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Sensitivity of streamflow to rainfall and temperature in south-eastern Australia during the Millennium drought

N.J. Potter, C. Petheram and L. Zhang

CSIRO Water for a Healthy Country National Research Flagship, CSIRO Land and Water, GPO Box 1666, Canberra ACT 2601

Abstract: The Millennium drought, generally defined from the mid-to-late 1990s until late 2010, is arguably the most severe drought in the historical record in south-eastern Australia (SEA). Reductions in rainfall between the years of 1997-2008 in SEA are comparable in magnitude to the reductions seen during the World War II Drought, and the Federation Drought. However, particularly in the southern Murray-Darling Basin, reductions in runoff during the Millennium drought were comparatively greater than during these two other 20th Century droughts. Increases in maximum air temperatures (Tmax) have been suggested as a primary reason for the severity of this drought. Other causes have also been suggested including changes in rainfall characteristics (e.g. variability and seasonality), loss of groundwater connectivity, as well as changes in land-use practice.

We examine the annual rainfall-temperature-streamflow relationships in 34 largely unregulated catchments in SEA. Using a regression approach, we test whether the annual rainfall-streamflow relationship and the annual rainfall-Tmax relationship were significantly different during the drought (1997–2008) compared to the pre-drought data. Approximately two-thirds of the catchments showed evidence of significantly lower streamflow for the same annual rainfall, whereas a little over half of the catchments had significantly increased residual Tmax (i.e. higher annually averaged daily maximum temperatures for the same annual rainfall). However, the spatial coherence between significant test results was low, and a chi-squared test suggests that the incidence of significantly lower streamflow and higher residual Tmax can be considered independent. In other words, the proportion of catchments with significantly less streamflow was not statistically higher in the group of catchments with increased residual temperatures.

We develop regression-based estimates of rainfall and temperature elasticities of streamflow, or sensitivities of annual streamflow to annual rainfall and annual Tmax anomalies. Most of the rainfall elasticities of streamflow lie within the range of about 1.5 to 3.0, meaning that a 10% decrease in annual rainfall leads on average to a 15%–30% reduction in annual streamflow, which is consistent with other estimates in SEA. More arid catchments generally have both larger rainfall elasticities and larger uncertainties in these estimates, although all rainfall elasticities are statistically significant. In contrast, only 19 out of 34 catchments have statistically significant temperature elasticities of streamflow; less arid catchments are more likely to have significant temperature elasticities. The mean of the significant temperature elasticities of streamflow is $-0.19°C^{-1}$. However, the catchments with larger average annual Tmax anomalies during the drought tend to have smaller (absolute) values of temperature elasticity. In those catchments with average Tmax anomalies during the drought greater than 0.6ºC, the mean of significant temperature elasticities of streamflow is only $-0.12°C^{-1}$.

We obtain estimates of the effect on streamflow of rainfall and Tmax anomalies by multiplying the observed mean annual anomalies during the drought by the long-term rainfall and temperature elasticities of streamflow. There is some variability of these estimates between catchments, but when averaged over large regions, the proportion of the streamflow reduction explained by this method works out remarkably similar. Over all 34 catchments, the catchment area weighted average streamflow reduction is 46% of the long-term mean. Approximately two-thirds of this is explained by the observed reduction in annual rainfall during the drought, and 7% is explained by the increase in annually averaged maximum temperatures. When averaged over all catchments, the estimated effect of a 1ºC increase in maximum temperatures is a 5% reduction in streamflow.

Keywords: *Drought, South-eastern Australia, Streamflow sensitivity*

1. INTRODUCTION

The Millennium drought, generally defined from the mid-to-late 1990s until late 2010, is arguably the most severe drought in the historical record in south-eastern Australia (SEA). In terms of severity and duration, the Millennium drought is only comparable to the World War II Drought and the Federation Drought. Even though the magnitude of the reductions in annual rainfall has been similar to the WWII drought, the reductions in runoff in the southern Murray-Darling Basin (MDB) in particular were unprecedented during the Millennium drought (Potter et al., 2010; Kiem and Verdon-Kidd, 2010). At the same time, the capacity of major storages within the MDB has increased approximately five-fold, and surface water use reached almost the natural flow to the sea (CSIRO, 2008).

