The Impacts of Afforestation on Low Flows:Paired Catchment Data Revisited

J.J. Blight[1], M.B. Gush[2], D. Le Maitre[2], and G.P.W. Jewitt[1]

[1]School of Bioresources Engineering and Environmental Hydrology, University of Kwa-Zulu Natal, South Africa
[2] Environmentek, Council for Scientific and Industrial Research, South Africa

Abstract

Disruption of the hydrological regime caused by afforestation is well documented. Several sets of experimental catchments were set up in South Africa between 1935 and 1980 specifically to quantify such impacts. Data emanating from these experimental catchments have been used in several analyses, and have progressively directed the regulation of commercial forestry and its associated hydrological impacts in this country. Subsequent modelling efforts have sought to introduce improved accuracy by accounting for catchment- and species-specific variations in impacts. However, conventionally used one dimensional hydrological models which model soil moisture to limited depths have been shown to reproduce periods of low flow with limited accuracy. This is a considerable limitation since the evaluation of land use impacts on periods of low flow is particularly important in riverine and water resources management.

This paper presents a re-analysis of the data sets of several of the paired catchments, with focus on the low flow periods. Hydrological dynamics revealed by this analysis are to be used in future, improved modelling exercises.

Keywords: hydrological, impacts, afforestation, low flows

1 Introduction

As custodians of the National Water Resource of a water-scarce country with a history of discriminatory legislation, the South African Department of Water Affairs and Forestry (DWAF) recognises the importance of allocating water in a manner which “promotes equity, addresses poverty, generates economic growth, and creates jobs,” and which allows for ”sustainable use of water resources,” and promotes the “efficient and non-wasteful use of water.” Stream Flow Reduction Activities (SFRA’s) have been flagged as a priority water use for equitable re-allocation. (DWAF, 2005) Reliable quantification of SFRA’s, as well their associated potential to address poverty, economic growth, and sustainability should thus form a cornerstone in the implementation of equitable water allocation policy.

The impact of SFRA’s on low flows are of special significance in that it is during the dry period immediately prior to the rainy season that a reliable water supply is frequently most critical. Integration of predictive methods to assess the hydrological impact of SFRAs, particularly their impacts on low flows, into national water resources planning is thus crucial.

While forestry is by no means the only industry which may reduce stream flows, it is the only Stream Flow Reduction Activity (SFRA) which has been declared in terms of the National Water Act of 1998. (NWA) Ideally, in order to assess the sustainability of forestry as a water resource use, its impact on water resources, not only during the growing phase, but also throughout the lifecycle of the end-products should be considered.

2 Approaches to Quantification of Forestry Water Use

It is generally accepted that commercial forests decrease streamflow chiefly via the mechanisms which modify both stormflow and low-flow generating mechanisms viz:

- increased interception loss due to more extensive canopy cover, leaf area density and increased roughness of the surface;
- increased transpiration loss due to increased biomass and total leaf area, deep rooting and evergreen nature of commercial timber tree species;
- increased disturbance of the soil structure, infiltration and moisture holding capacity due to site preparation.

Methods of quantitatively assessing the hydrological impact of forestry (ie quantifying the impacts of the abovementioned factors)comprise three major classes:

- Paired catchment experiments and associated empirical models;
- Measurements of evapotranspirative losses and other components of the water balance;
- Mechanistic modelling

Modelling approaches are naturally somewhat dependent on experimental methods, since both mechanistic and empirical modelling rely on experimental data for parameterisation, calibration and validation. Approaches to measuring evapotranspirative losses and other elements of the water balance are many, none without criticism regards accuracy and reliability (eg Calder, 1990). Likewise, the paired catchment approach has been criticized widely (eg Hewlett 1971.)

