Development of a model for predicting the changes in flow duration curves due to altered land use conditions

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Abstract: Broad scale vegetation changes within a catchment are likely to lead to changes in water yield and flow regime. The Flow Duration Curve (FDC) represents the relationship between the magnitude and frequency of stream flow and provides a useful means for estimating changes in flow regime under altered land use conditions. The FDC for a catchment is dependent on the climate, soil, vegetation and other catchment characteristics. The ability to predict the change in FDC for a catchment undergoing land use change would provide a useful tool for water allocation and water quality management. This paper aims to develop a simple model for describing a catchment's FDC under current land use and assesses which of the model parameters change under altered land use conditions. Three potential models with different levels of complexity are considered. The three models have two common parameters, the proportion of zero flow days and the median discharge of the non-zero flow days. The models differ in the type of curve that is fitted to the normalised FDC when plotted in log-normal space. Data from forty seven paired catchment studies covering a wide range of climatic, vegetation and soil conditions were used to evaluate the ability of the models to describe the FDC. The results indicate that under altered land use conditions the major changes occur in the parameters common to all three models, while the most complex model provides the most accurate description of the FDC.

Keywords: *Paired catchment; Flow Duration Curve; Land use change*

1. INTRODUCTION

The impact of changes in vegetation type on flow regime can be depicted through the use of Flow Duration Curves (FDC). The FDC for a catchment provides a graphical and statistical summary of the streamflow variability at a given location, with the shape being determined by rainfall pattern, catchment size and the physiographic characteristics of the catchment. The shape of the flow duration curve is also influenced by water resources development and land use type (Smakhtin, 1999). The FDC (the cumulative distribution of the river flows) has been used widely as a measure of the flow regime as it provides an easy way of displaying the complete range of flows and how they would be changed under different land use scenarios.

FDCs can be constructed using different temporal scales of streamflow data: monthly or daily flows and depicted either using all the flows from all seasons (annual flow duration curve) or for a subset of flows (seasonal flow duration curve). One of the limitations of using FDC for a comparison of high and low flows under different vegetation types is that the relative distribution of high and low flows varies depending on whether a particular year is wet or dry. Therefore, where possible it is important to compare multiple years with a similar spread in meteorological conditions, to minimise the variations due to climate (Burt and Swank, 1992).

Various methods have been used to parameterize the FDC (Cigizoglu and Bayazit, 2000). These methods have generally been used to produce regionalised FDCs (Meunier, 2001; Fennessey and Vogel, 1990) or to predict the FDCs for ungauged catchments (Holmes et al. 2002). However, investigations into the changes in the FDC as a result of vegetation changes are limited. Burt and Swank (1992), used a regression model relating the percentile flow in the control and the treated basins during a seven year control period. This allowed the FDC for the treated catchment to be predicted using the FDC from the control catchment in the post treatment period and an assessment of change in FDC under alternate vegetation type to be made.

This paper aims to develop a simple model, based on the top down approach used by Zhang et al. (2001) for describing FDCs under different climatic and vegetation conditions. Paired catchment experiments have been used in this analysis as they provide a good source of information on the response of catchments to different land use conditions. The objectives of this paper are i) to determine the model that best describes the FDC for a range of climatic and vegetation conditions and ii) to investigate how the model parameters change as a result of alterations in vegetation. This paper does not investigate how the parameters of the model are related to catchment characteristics, but does provide a starting point for determining the changes in flow regime as a result of broad scale vegetation changes.

2. METHODOLOGY AND DATA

2.1. Model Description

Three different models have been developed for defining the FDC. The models differ in the complexity of the curve fitted to the normalised FDC (NFDC) when plotted in log normal space. Figure 1 depicts the three models considered for defining the FDC. Detailed descriptions of each of the models can be found in (1), (2) and (3).

Model 1 involves the fitting of a single linear curve to the NFDC, this results in a 3 parameter model as described in (1). Model 2, a four parameter model, involves fitting two linear curves, one to the upper section and one to the lower section of the NFDC, as described in (2). Model 3, a five parameter model, involves fitting an exponential curve to the upper and lower sections of the NFDC, as described in (3).

