THE IMPACT OF FARM DAMS ON STREAMFLOWS IN THE MARNE RIVER CATCHMENT

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ABSTRACT

This paper examines historic evidence for the impact of farm dams on streamflows in the Marne River catchment, located in South Australia. The investigation is comprised of two components: first, the assessment of the statistical significance of trends in streamflows independent of climatic variation, and secondly, the use of a simulation model to determine what proportion of the assessed trend is due to the impact of farm dams. The results obtained indicate that the nature and magnitude of trends estimated by the two largely independent methods is entirely consistent with the documented changes in farm dam development. There would appear to be a direct correspondence between the volume of farm dam development and the decrease in streamflow yield, i.e. for every 1 ML of farm dam development there would appear to be a corresponding decrease of 1 ML in streamflows.

KEYWORDS

Farm dams, impacts, catchment yield, trend analysis, water balance modelling, Marne River.

INTRODUCTION

Whilst there is considerable anecdotal evidence that farm dams do impact upon streamflows, there are very few published studies that have accurately quantified the nature and magnitude of the impacts. The primary reason for this general lack of concrete evidence is that there are few catchments with good streamflow records that are concurrent with a period of appreciable farm dam development. Streamflow records generally relate to periods over which the changes in farm dam development are negligible compared to the magnitude of mean (or even low) flows in the catchment. Thus, the impacts due to farm dams are usually hidden by the natural “noise” of climate-induced streamflow variability. It should be stressed that this general lack of evidence is not so much due to the uncertainty regarding the impact of farm dams, but is rather due to the difficulties of obtaining suitable historical information to analyse.

This paper examines historic evidence for the impact of farm dams on streamflows in the Marne River catchment, located in South Australia. This catchment was selected because the available evidence indicated that there has been significant farm dam development over the period of available streamflow records. Importantly, information was also available on the nature of farm dam development.

SITE DESCRIPTION

The Marne River is located in the Mount Lofty Ranges, about 80 km north-east of Adelaide. Information on streamflows is available for a gauging site located on the Marne River approximately 5 km west of Cambrai (GS 426529). The catchment area upstream of this gauge is 238 km^2.

The Marne River flows in an easterly direction from the ranges across the Lower Murray floodplain, and joins the River Murray approximately 30 km downstream of Swan Reach. Annual rainfall varies significantly across the catchment from a high of 775 mm in the west to a low of 350 mm in the east near Cambrai. This rainfall gradient reflects variations in topography, as the western headwaters of the catchment are at an elevation of around 500 m AHD, falling away to the east to a low of 110 m AHD. This difference in elevation occurs over a main stream length of 37 km, and thus represents a total gradient of approximately 1 in 100. More information on the site can be found in Good (1992).

The hydrology of the catchment is markedly seasonal, with 60% of the annual flows occurring on average in the winter months, and less than 0.2% in the summer months. The streamflows are highly variable, and the river ceases to flow around 10% of the time. Central tendency statistics describing monthly flows within the catchment are provided in Table 1.

Table 1. Descriptive statistics for monthly streamflows.

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Minimum	0.0	0.0	0.0	0.0	1.7	0.0	0.0	20.8	2.1	1.9	1.4	1.1	80.4
Maximum	7.4	14.5	135.5	338.8	3191.5	2037.0	8609.9	13708.8	3540.0	7046.9	477.5	47.3	29331.1
Average	1.5	1.7	9.6	29.8	226.9	257.4	1426.1	2278.0	1370.4	1134.5	98.9	7.7	6845.1
Std Dev	1.7	3.4	32.5	81.7	794.3	542.9	2696.2	3450.4	1215.8	1942.9	154.4	12.7	8469.3
Cv	1.11	2.08	3.39	2.74	3.50	2.11	1.89	1.51	0.89	1.71	1.56	1.64	1.24
Skewness	2.70	3.72	4.11	3.81	3.94	2.80	2.18	2.76	0.49	2.39	1.68	2.58	2.06
AutoCorr.	-0.02	0.12	-0.03	-0.11	-0.06	-0.08	-0.01	-0.22	0.01	0.19	0.20	0.00	-0.04

DATA PREPARATION

Hydroclimatic Data

Both rainfall and streamflow data was obtained from the Department of Environment, Heritage, and Aboriginal Affairs (South Australia). Monthly streamflow data was obtained for the Marne River gauge located at Cambrai (GS 426529). The available length of record for the site extends from January 1973 to April 1989, a period of just over 16 years. Monthly rainfall information consisted of the arithmetic mean of four rainfall stations located in or near to the catchment. These sites were Black Hill (024502), Kongolia (024513), Sanderstone (024529), and Keyneton (023725). A simple arithmetic mean was considered sufficient as the focus of interest is on capturing the inter-annual variability of rainfall rather than its absolute magnitude. While theoretically only one rainfall station is required to characterise climatic variability, in practice it is preferable to combine data from a number of sites to ensure that the time series used is reasonably stationary and free from the effects of systematic errors that can arise with single-station records. The mean monthly rainfalls relevant to the arithmetic mean are provided in Table 2.