3 Paired Catchment Data – Is it Worth Revisiting ?

The South African Paired catchments (described in Section 6 below,) have been criticized for being too small to yield results representative of catchment scale processes, as well as for being subject to groundwater "leaks". (Schulze, 2005) Indeed the validity and reliability of results of paired experimental catchments throughout the world have criticized for similar reasons. (eg Penman, 1963 cited by Hewlett, 1971) Criticisms of the paired catchment approach were examined by (Hewlett, 1971) who concluded that:

- Each catchment should contain at least a first order perennial stream, and the effect of the treatment should be anticipated to ensure that drying up of the stream does not confuse the analysis.
- Meterological and edaphic effects of treatments are sufficiently represented at scales of 10 to 20 ha or larger.
- Basins of the order of 100 ha are approaching the approaching the size of areas often used as watersheds for municipal and industrial water supplies. (Therefore data from experimental catchments of these sizes are applicable in practice, in some cases.)
- It is impractical to apply an experimental treatment uniformly over basins of 1000ha or more; and control is lost of some elements of the hydrologic cycle. (With modern advances in monitoring, this may no longer be such an important constraint.)
- Only groundwater leaks which form a substantial portion of the total water balance detract from the utility of the study.
- Comparative partial solutions of water balance are valuable management tools
- The ultimate model of the mass input-output relations of the drainage basin must rely on sophisticated understanding of hydrologic processes.(More sophisticated than, according to Hewlett, than was state-of-the-art in 1971.)

The South African paired catchments used in this study vary between 30 ha and 195 ha in size (See Table 1, Appended) Thus, according to the criteria cited above, these catchments should be sufficiently large for studying the hydrological effects of land-use change.

The South African Paired catchments have been criticized for the fact that none of them fall within zones of mean annual precipitation (MAP) less than 1000 mm, while less than 30% of all afforested land in South Africa in South Africa has an MAP of greater than 1000mm. (eg Gush et al, 2002.) Despite their situation in high rainfall areas, some of the streams (eg the Westafalia catchments) have dried out completely at stages during their history. For paired catchment streamflow data to be useful in areas of lower MAP, the size of the catchment would thus have to be considerably greater to ensure perennial flow, (unless streamflow data can be supplemented with data describing soil moisture status.)

The understanding of hydrological processes has probably become more sophisticated since Hewlett made his argument: Advances in the science of hydrology include those which have been made as a result of electronic innovation which enable parts of the hydrological cycle to be monitored continuously (and perhaps with a greater degree of accuracy.) Examples include:

- Continuous measurement of small heat and vapour fluxes, (from which evapotranspiration can be deduced,)
- Continuous, non destructive monitoring of soil moisture,
- Isotopic tracers to monitor groundwater water movement,
- Geophysical methods to map pedological and geological features

(Lorentz, 2005) proposes that the increase in understanding of hillslope hydrological processes has been a major factor in the recent development of hydrology. Although computing power is now such that these effects can be modelled, many hydrological models remain in the one-dimensional or quasi two dimensional domain (usually aligned with the longitudinal river section,) such that hillslope processes are not modelled.

It is contended that distribution of plant roots within the subsurface strata are a major factor which influence accurate modelling of evapotranspiration (Roberts, Kelbe, Schulze, 2005) This is however, an aspect in which hydrological understanding has perhaps not made great progress with respect to data collection. (Roberts, 2005)

4 Paired Catchments: Review of Prior Studies

Data from the South African paired catchments has been used in a number of studies including:

- (Nanni, 1970,) who derived an empirical relationship between annual runoff from indigeneously vegetated catchments, annual rainfall and annual decrease in runoff.
- (Van der Zel, 1990, cited by Gush et al, 2002) who bolstered the analysis with additional data from other parts of the world.
- (Scott and Smith, 1997) derived a set of curves expressing percentage reduction of either mean annual runoff, or low flows arising from plantations of increasing age. The effects of pines and eucalypts were examined; and optimal and suboptimal growing conditions were considered.
- (Scott et al, 2002) found that the empirical models emanating from their earlier study reproduced the form of reductions correctly, but the timing of the onset of reductions, and degree and timing of the peak reductions were not reliably calculated. This study also showed a diminishing effect of forestry on streamflow with time. The onset of the diminishing effect was found to be highly variable.
- (Brown et al, 2005) review studies carried out on 166 paired catchment experiments, including the South African pairs.. Their review includes the following categories of data analysis:
    - Studies dealing with changes in magnitude of mean annual runoff,
    - Studies of vegetative change response time
    - Thee “Zhang curves” which use mean annual rainfall and annual evapotranspiration to predict changes in water yield
    - Studies dealing with seasonal responses of catchments to land use change (including absolute and proportional responses)
    - Studies examining changes in quickflow and baseflow components under the influence of vegetative changes

