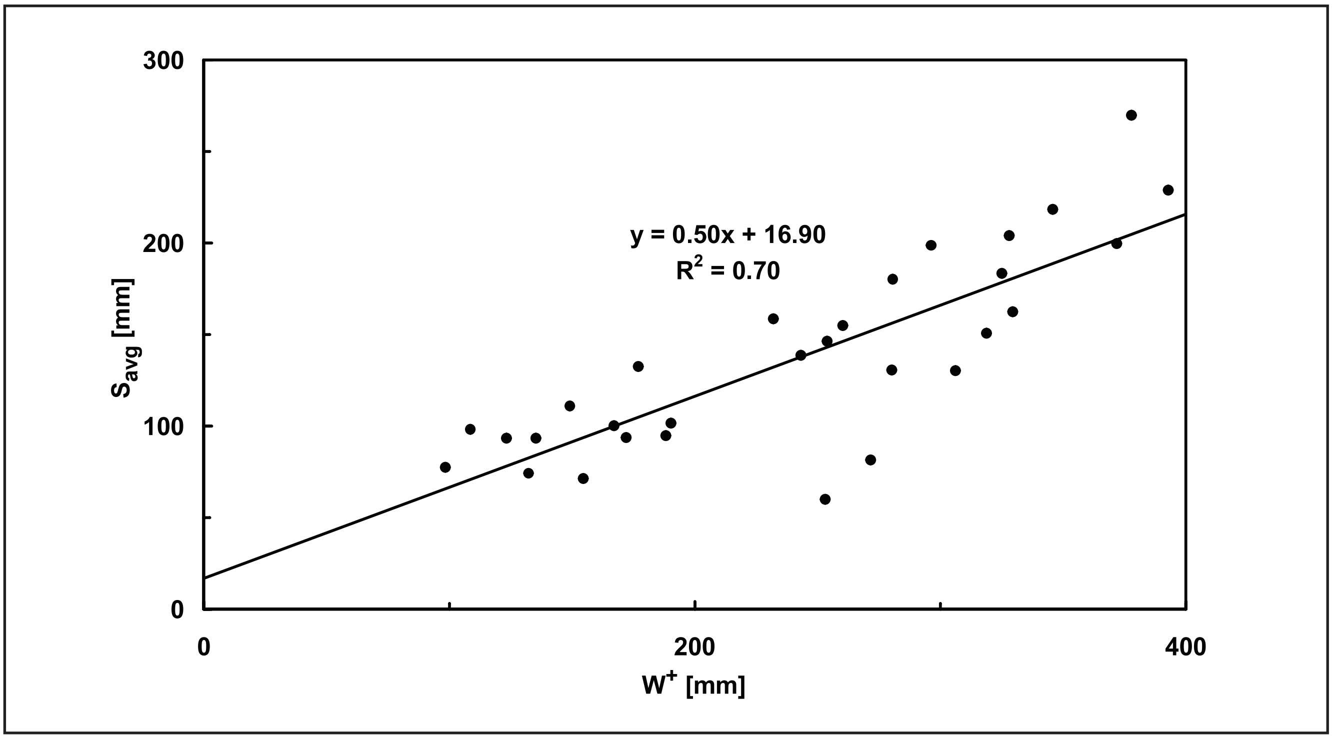


Figure 8. Relationship between average effective storage ($S_{avg}$) and $W^+$ for catchments with uniform rainfall.

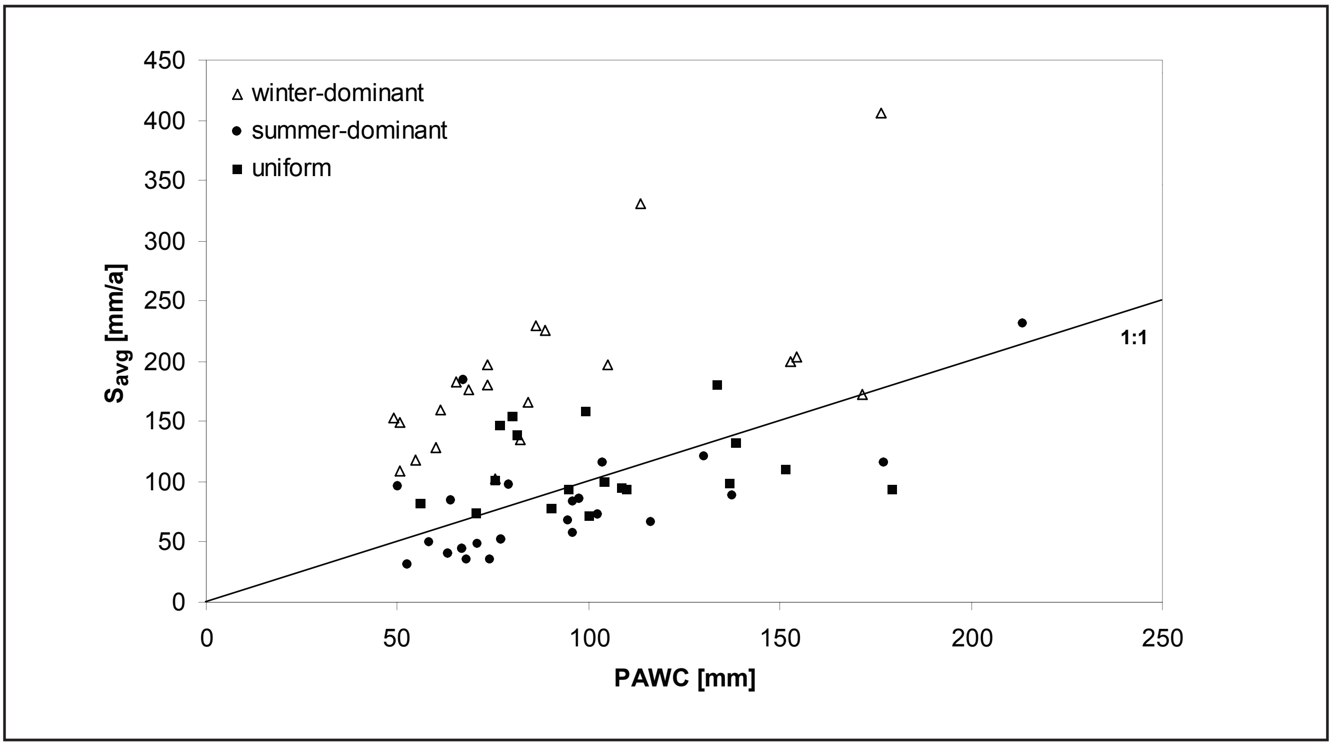


Figure 9. Comparison of plant available water-holding capacity (*PAWC*) and effective seasonal storage ($S_{avg}$) for dry catchments ($W^-/W^+ > 1.5$).

## 5.2 Relationships Between Storage-controlled Evapotranspiration and Effective Storage

For the purpose of predicting storage-controlled evapotranspiration ($E_{stor}$), it is necessary to find relationships between $E_{stor}$ and other factors. In particular, this section will describe the relationships between $E_{stor}$ and effective seasonal storage ($S_{avg}$).

Considerations of the energy- and water limits on evapotranspiration reveal two obvious boundary conditions for storage-controlled evapotranspiration $E_{stor}$, which can be written as:

$$E_{stor} \le S_{avg} \le W^{+} \qquad \text{(Water-limited)}$$

$$E_{stor} \le W^{-} \qquad \text{(Energy-limited)}$$

In Figure 10 the storage-controlled evapotranspiration ($E_{stor}$) is plotted against the effective seasonal storage ($S_{avg}$). It is clear that for all the catchments considered $E_{stor}$ increases with the effective seasonal storage ($S_{avg}$). It can also be seen that the relationships for all the rainfall regimes are reasonably similar (Figure 10), but with winter-dominant catchments having relative higher storage-controlled evapotranspiration.