The seasonal distributions of monthly evaporation and irrigation demands required for the simulation modelling are listed in Table 2. The evaporation figures were obtained from pan evaporation data from Nildottie (024564), and the irrigation demand pattern was assumed to be the same as for the nearby region of Mypolonga.

Table 2. Rainfall, Evaporation and Irrigation Demands

Month	Rainfall (mm)	Evaporation (mm)	Irrigation Demand (% of total)
January	21.4	243.0	12.9
February	15.2	188.9	11.7
March	20.3	153.2	10.4
April	26.4	92.9	8.6
May	37.8	56.4	5.8
June	29.2	37.7	3.9
July	41.7	46.1	3.5
August	42.3	66.0	5.1
September	39.4	97.2	6.6
October	46.9	134.3	8.7
November	24.8	188.9	11.0
December	17.3	229.0	11.9
Annual	363	1534	100

Catchment Development

Detailed information on catchment development is provided by Good (1992). He reports that urban development within the catchment is generally scattered, or of such a density as to not have any measurable effects on streamflow (Good, 1992). The catchment was subject to large-scale clearing of native vegetation before streamflow records began. While it is not clear whether this clearing has impacted on groundwater levels, Good concludes that the major impact on streamflows over the period of available record is likely to be due solely to farm dams.

Information was collected on the extent of farm dam development three times over the period of available streamflow record (Good, 1992). For the sixteen years between 1973 and 1989, Good reports a near uniform increase in farm dam development of around 800 ML (from approximately 700 ML in 1973 to 1500 ML in 1989); this represents an increase of 47 ML/year. While this degree of development is small (less than 1%) relative to the mean annual flow, it is very appreciable when compared to the mean summer flows of 3.6 ML/month.

The frequency distribution of farm dams by storage size was estimated by McMurray (1996) and clearly indicated that the majority (over 94%) of individual farm dams are less than 5 ML, though there is a trend towards larger dams.

METHODOLOGY

Background

One of the major problems with identifying the impacts of farm dams on streamflows is that it is necessary to separate out the changes due to natural variations in climate as opposed to those attributable to catchment activities. Ideally, the parameters of the rainfall-runoff model should be determined jointly with a function that explains their variation with increasing farm dam development. Fitting time-dependent parameters is feasible with simple rainfall-runoff models, but at present there are a number of technical problems associated with identifying time-dependent parameter values for more complex models. The use of more complex models is often required, however, to adequately simulate the rainfall-runoff process, especially in semi-arid regions.

The selection of a suitable modelling approach thus represents the trade-off between the need to increase model complexity so as to adequately simulate the rainfall-runoff process, and the desire to use as simple a model as possible to facilitate the fitting of time-dependent parameters. Unfortunately, in many catchments the degree of model complexity required to simulate the soil-moisture accounting processes of streamflow generation is too great to allow the joint fitting of time-dependent parameters.

While it is possible to formulate a rainfall-runoff model that explicitly incorporates the influence of farm dams, such an approach would add even greater complexity to the identification of parameter values, and hence further confound attempts at identifying trends.

Overall Approach

The methodology used here to identify the impact of farm dams consists of two major components:

- a statistical trend analysis of streamflows in which the exogenous influence of climate is removed; and,
- the application of a simulation model to determine the proportion of the identified trend that is attributable to farm dam development.

The first component addresses the problem of jointly fitting a simple rainfall-runoff model with time-varying parameters, and the second specifically address the issue of farm dam development.