  Brown et al propose that presenting the impact of vegetation by means of a flow duration curve is a useful graphical and statistical summary. This approach is alleged to have one major shortcoming: ie not enabling comparison between the effects of wet and dry years. Nonetheless, if a long hydrological record is available, this constraint will largely be taking care of as the record will contain wet and dry spells. Flow Duration Curves (FDC’s) for four sets of catchments subject to land use changes are presented. The authors conclude that while these results are useful for determining yield in small homogeneous catchments, methods are needed for scaling these results to larger catchments where the degree of homogeneity will invariably be lower.

  (Schulze, 2005,) however, observes that it is in general easier to model large catchments mechanistically than small ones. This is presumably due to the nature of parameterization of mechanistic models where uncertainties in one parameter tend to compensate for uncertainties in others (eg Sorooshian and Gupta, 1983)

- (Lane et al, 2005) used paired catchment data (including the South African experiments) to develop a regression model to predict the impact of afforestation on any given decile of the flow duration curve, assuming that the time series is principally a function of climate and vegetation characteristics, (including age of plantation.) The model predicted reduction in low flows well. The model was then used to account for changes in streamflow due to rainfall variability, thus predicting the effect of vegetative changes alone. This approach is dependent on calibration of individual catchments, so that results cannot easily be generalized to larger catchments.
- (Gush et al, 2002) carried out an extensive mechanistic modelling exercise of four sets of South African paired catchments, using ACRU Agrohydrological Model. This study found that the modelled results consistently overestimated the reduction of low flows. (This effect has been attributed (at least partly) to failure to employ the ACRU routine which allows for variable baseflow decay (Schulze, 2005.)) Another limitation of the study was that an “average” tree age was used so that the variability of impact of flow reduction through the growing cycle was not modelled.
- (Everson et al, 1998) applying the same model to a grassland catchment in the Cathedral Peak suite of experimental catchments found that in general, streamflow was underestimated by 15%, although estimates of evaporation by the model closely followed actual values measured using the Bowen Ratio technique. The discrepancy between measured and modeled streamflow was attributed to limitations in ability to account for subsurface soil water flow .

5 Re-Examining the Paired Catchment Data

On the basis of the arguments and evidence reviewed in sections 3 and 4 above it has been concluded that a revision to the mechanistic modelling approach used in ACRU may indeed yield a better estimate of mass input-output relations of afforested drainage basins at scales appropriate to management. The drawback of using the paired catchment data for this approach is however, that there is little data regarding components of the hydrological cycle. Re-analysis of the data in innovative ways may nonetheless produce insights which may lead t enhances modelling. The possibility of supplementing this long time series with data showing individual components of the hydrological cycle should perhaps be considered.

6 South African Paired Catchment Experiments: Location, History, Physical Attributes

The Jonkershoek Forest Hydrological Research Station was established in 1935, followed by stations at Cathedral Peak in 1945, and Mokubulaan in 1955. (van der Zel, 1987) Additional research stations were set up at Westfalia in 1975 and at the Witklip State Forest in 1980.

For the purposes of this study experimental sites were selected where good quality data were available for both control and treated catchments, to enable comparative analyses. This limited the potential catchments to Cathedral Peak (catchment IV = control, catchment II = treated), Westfalia (catchment B = control, catchment D = treated) and Jonkershoek (Langrivier = control, Lambrechtsbos A & B = treated). While the Mokobulaan paired catchments provide interesting data, the quality of the data is uncertain since it appears that the catchments may “leak” substantially due to the natural geology. This catchment has therefore not been considered.

The location of these catchments (together with other catchment experiment sites) is shown in Figure 1 below (after Gush et al, 2002, citing Low & Rebelo, 1996.) The location of the catchments within the natural biomes of South Africa is indicated. The hydrological properties of the catchments is summarized in Table 1, Appendix 1.