As indicated before, $E_{stor}$ is calculated as difference between total and climate-controlled evapotranspiration ($E - E_{clim}$). This difference becomes less than zero for some catchments, which could mean that there are errors in inputs (e.g. rainfall, potential evapotranspiration, or runoff data), or that one or both of the assumptions for the estimation of climate-controlled evapotranspiration described in Section 3.1 are not valid. In total, 18 such catchments were removed from the dataset. These catchments are mainly subtropical catchments in coastal Northern NSW and Southern QLD, but also two Tasmanian catchments with winter-dominant rainfall and one catchment of the South Coast (Tuross River Basin).

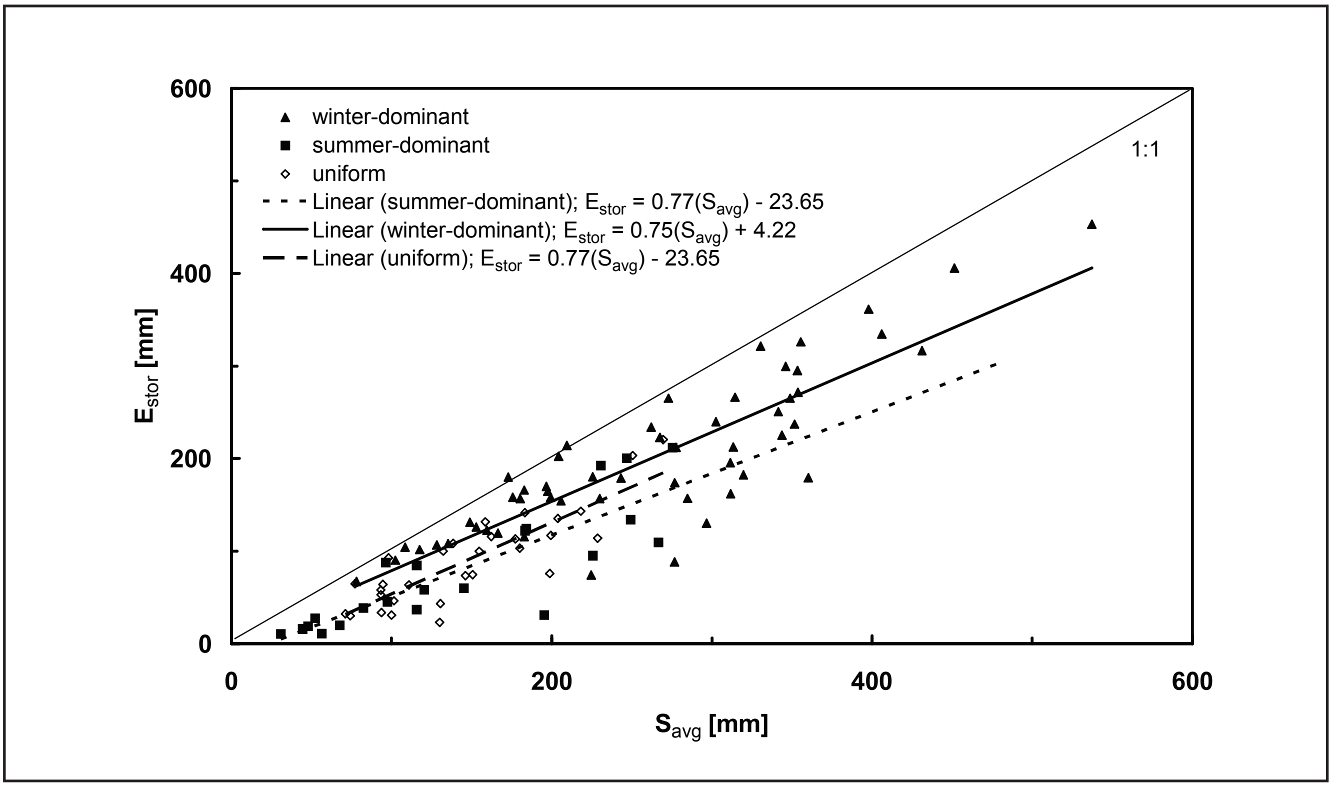


Figure 10. Relationships between storage-controlled evapotranspiration $E_{stor}$ and effective seasonal storage $S_{avg}$ ($R^2 = 0.74$ for all trendlines).

# 6. Dryness Index, Climate and Storage-controlled Evapotranspiration

The framework described earlier aims to estimate mean annual evapotranspiration by considering the effect of climate and storage separately. The distinction between climate-controlled and storage-controlled evapotranspiration was made in order to understand how mean annual evapotranspiration from different catchments would be affected by climate and catchment characteristics. This will have the potential for the method to be applied to ungauged catchments. Climate-controlled evapotranspiration ($E_{clim}$) can be described by the dryness index ($E_0/P$) with knowledge of regional *b*-values (Equation 13). The relationship described by Equation 13 is similar to the group of mean annual water balance model known as Budyko curves (Zhang *et al*., 2001). Examination of these relationships will allow the relative contribution of climate-controlled evapotranspiration to be estimated independently. For this purpose, the mean annual evapotranspiration model of Fu (1981) was used in the analysis, which was recently reviewed by Zhang *et al*., (2003):

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P}\right)^{\alpha}\right]^{1/\alpha} \tag{14}$$

where $\alpha$ is a shape parameter.

Figure 11 shows comparisons between the climate-controlled evapotranspiration and total evapotranspiration as a function of the dryness index for different rainfall regimes. It is clear that the climate-controlled evapotranspiration ratio ($E_{clim}/P$) showed much less scatter around the relationship described by Equation 13 than the total evapotranspiration ratio ($E/P$) around Fu's curve (Equation 14). This is consistent with the conceptualisation of the water balance model and it also indicates that the prediction of climate-controlled evapotranspiration ratio using the

Table 2. RMSE and coefficient of determination for the prediction of mean annual evapotranspiration ratio using Equations 13 and 14.

| **Rainfall Regime** | | $E_{clim}/P$ | $E/P$ |
|---|---|---|---|
| **Winter (SE, SW)** | RMSE/$\sigma$ | 0.39 | 0.54 |
| | $R^2$ | 0.89 | 0.61 |
| **Summer; South/South East** | RMSE/$\sigma$ | 0.23 | 0.35 |
| | $R^2$ | 0.95 | 0.86 |
| **Summer; North/North East** | RMSE/$\sigma$ | 0.42 | 0.40 |
| | $R^2$ | 0.88 | 0.81 |
| **Uniform (n)** | RMSE/$\sigma$ | 0.41 | 0.73 |
| | $R^2$ | 0.83 | 0.46 |

dryness index is more accurate than the prediction of mean annual evapotranspiration ratio with the dryness index. The mean annual evapotranspiration ratios were higher for winter-dominant catchments than for summer-dominant catchments. However, the climate-controlled evapotranspiration ratios exhibited the opposite behaviour.

In order to estimate the impact of climate and storage on evapotranspiration, root mean squared errors (*RMSE*) were calculated for the mean annual evapotranspiration ratio ($E/P$) using Equation 14 and for the climate-controlled evapotranspiration ratio ($E_{clim}/P$) using Equation 13. To account for the difference in magnitudes of ($E_{clim}/P$) and ($E/P$), the *RMSE* divided by the standard deviation ($\sigma$) is used as a measure of the degree of scatter in the predictions (Table 2). The coefficients of determination are also calculated and shown in Table 2. With the exception of summer-dominant north/north-eastern catchments, all catchments have a lower degree of scatter in the climate-controlled evapotranspiration ratio than in the mean annual evapotranspiration ratio. In addition, the correlation coefficients are always higher for the climate-controlled evapotranspiration ratio.

Because climate-controlled evapotranspiration ratio ($E_{clim}/P$) has significantly less scatter than the mean annual evapotranspiration ratio ($E/P$), the larger proportion of scatter in the data must come from storage-controlled evapotranspiration ratio ($E_{stor}/P$). Figure 12 shows the dependence of the storage-controlled evapotranspiration ratio ($E_{stor}/P$) on the dryness index ($E_0/P$) and it is clear that there is large scatter in the storage-controlled evapotranspiration ratio ($E_{stor}/P$), especially when the dryness index is about 1.0. Results shown in Figure 11 and and Figure 12 suggest that the climate-controlled evapotranspiration ratio is strongly dependent on the dryness index, while the storage-controlled evapotranspiration ratio is not directly correlated with the dryness index. As a result, any attempts to predict total evapotranspiration with the same functional relationship as is used for climate-controlled evapotranspiration will introduce additional scatter in the predictions.