Trend Analysis

The basis of the approach used to remove the influence of climate from the detection of trends in streamflows was to jointly fit a simple rainfall-runoff model with a time-dependent function of yield response. The simple model used to estimate streamflows (Q) from rainfall (R) can be stated as:

$$log(Q) = \beta_0 + \beta_1 S\{log(R\ );3\} + \beta_2\ sin(2\pi i/12) + \beta_3\ cos(2\pi i/12) + AR1(\varepsilon) \qquad (1)$$

where $S\{log(R\ );3\}$ represents the use of a spline function with three degrees of freedom to relate log-transformed monthly rainfalls to log-transformed values of streamflow. The *sin* and *cos* terms represent the seasonality of streamflow variation, and the *AR1* term is an autoregressive function that represents the influence of streamflow in the preceding month on the streamflow of the current month. The β_n terms represent model coefficients that require fitting by calibration to observed rainfall and streamflow data.

Allowance for time variation in the yield response is provided by adding a further term related to the month of simulation. In the approach adopted here, a spline function with two degrees of freedom is used to relate the month of simulation to changes in flow. The joint model can thus be stated as:

$$log(Q) = \beta_0 + \beta_1 S\{log(\ R\ );3\} + \beta_2\ sin(2\pi i/12) + \beta_3\ cos(2\pi i/12) + \beta_4\ S\{t;2\} + AR1(\varepsilon) \qquad (2)$$

where β_4 is a further coefficient that requires fitting.

The above model is an example of a Generalised Additive Model (GAM) based on smoothing splines. Further explanation on the use of smoothing splines in GAMs can be found in Hastie and Tibshirani (1990).

Once the model parameters have been fitted by least squares, the statistical significance of any one component can be assessed in the same manner as used in traditional multiple linear regression analysis. To ensure that the statistical inferences are valid, it is necessary to ensure that the resulting error terms are (i) independent, (ii) have constant variance, and (iii) are normally distributed. To this end, it is necessary to inspect a range of diagnostic criteria to ensure that the necessary assumptions are satisfied. Where necessary, transformations are applied to the variates and additional corrective terms may sometimes be included. Further details on the use of GAMs to identify trends in hydrologic time series data can be found in Nathan et al. (1999).

Farm Dam Simulation

The likely influence of farm dams on streamflows was assessed using TEDI, which is an acronym for Tool for the Estimation of Dam Impacts. This is a computer-based model that was recently developed by Sinclair Knight Merz for the Murray Darling Basin Commission (ICAM/SKM, 1999).

The model explicitly simulates the water balance components of individual farm dams in a catchment. TEDI does not model the influence of farm dams in a spatially explicit manner, rather it undertakes the water balance computations for a specified number of farm dams, whose sizes are selected stochastically from the known distribution of farm dam sizes in the catchment. A detailed description of TEDI may be found in ICAM/SKM (1999).

In order to assess the impact of the progressive development of farm dams, the TEDI model was applied to a de-trended data series based on the observed flow record. The overall sequence of steps was to:

(i) determine the nature and magnitude of trend in the observed data series using the GAM approach;

(ii) apply the opposite of the trend derived from step (i) to the observed streamflow series to obtain a stationary time series of streamflows;

(iii) apply the TEDI model to the de-trended observed data from step (ii) to derive a synthetic time series of streamflows that incorporates the impacts of the known increase in farm dam development;

(iv) determine the nature and magnitude of trend in the synthetic streamflows output from TEDI (step iii) and compare to the trends found in the observed data (step i).

RESULTS

Trend Analysis Results

The GAM model as specified by Equation (2) was applied to the concurrent monthly time series of streamflows and averaged catchment rainfall. All terms used in the model were found to be highly significant (at the 5% level). Thus, rainfall, seasonality, serial correlation, and importantly time, were found to be highly significant in explaining variations in streamflow.

The overall quality of the GAM model fit is illustrated in Figure 1. It is seen that the overall fit of the GAM model (thin solid line) reproduces the observed streamflows (solid symbols) reasonably well, especially considering the simplicity of the model used. There is perhaps some tendency to underestimate both high and low flows, but the nature of this bias is not expected to influence the results. The time component of the trend is illustrated by the thick solid line. It is seen that the streamflows tend to decrease gradually throughout the period, though the rate of decrease reduces slightly from 1978 on.

The average linear trend in streamflows is a decrease of around 44 ML/year, which equates to around 0.6% of the mean annual flow. Although small in magnitude, this trend is statistically highly significant (at the 5% level).