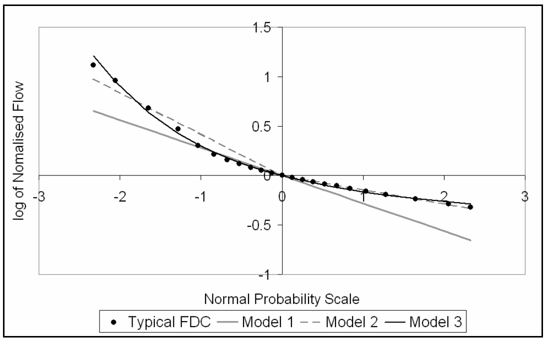

Figure 1: The three different model types for defining the FDC when normalised and plotted in log normal space. Model 1 – linear fit to entire FDC, Model 2 – two linear fits to upper and lower sections of FDC, Model 3 – exponential fits to upper and lower sections of FDC.

$$\hat{y} = \begin{cases} \left(10^{a\times F^{-1}\left(\frac{x}{CTF}\right)}\right) P_{50}, x \le CTF \\ 0, x \ge CTF \end{cases} \quad (1)$$

$$\hat{y} = \begin{cases} \left(10^{b_1\times F^{-1}\left(\frac{x}{CTF}\right)}\right) P_{50}, x \le \frac{CTF}{2} \\ \left(10^{b_2\times F^{-1}\left(\frac{x}{CTF}\right)}\right) P_{50}, \frac{CTF}{2} \le x \le CTF \\ 0, x \ge CTF \end{cases} \quad (2)$$

$$\hat{y} = \begin{cases} \left(10^{a/c_1 \times \exp\left(F^{-1}\left(\frac{x}{CTF}\right)c_1\right) - a/c_1}\right) P_{50}, x \le \frac{CTF}{2} \\ \left(10^{a/c_2 \times \exp\left(F^{-1}\left(\frac{x}{CTF}\right)c_2\right) - a/c_2}\right) P_{50}, \frac{CTF}{2} \le x \le CTF \\ 0, x \ge CTF \end{cases} \quad (3)$$

Where

$\hat{y}$ = predicted flow

F^{-1} = inverse of the standard normal cumulative distribution

P_{50} = median of the non-zero flow days

CTF = cease to flow point (expressed as a percentage)

x = probability value (0-100%)

a, b_1, b_2, c_1, c_2 are curve fitting parameters

Each of the models was fitted to the NFDC, using unconstrained nonlinear minimization (Nelder-Mead method), for each year of the daily data in the paired catchment experiments. This was done to allow the change in the model parameters with time to be investigated, as discussed in Section 2.3.

The three models have two parameters in common; the number of zero flow days and the median flow of the non-zero flow days (or the days when flow is greater than a specified threshold). The number of zero flow days can also be expressed as the probability at which the flow ceases or the cease to flow point (CTF). The CTF can be defined as the ratio of the number of non-zero flow days to the total number of days. In the determination of the zero flow days it was assumed that any flow less than 1% of the mean daily flow was zero.

The number of other parameters in each of the models depends on the curve fitted to the Normalised Flow Duration Curve (NFDC). The FDC was normalised by dividing all discharges by the median discharge of all non-zero flow days. This results in the log of the fiftieth percentile being equal to 0 for all NFDCs and when plotted in log normal space the NFDC will intersect the axis at origin.

To assess how well each of the models reproduced the FDC two criteria were used to determine the model performance. The first criterion was assessed by comparing the area under the sampled FDC to the area under the fitted FDC. The second criterion, assessed how well the model reproduced the discharges for each percentile, was assessed by determining the coefficient of efficiency (Legates and McCabe, 1999) for the predicted FDC. The coefficient of efficiency is defined as

$$E = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2} \qquad (4)$$

where O is the observed percentile, P is the predicted percentile $\overline{O}$ is the mean of the observed percentiles and N is the number of percentiles, 100 in this analysis.

2.2. Data

Paired catchment data from sixteen worldwide experimental catchment groups were used in the assessment of the model and the changes in parameter values with time. This yielded a set of 47 paired catchments that are briefly summarised in Table 1.