This demonstrates that the climate-controlled evapotranspiration is closely linked to the dryness index and the Budyko-type relationships would be adequate for estimating this component of the total evapotranspiration. However, the storage-controlled evapotranspiration is affected by climate regimes in different ways to that of the climate-controlled evapotranspiration and catchment characteristics (e.g. soil water storage capacity) play an important role in determining the storage-controlled evapotranspiration. These factors may be considered as second order factors compared to the dryness index and inclusion of these factors can improve predictions of total evapotranspiration.

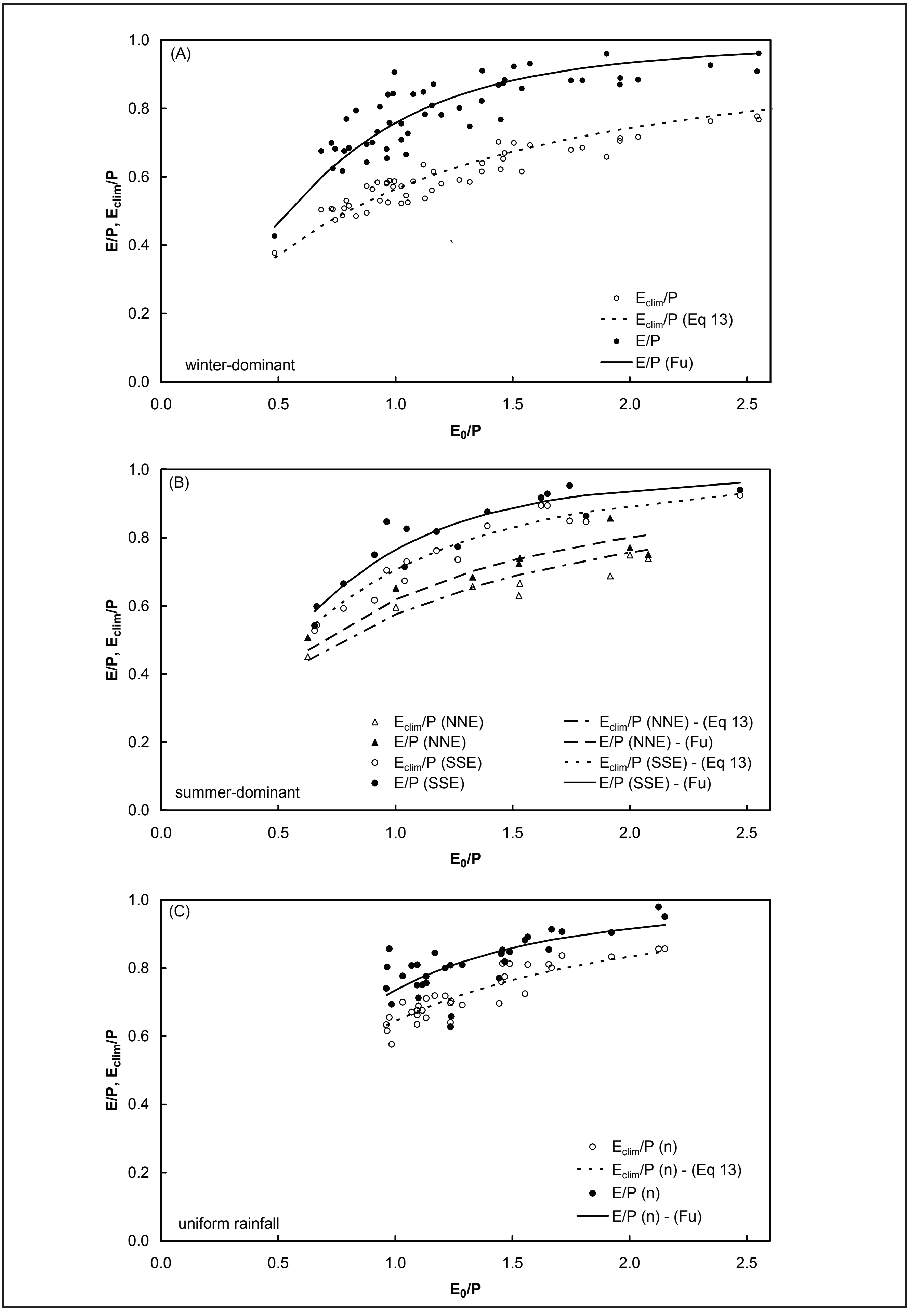


Figure 11. Mean annual evapotranspiration ratio and climate-controlled evapotranspiration ratio as function of dryness index (*$E_0/P$*) for catchments with (A) winter-dominant rainfall, (B) summer-dominant rainfall, and (C) uniform rainfall.

It can also be observed in Figure 12 that storage-controlled evapotranspiration is generally larger in areas with winter-dominant rainfall and smaller where there is summer-dominant rainfall. This clearly shows that the impact of seasonal storage is more pronounced in the case of winter-dominant rainfall than of summer-dominant rainfall.

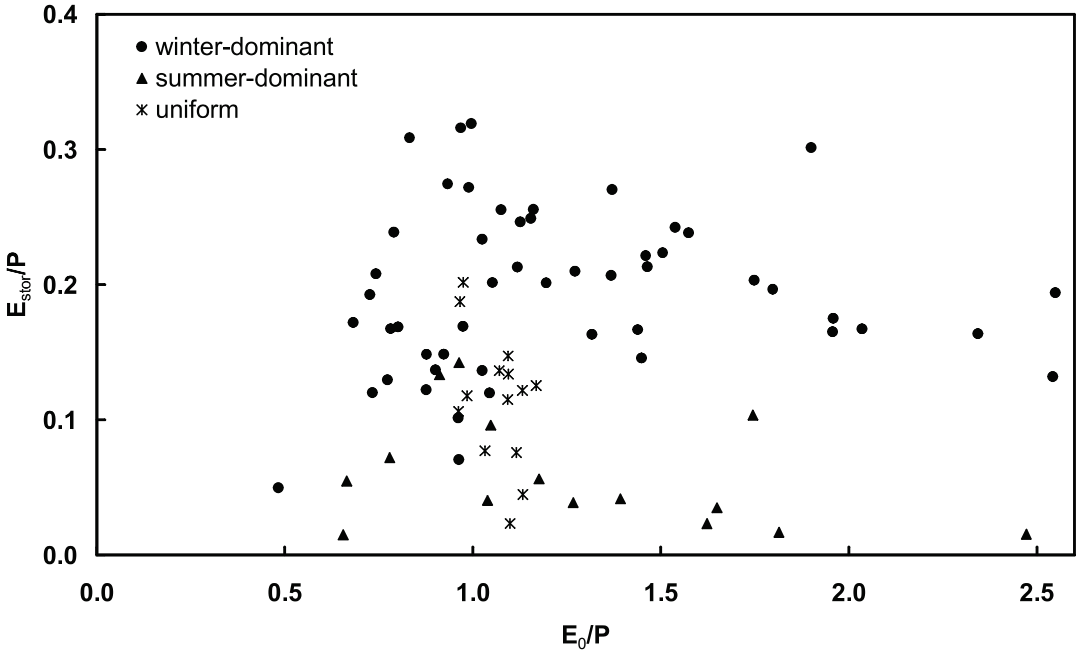


Figure 12. Storage-controlled evapotranspiration ratio versus dryness index ($E_0/P$) for catchments under different climate regimes.

# 7. Model Testing

In the previous sections, monthly values of rainfall, potential evapotranspiration, runoff, and catchment characteristics from more than 100 catchments in Australia were used to develop the water balance model with seasonal water storage. It is clear that the top-down approach was applied and the model is built on the relationships extracted from the dataset. In the following section, the model will be tested using data from other catchments.