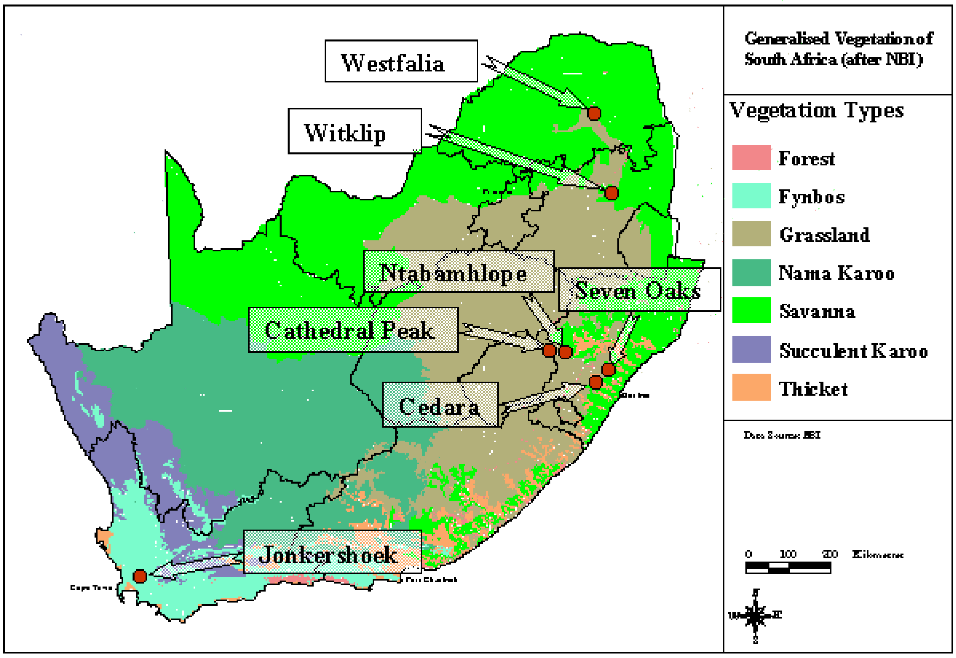


Figure 1 Map of South Africa illustrating the generalised vegetation types / biomes for the country (after Low and Rebelo, 1996).

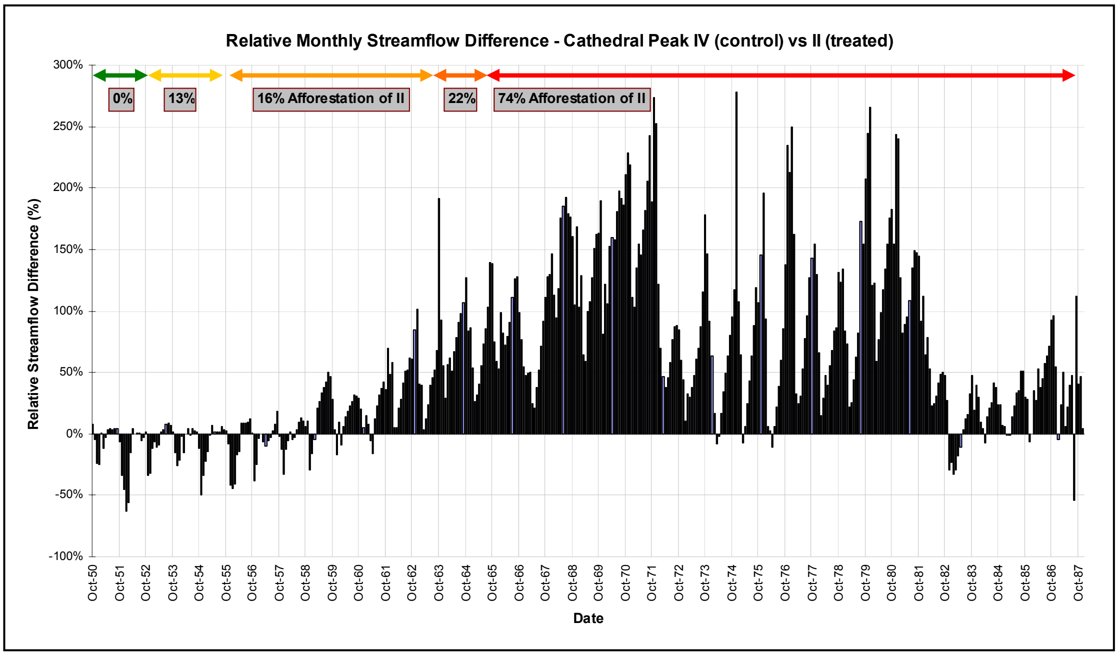


Figure 1 (a) - Relative (%) differences in monthly streamflow between Cathedral Peak catchments (IV (control) and II (treated)), between 1950 and 1987. The progressive afforestation treatments applied to catchment II are annotated on the figure