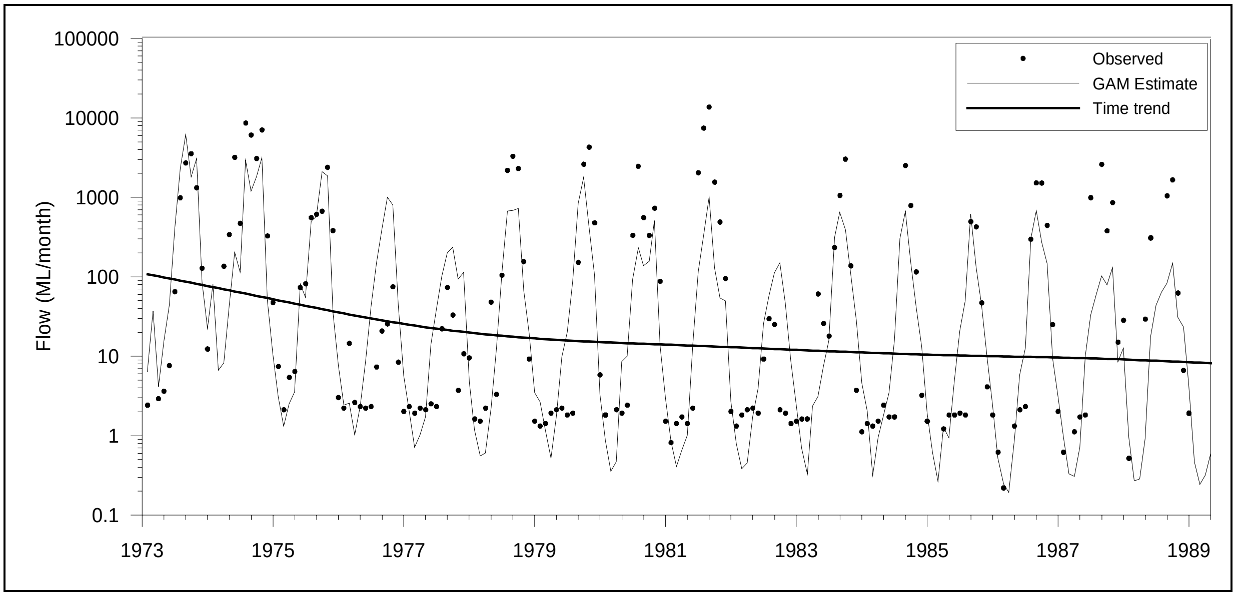

Figure 1: GAM fit to all monthly streamflows at Cambrai Stream gauging station.

In order to assess whether this trend is evident in the low flow regime, the GAM model was fitted to only those flows that were below half the median monthly flow (ie below 13 ML/month). For the purposes of brevity, these results are not shown in this paper, however the GAM model reproduced the observed streamflows reasonably well. The low flows tended to decrease gradually throughout the period, though again the rate of decrease reduced slightly from 1978 on. The average linear trend in the low flow regime was a decrease of around 2.9 ML/year, which equates to around 10% of the mean monthly low flow (based on an upper limit of 13 ML/month). Again, it is important to note that this trend is statistically highly significant (at the 5% level).

Simulation Modelling Results

In order to assess the proportion of the trend detected using the GAM approach that could be attributed to farm dams, the computer model TEDI was used to estimate the impact of the progressive development in farm dams. The de-trended observed streamflows were input into the TEDI model and a time series of synthetic flows reflecting the farm dam development was then subjected to a similar trend analysis as the observed flows. It was found that the trends in both the total and low flows from the synthetic time series are again highly significant (at the 5% level). The trend obtained for the total synthetic flows was found to be a decrease of 48 ML/year (shown in Figure 2), and that for the low flow range was found to be a decrease of 2.8 ML/year (not shown).