One hypothesis is that increased maximum air temperatures (Tmax) have been largely responsible for this lower runoff (e.g. Nicholls, 2004; Cai and Cowan, 2008b). Alternatively, other hydroclimatic features of the drought have been suggested as being more important in reducing runoff, such as lower rainfall variability, and proportionally less autumn and winter rainfall (Potter and Chiew, 2009, 2011). The sensitivity of runoff or streamflow to a 1ºC increase in maximum temperature in SEA has been estimated at around 15-25% (Cai and Cowan, 2008b; Yu et al., 2010). However, it is not clear what hydrological mechanism can be responsible for this (Kiem and Verdon-Kidd, 2010).

In this paper we examine the annual rainfall-temperature-streamflow relationship for several streamflow gauges with long records in the SEA region. Section 2 applies regression techniques in order to determine whether there have been significant differences in both the annual rainfall-streamflow relationship and the annual rainfall-Tmax relationship during the drought compared to the pre-drought data. In section 3, we develop a regression-based method for estimating the sensitivities of streamflow to changes in annual rainfall and Tmax, and use this to estimate the proportion of the observed runoff reduction explained by rainfall and Tmax during the drought.

2. CHANGES IN THE RELATIONSHIPS BETWEEN RAINFALL, TEMPERATURE AND STREAMFLOW

2.1. Data used

We selected catchments in SEA that had over 40 years of complete data, and less than 30 days of missing data in the drought period (assumed to be from 1997 to 2008). Candidate catchments were visually examined using Google Earth to ensure any potential land-use change effects were minimal: catchments consisting of more than 10% forestry plantations, large farm dams, or substantial agriculture were excluded. In total, we found 34 catchments in SEA. Fourteen of these are located in the north-east coastal strip of NSW, and 20 are located in the southern MDB. Daily catchment-averaged rainfall and maximum temperature data were taken from the SILO data drill (Jeffrey et al., 2001), and missing streamflow data was infilled using the Sacramento model (Burnash et al., 1973). Thereafter the rainfall, Tmax and streamflow data were annually collated.

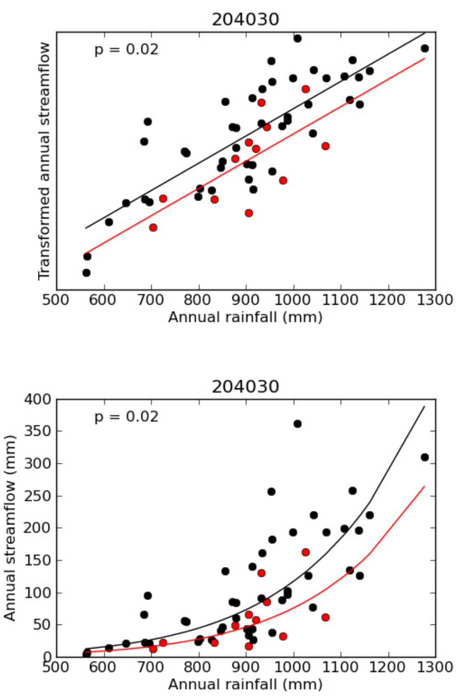

Figure 1: Testing the annual rainfall/streamflow relationship (catchment #204030 with maximum-likelihood Box-Cox parameter of 0.1). Red points and curves are for 1997−2008 data; black points and curves are for pre-1997 data.

2.2. Changes in the rainfall/streamflow relationship

Firstly, we test whether the annual rainfall-streamflow relationship during the drought is statistically different from the pre-drought rainfall-streamflow relationship. A difference in the relationship indicates that streamflow has been lower or higher than expected based on annual rainfall alone. In the case of lower streamflow, some of the subsidiary features of the drought (such as increased temperatures, increased potential evapotranspiration, changes to the seasonal distribution of annual rainfall, surface water/groundwater interactions, changes to land use, etc.) may thus be hydrologically important.