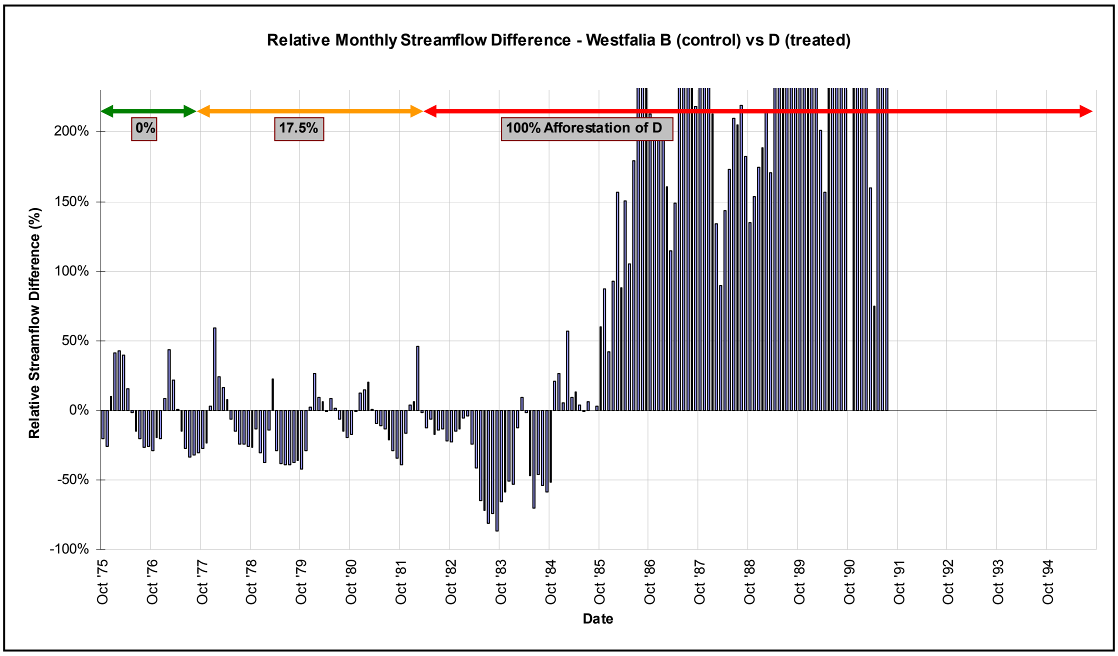


Figure 1 (b) - Relative (%) differences in monthly streamflow between Westfalia catchments (B (control) and D (treated)), between 1975 and 1994. The progressive afforestation treatments applied to catchment D are annotated on the figure.