## 7.1 Modelling Procedure

The procedure separately calculates $E_{clim}$ and $E_{stor}$ as they have been established in the previous sections 3.2 and 3.3. The sum of these equals the predicted total evapotranspiration (Equation 6). The model is tested on the validation dataset with 202 catchments in Australia.

Climate-controlled evapotranspiration $E_{clim}$ is estimated by application of Equation 13 and knowledge of the local dryness index ($E_0/P$) and *b*-parameter. Calculation of residual rainfall ($W^+$) and residual potential evapotranspiration ($W^-$) using Equations 10a and 10b allow prediction of the effective seasonal storage ($S_{avg}$) which in turn allows estimation of storage-controlled evapotranspiration ($E_{stor}$). Table 3 and Table 4 summarise the applied relationships for the estimation of effective seasonal storage ($S_{avg}$) and storage-controlled evapotranspiration ($E_{stor}$).

Table 3. Summary of Equations for estimation of $S_{avg}$

| **Rainfall Regime** | | $W^-/W^+ \geq 0.7$ | $W^-/W^+ < 0.7$ |
|---|---|---|---|
| **Winter** | **SE, SW** | $S_{avg} = 0.61 \min\{W^-, W^+\} + 24.4$ | $S_{avg} = 1.01W^-$ |
| **Summer** | **SSE** | $S_{avg} = 0.30\,(W^+) + 16.7$ | |
| **Summer** | **NNE** | $S_{avg} = 0.30\,(W^+)$ | |
| **Uniform** | **SE** | $S_{avg} = 0.50\,(W^+) + 16.9$ | |

Table 4. Summary of Equations for estimation of $E_{stor}$ by $S_{avg}$ (taken from Figure 10).

| **Rainfall Regime** | | |
|---|---|---|
| Winter | SE, SW | $E_{stor} = 0.75\,S_{avg} + 4$ |
| Summer | SSE, NNE | $E_{stor} = 0.77\,S_{avg} - 24$ |
| Uniform | SE | $E_{stor} = 0.67\,S_{avg} - 16$ |

## 7.2 Results

Estimates of mean annual evapotranspiration using the water balance model with seasonal storage effect considered are first compared with the observed mean annual evapotranspiration and then compared to mean annual evapotranspiration calculated using the model of Fu (1981).

The root mean squared error (*RMSE*) and coefficient of determination are listed in Table 5. For all the catchments considered, the water balance model developed in this study yields *RMSE* of 61 mm in the predicted mean annual evapotranspiration with the coefficient of determination equal to 0.86. This represents an improvement compared to the model of Fu (1981). To evaluate the performance of the water balance model under different rainfall regimes, the catchments are divided into three categories. In all the rainfall regimes, the water balance model yields a slightly higher coefficient of determination compared with Fu's model. However, the *RMSE* are higher for uniform and summer-dominant rainfall regimes compared with Fu's model. The maximum improvement in *RMSE* and coefficient of determination is for catchments with winter-dominant rainfall.

Table 5. RMSE and coefficient of determination from model validation.

| **Rainfall Regime** | **Number of Catchments** | **RMSE [mm]** | | **$R^2$** | |
|---|---|---|---|---|---|
| | | ***Eq (6)*** | ***Fu*** | ***Eq (6)*** | ***Fu*** |
| All | 202 | 61 | 62 | 0.86 | 0.80 |
| Uniform | 44 | 44 | 41 | 0.78 | 0.76 |
| Winter | 78 | 67 | 74 | 0.84 | 0.71 |
| Summer | 80 | 70 | 66 | 0.85 | 0.82 |

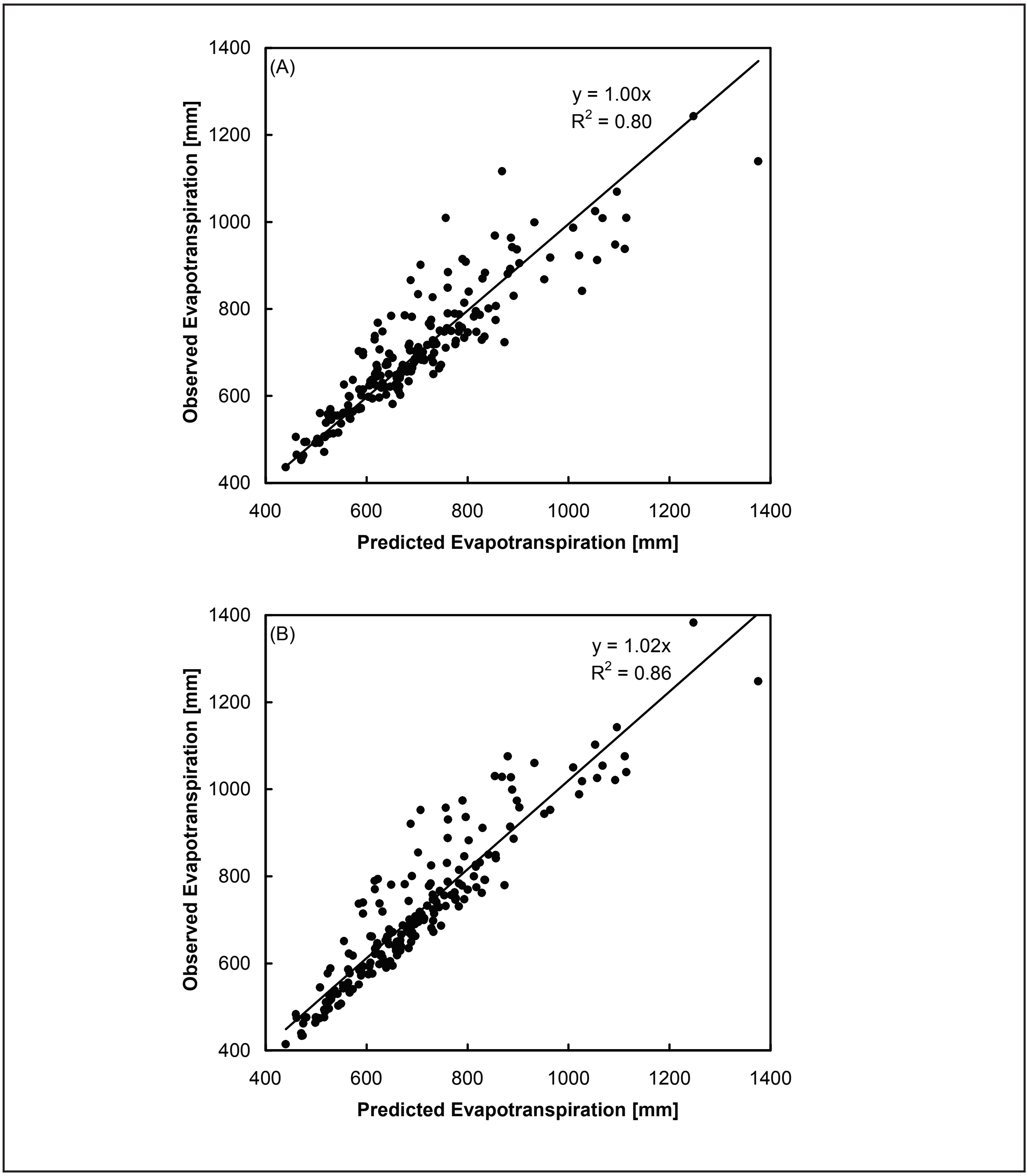


Figure 13. Comparison between mean annual evapotranspiration calculated using Fu's model (A) and the water balance model (B) against observed mean annual evapotranspiration

# 8. Discussion

This paper describes the development and testing of a conceptual framework for incorporating the impact of rainfall seasonality on average annual water balance. A number of studies have shown that mean annual water balance is chiefly controlled by climatic factors such as dryness index (Budyko, 1958, Milly, 1994, Zhang *et al*., 2003) and mitigated by seasonal water storage (Milly, 1994). It has been suggested that when the seasonal variations of rainfall and potential evapotranspiration are in phase, the conditions are believed to be favourable for evapotranspiration, while limited seasonal water storage and high rainfall intensity may have opposite effects on evapotranspiration. In this study, it is assumed that annual water balance can be considered separately for distinct periods of the annual climate cycle: storage recharge and discharge periods. During storage recharge periods, rainfall exceeds potential evapotranspiration and actual evapotranspiration is assumed to occur at a rate equal to the potential evapotranspiration. In storage discharge periods, potential evapotranspiration is greater than rainfall and actual evapotranspiration is determined by the amount of rainfall during this period, and a fraction of the stored water. The effect of seasonality and hence seasonal water storage on annual evapotranspiration can be included by dividing annual water balance into these periods.