2.3. Change in model parameters as a result of land use change

In order to investigate how the model parameters changed with time the parameters for each of the model types were calculated for the FDC for each year of record for each of the paired catchment studies. The Mann-Kendall non-parametric test for trends was used on the different periods depending on the type of treatment. The paired catchments were divided into the four treatment types and the periods used to assess the change in parameters depend on the both the period of record and the treatment undertaken. Table 2 outlines how the record was divided in order to test for trends in the different treatment types. The Mann-Kendall test was used in this analysis as in many of the paired catchment studies a steady state is not reached under the new vegetation conditions and a test for change in the mean was not possible.

The same test period was used for the control catchment. The pre-treatment period was used for the control and the treated catchment, regardless of the actual length available so that the same meteorological conditions were being compared. This approach was adopted as it allows an investigation into the cause of the trend. For example if a trend in the median flow is due to a climatic shift then it would be expected that both the control and the treated catchment would show a significant and similar trend, while if the change is due to an alteration to vegetation then the trend will only be detected in the treated catchment.

Table 1: Summary of experimental catchment groups (Details and key references can be found in Best et al., 2002).

Experimental catchment group	Number of Treated catchments (number of control catchments)	Treatment Type
South Africa		
Cathedral Peak	2 (1)	A
Jonkershoek	5 (1)	A,D
Mokobulaan	2 (1)	A
Westfalia	1 (1)	A
Witlip	1 (1)	D
United Kingdom		
Plynlimon	1 (1)	A
New Zealand		
Glendhu	1 (1)	A
U.S.A		
H.J. Andrews	7 (3)	R
Coyote Creek	3 (1)	R
Fox Creek	2 (1)	R
Australia		
Collie Basin	3 (1)	D
Melbourne Water Catchments	12 (5)	R
Red Hill	1 (1)	A
Stewarts Creek	1 (1)	FC
Tantawangalo	2 (1)	R
Yambulla	3 (1)	R

A – Afforestation experiments, D – deforestation experiments, R – regrowth experiments and FC – forest conversion experiments.

Table 2: Period of record used to test for trends in change in water yield.

Type of Treatment	Type of Test used
Afforestation	Mann-Kendall from beginning of record to either end of record or clear felling of catchment
Deforestation	Mann-Kendall from beginning of record to end of record or replanting in the catchment.
Regrowth	Mann-Kendal from beginning of record to 5 years post treatment (increase in water yield anticipated due to reduction in vegetation). Mann-Kendall from the 1st year after treatment to end of record.
Forest Conversion	Mann-Kendal from beginning of record to 5 years post treatment (increase in water yield anticipated due to reduction in vegetation). Mann-Kendall from the 1st year after treatment to end of record.

3. RESULTS

3.1. Model Performance

As discussed in the methodology section, two measures were used to assess how well each of the models described the FDC. The first criterion is the ability of the model to replicate the annual flow volume (the area under the FDC). Figure 2 depicts box plots for each of the model showing the ratio of the predicted to the observed volume, for the Jonkershoek catchment group. Figure 3 shows the percentage of catchments where the predicted volume is within 1%, 5% and 10% of the actual volume, for each of the models.

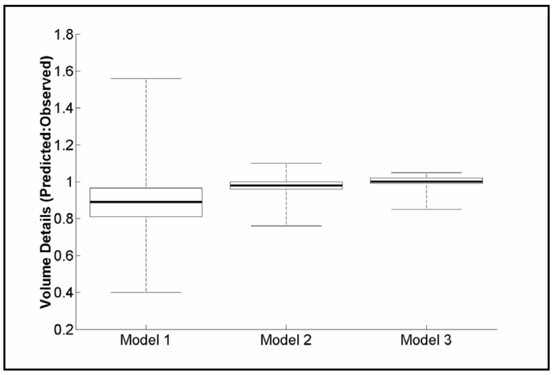

Figure 2: Volume comparison for all catchments in the Jonkershoek experimental group. The thick line represents the median, the box the 25th and 75th percentile and the whiskers the range.