Simple functional relationships between annual rainfall and evapotranspiration have long been recognised. (e.g. Budyko, 1974; Arora, 2002). One drawback of many of the traditional rainfall-streamflow relationships based on Budyko's curve is that in most cases statistical tests on the curve parameters are difficult to perform. For this reason, we consider a linear regression between annual rainfall and Box-Cox transformed annual streamflow data (see Figure 1). The Box-Cox transform is given by

$$\hat{Q}_i = \begin{cases} \left(Q_i^{\lambda} - 1\right)/\lambda, & \lambda \neq 0 \\ \ln \lambda, & \lambda = 0 \end{cases} \tag{1}$$

Optimising the parameter using a maximum likelihood procedure (see e.g. Myers, 1990) allows for a linear relationship between annual rainfall and streamflow (for Box-Cox parameter λ=1) in higher rainfall catchments, and non-linear relationships (Box-Cox parameter close to zero) for lower rainfall catchments. Specifically, we consider the following linear model:

$$\hat{Q}_i = \alpha_{\text{pre}-97}.I_{\text{pre}-97} + \alpha_{\text{post}-97}.I_{\text{post}-97} + \beta.P_i + \varepsilon_i \tag{2}$$

where $\hat{Q}_i$ is transformed annual streamflow, $I_{\text{pre}-97}$ and $I_{\text{post}-97}$ are pre-1997 and post-1997 indicator variables, and P_i is annual rainfall. An F-test can be used to test the null hypothesis that the intercepts are equal:

$$H_0 : \alpha_{\text{pre}-97} - \alpha_{\text{post}-97} = 0 \tag{3}$$

We found that 22 catchments had significantly different rainfall/streamflow relationships during the drought compared to the pre-drought time period (Table 1). All of these had lower streamflow for a given annual rainfall (as in Figure 1). Thus, observed annual streamflow in these catchments was significantly lower than expected based on the annual rainfall and the long-term relationship between rainfall and streamflow.

2.3. Changes in the rainfall/maximum temperature relationship

At monthly and annual timescales in SEA, rainfall and average daily maximum temperature are generally inversely related (i.e. high temperatures are associated with low rainfall and vice versa) (Nicholls, 2004). Data analysis has revealed a trend for higher annually averaged maximum temperatures for a given mean annual rainfall in SEA (Nicholls, 2004; Cai and Cowan, 2008b). Here we test whether the rainfall-maximum temperature relationship is significantly different during the drought for the selected catchments in SEA.

Table 1: Number of catchments with significantly different rainfall/streamflow relationships and rainfall/Tmax relationships.

		rainfall vs. streamflow		
		significantly different	not significantly different	
rainfall vs. Tmax	significantly different	13	5	18
	not significantly different	9	7	16
		22	12	34

In contrast to the annual rainfall-streamflow relationships described above, the relationship between annual rainfall and annual average maximum temperature is typically linear (see Figure 2). Thus the Box-Cox transform is not needed for the temperature data. We consider the following linear model:

$$T_{\max,i} = \alpha_{\text{pre}-97}.I_{\text{pre}-97} + \alpha_{\text{post}-97}.I_{\text{post}-97} + \beta.P_i + \varepsilon_i \tag{4}$$

where $T_{\max,i}$ is annually averaged daily maximum temperatures, with the null hypothesis given again by equation (3) to determine whether the intercepts differ significantly before and during the drought. Out of the 34 catchments, 18 were found to have significantly different rainfall/Tmax relationships (Table 1) during the drought compared to the pre-drought time period. In these catchments, residual maximum temperature has thus been significantly higher during the drought.

Spatially, the catchments with significantly different rainfall/streamflow relationships are primarily located around the southern Murray-Darling Basin, while the catchments with significantly different rainfall/Tmax relationships are more uniformly spread across the study region. Although the majority of catchments have significantly different rainfall/streamflow relationships and significantly different rainfall/Tmax relationships, there are several with only one significantly different relationship (Table 1).

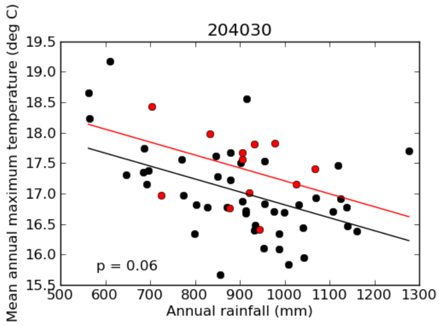

Figure 2: Relationship between annual rainfall and mean annual maximum temperature. Red points and line are for 1997−2008 data; black points and line are for pre-1997 data.