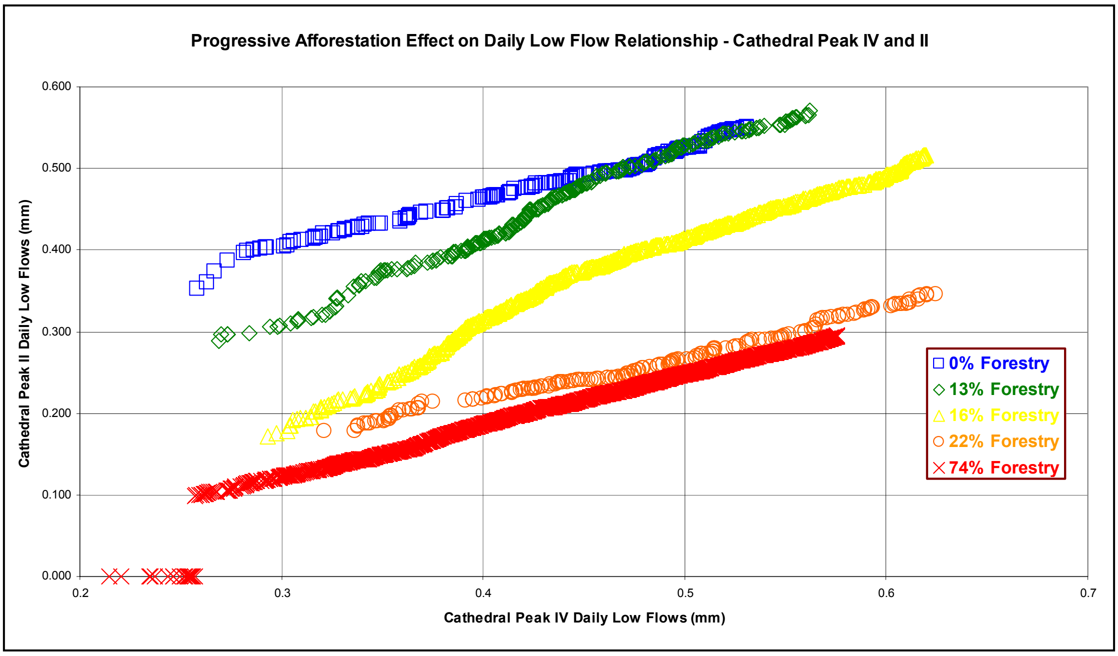


Figure 2 (a) - Effect on the low flow relationship between Cathedral Peak catchments IV (control) and II (treated), caused by the progressive introduction of forestry to catchment II

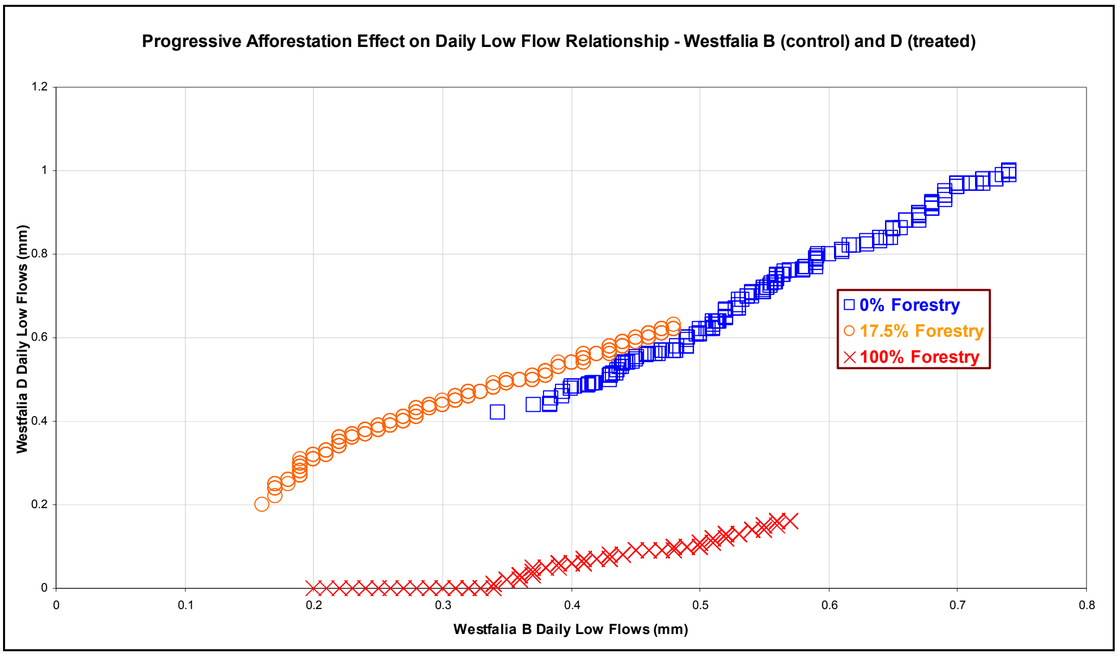
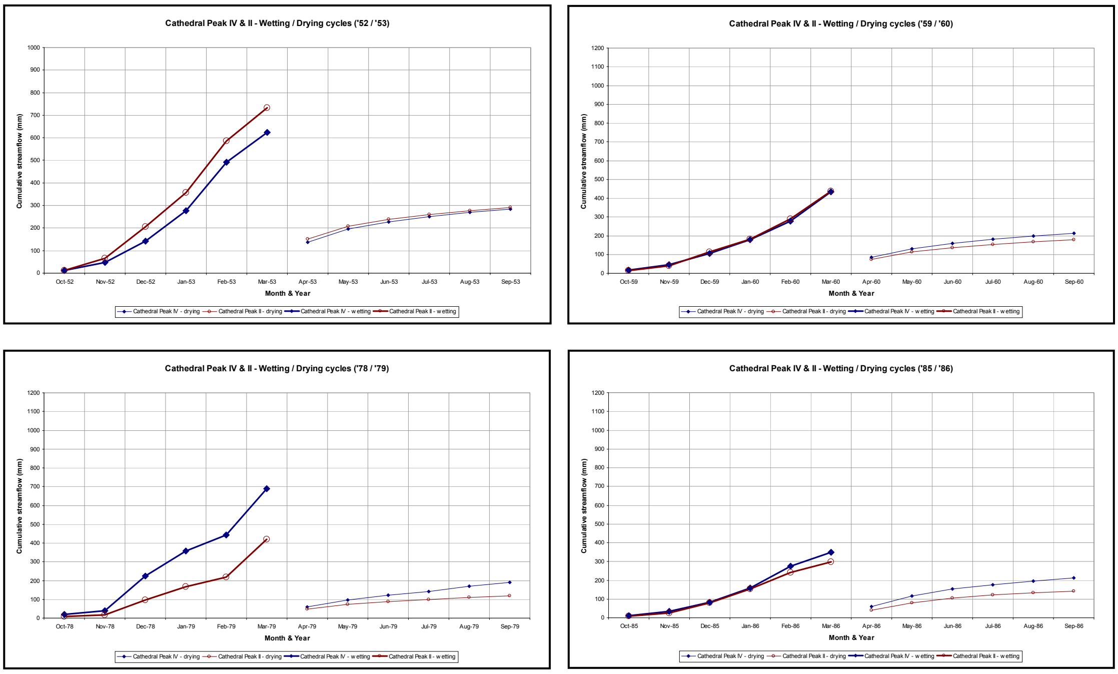