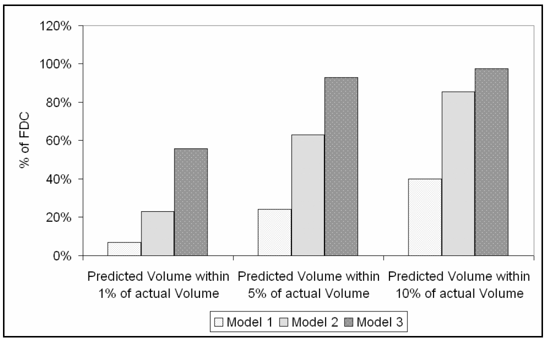

Figure 3: Volume comparison for all years for all catchments (total of 1838 FDC). Showing the % of catchments where the predicted volume is within 1%, 5% and 10% of actual volume.

The second measure used was the ability of the model to replicate the percentile values on the FDC. The coefficient of efficiency, (4), for the each of the FDC was calculated, these results are presented in Table 3. Figure 4 shows the typical spread in residuals (observed – predicted) for each of the model types for the Jonkershoek catchments in South Africa. Figure 4 shows that Model 1 gives a poor model fit for the extreme percentiles. This is supported by the coefficient of efficiency in Table 3, where Model 3 has an average coefficient of efficiency of 0.95, compared to 0.61 for Model 1.

Table 3: Average coefficient of efficiency for each catchment group.

Catchment Group	Model 1	Model 2	Model 3
Cathedral Peak	0.86	0.85	0.97
Jonkershoek	0.83	0.95	0.98
Mokobulaan	0.59	0.92	0.91
Westfalia	0.79	0.93	0.97
Witlip	0.82	0.88	0.97
Plynlimon	0.71	0.92	0.97
Glendhu	0.65	0.89	0.97
H.J. Andrews	0.10	0.90	0.91
Coyote Creek	0.62	0.80	0.96
Fox Creek	0.27	0.94	0.94
Collie Basin	0.50	0.86	0.97
Melbourne Water Catchments	0.79	0.94	0.96
Red Hill	0.56	0.90	0.95
Stewarts Creek	0.46	0.95	0.95
Tantawangalo	0.81	0.83	0.97
Yambulla	0.78	0.87	0.97
Average Coefficient of Efficiency	**0.61**	**0.90**	**0.95**

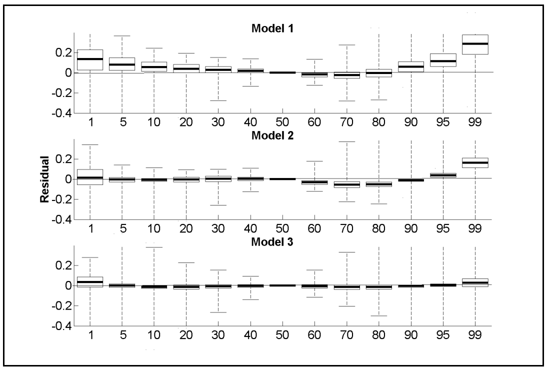

Figure 4: Spread in residuals for selected model percentiles for the Jonkershoek experimental group.

3.2. Impact of vegetation change on model parameters

The link between the model parameters and vegetation type is important for the prediction of changes in flow regime under altered vegetation conditions. Only the Model 3 results are presented here as Model 3 provides the best description of the FDC.

The Mann-Kendall test was used to test for significant trends in the control and treated catchments. As only the catchments with large areas of treatment are likely to show a trend the data set was reduced from 47 paired catchment studies to 22 paired catchment studies by selecting those catchments in which at least 50% of the catchment was treated.

Table 4: Results for the Mann-Kendall test for trend at the 0.05 level of significance. Values are the number of catchments showing a statistically significant trend in positive or negative direction.

	Treated Catchments										Control Catchments									
Treatment	Median		CTF		a		c_1		c_2		Median		CTF		a		c_1		c_2	
	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓
AF (13)		12		2	3		1	2	6	2					2					
DF (5)	4		2		1		1			3						2				
RG (13)[1]	3		1				1		1		2						2			
RG (16)[2]	3		1		2	1		1	2		2				1				3	
FC (1)[1]																				
FC (1)[2]				1																

AF – Afforestation experiments, DF – Deforestation experiments, RG – Regrowth experiments, FC – Forest Conversion experiments. Number in brackets indicates the number of experiments in each treatment type. ↑ indicates an increase in parameter value and ↓ indicates decrease in parameter value. [1]Tread in data from start of record to 5 years post treatment [2]Trend in data from first year post treatment to end of record.