Given these assumptions annual evapotranspiration is calculated as the sum of climate-controlled and storage-controlled evapotranspiration. This distinction allows the effects of climate and seasonal storage on mean annual evapotranspiration to be evaluated separately. Climate-controlled evapotranspiration is dominated by climatic characteristics and shows strong dependence on the dryness index. As a result, regional relationships between the climate-controlled evapotranspiration and dryness index have been developed, which enable the effects of seasonal climate on evapotranspiration to be evaluated within the regional context. Results showed that the observed mean annual evapotranspiration ratio was higher for winter-dominant catchments than for summer-dominant catchments, which is the opposite of the assertion that the effect of seasonality on mean annual evapotranspiration is to increase evapotranspiration when rainfall and potential evapotranspiration are in phase and to decrease evapotranspiration when they are out of phase (Milly, 1994). It can be argued that evapotranspiration ratio would be higher for summer-dominant catchments if the water storage capacity and permeability were sufficiently large to overcome seasonal variations in the difference between rainfall and potential evapotranspiration. Further examination of the results showed that catchments with summer-dominant rainfall exhibited higher ratios of climate-controlled evapotranspiration to rainfall compared to catchments with winter-dominant rainfall. The climate-controlled evapotranspiration ratios for catchments with uniform rainfall lie in between. It can be noted that the definition of the climate-controlled evapotranspiration is similar to the scenario of sufficiently large water storage capacity and permeability. It is interesting to note that the climate-controlled evapotranspiration ratios for Western Australia catchments are much lower than those of the catchments in the southeast with the same rainfall regime. This may be due to the fact that the rainfall and potential evapotranspiration for Western Australia catchments have larger seasonal variations and are completely out of phase.

Storage-controlled evapotranspiration is believed to be a function of seasonal water storage and relationships have been developed between the storage-controlled evapotranspiration and effective seasonal storage for different rainfall regimes. These relationships suggest that in catchments with winter-dominant rainfall a greater proportion of the total evapotranspiration is due to seasonal water storage compared to catchments with summer-dominant rainfall. Estimation of storage-controlled evapotranspiration requires knowledge of seasonal water storage under different rainfall regimes. The average annual effective water storage inferred from the model showed reasonable agreement with independent estimates of plant available water-holding capacity for dry catchments (e.g. $E_0/P > 1.5$). However, no correlation was found for wet catchments. This may be due to the fact that in dry catchments changes in storage occur within a year and the plant-soil system will evolve to capture and use all available rainfall. However, for wet catchments storage changes occur over several years with climate cycles and therefore on mean annual basis there is no consistent storage change.

# 9. Conclusions

The effect of rainfall seasonality on mean annual evapotranspiration can be estimated by assuming annual evapotranspiration as the sum of climate- and storage-controlled evapotranspiration. The climate-controlled evapotranspiration can be estimated accurately from the dryness index and knowledge of rainfall regimes. This enables the effect of rainfall seasonality on evapotranspiration to be evaluated within the regional context. The storage-controlled evapotranspiration relates more to catchment properties and can be characterised by the effective seasonal storage. Inclusion of the rainfall seasonality effect improved evapotranspiration predictions for catchments with winter dominant rainfall. The seasonality effect on mean annual evapotranspiration can not be adequately represented by phase difference between rainfall and potential evapotranspiration alone and the effect of seasonal water storage needs to be considered. The development of the framework followed a downward approach (Sivapalan *et al*., 2003) and was guided by observational data. One of the advantages of the method is that inputs required are readily available for most Australian catchments.

## References

Brutsaert, W.F., Evaporation into the Atmosphere, D. Reidel Publishing Company, Dordrecht, Holland, 299 pp, 1982.

Budyko, M.I., Climate and Life, 508 pp., Academic, San Diego, Calif., 1974.

Budyko, M.I., The Heat Balance of the Earth's Surface. U.S. Department of Commerce, Washington, D.C., 1958.

Choudhury, B.J., Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model. J. Hydrol. 216, 99-110, 1999.

Fu, B.P., On the calculation of the evaporation from land surface. Scientia Atmospherica Sinica, 5, 23-31, 1981 (in Chinese).

Ladson, A., Lander, J., Western, A., Grayson, R., and Zhang, L., Estimating extractable soil moisture content for Australian soils. Proceedings of Hydrology and Water Resources Symposium, Melbourne, 2002.

McKenzie, N.J., Gallant, J.C., and Gregory, L.J., Estimating water storage in soil at catchment scales, Cooperative Research Centre for Catchment Hydrology, Technical Report 03/13, 2002.

Milly, P.C.D., Climate, soil water storage, and the average annual water balance. Water Resour. Res., 30, 2143-2156, 1994.

Peel, M.C., Chiew, F.H.S., Western, A.W., and McMahon, T.A., Extension of unimpaired monthly streamflow data and regionalization of parameter values to estimate streamflow in ungauged catchments. Report to National Land and Water Resources Audit, 2000.

Pike, J.G., The estimation of annual runoff from meteorological data in a tropical climate. J. Hydrol., 2, 116-123, 1964.

Priestley, C.H.B., Taylor, R.J., On the assessment of the surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev., 100, 81-92, 1972.

Raupach, M.R., Kirby, J.M., Barrett, D.J., Briggs, P.R., Lu, H., and L. Zhang, Balances of water, carbon, nitrogen and phosphorus in Australian landscapes: (2) model formulation and testing. CSIRO Land and Water Technical Report 41/01, 2001.

Ritman, K.T., Structural Vegetation Data: a specification manual for the Murray Darling Basin Project M305. 1995.

Schaake, J.C. Jr. And C. Liu. Development and application of simple water balance models to understand the relationship between climate and water resources, in New Directions for Surface Water Modelling (Proceedings of the Baltimore Symposium, May, 1989), IAHS Publ., 181, 343-352, 1989.

Schreiber, P., Über die Beziehungen zwischen dem Niederschlag und der Wasserführung der Flüße in Mitteleuropa, Z. Meteorol., 21, Pt. 10, 1904.

Sivapalan, M., Zhang, L., Vertessy, R., and Blöschl, G., Downward approach to hydrological prediction: A critical review, Hydrological Processes (in press), 2003.

Woods, R., The relative roles of climate, soil, vegetation and topography in determining seasonal and long-term catchment dynamics. Advances in Water Resources (in press), 2003

Zhang, L. Hickel, K., Dawes, W.R., Chiew, F. , Western, A., A rational function approach for estimating mean annual evapotranspiration. Water Resources Research (submitted). 2003

Zhang, L., Dawes, W.R., Walker, G.R., Predicting the effect of vegetation changes on catchment average water balance, Cooperative Research Centre for Catchment Hydrology, Technical Report 99/12, 1999.

Zhang, L., Dawes, W.R., Walker, G.R., The response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research, Vol. 37, 701-708, 2001.

# Appendix A

The following graphs show monthly water and energy input into the catchment and runoff response compared to the difference between rainfall and potential evapotranspiration.