Figure 2 (b) - Effect on the low flow relationship between Westfalia catchments B (control) and D (treated), caused by the progressive introduction of forestry to catchment D.

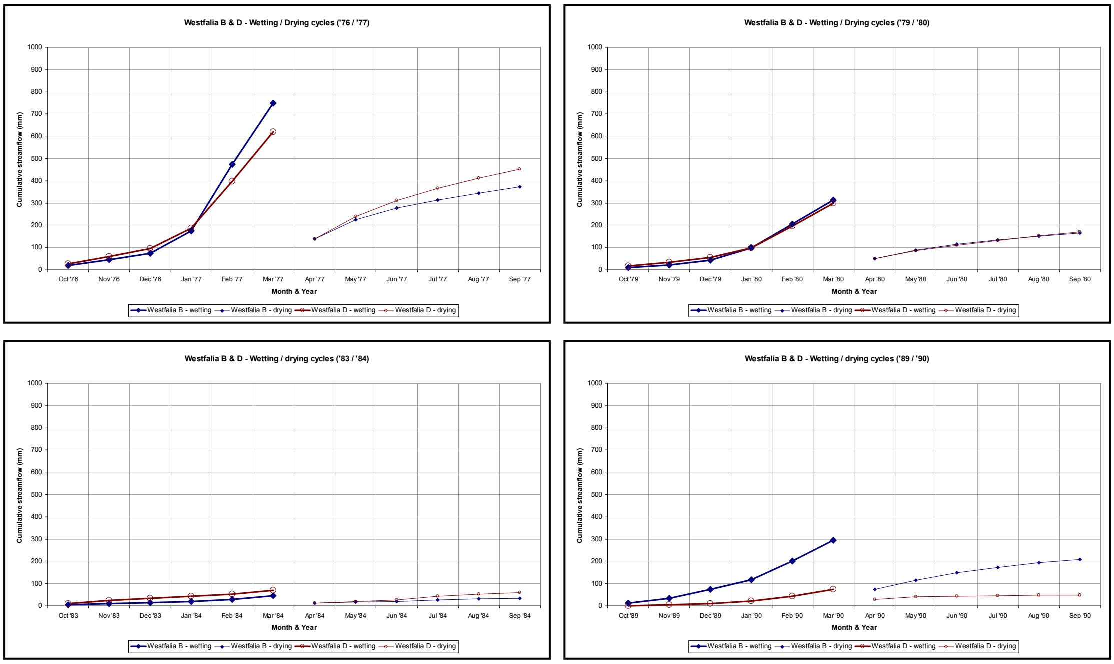

Cathedral Peak IV & II - Wetting / Drying cycles ('52 / '53)

Cathedral Peak IV & II - Wetting / Drying cycles ('59 / '60)

Cathedral Peak IV & II - Wetting / Drying cycles ('78 / '79)

Cathedral Peak IV & II - Wetting / Drying cycles ('85 / '86)

Figure 3(a) - Differences in wetting-up (October to February) and drying out (March to September) cycles between Cathedral Peak catchments (IV (control) and II (treated)), for the 1952/1953, 1959/1960, 1978/1979 and 1985/1986 hydrological years.


Westfalia B & D - Wetting / Drying cycles ('76 / '77)

Westfalia B & D - Wetting / Drying cycles ('79 / '80)

Westfalia B & D - Wetting / drying cycles ('83 / '84)

Westfalia B & D - Wetting / drying cycles ('89 / '90)

Figure 3(b) - Differences in wetting-up (October to February) and drying out (March to September) cycles between Westfalia catchments (B (control) and D (treated)), for the 1976/1977, 1979/1980, 1983/1984 and 1989/1990 hydrological years.

7 Discussion & Conclusions

The trend analyses presented above are useful in highlighting the behaviour of the catchments under different land-uses. The regression relationships may possibly be used to extend the results to similar catchments . The analysis does not essentially provide greater predictive power than any of the prior studies cited above. The review above suggests that perhaps the greatest chance of improvement in predictive power lies in refinement of mechanistic models, in particular, refinements of those aspects which are important in controlling low flows. While modelers often display an intuitive sense of the most sensitive mechanisms incorporated in a model, and comprehensive analysis of sensitivity/uncertainty, may help identify the modelling aspects (or parts of the modeled hydrological cycle) which can most profitably be improved upon.

There is however, not data extant on the rest of the hydrological cycle, for these pairs of catchments. Monitoring these respective parts (ie. evapotranspiration, drainage, and soilmoisture) may prove useful in analyzing the historical record. Separation of the hydrograph into baseflow, interflow, and quickflow may also shed additional light on the historical record.

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Table 1: Hydrological properties of selected experimental catchments

Features & Land cover History	**Cathedral Peak IV (Control)**	**Cathedral Peak II (Treated)**	**Westfalia B (Control)**	**Westfalia D (Treated)**
Mean Annual Precipitation (mm)	1660	1670	1390	1390
Area (ha)	99	195	33	40
Mean Elevation (m)	2000	2000	1250	1150
Pedology	Basalt overlying sandstone		Granite gneiss	
Depth of A horizon (m)	0.2		0.3	
Depth of B horizon (m)	0.6		0.8	
1950	Grassland	Grassland		
1951				
1952				
1953				
1954				
1955		13% pine		
1956				
1957				
1958				
1959				
1960				
1961				
1962				
1963		16% pine		
1964				
1965		22% pine		
1966		74% pine		
1967				
1968				
1969				
1970				
1971				
1972				
1973				
1974				
1975				
1976			Indigenous Forest	Indigenous
1977				18% eucalypt
1978				
1979				
1980				
1981		Clear Felled		10% cleared
1982				82% cleared
1983				92% eucalypt
1984				
1985		Rehabilitated Grassland		
1986				
1987				
1988				
1989				
1990				
1991				
1992				
1993				
1994				
1995				10% cleared
1996				
1997				
1998				