Table 4 shows a summary of the result for the Model 3 parameters for the control and the treated catchments. A number of the afforestation catchments in South Africa have long treatment histories with more than one planting rotation. Where this was the case, the period of record was divided to allow trends to be detected during the first and second rotation. The clear felling of the catchment at the end of the first rotation was also considered to be a deforestation experiment.

4. DISCUSSION

The results presented in the Table 3 and Figure 3 show that Model 3 provides the best model fit for most situations in the majority of catchments. This is to be anticipated for two reasons, firstly, the additional parameters in Model 3 provide more degrees of freedom and secondly, the linear models will only fit log-normally distributed flows well, particularly for the upper and lower percentiles. However, as this analysis has only been carried out on small experimental catchments, it may be found that for larger catchments the flows are log normally distributed (Nathan and McMahon, 1992). In this case Model 1 or Model 2 would be appropriate. The decision to base the current analysis on small experimental catchments was to allow the investigation of the change in model parameters under altered vegetation conditions.

Table 4 shows the effect of vegetation on Model 3 parameters. Changes can occur in all parameters under altered vegetation conditions. However, the major alterations are in the Median flow parameter for perennial streams and in either or both of the median flow and the cease to flow (CTF) probability for intermittent streams or streams that become intermittent after vegetation change.

The long term change in water yield under alternate vegetation types can be estimated using the Zhang model (Zhang et al., 2001). The Zhang model is a simple two parameter model which can be used to estimate the mean annual evapotranspiration (ET). The estimated ET can be changed into a water yield estimate, by assuming that the mean annual water yield is equal to the mean annual rainfall minus the mean annual ET. The change in water yield predicted by the Zhang model could then be linked to the median of the non-zero flow days by an empirical relationship. It would be anticipated that this empirical relationship varies depending on the rainfall of the catchment. In high rainfall areas, all the change in water yield will be reflected as changes in the median of the non-zero flow days, as under forested conditions the flow remains perennial. In lower rainfall areas, it is possible that no change will occur in the median of the non-zero flow days and the change in water yield will be entirely reflected as a change in the CTF point.

Predicting the change in the CTF point under altered land use conditions is necessary for streams in low rainfall areas. However the CTF point is also dependent on the seasonality of rainfall and the geology of the catchment. Nathan and McMahon (1992) used the baseflow index as in indication of intermittent and perennial streams, with catchments with a baseflow index less then 0.3 being intermittent. It may therefore be possible to predict the change in baseflow index and relate this to the CTF point.

The controls over the, *a*, c_1 and c_2 parameters relate to different sections of the FDC, *a* being the slope at the origin of the NFDC and c_1 and c_2 being the exponents for the upper and lower percentiles. It is hypothesised that the response of the FDC to vegetation changes appears to occur in two ways depending on the rainfall. In high rainfall areas it is anticipated that all flow percentiles are reduced by equal amount, while for catchments in lower rainfall areas the higher percentiles (lower flows) are reduced by a greater proportion than the higher flows. In catchments with high rainfall it is hypothesised that the exponents will not change under altered land use conditions, however for lower rainfall areas it would be anticipated that the c_2 parameter will be altered as a result in changes to the low flow conditions.

The slope parameter (*a*) can potentially be linked to the ratio of the mean to median flow. If this is the case the empirical relationship that is determined for mean and median relationship could also be used to predict the slope. The upper exponent (c_1) is primarily going to be linked to rainfall and rainfall intensity, while the lower exponent (c_2) will relate to geology and the CTF point.

5. CONCLUSIONS

This paper shows that the five parameter model provides the best description of the FDC and that changes can be expected in some or all of the model parameters under vegetation change. The change in model parameters depends on the type of treatment and prevailing climatic conditions. The results also indicate that the major changes occur in the parameters relating to the median flow and the proportion of zero flow days.

In order for this approach to be used for the prediction of the FDC under changed vegetation conditions, the parameters would need to be linked to catchment characteristics and the anticipated change in water yield under the new vegetation type. The methodology outlined in this paper has the potential to be used for prediction of the FDC in ungauged catchments provided the parameters can be correlated to catchment characteristics. Analysis of such correlations is continuing.

6. ACKNOWLEDGEMENTS

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