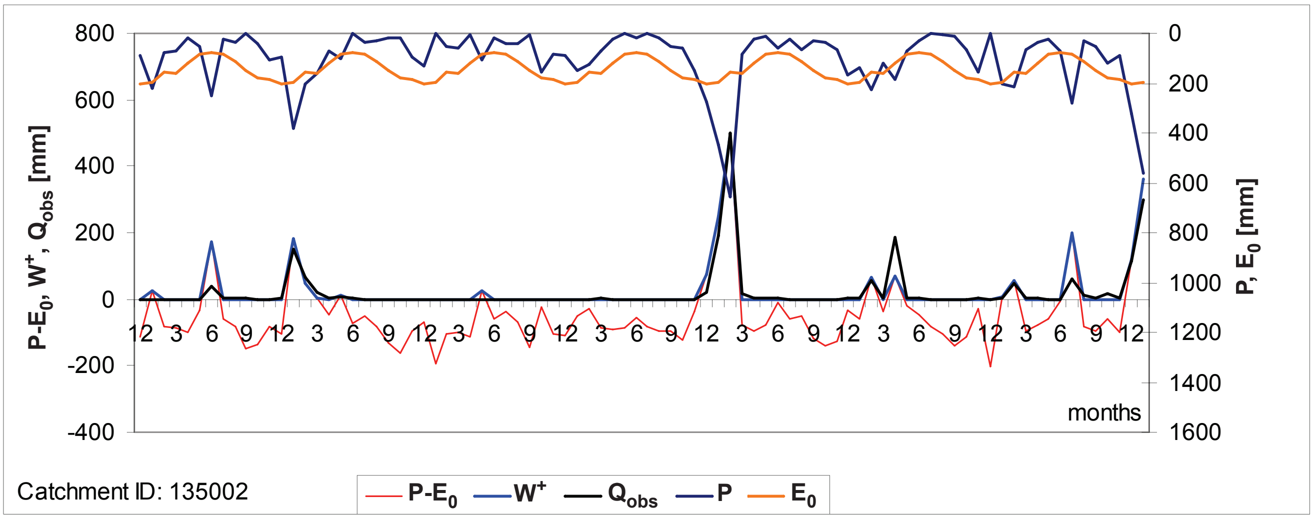


Figure 14. Kolin River at Springfield, Northeast Coast Division, QLD. (Summer, SSE)

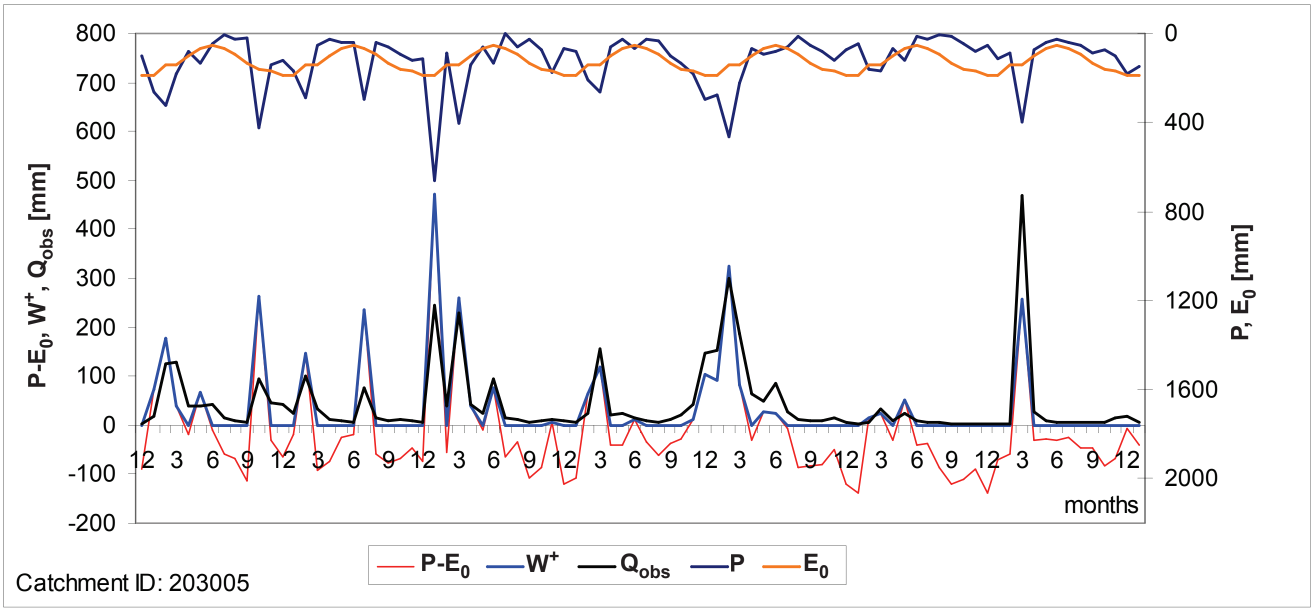


Figure 15. Richmond River at Wiangaree, Southeast Coast Division, NSW. (Summer, SSE)

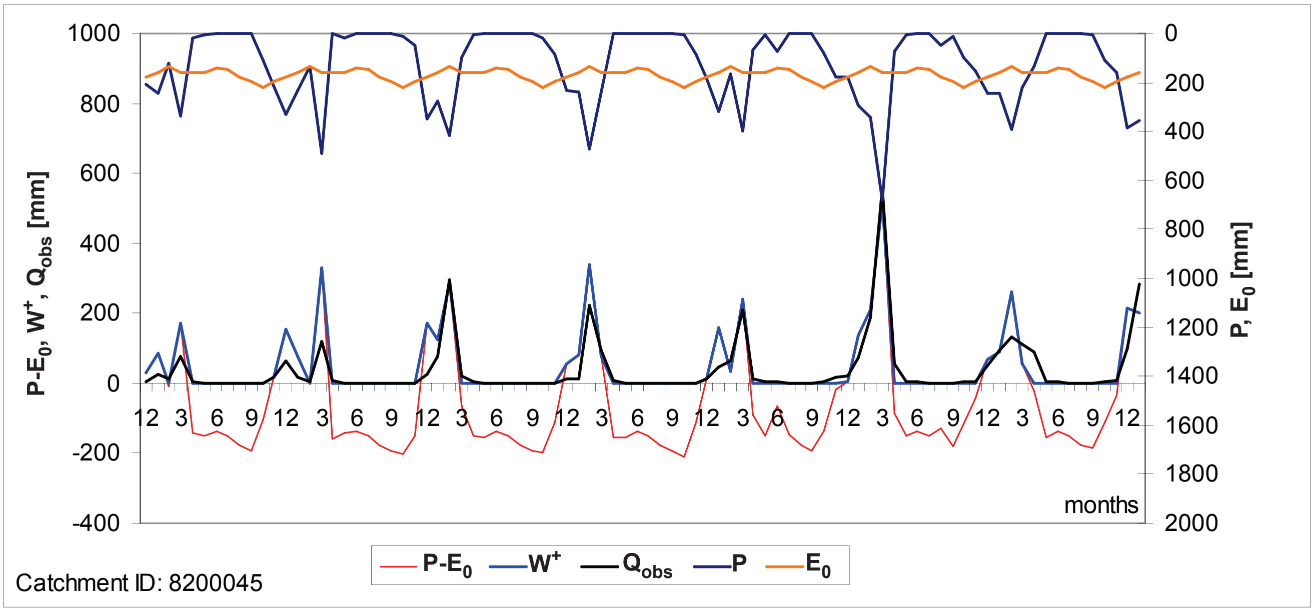


Figure 16. South Aligator River at El Sharana, NT. (Summer, NNE)