The chi-squared test statistic for independence of rows and columns of Table 1 is 0.95, which is much less than the 5% critical value of 3.84. This means that the incidence of different rainfall/streamflow and different rainfall/Tmax relationships can be considered statistically independent. Or, equivalently, the proportion of catchments with lower streamflow during the drought does not appear to be greater in the group of catchments with significantly increased temperature. This suggests that other features of the drought, such as reduced rainfall in winter and reduced interannual rainfall variability have a greater effect on runoff than increased temperatures (Potter and Chiew, 2009, 2011).

3. SENSITIVITY OF ANNUAL STREAMFLOW TO ANNUAL RAINFALL AND MAXIMUM TEMPERATURE

There are several approaches to estimating the sensitivity of streamflow to rainfall. One approach is to use calibrated rainfall-runoff or process-based models to directly measure the sensitivity of streamflow to changes in rainfall and temperature (Chiew, 2006; Potter and Chiew, 2009, 2011). Alternatively, sensitivities can be calculated analytically from semi-empirical relationships such as those based on Budyko’s (1974) curve described above (e.g. Arora, 2002). These approaches however rely on model assumptions. Data-based approaches, either parametric (e.g. Vogel et al., 1999) or non-parametric (e.g. Sankarasubramanian et al., 2001) allow for estimation of streamflow sensitivity without the need for model assumptions.

The effect on streamflow of changes in maximum temperature is less easily estimated. This is because there is considerable correlation between rainfall and temperature (Figure 2), and any effect from residual temperature is generally much less apparent than the direct effect of changes in rainfall. Here we follow the approach of Vogel et al. (1999) and estimate the rainfall and temperature elasticities of streamflow using a multiple regression approach. Regression is ideally suited to this problem as any correlation between annual rainfall and annual average air temperature is incorporated into the parameter estimation procedure.

In semi-arid catchments, the relationship between annual rainfall and streamflow can be far from linear (e.g. Figure 1). Fitting a linear regression without first transforming streamflow in these catchments can result in negative predicted streamflow. Thus in low rainfall years, streamflow predicted from rainfall alone will be much smaller than observed streamflow, resulting in a large residual. But in low rainfall years, the temperature anomaly is typically large and so data from these years will exert a large and erroneous influence on the estimate of temperature elasticity of streamflow. As such, we regress rainfall and temperature anomalies against transformed streamflow. In this way, streamflow residuals during low rainfall years are constrained. We fit the linear model on pre-1997 data only:

$$\hat{Q}_i = \hat{\eta}_P \delta P_i + \hat{\eta}_T \Delta T_{\max,i} + \varepsilon_i \tag{5}$$

where $\hat{Q}_i$ is annual streamflow transformed using equation (1), $\delta P_i = \left(P_i - \overline{P}\right)/\overline{P}$ is the relative difference in annual rainfall and $\Delta T_{\max,i} = T_{\max,i} - \overline{T_{\max}}$ is the annual maximum temperature anomaly. The regression coefficients $\hat{\eta}_P$ and $\hat{\eta}_T$ can be interpreted as the sensitivity of transformed streamflow to changes in annual rainfall and maximum temperature, with the other variable held constant. However, these estimates are not directly usable as they relate to transformed streamflow.

To obtain estimates of the rainfall and temperature elasticities of un-transformed streamflow, we first calculate the expected value of un-transformed streamflow for average rainfall and average annual temperature:

$$E\left(Q_i \mid \delta P_i = 0, \Delta T_{\max,i}\right) \tag{6}$$

$$E\left(Q_i \mid \delta P_i, \Delta T_{\max,i} = 0\right) \tag{7}$$

To ensure that these estimates from the inverse Box-Cox transform are unbiased (Miller (1984) discusses this problem), we use the plug-in density method (see Collins, 1991). Then we define the rainfall elasticity of streamflow η_P as the least-squares slope between δP_i and $\delta Q_i - E\left(Q_i \mid \delta P_i = 0, \Delta T_{\max,i}\right)$, and the temperature elasticity of streamflow η_T as the least-squares slope between $\Delta T_{\max,i}$ and $\delta Q_i - E\left(Q_i \mid \delta P_i, \Delta T_{\max,i} = 0\right)$. Note that if the streamflow data were not transformed initially (or equivalently if the Box-Cox transform parameter λ=1), then $\hat{\eta}_P = \eta_P$ and $\hat{\eta}_T = \eta_T$. As before, η_P and η_T can be interpreted as the sensitivity of annual streamflow to changes in annual rainfall and maximum temperature, with the other variable held constant. As such η_T is the effect of residual temperature (i.e. after any related effect from changes in rainfall has been removed).

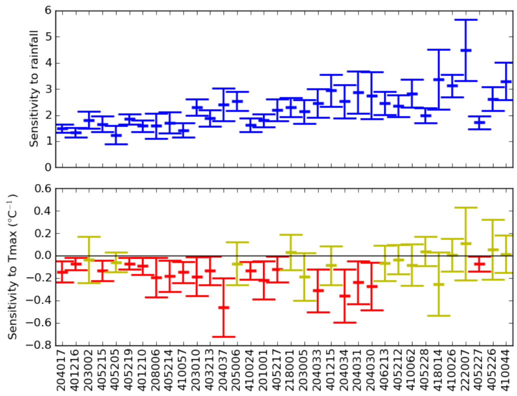

Figure 3: rainfall and temperature elasticities of streamflow (η_P and η_T). Mustard coloured ranges for η_T contain zero and are thus not statistically significant. Catchments are ordered by increasing dryness index.

The calculated rainfall elasticities of streamflow are shown in Figure 3. The catchments are ordered by increasing dryness index. Most of the rainfall elasticities lie within the range of about 1.5 to 3.0, meaning that a 10% decrease in annual rainfall leads on average to a 15%–30% reduction in annual streamflow, which is consistent with other estimates in SEA (Chiew, 2006; Potter et al., 2008). As the estimates are least-squares regression estimates, confidence intervals for these elasticities are straight-forward to calculate, and 95% confidence intervals are shown as well. The less arid catchments tend to have smaller rainfall elasticities. The uncertainty is generally larger for larger values of the rainfall elasticity. This is principally due to the greater year-to-year variability of streamflow in these catchments. Nevertheless, all values of η_P are statistically significant.

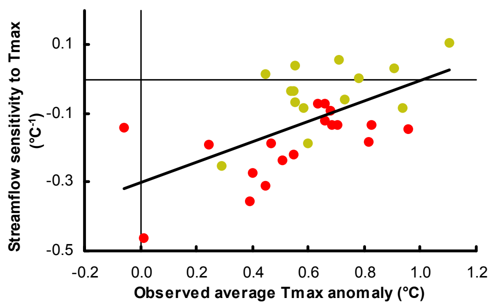

Figure 4: Relationship between streamflow sensitivity to Tmax and average Tmax anomaly during the drought (1997–2008 data compared to pre-1997 data).

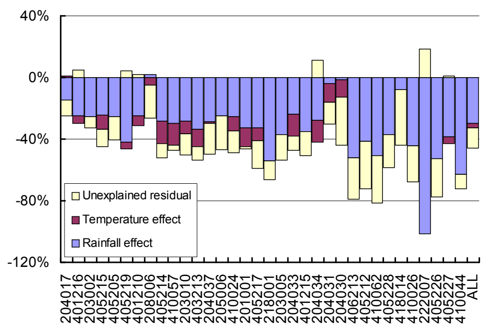

Figure 5: Proportion of observed streamflow reduction explained by streamflow sensitivity factors.

Similarly, the less arid the catchment, the smaller (in absolute value) is the temperature elasticity. However, for more arid catchments, the temperature elasticity generally becomes insignificant (mustard-coloured confidence intervals in Figure 3). This is because runoff in water limited (arid) catchments is principally determined by the availability of rainfall and so temperature and potential evaporation thus play a less significant role. Also, the greater year-to-year variability of streamflow in these catchments makes the detection of any effect from temperature more difficult to detect in the data. The temperature elasticity of streamflow is not statistically significant in 15 of the 34 catchments. The mean of all of the statistically significant values of η_T is $-0.19°C^{-1}$. However, more negative values of η_T are located in those catchments that have seen the least increase in average Tmax during the drought (Figure 4).