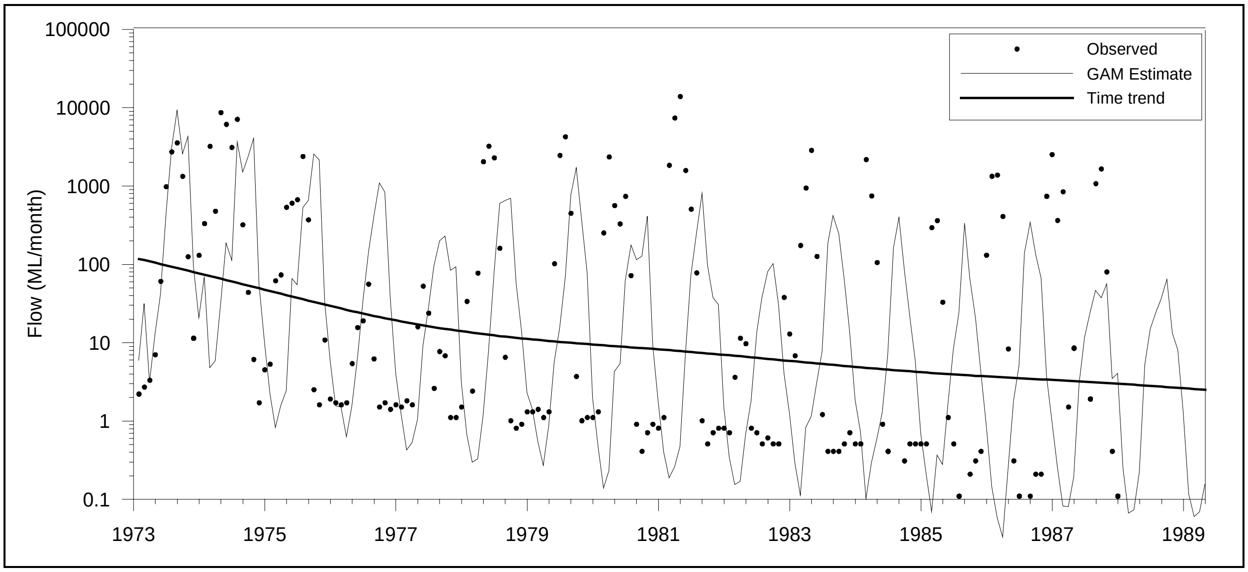

Figure 2: GAM fit to total synthetic streamflows derived from TEDI.

DISCUSSION

The most noticeable outcome of the results is the high degree of consistency between the estimated and observed trends. The documented average increase in farm dam development over the period of available streamflow record is 47 ML/year. The trend analysis of the observed streamflow data undertaken using the GAM model indicated an average decrease in annual streamflow volumes of 44 ML/year. Another completely independent analysis based on the water balance simulation of farm dam development yielded a decrease in total streamflows of 48 ML/year. All estimated trends were statistically highly significant, despite representing less than 1% of the mean annual flow.

While the level of agreement between the different sets of results gives provides good cross-validation of the analyses used, the degree to which the estimated trends mirror the documented changes in farm dam development is surprising. The results indicate that there is a direct correspondence between the volume of farm dam development and the decrease in streamflow yield, ie for every 1 ML of farm dam development there would appear to be a corresponding decrease of 1 ML in streamflows. The high level of agreement between the estimates should be regarded as partly fortuitous, and should not be interpreted as providing unequivocal evidence for the direct correspondence between farm dam development and streamflow reduction.

It is worth noting that the results reported by ICAM/SKM (1999) indicate that the impact of farm dams is clearly evident in catchments where the annual increase in farm development is greater than around 1.5% of the mean annual flow, whilst no statistically significant impacts were recorded in catchments where this increase was less than 0.3% of mean annual flow. This result in the Marne catchment, where the increase in farm dam development is approximately 0.6% of mean annual flow, indicates that catchments may be more sensitive to the impacts of farm dams than previously known. This statistically significant impact at a lower level of development may also be due to the pronounced seasonality of the streamflow regime in the Marne catchment; the volume of farm dams may be small compared to the mean annual flows, but they are sizeable compared to average summer flows. This marked seasonal impact is clearly evident in the trend analysis undertaken on low flows in the catchment.

In addition, the ICAM/SKM results indicate that the associated annual decrease in streamflows due to farm dam development is several times the rate of farm dam development. This amplification of response was assumed to be due to land use changes associated with farm dam development, an effect that does not seem to be apparent in the Marne River catchment.

CONCLUSIONS

The conclusions that can be drawn from this study can be summarised as follows:

- The trend analysis of observed streamflows indicates an average annual decrease of 44 ML/year; this trend is the result of changes in the relationship between rainfall and runoff, and is independent of any climatic trends.
- Water balance simulation indicates that the average annual decrease in streamflows can be wholly explained by the increase in farm dams and is not the result of associated land use changes.
- The nature and magnitude of trends estimated by two largely independent methods is entirely consistent with the documented changes in farm dam development; there would appear to be a direct correspondence between the volume of farm dam development and the decrease in streamflow yield, ie for every 1 ML of farm dam development there would appear to be a corresponding decrease of 1 ML in streamflows.
- The necessary information and conditions required to detect trends in historical streamflow records are generally not available; the results indicate that the use of a simulation approach based on water balance computations (ie TEDI) provides a robust alternative to techniques based on the analysis of historical evidence.

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