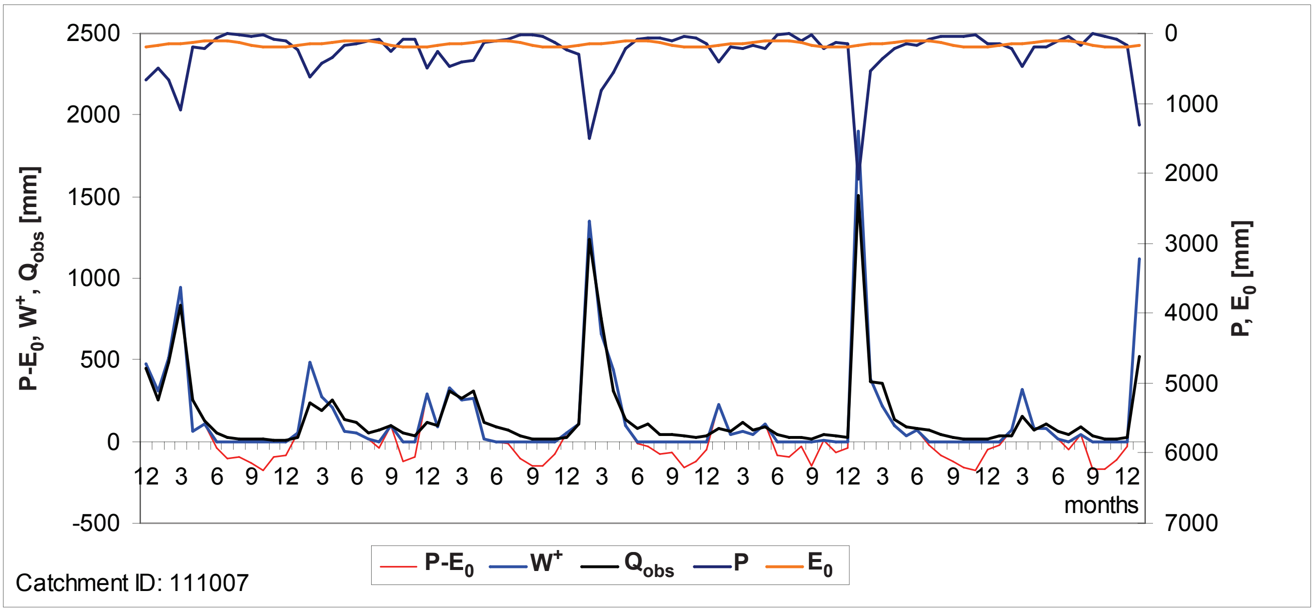


Figure 17. Mulgrave River at Peets Bridge, Northern Qld. (Summer, NNE)

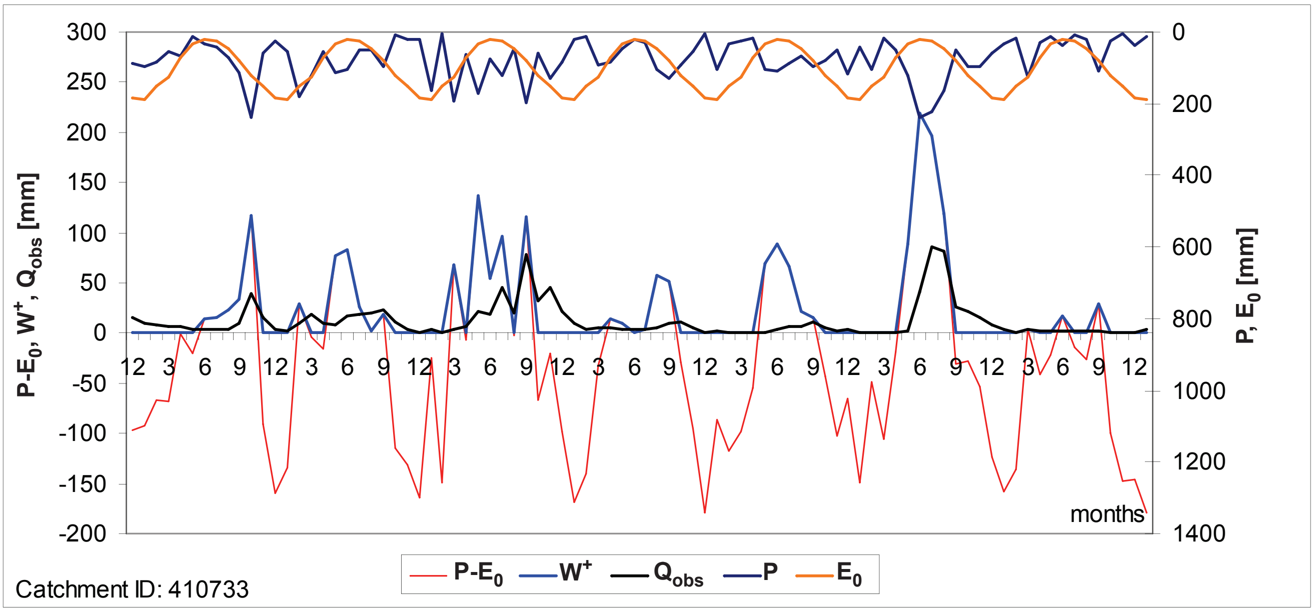


Figure 18. Coree at Threeways, MDB, NSW. (Uniform, SE)

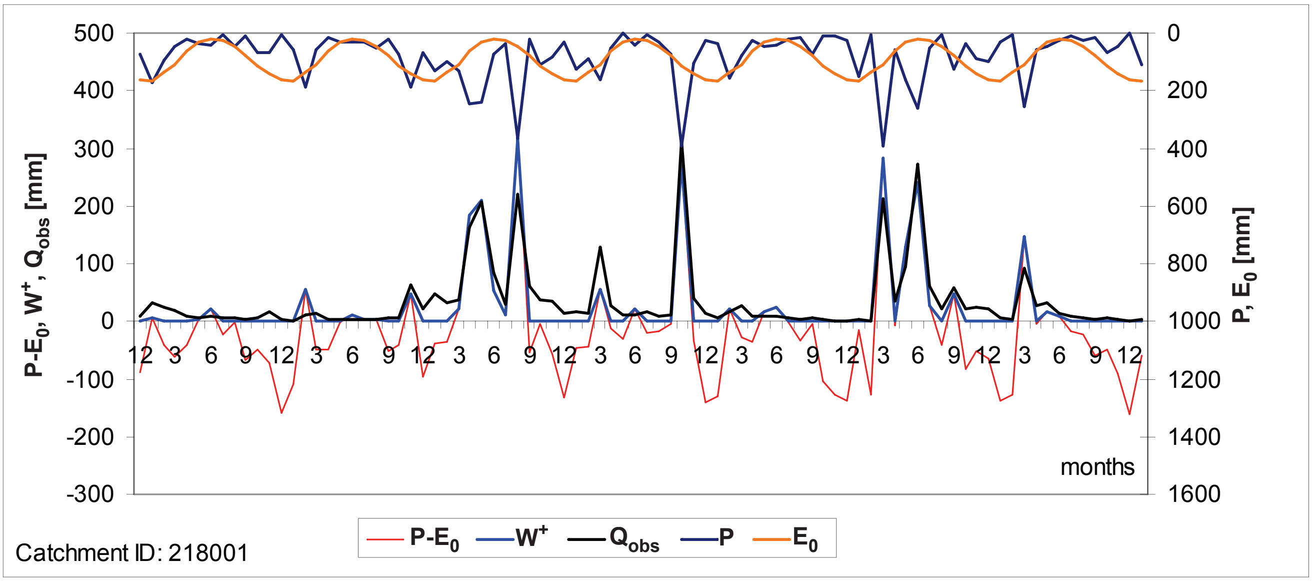


Figure 19. Tuross River At Tuross Vale, Southeast Coast Division, NSW. (Uniform, SE)