Note that since the elasticities are calculated on pre-1997 data only, the observed temperature anomalies during the drought can not have influenced the elasticities directly. It is unclear whether the heterogeneity of temperature increases is climatically based. Presumably, differences in regional evaporation between catchments could be linked to different energy budgets. In catchments with average Tmax anomalies greater than 0.6ºC, the mean of significant η_T is only −0.12°C^{-1}.

Care must be taken in interpreting these temperature elasticities. At face value, η_T measures the expected percentage reduction in streamflow for a one degree increase in Tmax. However, this should not be interpreted as a direct effect of increasing potential evaporation. For example, the trend during the second half of the twentieth century for decreasing autumn and winter rainfall in south-eastern Australia (Cai and Cowan, 2008a; Kiem and Verdon-Kidd, 2010; Potter et al., 2010) due to increasing CO_2 (Frederiksen et al., 2011) has occurred at the same time as increasing air temperatures. Any such effect that is correlated with positive temperature anomalies, even if it is not caused directly by temperatures, will be included in the temperature sensitivities estimated using the regression method used in this study.

Next, we compare the reduction in streamflow during 1997−2008 to the long-term pre-drought mean for each catchment. Multiplying the elasticities by the observed average rainfall and Tmax anomalies for each catchment yields estimates of the proportion of the observed streamflow reduction explained by differences in rainfall and Tmax during the drought (Figure 5). Here, a temperature effect is only included if the temperature elasticity η_T is statistically significant. Averaged over all catchments, weighted by the catchment area, we obtain estimates for the rainfall and Tmax effect on streamflow for all catchments, those in the MDB, and those in the NE coastal strip of NSW (Table 2). The effect on streamflow of an average increase in maximum temperature of 0.61ºC during the drought works out remarkably consistent in the two regions at a 3% reduction from the long-term mean of streamflow (or 7% of the observed reduction). Assuming that the relative size of the changes in temperatures seen during the drought (Figure 4) are maintained, we estimate that a 1ºC increase in maximum temperatures results in a 5% reduction in streamflow.

Table 2: Estimate of the effect of the observed reduction in rainfall, and the observed increase in maximum temperatures during the recent drought (1997−2008). The first percentages show reductions from the long-term mean; the bracketed percentages are the proportion of the observed reduction in streamflow

	Rainfall effect	Tmax effect	Residual	Total
Outside MDB	-23% (55%)	-3% (7%)	-16% (38%)	-42%
MDB	-34% (69%)	-3% (7%)	-11% (24%)	-48%
All	-30% (65%)	-3% (7%)	-13% (28%)	-46%

4. CONCLUSIONS

We examined the annual rainfall-temperature-streamflow relationships in 34 largely unregulated catchments in SEA. Approximately two-thirds of the catchments showed evidence of significantly lower streamflow for the same annual rainfall, whereas a little over half of the catchments had significantly increased residual Tmax. However, the spatial and statistical coherence between significant test results was low, suggesting that other features of the Millennium drought are important in reducing streamflow in SEA.

We developed regression-based estimates of the sensitivity of annual streamflow to annual rainfall and Tmax anomalies. More arid catchments generally have both larger rainfall and temperature elasticities as well as larger uncertainties in these estimates. The mean of the significant temperature elasticities of streamflow is −0.19°C^{-1}. However, the catchments with larger average annual Tmax anomalies during the drought tend to have smaller (absolute) values of temperature elasticity. In those catchments with average Tmax anomalies during the drought greater than 0.6ºC, the mean of significant η_T is only −0.12°C^{-1}. By multiplying the observed mean annual rainfall and Tmax anomalies by the elasticities, we estimated that approximately two-thirds of the observed area-weighted reduction in annual streamflow during the drought is explained by the observed reduction in annual rainfall during the drought, and 7% is explained by the increase in annually averaged maximum temperatures. We examine other processes responsible for the residual elsewhere (Petheram et al., 2011).

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