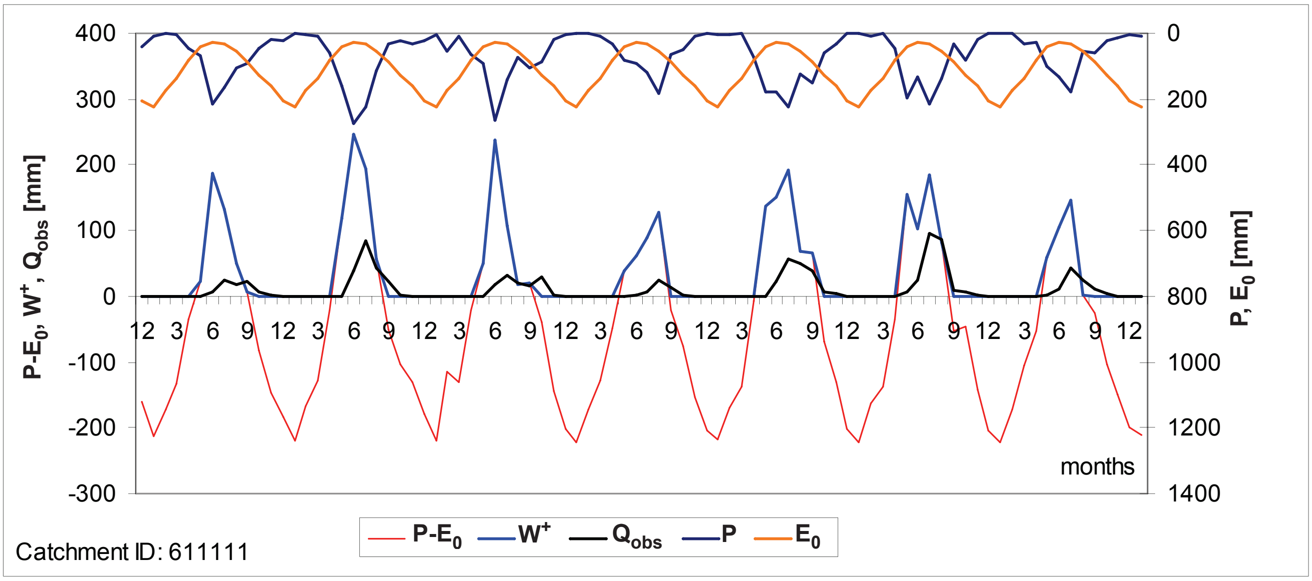


Figure 20. Thomson Brook at Woodperry Homestead, SW Coast Division, WA. (Winter, SW)

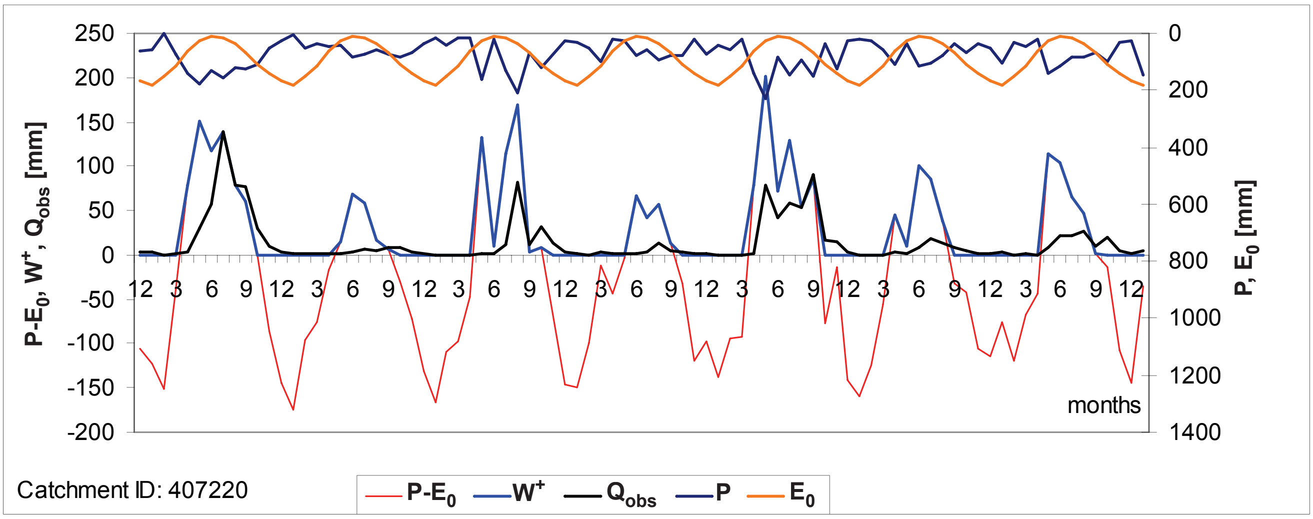


Figure 21. Bet Bet Creek at Norwood, MDB, Victoria. (Winter, SE)

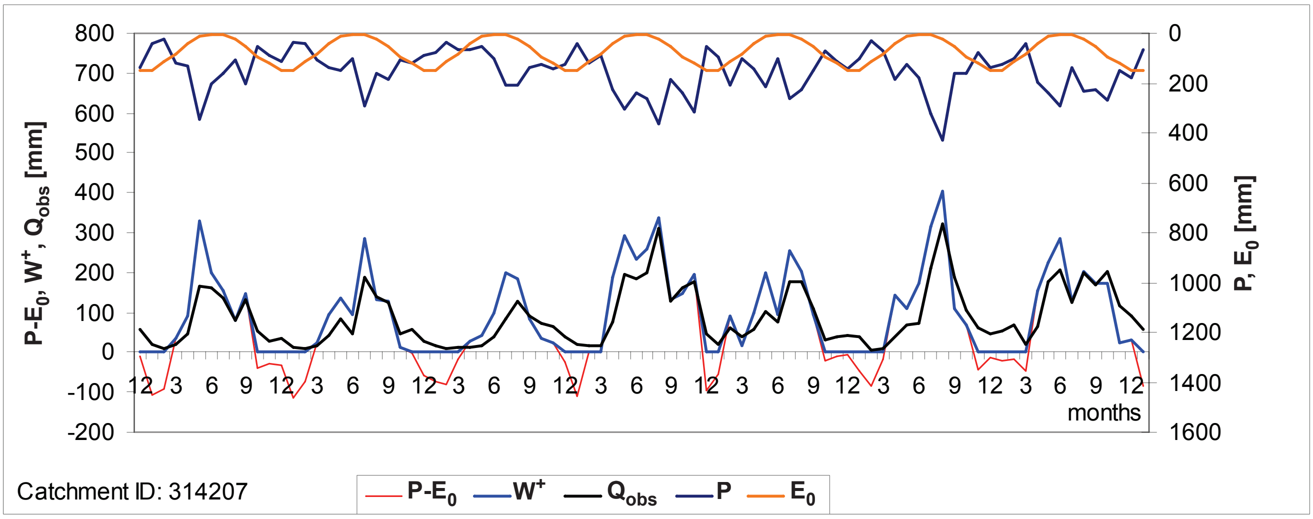
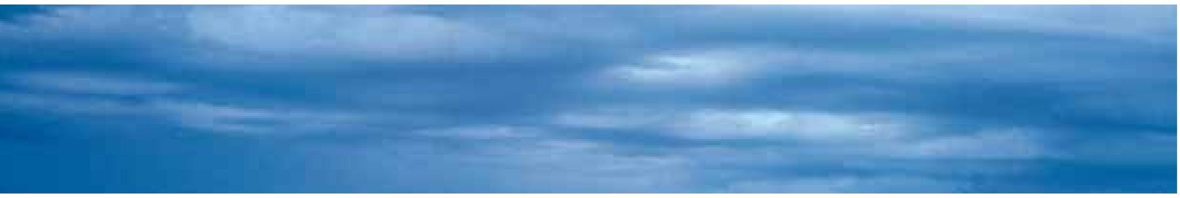


Figure 22. Leven River D/S Bannons Bridge, Northern Tasmania. (Winter, SE)

COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

**CENTRE OFFICE**

Department of Civil Engineering Building 60 Monash University VIC 3800 Australia
Telephone +61 3 9905 2704 Facsimile +61 3 9905 5033 Email crcch@eng.monash.edu.au www.catchment.crc.org.au



The Cooperative Research Centre for Catchment Hydrology is a cooperative venture formed under the Commonwealth CRC Program between:

- Brisbane City Council
- Bureau of Meteorology
- CSIRO Land and Water
- Department of Infrastructure, Planning and Natural Resources, NSW
- Department of Sustainability and Environment, Vic
- Goulburn-Murray Water
- Griffith University
- Melbourne Water
- Monash University
- Murray-Darling Basin Commission
- Natural Resources and Mines, Qld
- Southern Rural Water
- The University of Melbourne
- Wimmera Mallee Water

Associate:

- Water Corporation of Western Australia

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

CRC
AUSTRALIA

Established and supported
under the Australian
Government's Cooperative
Research Centre Program